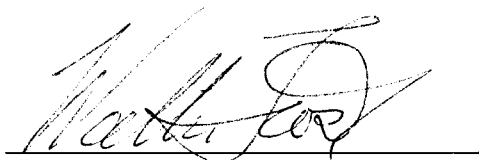


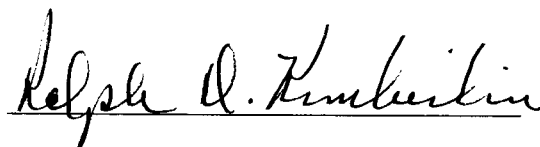
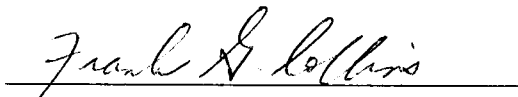
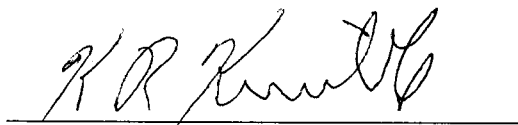
To the Graduate Council:

I am submitting herewith a dissertation written by Charles K. Hill entitled "Feasibility of Measuring Prelaunch Wind Profiles in Support of STS Operations with an Instrumented Aircraft". I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Engineering Science.



Walter Frost, Major Professor

We have read this dissertation and recommend its acceptance:



Accepted for the Council:



Vice Provost and Dean
of the Graduate School

FEASIBILITY OF MEASURING PRELAUNCH WIND PROFILES
IN SUPPORT OF
STS OPERATIONS WITH AN INSTRUMENTED AIRCRAFT

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Charles K. Hill

May 1990

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ABSTRACT

A feasibility study of using an instrumented aircraft to measure prelaunch wind profiles for the Space Transportation System (STS) operations is reported. A NASA F-104 aircraft was instrumented with airspeed sensors, and an INS system to measure the inertial vector. The aircraft was also tracked with a FPS-16 radar to provide a second ground speed measurement. The algorithms for extracting wind speeds from the measured data were developed. Four experimental flights were carried out at NASA Dryden Flight Research Facility to an altitude of 40,000 ft. In turn Jimsphere measurements, which are routinely used for STS launch wind profiles, were carried out at enveloping times and positions. Comparison of the aircraft measured wind speeds with those of the Jimsphere were made. Ninety-two percent of the data fell within the established statistical goodness of fit criteria. It is concluded that an instrumented aircraft can measure statistically equivalent winds to those of the Jimsphere up to altitudes of 40,000 ft. Experiments are continuing to measure winds at higher altitudes where flight speeds are supersonic.

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1.0 INTRODUCTION

The results of a study to determine the feasibility of using an instrumented aircraft to measure day of launch wind profiles for predictions of Space Shuttle trajectory and loads for go/no-go launch decisions are reported in this dissertation. Shuttle prelaunch wind profiles are presently measured with slow rising Jimsphere balloons tracked by an FPS-16 radar. In the past, the balloons have been released some 3.5 hours before launch. On a day of strong winds the balloon can drift as much as 50 miles from the shuttle launch path. If these measurements were augmented with a more rapid profiling technique used closer to the scheduled launch time and launch path, it would be possible to reduce the safety margins added to calculated wind loads and to decrease the risk of launching under adverse wind conditions.

A Shuttle Launch Aircraft Wind Profile Measurement Experiment was carried out to demonstrate the capability of an aircraft to perform these measurements in a timely manner. An F-104 aircraft was instrumented with air data and inertial systems to perform the necessary measurements and with telemetry equipment to transfer the data to the ground for post flight analysis. Wind profiles measured during flight experiments at the NASA Dryden Flight Research Facility (DFRF) were compared to quasi-simultaneous Jimsphere measured profiles in the same area. The goal of the program is to develop a system capable of measuring day of launch winds as quickly as possible up to an altitude of 18 km (60,000 feet). The accuracy of these measurements must be equivalent to that of the Jimsphere wind measurement

system.

The approach used to demonstrate that winds equivalent to those measured by a Jimsphere can be obtained with the instrumented F-104 aircraft is reported in this study. The Jimsphere was taken to represent the wind measurement standard and the aircraft measurements were compared with it. Note, there is no national standard for wind measurements. The Jimsphere system and a discussion of its reported accuracy is provided in Section 2.0. The principal of measuring wind from an instrumented aircraft, the instrumentation utilized, the governing equations for data reduction, and the measurement procedures are described in Section 3.0. These were carefully analyzed for sources of error as also described in Section 3.0. In comparing winds measured with a balloon versus those measured with an aircraft it is not possible to measure winds precisely at the same time nor the same location. Therefore, in order to make meaningful comparisons, statistical analysis must be carried out. Section 4.0 describes a number of flight experiments carried out at the NASA/DFRF and defines the method of comparing wind profiles measured by Jimsphere and aircraft at quasi-equivalent times and positions. The criteria used to determine equivalency of wind speeds is discussed. The results of the several comparison tests are then presented. Finally, it is concluded in Section 5.0 that the instrumented aircraft can indeed measure winds equivalent to, and in some cases better, than those of the Jimsphere.

2.0 JIMSPHERE SYSTEM

2.1 Background

The knowledge of detailed wind profile structure along an aerospace vehicle flight path trajectory prior to launch is a crucial parameter in the success or failure of a particular mission. A system composed of a radar tracking the motion of a balloon which is released into the atmosphere (Jimsphere system) has been developed and deployed in an operational mode to minimize space vehicle failure risk. The Jimsphere alibeit slow is recognized by the Range Command as the standard and was therefore used as the standard for the present investigation.

The Jimsphere (balloon) is tracked with an FPS-16 radar and provides a wind profile measurement from the surface to an altitude of approximately 18 km (60,000 ft) in a period of less than 1 hour. The vertical spatial frequency resolution of the measurement is approximately 1 Hz per 100 m (330 ft). The wind profile is used in vehicle dynamic computations to obtain a simulated flight trajectory and an analysis of the structural loads on the aerospace vehicle during the critical high dynamic pressure phase of the predicted flight. The results of this analysis becomes part of the go/no-go decision criteria.

2.2 Jimsphere Measurement System and Data Reduction

The Jimsphere measurement system consists of a 2 m (6.5 ft) diameter, 0.5 mil mylar (aluminized), constant-volume balloon. The balloon itself weighs approximately 400 gm (0.91 lb_m) and contains 398 conical protrusions, equally distributed

over the surface, each of which is 7.5 cm (3 in.) in base diameter and 8 cm (3.1 in) in height (Figure 2.1). A valve in the balloon maintains in excess of 5 mb (0.07 psi) overpressure resulting in a rise rate of approximately 300 m/min (985 ft/min) with a floating altitude near 18 km (60,000 ft).

The tracking radar is an AN/FPS-16 or equivalent high-precision radar system and provides space position (range, azimuth, and elevation) data each 0.1 s of the Jimsphere balloon flight. The radar tracking accuracy (RMS) is 4.6 m (15 ft) in range and 0.01 deg in angular measurement (azimuth and elevation angle). The scheme as utilized in acquisition of data for prelaunch monitorship of aerospace vehicle launches is illustrated in Figure 2.2.

The sources of errors introduced in the wind measurement result from the digitized radar coordinate data, the smoothing process of data, and the assumption that the balloon velocity equals wind velocity. The roughness elements on the surface of the balloon provide a larger drag which reduces part of the aerodynamically induced motion of the sphere. The Jimsphere still contains a spiral mode of oscillation with a period of approximately 4-5 seconds as revealed by Doppler radar. The smoothing of wind data to 25 m (83 ft) intervals translates to a 5 second period, eliminating the effect of spiral motion. Figure 2.3 shows the RMS error of the Jimsphere/radar system as a function of altitude for different smoothing intervals. Large errors are introduced at 10 m (33 ft) smoothing intervals. At 100 m (330 ft) smoothing intervals, the errors are negligible, however, an insufficient amount of wind detail is provided by the resulting profile. The range of 25 (83 ft) to 37.5 m

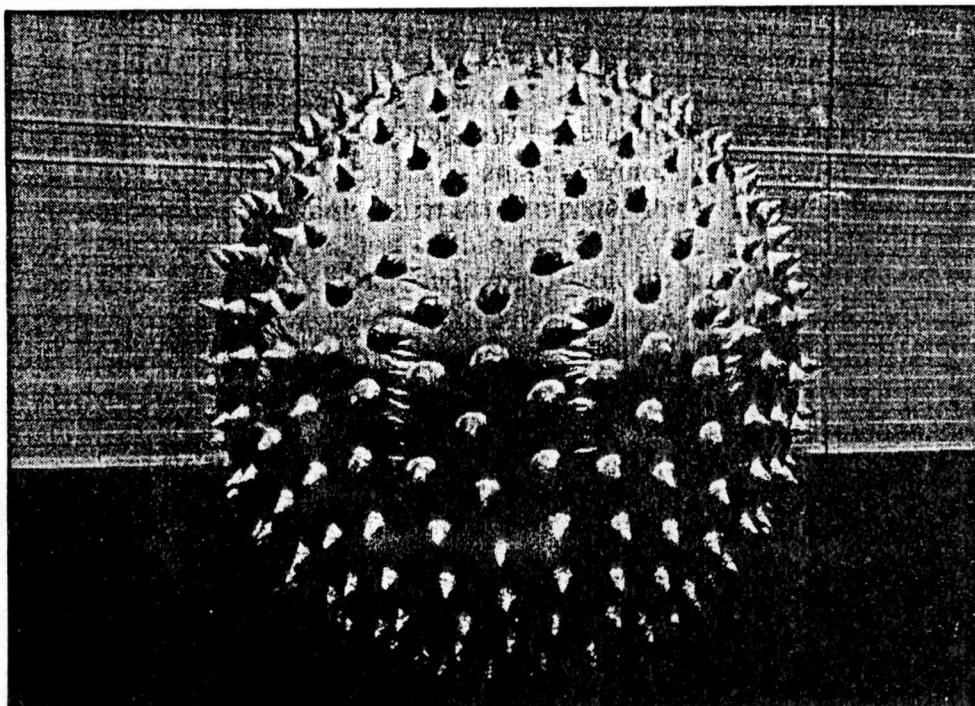


Figure 2.1 The Jimsphere Balloon Configuration.
(Note the conical roughness elements.)

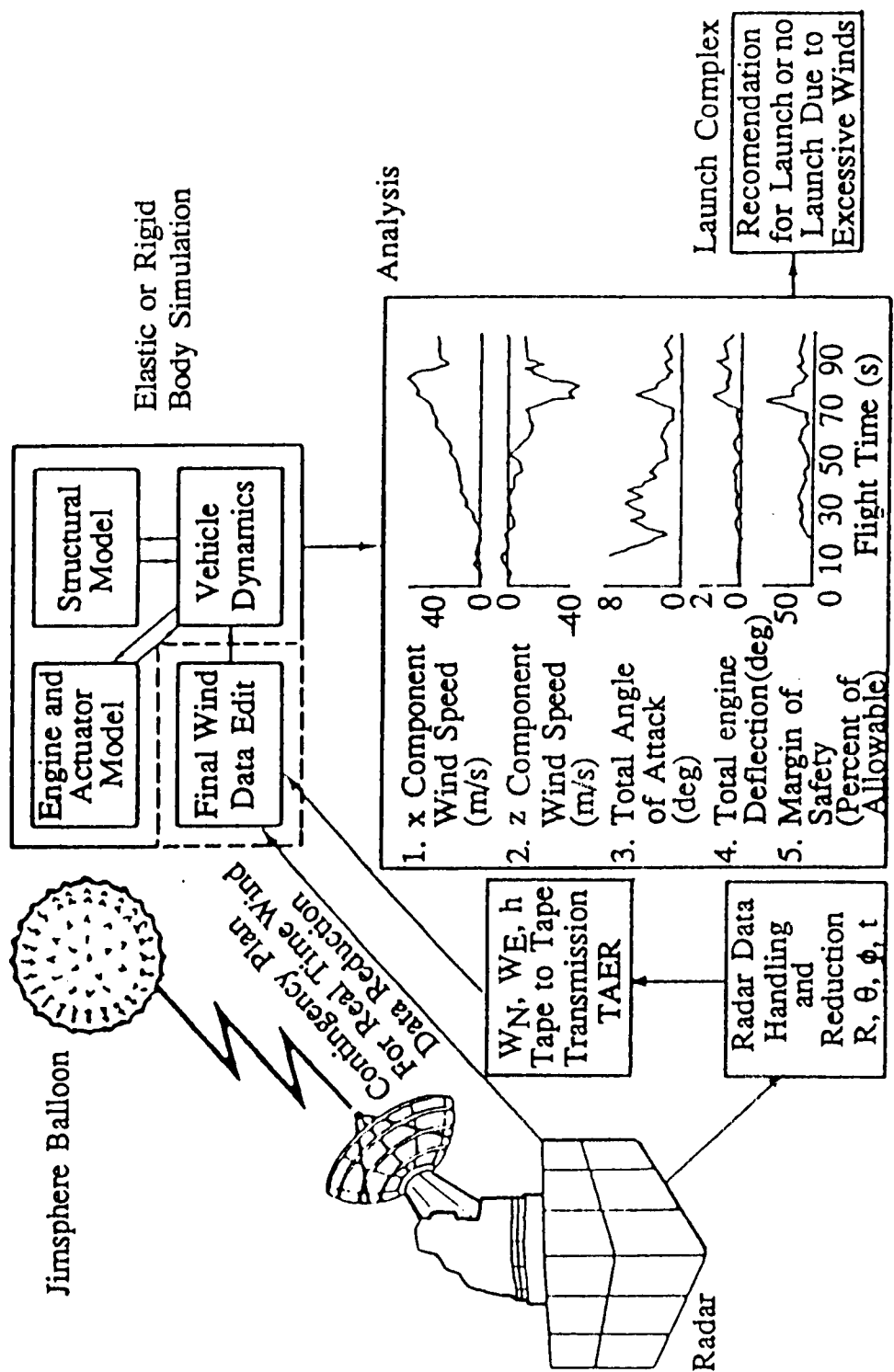


Figure 2.2 Operation of the FPS-16 Radar/Jimsphere System.

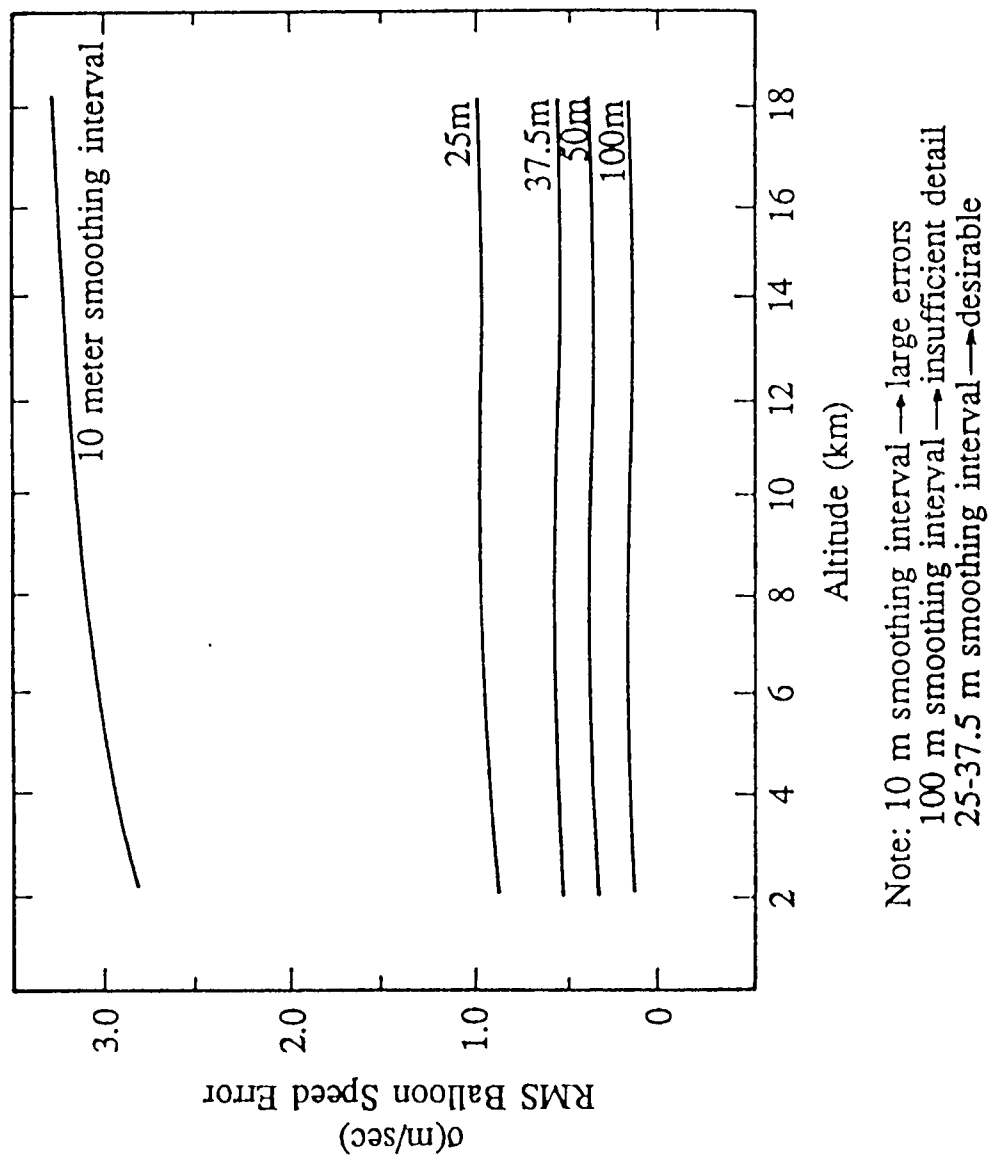


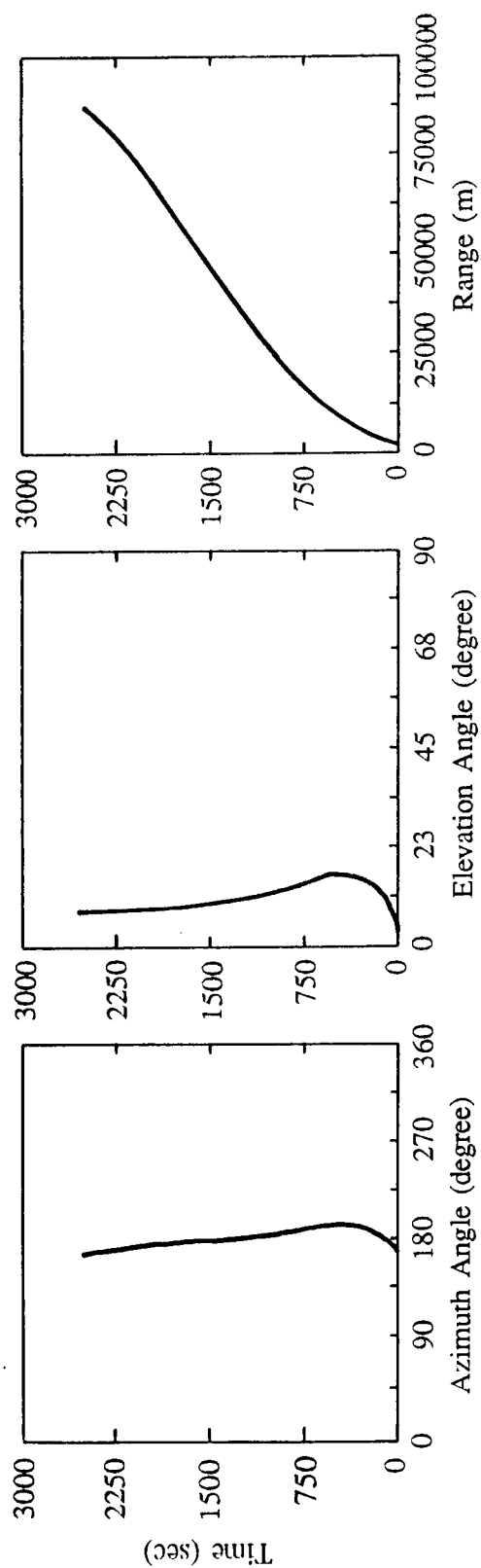
Figure 2.3 The Limitations of Wind Measurement Accuracy for FPS-16/Jimsphere System.

(123 ft) intervals proves to be desirable.

The Jimsphere data reduction program presently used as the standard on the meteorological ranges is called ROSE. It was originated at the University of Dayton Research Institute, Ohio. The radar obtained 10 Hz raw data, TAER, consisting of time and of balloon position in a spherical coordinate system azimuth angle, elevation angle, and range (θ, ϕ, R). Figure 2.4 shows plots of raw Jimsphere data θ, ϕ and R as functions of time for a typical flight. The spherical coordinates are transformed to cartesian coordinates (X,Y,Z) and edited to take out wild points. Wind components, averaged over layers to minimize the wind error, are computed at 25 m (83 ft) intervals. The resulting data are differenced over 50 m intervals to produce wind profile data points. Figure 2.5 provides an error analysis result which illustrates the accuracy of the wind profile data points. A flow chart of the Jimsphere/radar data reduction algorithm is given in Figure 2.6.

The Jimsphere/radar system is routinely used in the prelaunch wind monitoring of NASA's Space Shuttle missions. The accuracy of the wind profile measured by this system is specified as 0.5 m/s (1 kt). This in truth is the accuracy with which two radars can track the same balloon.

Additional details of the Jimsphere radar measurement system, data reduction scheme, system performance, and Jimsphere performance and design are available in a multitude of studies and reports (DeMandel, et al. (1969)).



Zero Time Corresponds to 37931.00 (10:32:11)

Figure 2.4 Jimsphere Raw Data, Flight 1208, 1/19/88 Acquired by NASA/DFRF.

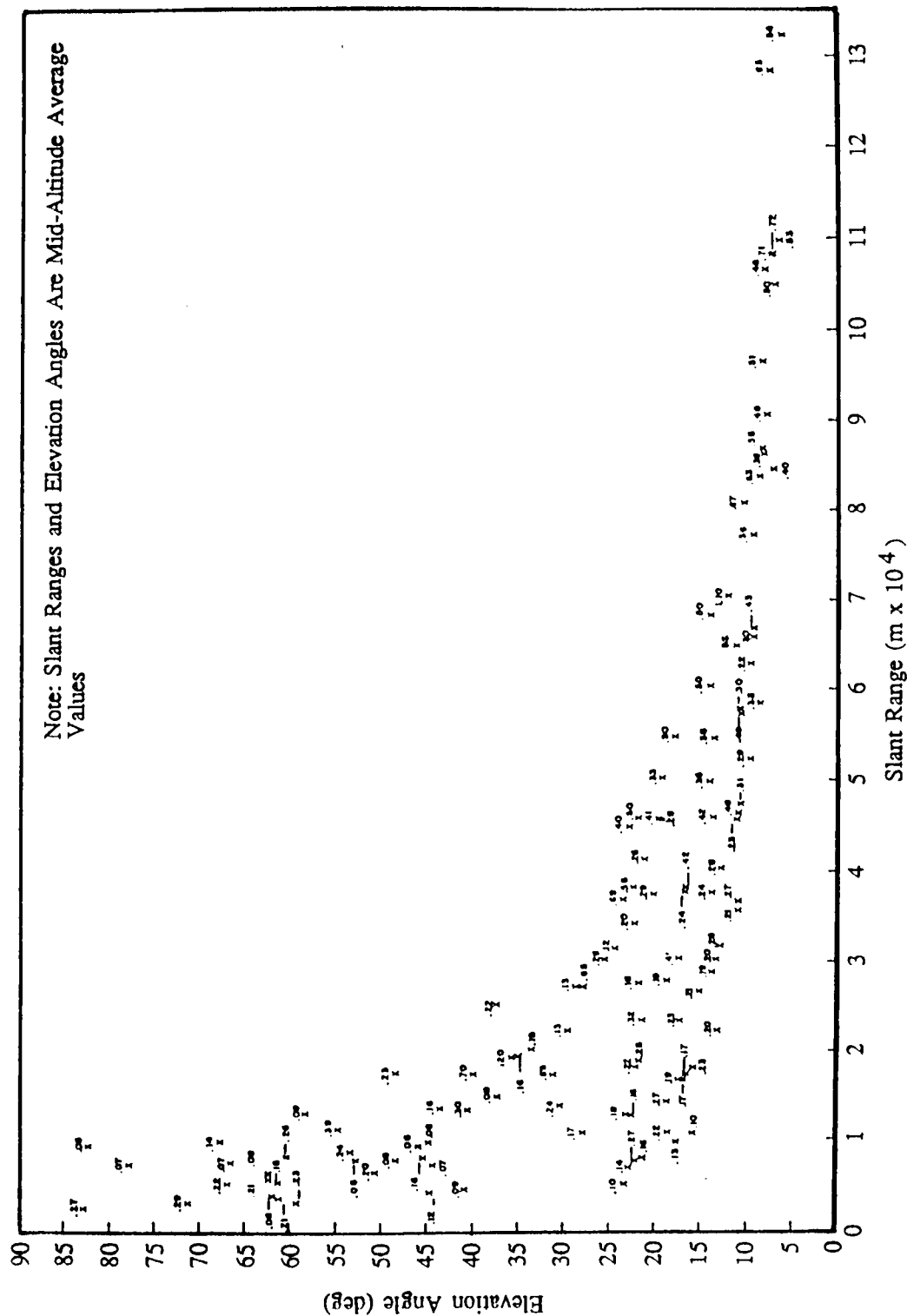


Figure 2.5 RMS Errors of Wind Speed (W) as a Function of Slant (R) versus Elevation Angle (θ) for Dual FPS-16 Radar/Jimsphere Tracking at Cape Canaveral, Florida.

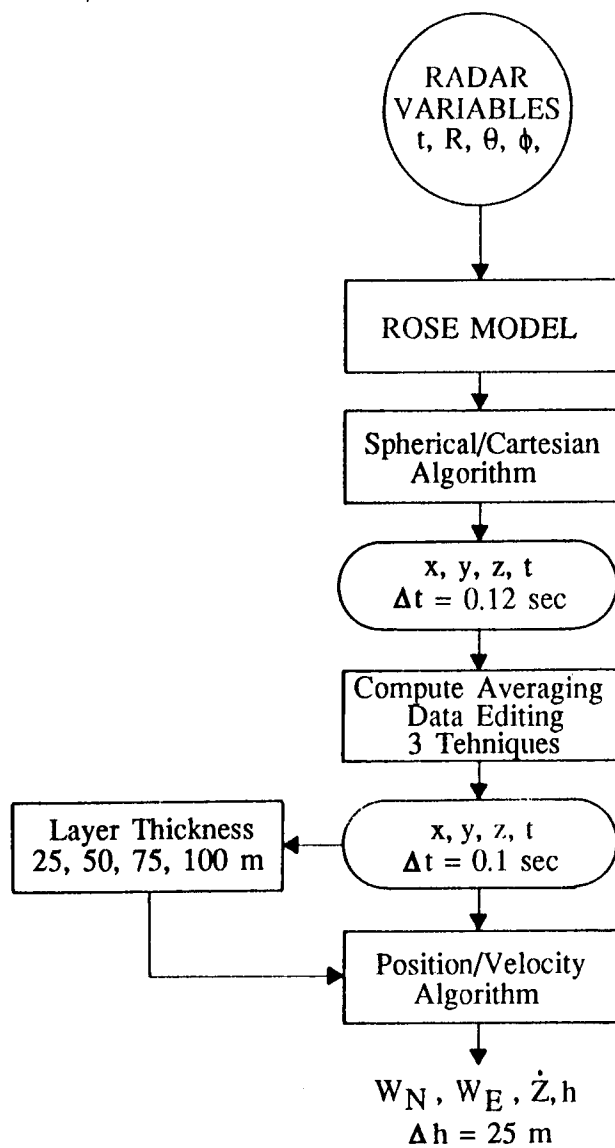


Figure 2.6 Radar Data Flow Chart.

3.0 PRINCIPLE OF MEASURING WINDS WITH AN AIRCRAFT

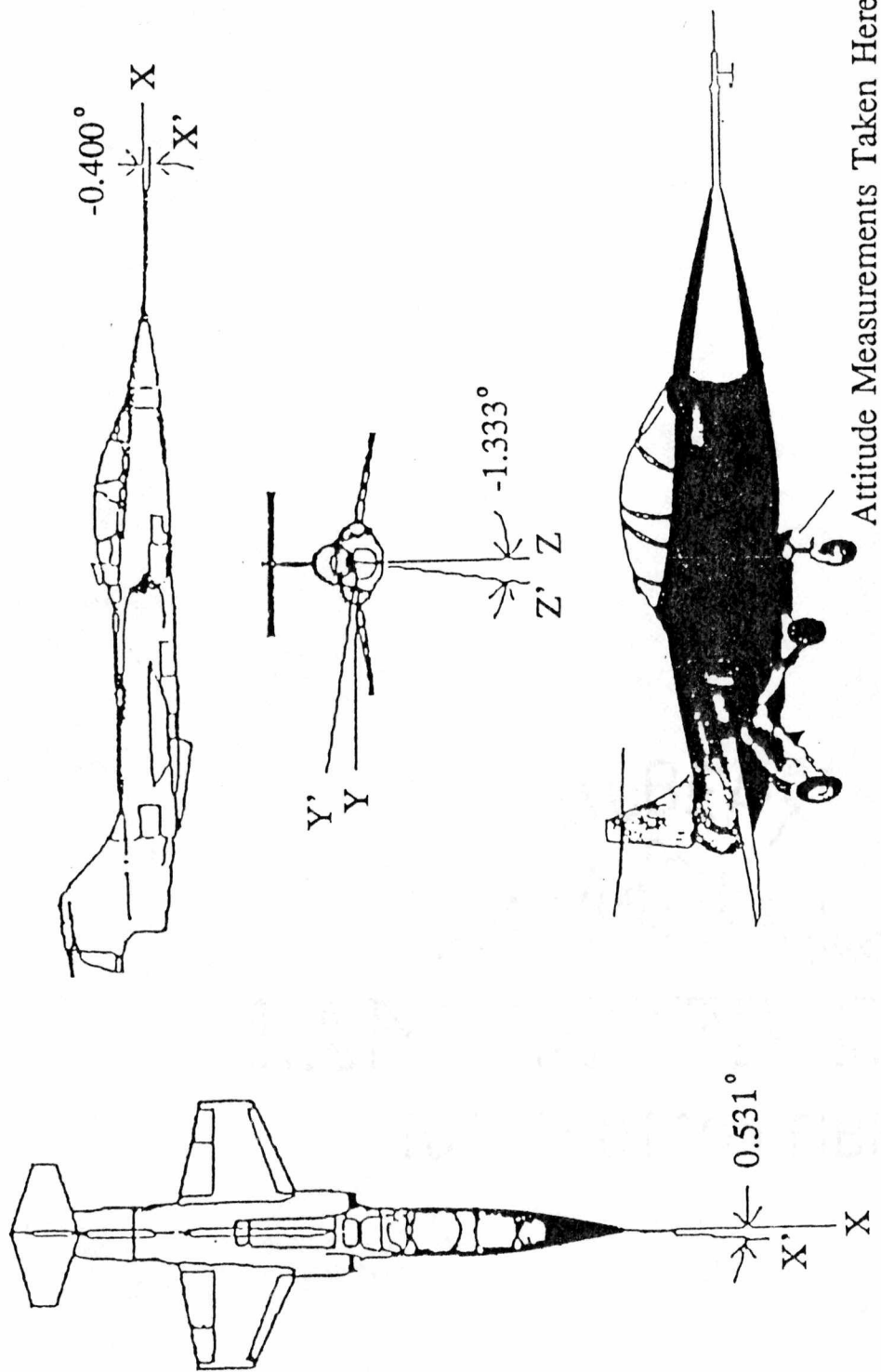
3.1 Aircraft Instrumentation

An F-104 aircraft (Figure 3.1) was instrumented by NASA/DFRC with air data and inertial systems to perform the necessary measurements for computing wind velocity. The velocity of a moving airmass with respect to the earth (i.e., wind) is obtained by vectorially subtracting the velocity of the air with respect to the aircraft (airspeed) from the velocity of the aircraft with respect to the earth (ground speed) i.e.:

$$\vec{W} = \vec{V}_G - \vec{V}_A$$

The components of the airspeed vector are obtained from accurate measurements of temperature, pressure, and airflow angles using sensors mounted on the aircraft. The components of the ground speed vector are obtained from the integrated accelerometer outputs of an inertial navigation system (INS). The instrumentation on the F-104 include the airspeed probes (Pitot tubes) located at the nose section (see Figure 3.1). The flight angles, sideslip, and angle-of-attack, are measured with vane wind direction sensors at the same location. Also, an accelerometer is placed at the center of gravity (c.g.). Inertial velocity components (ground speed), Euler angles, angular rates, acceleration components, and geographical location are provided by a Ring Laser Inertial Navigation System (INS). A brief description of the components of the instrumentation system is given next.

Air Data System: The air data system consists of a NACA type noseboom de-



Attitude Measurements Taken Here

Figure 3.1 Instrumented F-104.

scribed by Richardson and Pearson (1959). The noseboom has total and static pressure ports and angle of attack and angle of sideslip vanes. In addition a total temperature probe is mounted on the chin of the aircraft. The noseboom has two sets of static pressure ports: one of which is used for cockpit display and the other for research data. There are separate pressure transducers for each set of static pressure ports and for the total pressure port. The angle of attack and angle of sideslip vanes were mounted behind the pressure orifices and potentiometers were used to measure the angles.

Accelerometers and Rate Gyros: A three axis accelerometer package was mounted in the electronics bay. Pitch and roll rate gyros were also mounted in the electronics bay. All these measurements except for normal acceleration were used as backups for the experiment. Normal acceleration was used to correct angle of attack for boom bending.

INS: To obtain ground speeds and angles as well as Euler angles and angular rates, a ring laser gyro inertial navigation system (INS) was installed in the nose cone of the aircraft. The unit requires that the starting longitude and latitude be input prior to alignment. In addition, certain air data parameters must be input continuously. These parameters include Mach number, pressure altitude, calibrated and true airspeed, and ambient temperature.

AICS: In order for the INS to interface with the existing aircraft instrumentation system, a custom computer system had to be designed and fabricated. The function of this computer system was twofold: 1) to calculate and provide the required air

data inputs to the INS and 2) to merge the output from the INS on to the PCM data stream. A detailed description of the AICS system can be found in Bever (1984).

3.2 Analysis

Prior to initiating the NASA Shuttle Launch Aircraft Wind Profile Measurement Experiment, the capability and accuracy of instrumented aircraft had to be demonstrated. A major effort of this study was to establish these parameters. Based on previous experience and experimental data obtained from measuring turbulence with an instrumented B-57 NASA research aircraft during the NASA Gust Gradient Program, the following analysis was carried out.

3.2.1. Aircraft Performance

The potential of an aircraft to provide winds as close as possible (spatially and temporally) to the shuttle launch trajectory required investigation. Figure 3.2 is a plot of a typical space shuttle trajectory. Superimposed on this plot are two potential trajectories of a Jimsphere balloon under different wind conditions. Based on the characteristics of aircraft given in Jane's Book of Aircraft (1985) a study of needed performance capability was carried out. The flight path potential of an F-16 and a Lear Jet were compared with the trajectory of the Space Transportation System (STS) and the balloon in Figure 3.2. It is apparent that, in general, the type of aircraft necessary to climb along a trajectory close to that of the space shuttle is a high performance fighter aircraft.

The possibility of descending along the trajectory (see Figure 3.3) was also

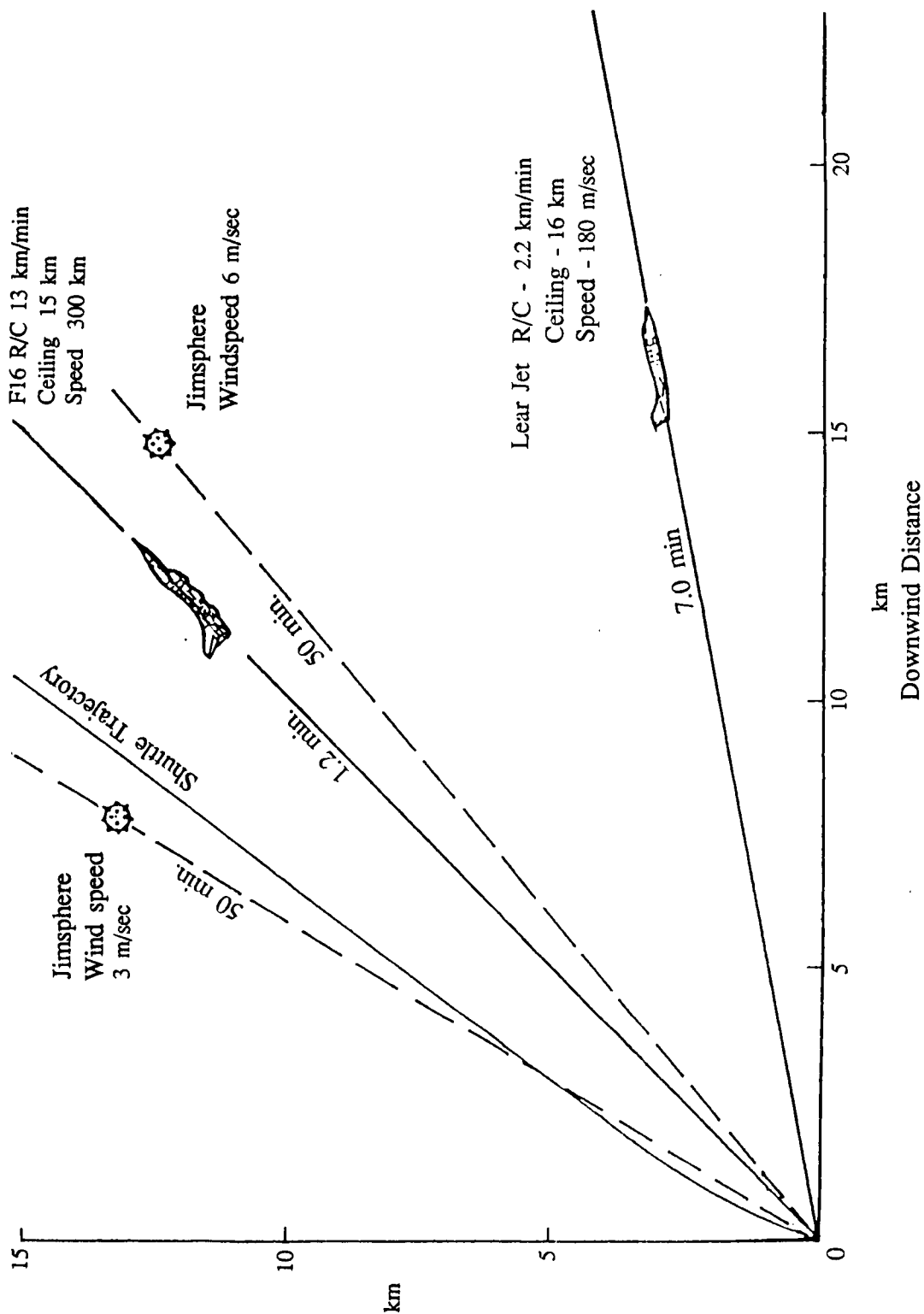


Figure 3.2 Feasible Climb Flight Paths.

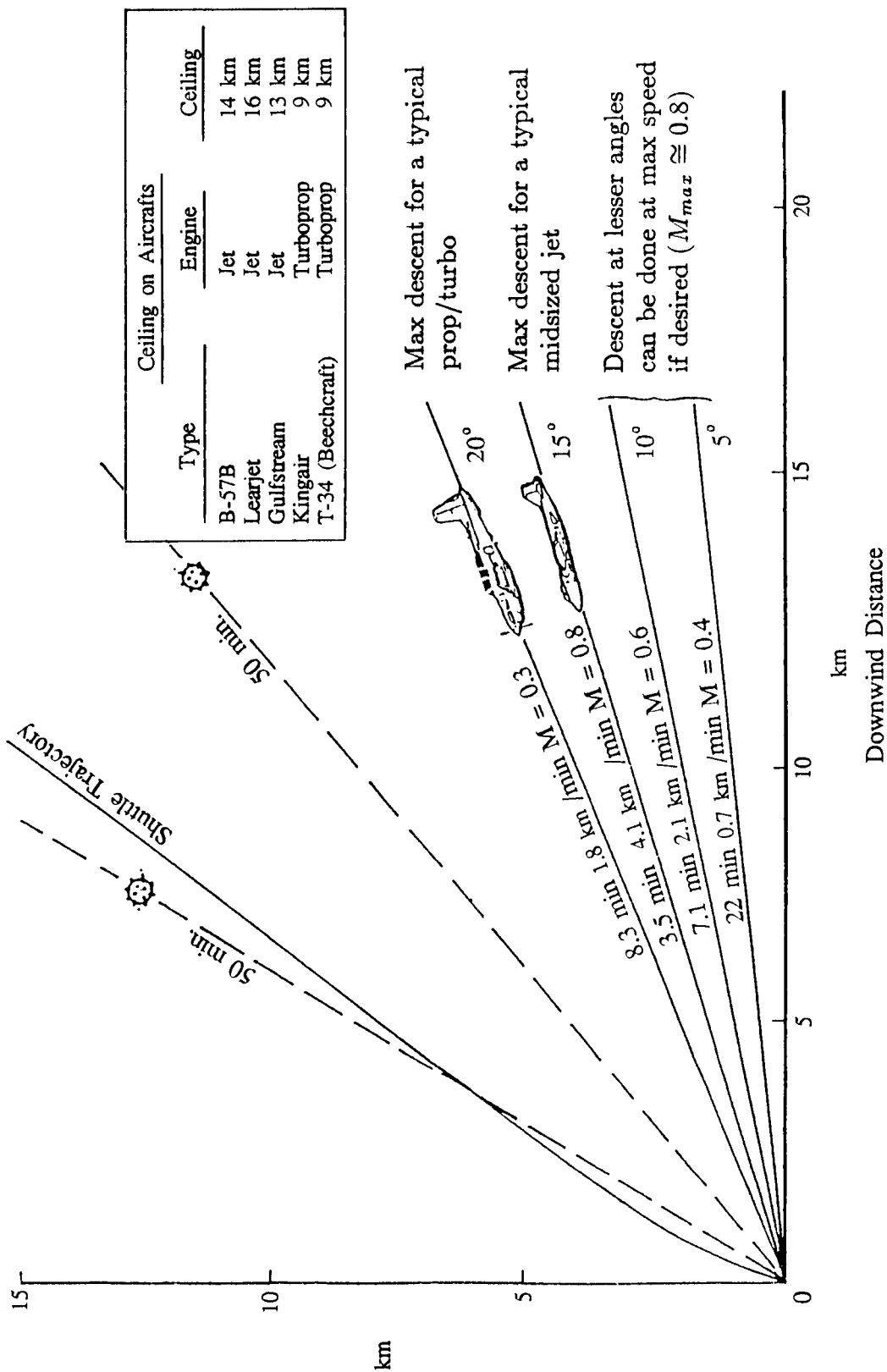


Figure 3.3 Feasible Descent Flight Paths.

investigated. In discussions with NASA Langley personnel who had, in the past, attempted to instrument an aircraft to measure the chemical composition of the Shuttle plume, it was concluded that the best type of aircraft to fly down the trajectory was a T-38. In doing this, however, the aircraft employed its flaps and landing gear to dirty the aerodynamic characteristics in order to avoid supersonic speeds. This was not found to be very satisfactory. Thus it was determined that to either climb or descend along a STS trajectory required a high performance fighter type aircraft.

In the early stages of the program an F-16 was proposed for the experimental program since it, in principal, can climb to 18-21 km (60,000-70,000 ft) altitude in 5 minutes. The F-104, which was eventually selected for the experiment because of its availability, has been found to be able to climb to the 18-21 km (60,000-70,000 ft) within a 10 minute period. The F-104, however, does require a two-step climb. It initially climbs to 12 km (40,000 ft) at subsonic speeds, then levels out, and after horizontal acceleration to supersonic speeds, it climbs the remaining distance to the 18-21 km (60,000-70,000 ft) level. This approach has worked well for the experimental program, but it is not ideal for an operational program because of the hiatus in the wind measurement. Therefore, when an airplane is placed into an operational mode a better performance aircraft than the F-104 is recommended.

3.2.2. Wind Velocity Equations

The velocity of a moving airmass (or the wind) with respect to earth, is obtained by vectorially subtracting aircraft velocity with respect to the airmass from aircraft

velocity with respect to earth. Since airspeed is measured in a body-axis (airplane fixed reference system), it is necessary to rotate the airspeed vector into the inertial (earth fixed) frame of reference. The governing equations are listed below. For a detailed derivation of these equations; see Frost (1981), Crooks et al. (1967), Houbolt et al. (1964), Lenschow (1972), and Axford (1968).

The wind velocity vector components at some position $\vec{r}$ measured from the c.g. of a rigid aircraft are designated W_N, W_E and W_Z . These are measured in the coordinate system with the x axis pointing north, the y axis pointing east, and the vertical axis pointing along the local vertical (gravity vector; positive downward). The coordinate system is called the true north coordinate system and is taken as the inertial system in this analysis (however, see Rhyne, 1976). * The W_N, W_E and W_Z components point north, east, and vertical, respectively, and are given by:

$$\begin{pmatrix} U + W_N \\ V + W_E \\ W + W_Z \end{pmatrix} = \begin{pmatrix} V_N \\ V_E \\ V_Z \end{pmatrix} + \begin{pmatrix} U_R \\ V_R \\ W_R \end{pmatrix} \quad (3-1)$$

The symbols U, V, and W designate the components of the aircraft velocity vector relative to the air mass measured in the true north coordinate system; V_N, V_E , and V_Z are the inertial velocity vector components of the c.g. of the aircraft; and U_R, V_R , and W_R are the rotational velocity components of the position $\vec{r}$ relative

* Grid north is true north at the platform alignment location, but as the platform moves east or west from its initial alignment point, its north-south axis is not torqued to point at true north but remains parallel to a vertical plane through the meridian at which it was aligned. (The north-south and east-west axes are torqued to be perpendicular to the local vertical at all times, however.) For all practical purposes, the inertial-platform axis system can be assumed to be aligned with true north, considering the latitudes of operation and the east-west distances flown.

to the c.g. (or INS) of the aircraft due to rotation of the frame of reference fixed in the airplane, i.e., the body coordinate system.

The velocity of a point $\vec{r} = l_x \vec{i} + l_y \vec{j} + l_z \vec{k}$ measured in the airplane frame of reference (i.e., body coordinates) which is rotating relative to the fixed frame of reference (i.e., inertial frame taken as the true north coordinate system in this study) is given by $\vec{\Omega} \times \vec{r}$, where $\vec{\Omega}$ is the angular velocity of the airplane frame of reference relative to the inertial frame of reference. The velocity components of the position $\vec{r}$ in body coordinates, U'_R, V'_R , and W'_R (rotational velocity) expressed in terms of the Euler angles (Ψ, θ, ϕ) are:

$$\begin{pmatrix} U'_R \\ V'_R \\ W'_R \end{pmatrix} = \begin{pmatrix} l_z(\dot{\theta} \cos \phi + \dot{\Psi} \sin \phi \cos \theta) + l_y(\dot{\theta} \sin \phi - \dot{\Psi} \cos \phi \cos \theta) \\ -[l_z(\dot{\phi} - \dot{\Psi} \sin \theta) + l_x(\dot{\theta} \sin \phi - \dot{\Psi} \cos \phi \cos \theta)] \\ l_y(\dot{\phi} - \dot{\Psi} \sin \theta) - l_x(\dot{\theta} \cos \phi + \dot{\Psi} \sin \phi \cos \theta) \end{pmatrix} \quad (3-2)$$

These rotational velocity components, U'_R, V'_R , and W'_R (in the body coordinate system) are transformed into the velocity components, U_R, V_R , and W_R in the inertial coordinate system by:

$$\begin{pmatrix} U_R \\ V_R \\ W_R \end{pmatrix} = L_{IB} \begin{pmatrix} U'_R \\ V'_R \\ W'_R \end{pmatrix} \quad (3-3)$$

where, the matrix L_{IB} transforms the velocity components in the body coordinate system to the inertial coordinate system. This transform matrix has the following form: roll angle (ϕ), yaw angle (Ψ), and pitch angle (θ).

$$L_{IB} = \begin{pmatrix} \cos \theta \cos \Psi & \sin \phi \sin \theta \cos \Psi & \cos \phi \sin \theta \cos \Psi \\ & -\cos \phi \sin \Psi & +\sin \phi \sin \Psi \\ \cos \theta \sin \Psi & \sin \phi \sin \theta \sin \Psi & \cos \phi \sin \theta \sin \Psi \\ & +\cos \phi \cos \Psi & -\sin \phi \cos \Psi \\ -\sin \theta & \sin \phi \cos \theta & \cos \phi \cos \theta \end{pmatrix} \quad (3-4)$$

The values of U , V , and W in Equation 3-1, which are the true airspeed components in the inertial coordinate system, are not measured directly in the flight experiments. Rather, the true airspeed of the aircraft, $\bar{V}$, is measured in a coordinate system aligned along the relative airspeed vector. The velocity components U' , V' , and W' (i.e., measured in body coordinates) are related to the true airspeed, $\bar{V}$, by the relationship:

$$\begin{pmatrix} U' \\ V' \\ W' \end{pmatrix} = L_{BW} \begin{pmatrix} \bar{V} \\ 0 \\ 0 \end{pmatrix} \quad (3-5)$$

where

$$L_{BW} = \begin{pmatrix} \cos \alpha \cos \beta & -\cos \alpha \sin \beta & -\sin \alpha \\ \sin \beta & \cos \beta & 0 \\ \sin \alpha \cos \beta & -\sin \alpha \sin \beta & \cos \alpha \end{pmatrix} \quad (3-6)$$

and α and β are the angle of attack ($\alpha = \tan^{-1} W'/U'$) and sideslip angle ($\beta = \sin^{-1} V'/\bar{V}$), respectively. L_{BW} transforms the velocity components measured in a frame of reference for which the x axis is located along the relative velocity vector (Etkin (1972)) calls this the "wind" coordinate system) to the body coordinate system.

The above assumes that the pitot tube measures actual magnitude of the relative velocity or true airspeed and not some fractional component. The aircraft velocity components U , V , and W in the inertial coordinate system are:

$$\begin{pmatrix} U \\ V \\ W \end{pmatrix} = L_{IB} \begin{pmatrix} U' \\ V' \\ W' \end{pmatrix} \quad (3-7)$$

Substituting Equations 3-3 and 3-7 into Equation 3-1, the wind velocity measured in the inertial coordinate system is thus given by:

$$\begin{pmatrix} W_N \\ W_E \\ W_Z \end{pmatrix} = \begin{pmatrix} V_N \\ V_E \\ V_Z \end{pmatrix} + L_{IB} \begin{pmatrix} U'_R - U' \\ V'_R - V' \\ W'_R - W' \end{pmatrix} \quad (3-8)$$

In fully expanded form, the nonlinear system of Equations for computing the wind velocity vector components in an inertial frame of reference is:

$$\begin{aligned}
W_N = & -\bar{V}[\cos \alpha \cos \beta \cos \Psi \cos \theta + \sin \beta(-\sin \Psi \cos \phi + \cos \Psi \sin \theta \sin \phi) \\
& + \sin \alpha \cos \beta(\cos \Psi \sin \theta \cos \phi + \sin \Psi \sin \phi)] + V_N \\
& - l_x(\dot{\Psi} \sin \Psi \cos \theta - \dot{\theta} \cos \Psi \sin \theta) \\
& + l_y[\dot{\theta} \sin \phi \cos \theta \cos \Psi + \dot{\phi}(\sin \phi \sin \Psi + \cos \phi \sin \theta \cos \Psi) \\
& - \dot{\Psi}(\cos \phi \cos \Psi + \sin \theta \sin \phi \sin \Psi)] \\
& + l_z[\dot{\theta} \cos \phi \cos \theta \cos \Psi + \dot{\phi}(\cos \phi \sin \Psi - \sin \phi \sin \theta \cos \Psi) \\
& + \dot{\Psi}(\sin \phi \cos \Psi - \sin \theta \cos \theta \sin \Psi)] \\
W_E = & -\bar{V}[\cos \alpha \cos \beta \sin \Psi \cos \theta + \sin \beta(\cos \Psi \cos \phi + \sin \Psi \sin \theta \sin \phi) \\
& + \sin \alpha \cos \beta(\sin \Psi \sin \theta \cos \phi - \cos \Psi \sin \phi)] + V_E \quad (3-9) \\
& - l_x(\dot{\theta} \sin \theta \sin \Psi - \dot{\Psi} \cos \phi \cos \theta) \\
& + l_y[\dot{\theta} \sin \phi \cos \theta \sin \Psi + \dot{\phi}(-\sin \phi \cos \Psi + \cos \phi \sin \theta \sin \Psi) \\
& - \dot{\Psi}(\cos \phi \sin \Psi - \sin \theta \sin \phi \cos \Psi)] \\
& + l_z[\dot{\theta} \cos \phi \cos \theta \sin \Psi - \dot{\phi}(\cos \phi \cos \Psi + \sin \phi \sin \theta \sin \Psi) \\
& + \dot{\Psi}(\sin \phi \sin \Psi + \sin \theta \cos \phi \cos \Psi)] \\
W_Z = & -\bar{V}[-\cos \alpha \cos \beta \sin \theta + \sin \beta \cos \theta \sin \phi + \sin \alpha \cos \beta \cos \theta \cos \phi] \\
& + V_Z + l_x \dot{\theta} \cos \theta - l_y[\dot{\theta} \sin \phi \sin \theta - \dot{\phi} \cos \phi \cos \theta) \\
& - l_z[\dot{\theta} \cos \phi \sin \theta + \dot{\phi} \sin \phi \cos \theta]
\end{aligned}$$

Variables required in computing wind velocity vector components are listed in Table 3-1 in the order of data acquisition channels and l_x, l_y, l_z are distances in meters from the INS measuring element to the probe measuring station along the three body axes, respectively.

For straight and level flight without large perturbations, small angle assumptions are made for the roll, pitch, and yaw angles, and for the angle of attack and sideslip angle. Furthermore, it is assumed that the product of sines of any of the small angles mentioned above vanishes and the cosines of small angles are unity. Based on the small angle, level flight assumptions, the following expressions are

used for computing wind velocity components from the measured parameters:

$$W_N = V_N - \bar{V} \cos(\Psi + \beta)$$

$$W_E = V_E - \bar{V} \sin(\Psi + \beta) \quad (3-10)$$

$$W_Z = V_Z - \bar{V} \sin(\theta + \alpha)$$

Note a positive wind is defined as a wind blowing towards the east, W_E , and north, W_N , which in meteorology is referred to as west and south winds, respectively.

TABLE 3-1 VARIABLES REQUIRED FOR WIND COMPUTATIONS.

CHANNEL	SYMBOL	DESCRIPTION
1	t	time (sec)
2	α	angle of attack (rad)
3	β	sideslip angle (rad)
4	ϕ	roll angle (rad)
5	θ	pitch angle (rad)
6	Ψ	heading angle (rad)
7	$\dot{\phi}$	roll rate (rad/sec)
8	$\dot{\theta}$	pitch rate (rad/sec)
9	$\dot{\Psi}$	yaw rate (rad/sec)
10	P	static pressure (Kpa)
11	T	temperature (Kelvin)
12	LAT	latitude (deg)
13	LONG	longitude (deg)
14	V_N	north-south airplane inertial velocity (m/sec)
15	V_E	east-west airplane inertial velocity (m/sec)
16	V_Z	vertical airplane inertial velocity (m/sec)
17	$\bar{V}$	true airspeed (m/sec)

3.2.3. Accuracy and Sources of Error

During extensive research by Chang and Frost (1985), Frost et al. (1985a), Ringnes and Frost (1985), using data gathered with the Cambera B-57 aircraft, various uncertainties in the measured wind velocities and turbulence measurements were observed. These uncertainties were traced to instrumentation characteristics. Instrumentation errors influence the quantities appearing on the right-hand side

of Equations 3-9 and 3-10 and thus the accuracy of the computed wind velocities. Instrumentation errors in the INS ground speed components, the airspeed, and the sideslip angle have been identified and studied. Errors in the yaw rate are negligible, and the yaw angle is believed to be accurate. Of these sources of instrumentation errors, the most difficult to correct is the dynamic error in the velocity inherent in the INS, termed the Schuler error which has a natural oscillation period but to which aircraft maneuvers contribute and confound the problem. All other errors can be removed by careful calibration. The effects on the magnitude of the measured wind and also turbulence calculations due to the sources of error in the instrumentation are presented next.

Error Analysis: The reported accuracy of the wind measurement required for loads analysis by NASA is based on the Jimsphere's reported 0.5 m/s. The 0.5 m/s accuracy documented for the Jimsphere is the RMS accuracy with which two radars can track the same balloon. Establishing 0.5 m/s as the specified accuracy for the aircraft measured wind components, the required RMS accuracy of the recorded variables can be estimated. The nonlinear equations for reducing the wind speed components are very complicated. Therefore, to approximately evaluate the required RMS accuracy of the aircraft measured variables, the linearized equations are used. The linearized equations for the wind speed components are functions of:

$$\begin{aligned}
 W_N &= f_1(V_N, V, \Psi, \beta) \\
 W_E &= f_2(V_E, V, \Psi, \beta) \\
 W_Z &= f_3(V_Z, V, \theta, \alpha)
 \end{aligned}
 \tag{3-11}$$

The standard propagation of error equations for the wind components are:

$$\begin{aligned}
\sigma_{W_N}^2 &= \left(\frac{\partial W_N}{\partial V_N} \right)^2 \sigma_{V_N}^2 + \left(\frac{\partial W_N}{\partial V} \right)^2 \sigma_V^2 + \left(\frac{\partial W_N}{\partial \Psi} \right)^2 \sigma_\Psi^2 + \left(\frac{\partial W_N}{\partial \beta} \right)^2 \sigma_\beta^2 \\
\sigma_{W_E}^2 &= \left(\frac{\partial W_E}{\partial V_E} \right)^2 \sigma_{V_E}^2 + \left(\frac{\partial W_E}{\partial V} \right)^2 \sigma_V^2 + \left(\frac{\partial W_E}{\partial \Psi} \right)^2 \sigma_\Psi^2 + \left(\frac{\partial W_E}{\partial \beta} \right)^2 \sigma_\beta^2 \quad (3-12) \\
\sigma_{W_V}^2 &= \left(\frac{\partial W_V}{\partial V_V} \right)^2 \sigma_{V_V}^2 + \left(\frac{\partial W_V}{\partial V} \right)^2 \sigma_V^2 + \left(\frac{\partial W_V}{\partial \theta} \right)^2 \sigma_\theta^2 + \left(\frac{\partial W_V}{\partial \alpha} \right)^2 \sigma_\alpha^2
\end{aligned}$$

The estimated accuracy of the key parameters measured by the Litton LTN-90 Inertial Navigation System used in the Gust Gradient program are shown in Table 3-2. Inspection of the error Equations 3-12 shows that the deviation of each wind speed component is from four independent terms. Assuming that these four terms contribute evenly to the total error. The achievable accuracy for the wind speed components is:

$$\begin{aligned}
\sigma_{W_N}^2 &= \sigma_{V_N}^2 + [\cos(\Psi + \beta)]^2 \sigma_V^2 + [V \sin(\Psi + \beta)]^2 \sigma_\Psi^2 + [V \sin(\Psi + \beta)]^2 \sigma_\beta^2 \\
\sigma_{W_N} &= 4.5 \text{ m/s} \\
\sigma_{W_E}^2 &= \sigma_{V_E}^2 + [\sin(\Psi + \beta)]^2 \sigma_V^2 + [V \cos(\Psi + \beta)]^2 \sigma_\Psi^2 + [V \cos(\Psi + \beta)]^2 \sigma_\beta^2 \\
\sigma_{W_E} &= 4.68 \text{ m/s} \\
\sigma_{W_V}^2 &= \sigma_{V_V}^2 + [\sin(\theta - \alpha)]^2 \sigma_V^2 + [V \cos(\theta - \alpha)]^2 \sigma_\theta^2 + [-V \cos(\theta - \alpha)]^2 \sigma_\alpha^2 \\
\sigma_{W_V} &= 4.04 \text{ m/s} \quad (3-13)
\end{aligned}$$

TABLE 3-2 ESTIMATED ACCURACY OF LTN-90 INERTIAL NAVIGATION SYSTEM FOR THE KEY MEASURED PARAMETERS.

Parameters	Order of Magnitude	Estimate of Accuracy
V	200 m/s	± 2 m/s
V _N , V _E , V _V	200 m/s	± 4 m/s
α, β	0.175 rad.	± 0.00857 rad.
θ, Ψ	0.175 rad.	± 0.00875 rad.

The dominant contribution to the error in the accuracy of the aircraft measured wind speed components is the inertial velocity measurement. The error is largely due to the Schuler oscillation effects of the INS readings. Significant improvements are possible by radar tracking or modifications of the INS to update inertial velocity in real time. This is clearly demonstrated as reported later in this study. The effects on the magnitude of the measured wind due to the sources of error in the instrumentation are presented next.

Inertial Velocity and Position Errors: The accuracy of the calculations of horizontal winds depends upon the performance of the INS and its capability to provide correct measurements of the inertial (ground) speed of the aircraft. In recent years mechanical and electronic advances have greatly improved INS accuracy. However, a cumulative oscillation in the INS stable platform element called the Schuler drift, first pointed out in the famous paper by Schuler (1923), can be quite significant. Inertial navigation theory including derivation of the Schuler pendulum effects is explained in many textbooks (see for example, Boxmeyer (1964)). The Schuler error is essentially periodic with a period near that of an earth radius pendulum, 84.4 minutes. The error behaves sinusoidally and will thus change polarity. The error caused by a slow oscillation of the INS stable platform causes the two horizontal accelerometers to detect a part of the gravity vector. This false indication of acceleration is carried through the integration for velocity and produces errors in the W_E and W_N values. Distance traveled or geographical position is obtained from a second integration of the measured accelerations. Thus the Schuler oscillations will cumulate errors in velocity and position. The following procedures were used to estimate the velocity errors associated with Schuler drift.

Position error can be computed from aircraft data during overflight of landmarks where exact geographical locations are known. Since acceleration, velocity,

and position errors are all interrelated the Schuler error can experimentally be investigated by obtaining data on either one of the three parameters having a Schuler oscillation induced error. The velocity error is generally small but increases with time, e.g., after several hours of operation it can be on the order of 3 to 5 m/s (6-10 kts) (Rhyne (1980), Lenschow (1983)). The magnitude of the position errors for a typical INS used in B-747 aircraft reported by Weber (1975) normally are on the order of 10 nautical miles or less even after transatlantic flights. These errors are not critical for pure navigation purposes, but when the objective is to calculate wind velocity to a high accuracy, the Schuler error can be quite important.

A NASA program has been carried out to determine time histories and various statistical characteristics of three components of gust velocity measured simultaneously at the wing tips and at the nose of a specially instrumented Cambera B-57 airplane. Several flights were conducted including Flights 60, 61, 63, and 66 where measurements of turbulent fluxes of momentum, heat, and moisture relative to orographic features were made. Results are presented in Chang and Frost (1985), Theon (1986), and Frost et al. (1985b). In an attempt to model inflight Schuler error, data from Flight 63 have been analyzed. A box pattern flight plan as shown in Figure 3.4 was flown sequentially at 305 m (1000 ft) levels over Boulder, Colorado in February 1984. Each time the B-57 flew the leg heading east, an event marker was activated to record the moment a north-south running road lined up perpendicular to the flight path. INS recorded longitude and latitude at the time of the event marker is compared with the known longitude and latitude of the road in Figure 3.5 to construct the Schuler position errors. In both cases, the error appears to have a sinusoidal behavior. Curve fits by simple trial and error techniques are also plotted on the two figures. The curve fits suggest the latitude error has a 77-minute period of oscillation, and the longitude has an 111-minute period. The latitudinal period is

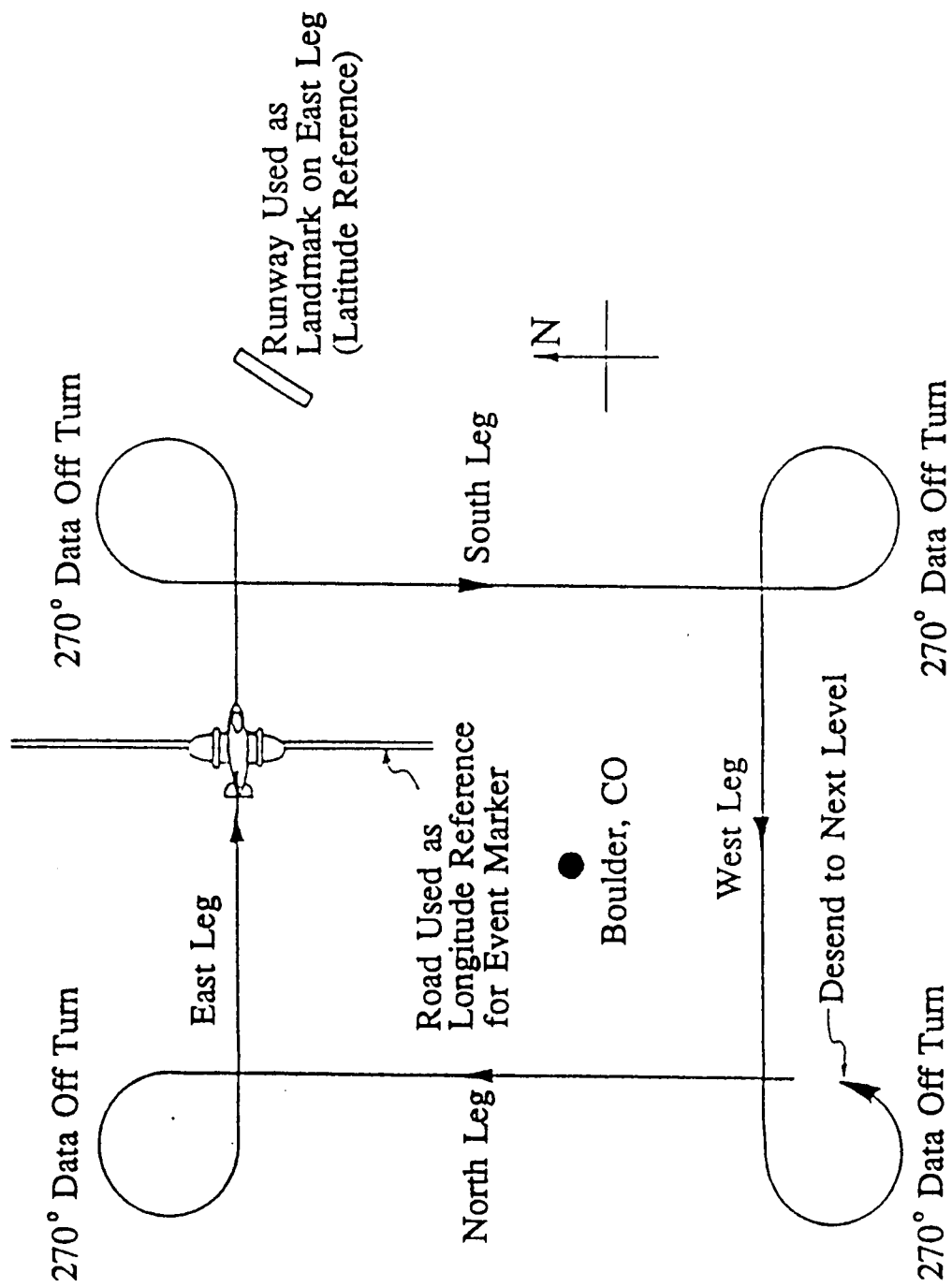
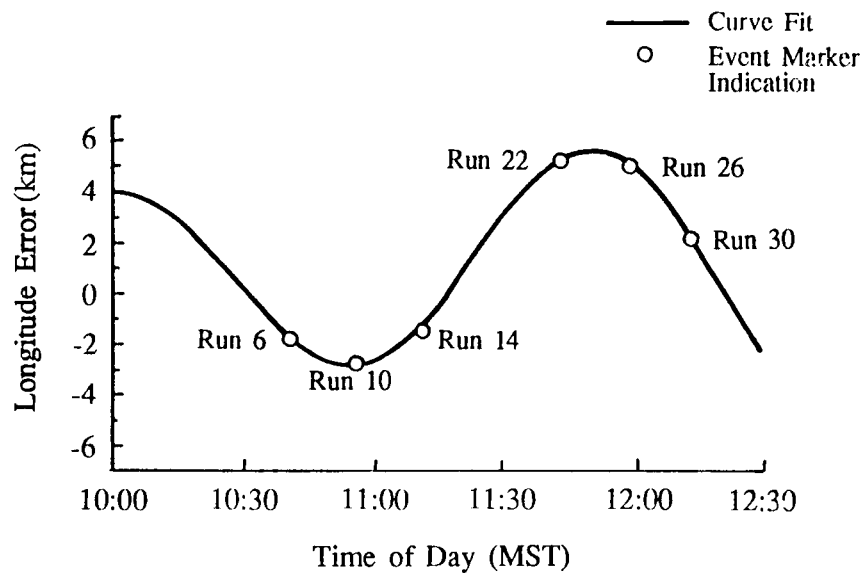
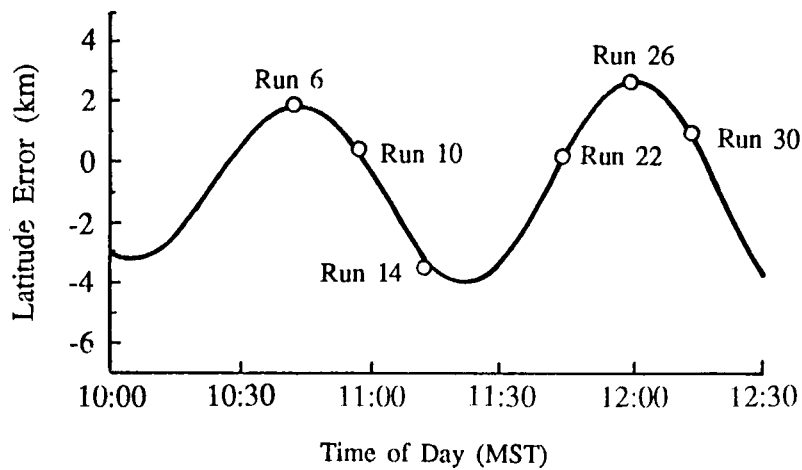


Figure 3.4 Event Marker Location of B-57B on Box Pattern Flights.



(a) Error in INS longitude indication



(b) Error in INS latitude indication

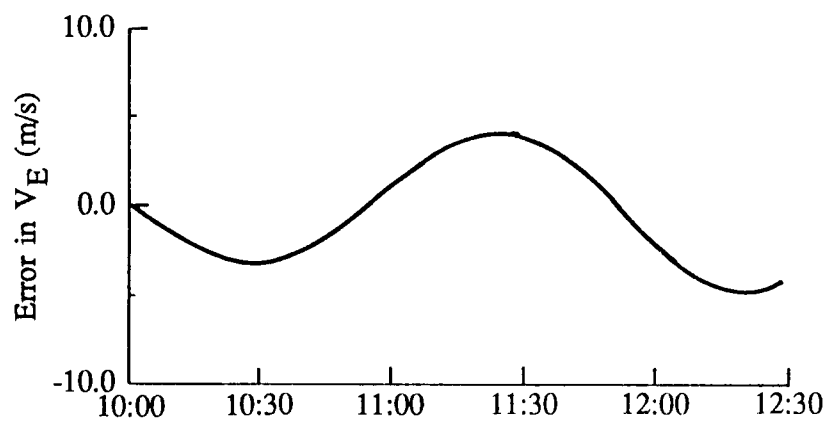
Figure 3.5 In-flight Schuler Position Error, Flight 63.

reasonably close to the Schuler constant of 84 minutes, but the longitudinal period does not conform to that for the particular latitude.

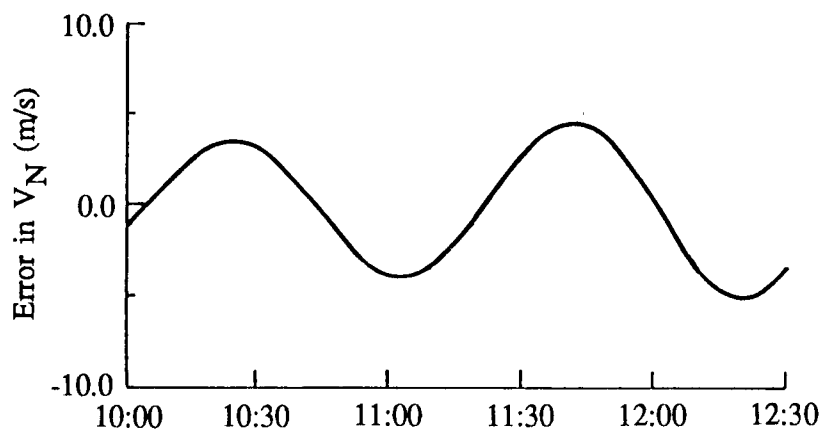
The magnitude INS position errors identified are within a range of less than 15 km (10 nautical miles). From a commercial aircraft operation standpoint, these errors are not a large problem. However, the INS velocity errors are especially important in the wind measurements where horizontal wind speed components are calculated based on Equation 3-10. As will be demonstrated, the velocity errors can be of the same order of magnitude as the wind speed, which will greatly alter the calculation of the wind vector. An estimate of these errors is presented in Figure 3.6. The velocity error curves are calculated by taking the derivative of the position error curve fits illustrated in Figure 3.5. The magnitude of the velocity errors determined is within the range of that quoted in the literature (Rhyne (1980), Lenschow (1983)). The influence of these errors is demonstrated in the next Section.

To further investigate the Schuler error Flights 73 and 74 were carried out where the aircraft was tracked by the NASA FPS-16 tracking radar. The radar track provided the location and the ground speed of the aircraft throughout the flight. Data on post-flight Schuler velocity errors recorded on the ground along with data from Flight 74 were investigated.

The north-south and east-west velocity errors of Flight 74 and the ensuing post-flight velocity measurements are plotted in Figures 3.7 and 3.8. The in-flight velocity errors are obtained by comparing aircraft and radar data assuming the radar indications are free of error. The data recorded on the ground is a direct measure of the indicated velocity from the INS while the aircraft was parked and hence not moving. This velocity fluctuation is attributed to the Schuler error. The INS was left on during the entire time span covered in the plots. The magnitude of the errors are within expected limits. Both figures show one complete cycle of a



(a) East inertial speed error



(b) North inertial speed error

Figure 3.6 In-flight Schuler Inertial Speed Error, Flight 63.

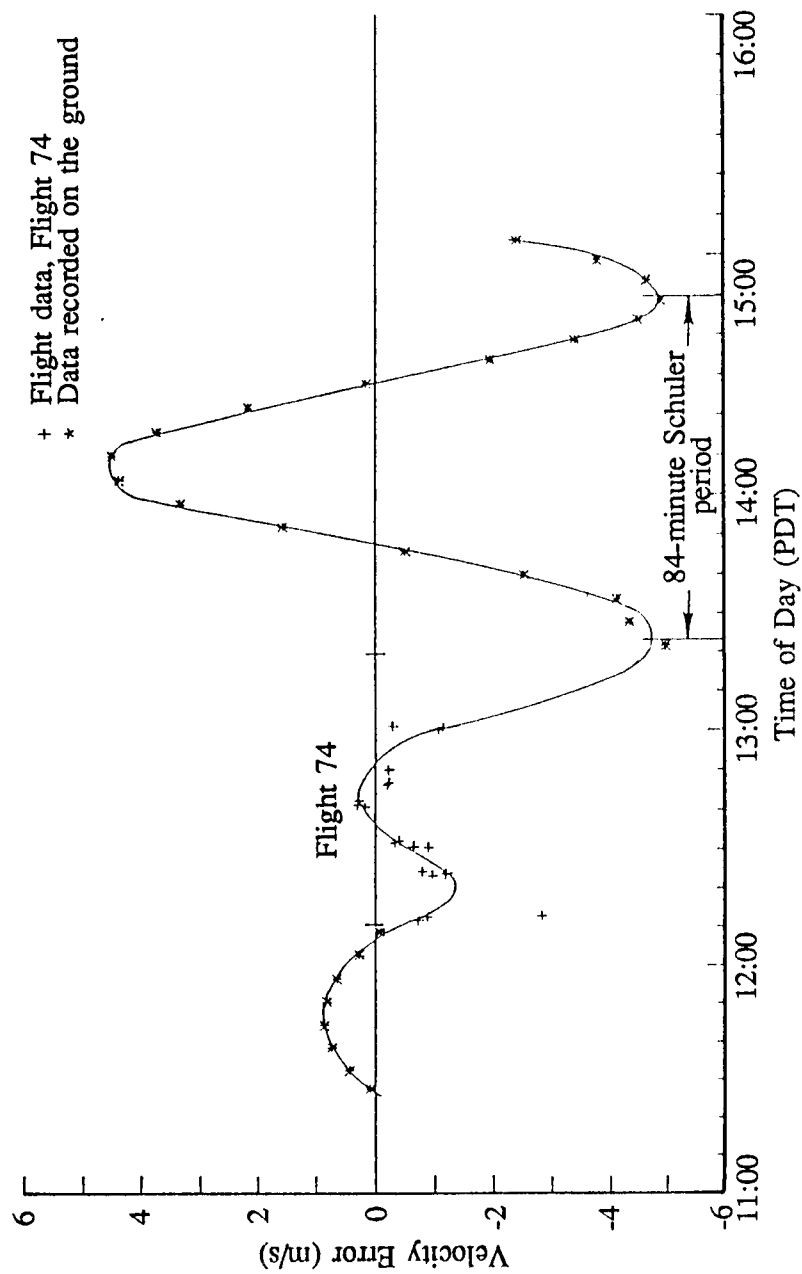


Figure 3.7 Error in East Inertial Speed on Flight 74.

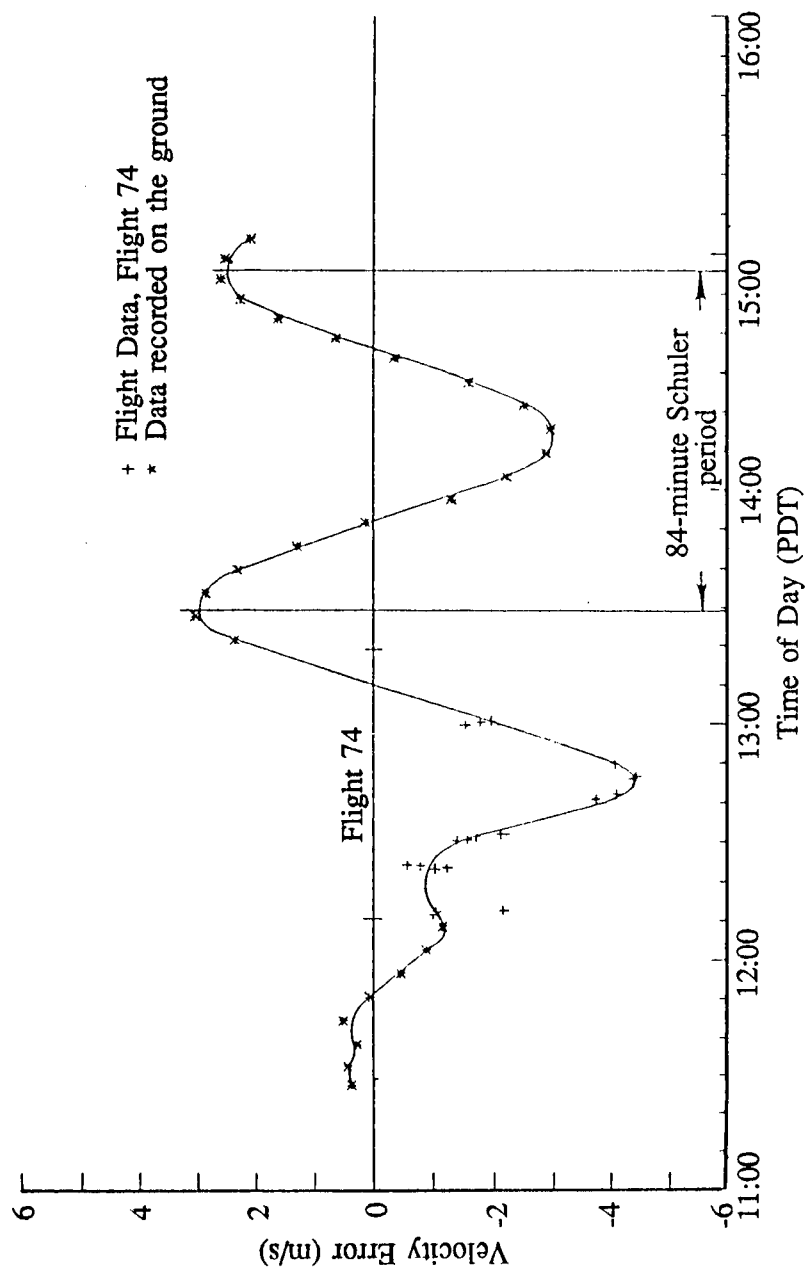


Figure 3.8 Error in North Inertial Speed on Flight 74.

near perfect 84-minute Schuler oscillation in the post-flight data in the latter part of the test period. This is in keeping with Huber and Bogers (1983) who noted that near the ground without accelerations involved the Schuler oscillations will have an 84.4-minute period. The inertial velocity measurement errors strongly influence the horizontal wind vector calculations, which is discussed next.

Horizontal Wind Vector Correction: In addition to the INS velocity and position errors described above, sideslip angle, and airspeed errors have an influence on the calculation of horizontal winds. All aircraft are designed directionally stable and will fly with zero average sideslip angle unless forcefully kept in a sideslip flight condition. The average sideslip angle of 2.23 degrees, for example, recorded at the centerboom on Flight 63 is therefore attributed to error. The source of the error is not clear but boom misalignment or problems with the data acquisition system are suspected causes. The average sideslip error affects the computed value of the horizontal wind vector noticeably.

The accuracy of the horizontal wind vector calculations also depends upon the quality of airspeed measurements. Possible instrument calibration, position errors, or conversion from indicated to true airspeed can cause these inaccuracies. Also, the lack of separate static pressure transducers at the wing tips could have contributed to the inconsistencies. A test flight conducted with the Cambera B-57 also revealed a value of horizontal wind speed of 2.5 m/s lower at the center boom than at the wing tip booms at a relative airspeed of roughly 122 m/s (236 kts) (Ehernberger (1987)). An approximate analysis based on a potential flow solution for a Rankine body (Karamcheti (1966)) predicted a 6 percent error.

This is expected to be high because the Cambera B-57 is a more streamlined body than a Rankine body, but the results do support the hypothesis that the airspeed may be retarded sufficiently by the aircraft body to produce the relative

airspeed difference a boom's length from the nose. This 6 percent error is accounted for in the following investigation of the influence of instrumentation errors on horizontal wind calculations.

The INS velocity and position, sideslip angle, and airspeed errors as described in this study have been removed from the recorded data on some runs of Flight 63. A series of wind vectors are plotted before and after corrections have been made along the flight path recorded by the INS. Each vector represents a one-second average from the 40 samples per second data tapes.

In Figure 3.9 one of the box patterns flown on Flight 63 is plotted. In this figure, no corrections have been made. There are some obvious inconsistencies in the wind vectors, particularly, at the corners where it is expected that the wind would agree closer between the two runs. The aircraft made 270- degree turns between runs which take less than two minutes. The wind direction is not expected to change significantly during that short of an interval. Instrumentation errors are, therefore, the probable cause for the discontinuities in wind direction. In Figure 3.10 corrections have been made for the known errors. The discontinuities in the wind vectors at the corners have all but vanished except for the bottom left-hand corner. However, as the numerical order of the runs indicates the box pattern was flown in a clockwise direction; thus, the beginning of Run 9 and the end of Run 12 are separated in time by approximately 15 minutes. Therefore, it is conceivable that the wind could have changed in that time span. The position errors are not severe for this box pattern but still noticeable.

Figure 3.11 is similar to Figure 3.9 except Runs 13 through 16 on Flight 63 have been plotted. No corrections have been made. Only the discontinuities in the direction of the wind in the upper left-hand corner and in the magnitude of the wind in the upper right-hand corner appear questionable. Figure 3.12 illustrates

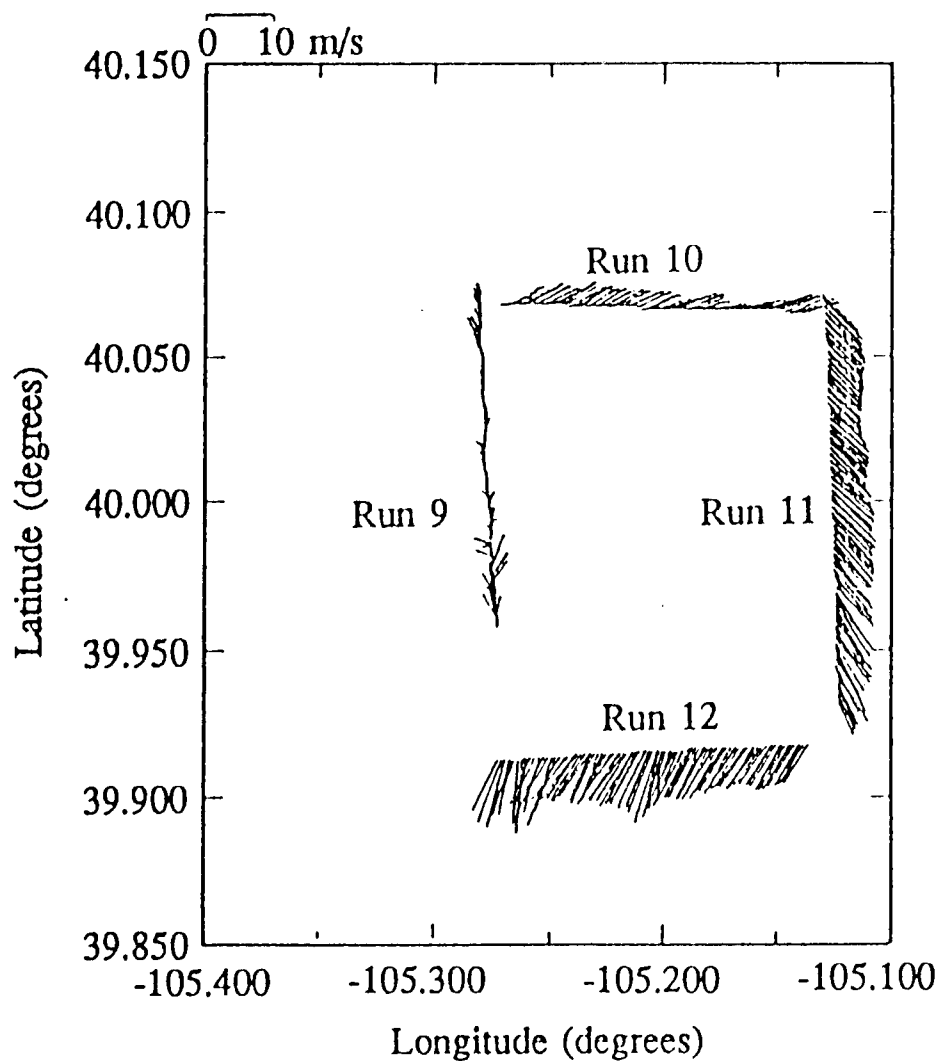


Figure 3.9 Horizontal Wind Vectors on Flight 63 Without Corrections (Runs 9 though 12).

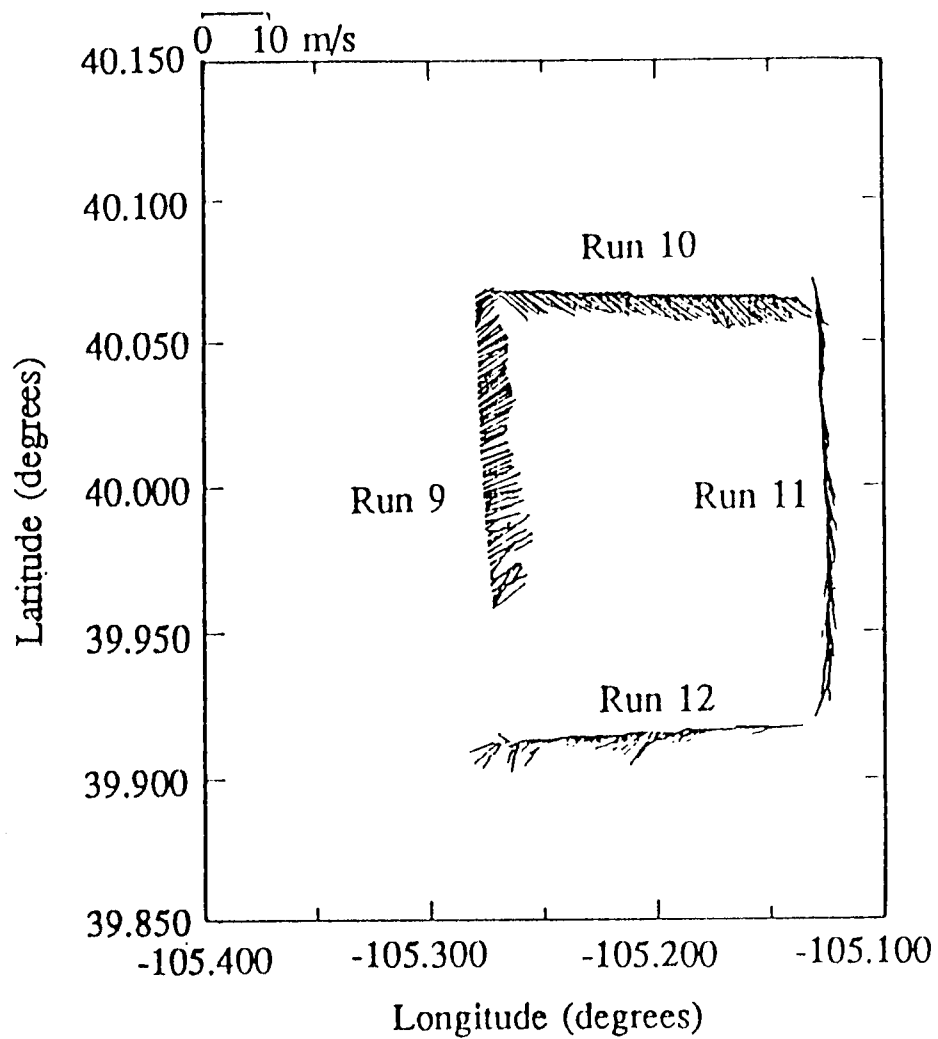


Figure 3.10 Horizontal Wind Vectors on Flight 63 After Airspeed, Beta, and Inertial Velocity and Position Corrections (Runs 9 through 12).

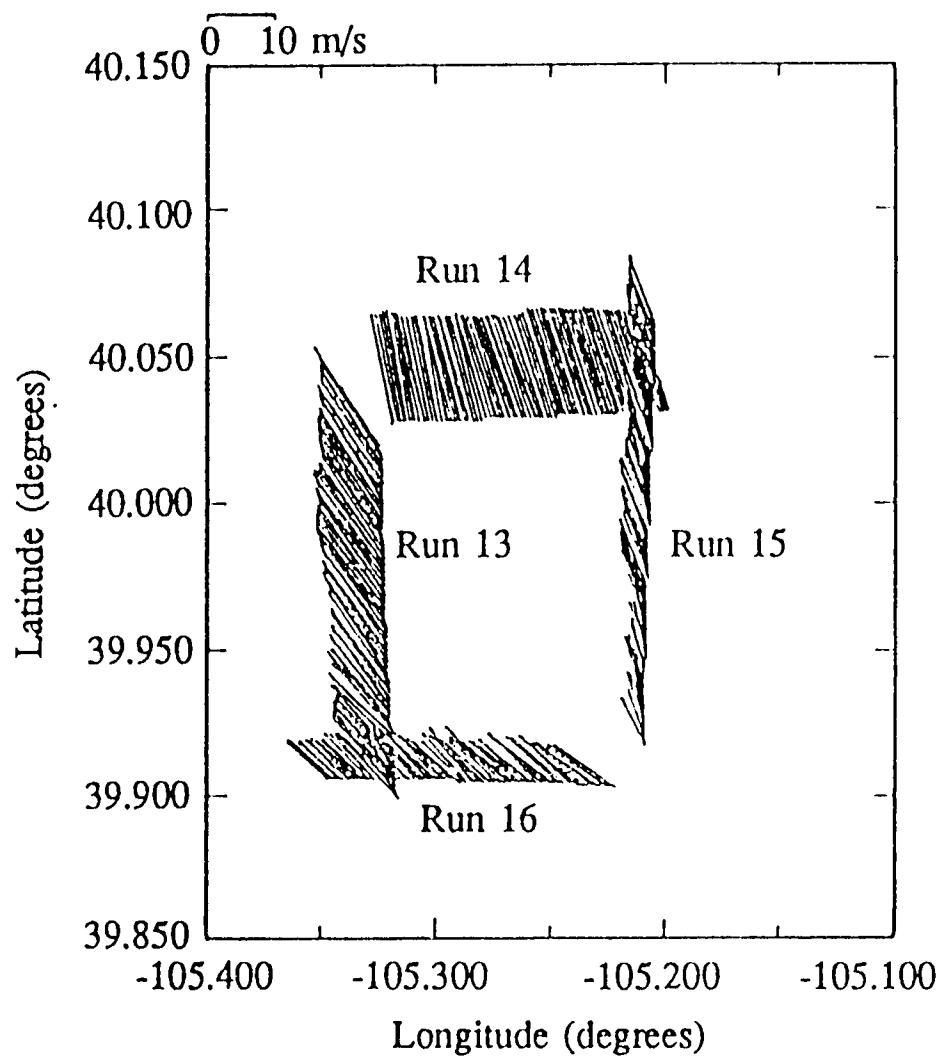


Figure 3.11 Horizontal Wind Vectors on Flight 63 Without Corrections (Runs 13 through 16).

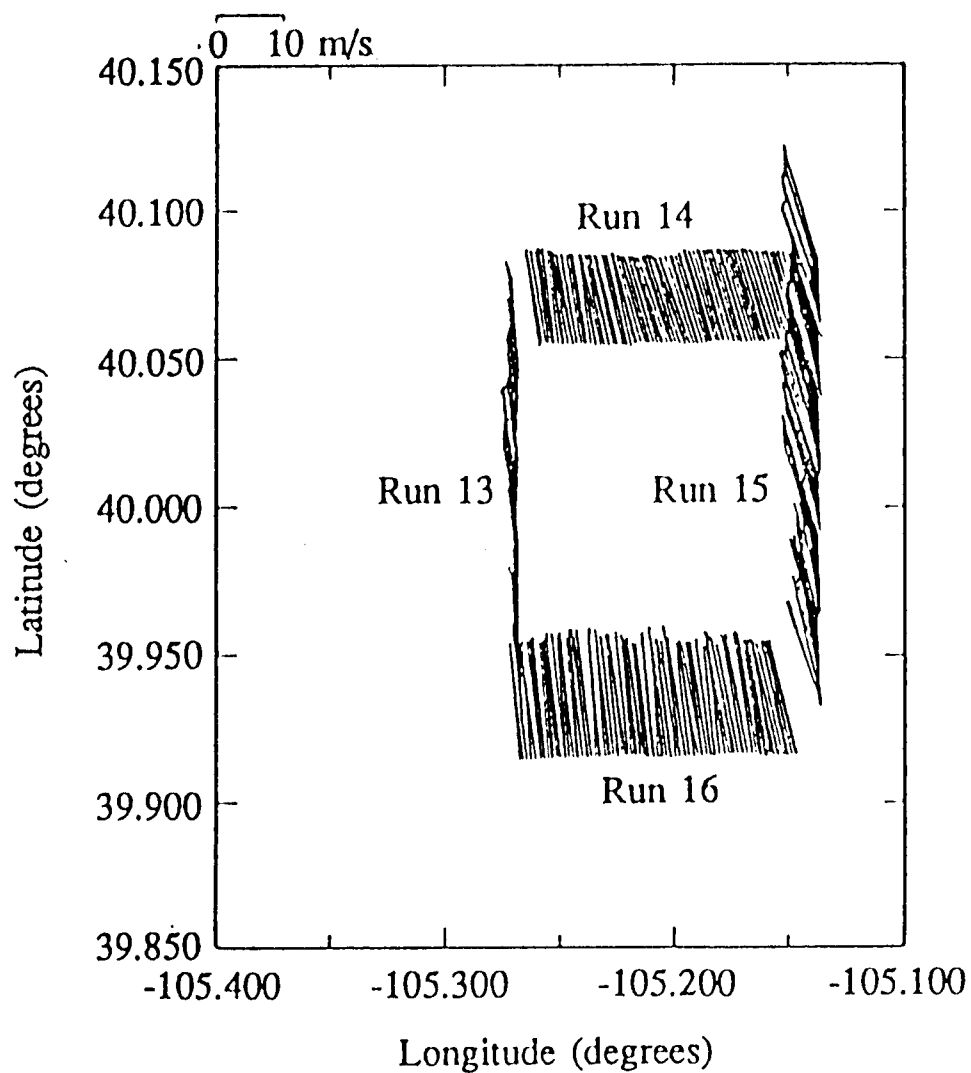


Figure 3.12 Horizontal Wind Vectors on Flight 63 After Airspeed, Beta, and Inertial Velocity and Position Corrections (Runs 13 through 16).

the effect of removing the errors on wind vectors and INS indicated locations. The horizontal wind vectors are more consistent and also the location of the runs are in better agreement with the flight plan.

Effects of Non-Level Flight: Data presented in previous sections were generally obtained to study the turbulent gust velocities from the measured aircraft data based on the assumption of straight, level flight. To study the effects of non-level flight, Flight 31 data are investigated. Flight 31 contains runs over sufficiently long distances, take-off, and touch-and-go runs to study non-stationary turbulence along the glide slope associated with the vertical variation of the horizontal wind. Figure 3.13a shows the altitude of Flight 31 during Run 2 relative to ground elevation. Because of the exaggerated vertical scale, the departure from level flight appears to be severe. However, the averaged pitch angle is approximately $+3^\circ$. Horizontal wind velocity (five-second average) along the flight path are plotted on Figure 3.13b. To investigate the effects of climb and descent angles on the horizontal wind speed, the non-linear Equation 3-9 is compared with the linear Equation 3-10. In Figures 3.14 and 3.15 time histories of difference of computed linear and non-linear North and East wind components are plotted, respectively. Each figure contains three plots where the effect of steep pitch angle (θ) is simulated. The actual values of θ are used in generating difference time histories (see the lower figures in Figures 3.14 and 3.15). The effect of steep pitch angle is simulated by adding a value of 10° and 20° to the actual θ values as shown in the middle and top plots of Figures 3.14 and 3.15, respectively. The RMS value of each time history is also shown in the figures. Note that θ is absent from the linear equations, the effect of steeper pitch angle is reflected by higher RMS value for the difference between linear and non-linear computed wind components.

To further investigate the effects of non-level flight, namely high bank angles

Location: Edwards Air Force Base
Flight 31, Run 2

Date: Nov. 29, 1982

Start Time: 10:39:16 (PST)

Duration: 213.8 seconds

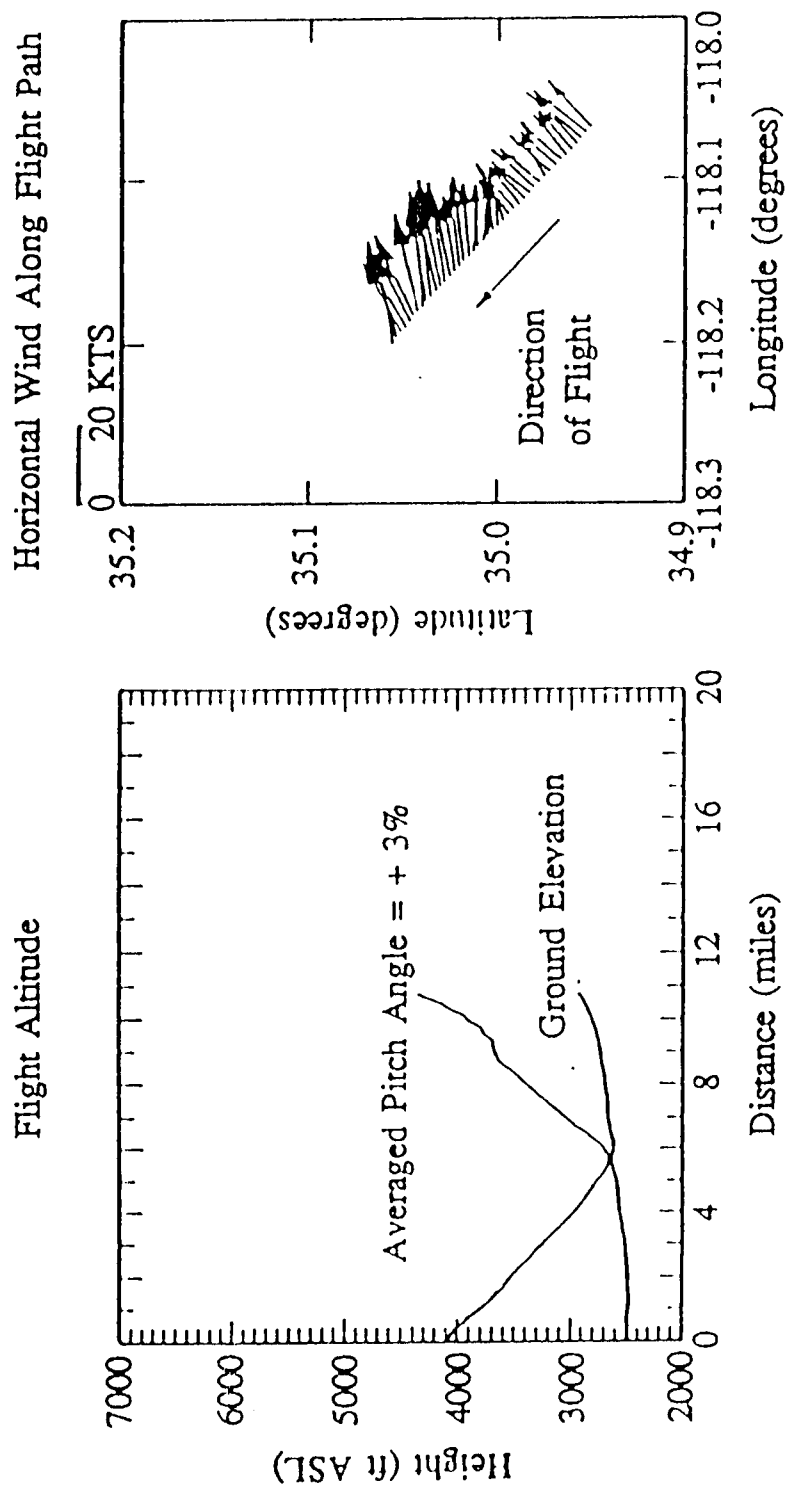


Figure 3.13 Flight Altitude and Horizontal Wind Flight Path, NASA B-57B Flight 31, Run 2.

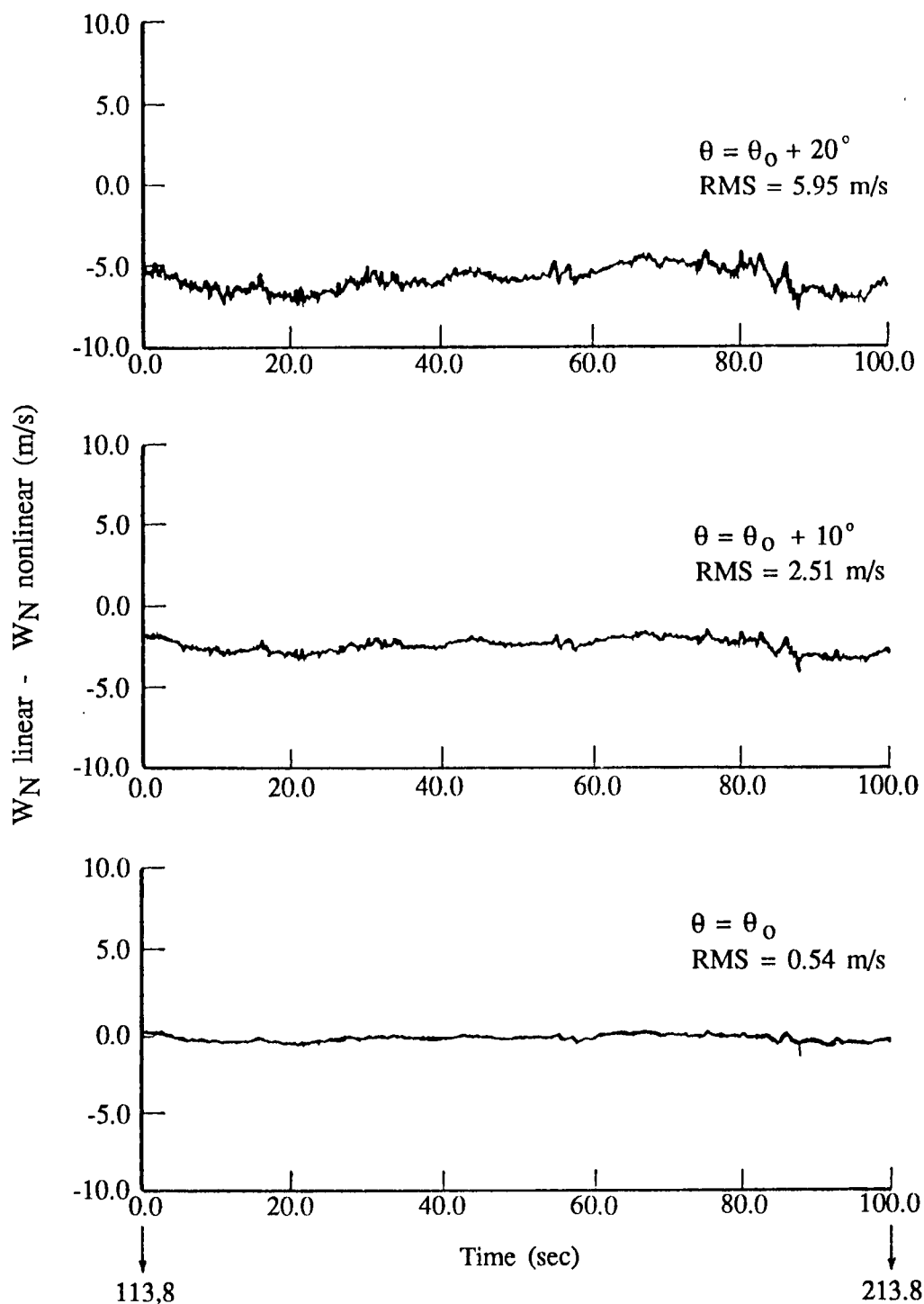


Figure 3.14 Calculated W_N Linear - W_N Nonlinear for Simulated Pitch Angles ($\overline{\theta^0} = 3^\circ$).

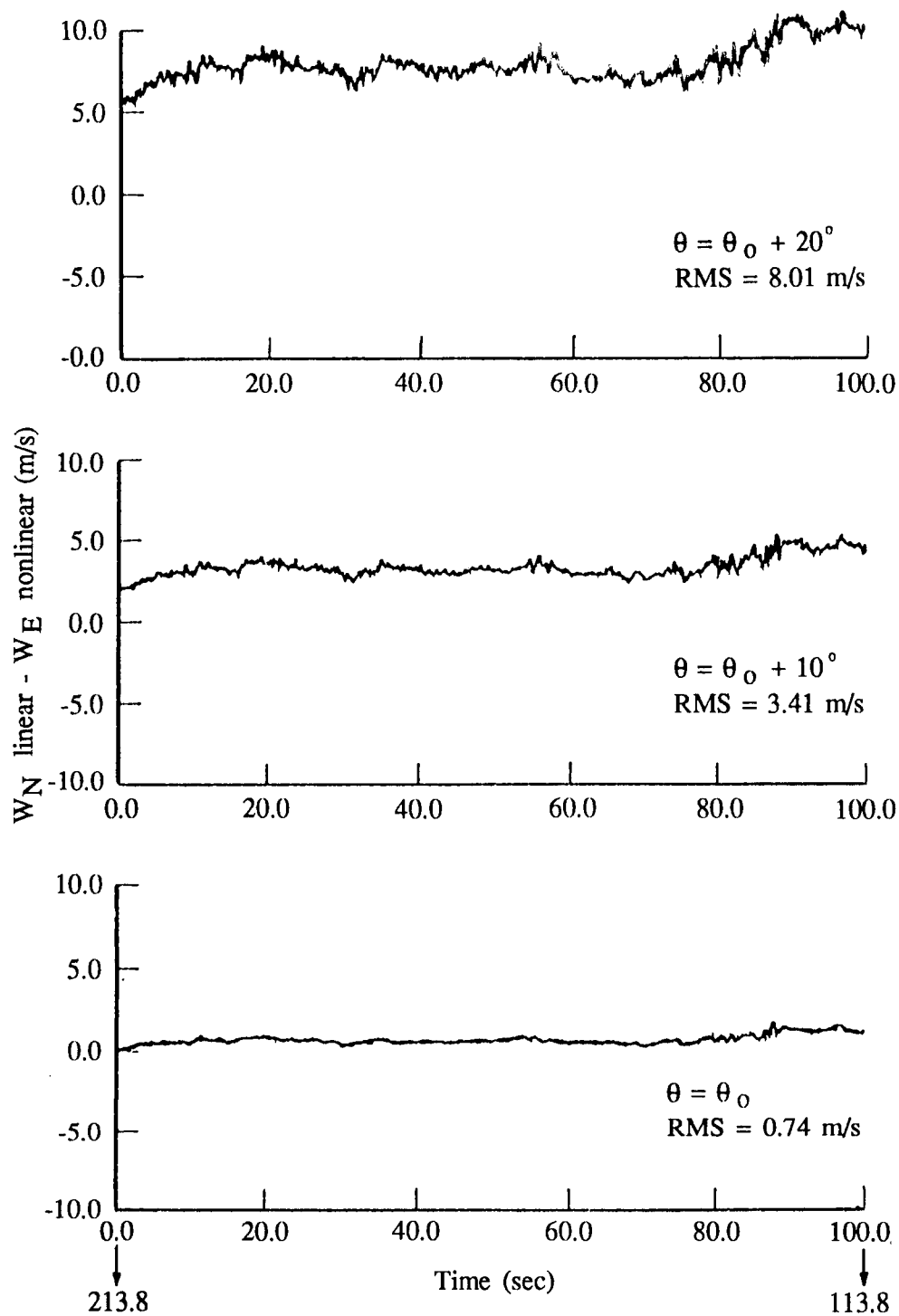


Figure 3.15 Calculated W_E Linear - W_E Nonlinear for Simulated Pitch Angles ($\bar{\theta}^0=3^\circ$).

(ϕ), flight data of the NASA B-57 aircraft at MSFC on May 10, 1983 is studied. Figure 3.16 shows the flight pattern and horizontal wind velocity along the flight path. Figures 3.17 and 3.18 simulate the effect of high bank angle similar to Figures 3.14 and 3.15. A summary of RMS errors in winds, affected by high pitch angle and high bank angle, is given in Table 3-3.

Inputs to F-104 Experiment from Results of Error Analysis: The result of the foregoing accuracy and error source analysis indicates that an instrumented aircraft can be an effective tool in obtaining wind profiles more rapidly and with the same qualities as the Jimsphere measured wind if: 1) careful attention is paid to the instrumentation accuracy and data reduction procedures; 2) the full non-linear system of equations are used to reduce the aircraft measured data; 3) the major source of error attributed to the INS measured ground velocity is removed by an independent ground speed measurement during flights of high maneuvering. For this reason, the F-104 aircraft was radar tracked to provide ground speeds independent of the INS. Introducing these measurements into the data analysis as shown later is effective in reducing the Schuler error.

3.2.4. Experimental Program

In order to verify that the aircraft measured winds are equivalent to Jimsphere measured winds for STS loads application, several flights of the instrumented F-104 accompanied with Jimsphere releases were carried-out. NASA/DFRF was selected as the test site because of the availability of synoptic weather conditions from rawinsondes or other systems such as windsonde/MSS at the site, access to at least two AN/FPS-16 radar systems, access to the runway for the F-104 aircraft, and the presence of limited complex terrain. Figure 3.19 shows a map of Edwards AFB and NASA/DFRF with some major landmarks including balloon release stations, radar sites, and airfield runways.

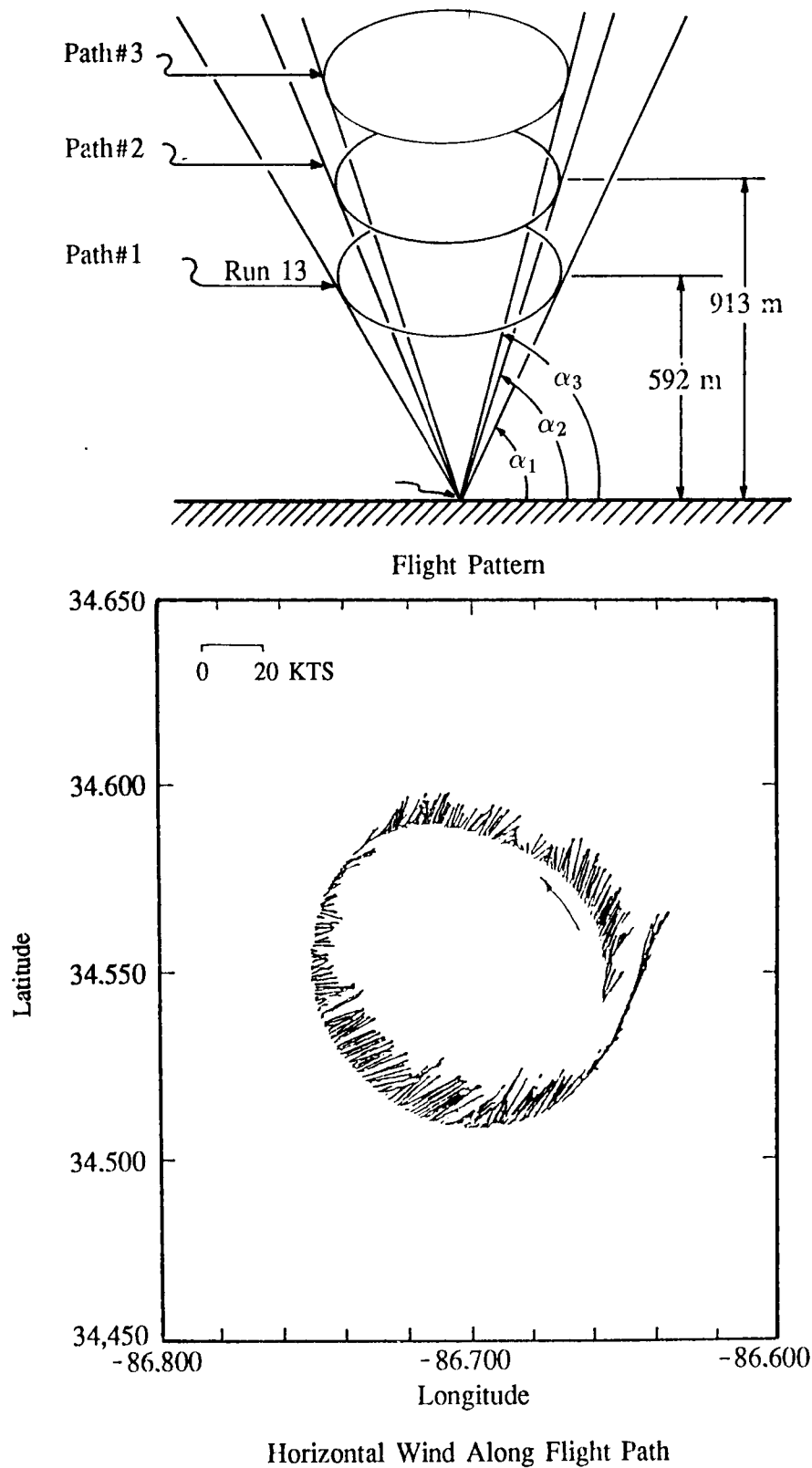


Figure 3.16 Flight of NASA B57-B Aircraft at MSFC on May 10, 1983.

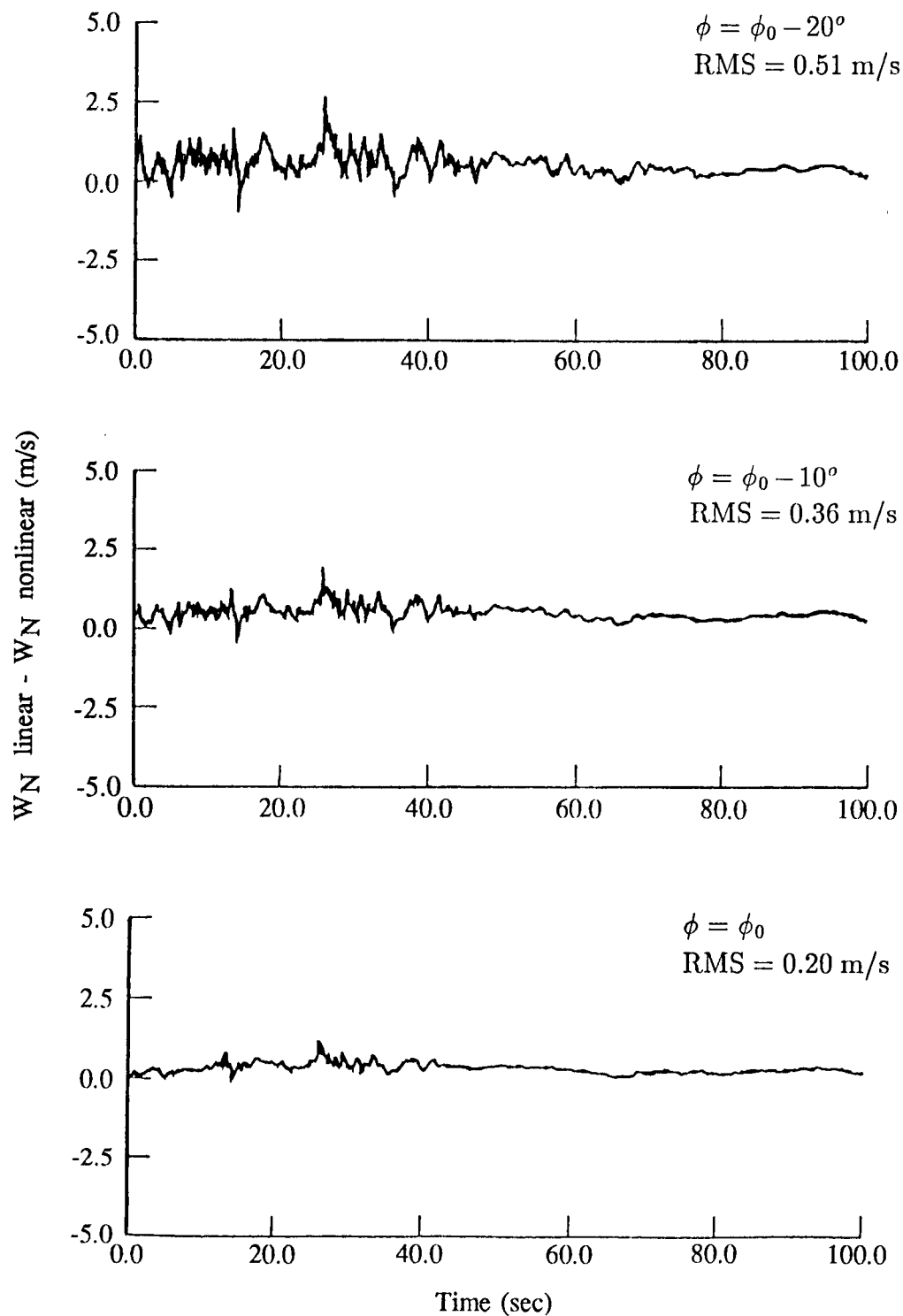


Figure 3.17 Calculated W_N Linear - W_N Nonlinear for Simulated Bank Angles ($\bar{\theta}_0 = -10^\circ$).

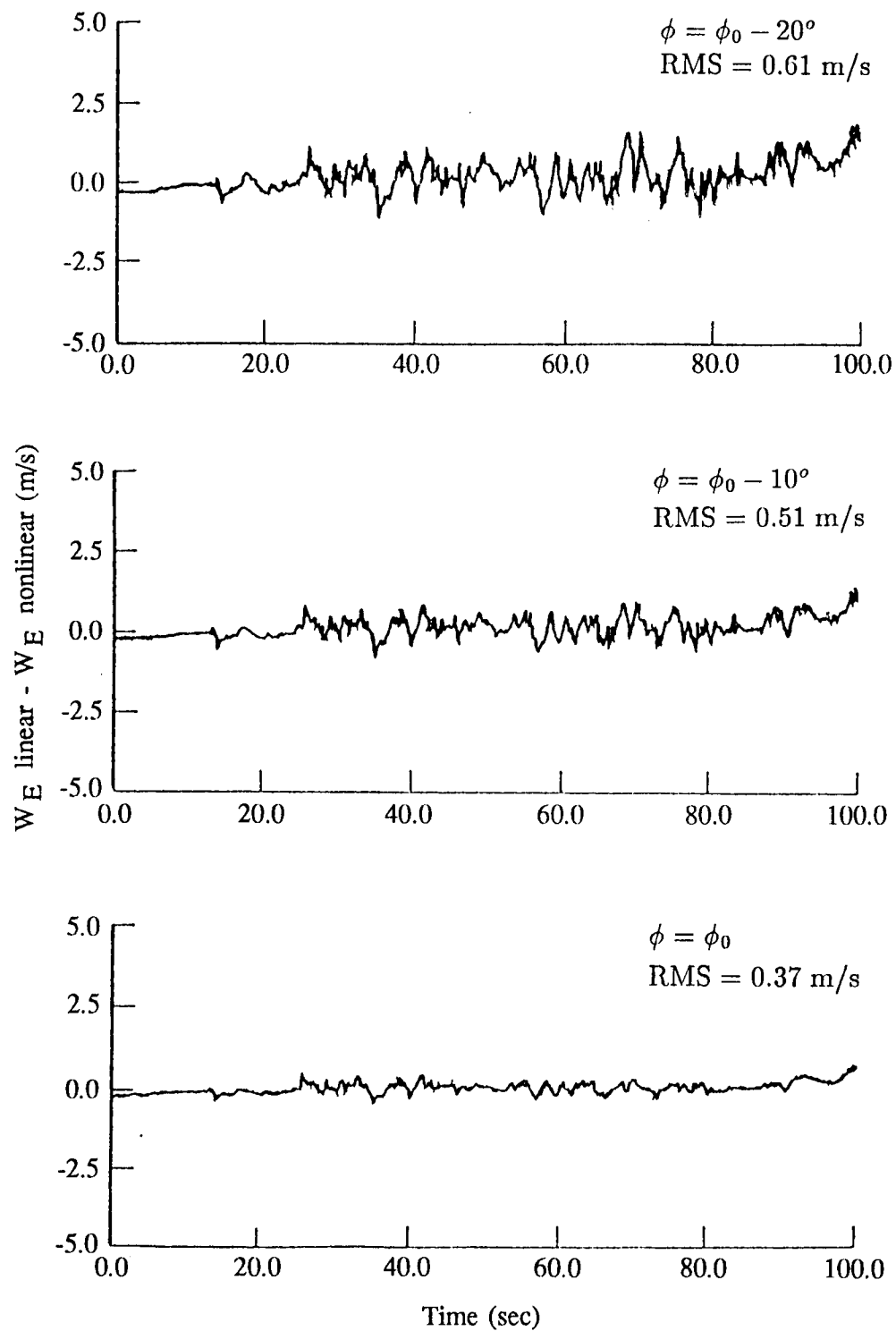


Figure 3.18 Calculated W_E Linear - W_E Nonlinear for Simulated Bank Angles ($\bar{\theta}_0 = -10^\circ$).

**TABLE 3-3 SUMMARY OF THE RMS ERROR IN WINDS COMPUTED
WITH LINEAR EQUATIONS.**

RMS Error m/s (kts) in Steep Climbing Flights			
	θ_o	$\theta_o + 10^\circ$	$\theta_o + 20^\circ$
W_N	0.54 (1.05)	2.52 (4.90)	5.95 (11.56)
W_E	0.74 (1.44)	3.41 (6.65)	8.01 (15.56)
RMS Error m/s (kts) in Circular-Level Flights			
	ϕ_o	$\phi_o - 10^\circ$	$\phi_o - 20^\circ$
W_N	0.2 (0.39)	0.36 (0.70)	0.51 (0.99)
W_E	0.37 (0.72)	0.51 (0.99)	0.61 (1.18)

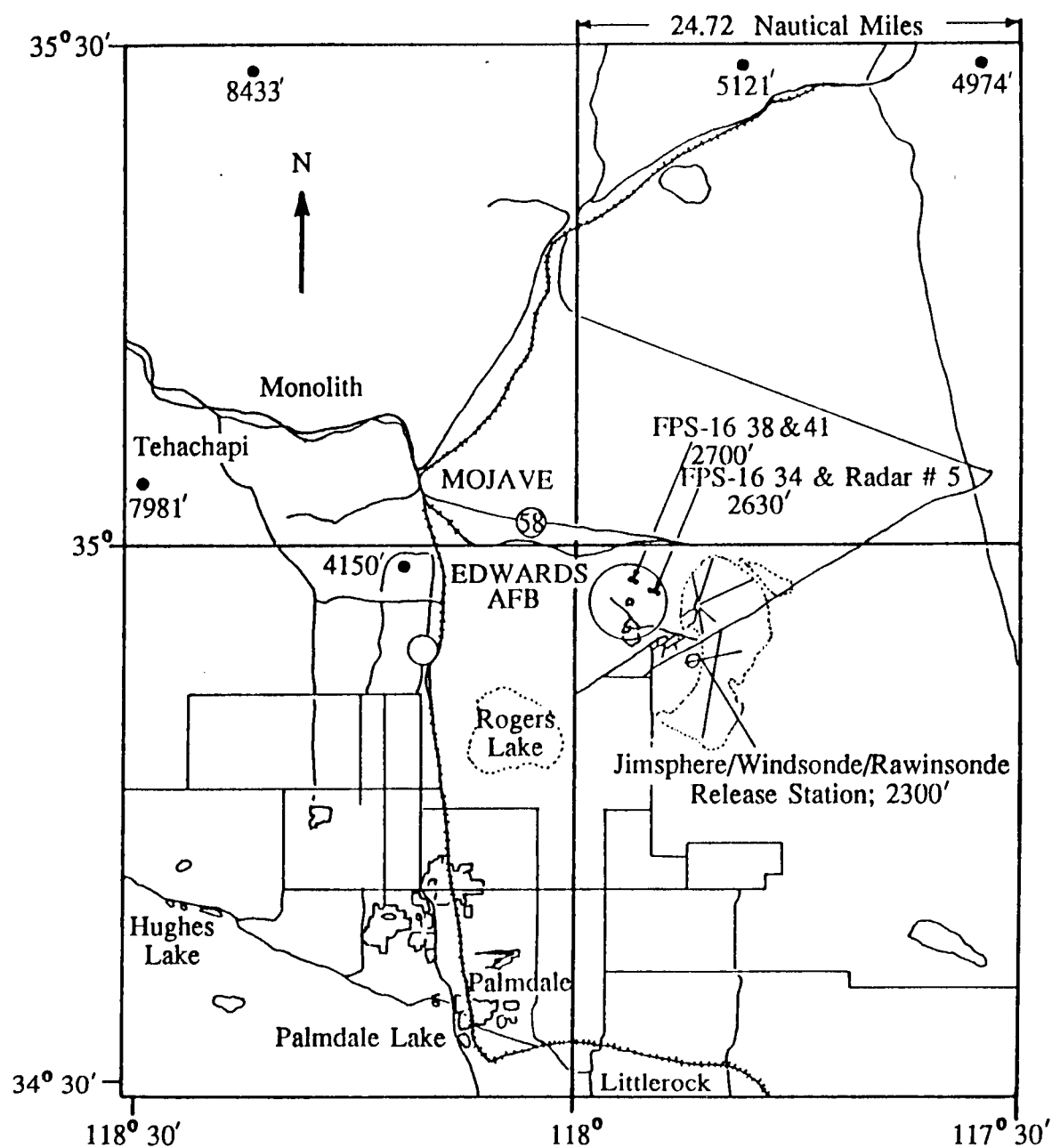


Figure 3.19 Map of Test Site at NASA Dryden Flight Research Center.

3.2.5. Data Collection

The F-104 aircraft is instrumented, operated, and maintained by NASA/DFRF for measuring the wind variables listed in Table 3-1. The instrumentation is similar to that of the B-57 aircraft used by NASA/Langley and NASA/DFRF for turbulence measurement in many earlier projects. The F-104 is equipped with a single airspeed (pitot tube) probe located on a boom at the nose. Figure 3.1 shows some physical characteristics of F-104 aircraft. In addition to the airspeed probe, wind direction sensors are located on the noseboom to measure the flight angles which are sideslip angles and angle-of-attack. Euler angles and angular rates, acceleration components, geographical location, as well as ground speed, are provided by the Litton LTN-90 Inertial Navigation System (INS). Aircraft measured variables are sampled at 180 Hz. The data, reduced to 20 Hz and expressed in engineering units, is forwarded to NASA/MSFC for input to the full, non-linear system of wind velocity equation computer algorithm.

The glide angle and the rate of ascent/descent of the aircraft are functions of wind speed and sampling rate. With an aircraft measuring system capable of producing 125 samples per second, in order to obtain two data points per one meter of height, the aircraft ascent/descent rate is 62.5 m/s (12,300 ft/min). Jimsphere elevation angle based on rise rate of 5 m/s (985 ft/min) and average horizontal wind speed of 13 m/s (25 kts) is approximately 21° . Thus with a glide angle of 21° and ascent/descent rate of 62.5 m/s (12,300 ft/min), the aircraft airspeed must be on the order of 193 m/s (375 kts). A plot of glide angle as a function of airspeed and horizontal mean wind is shown in Figure 3.20.

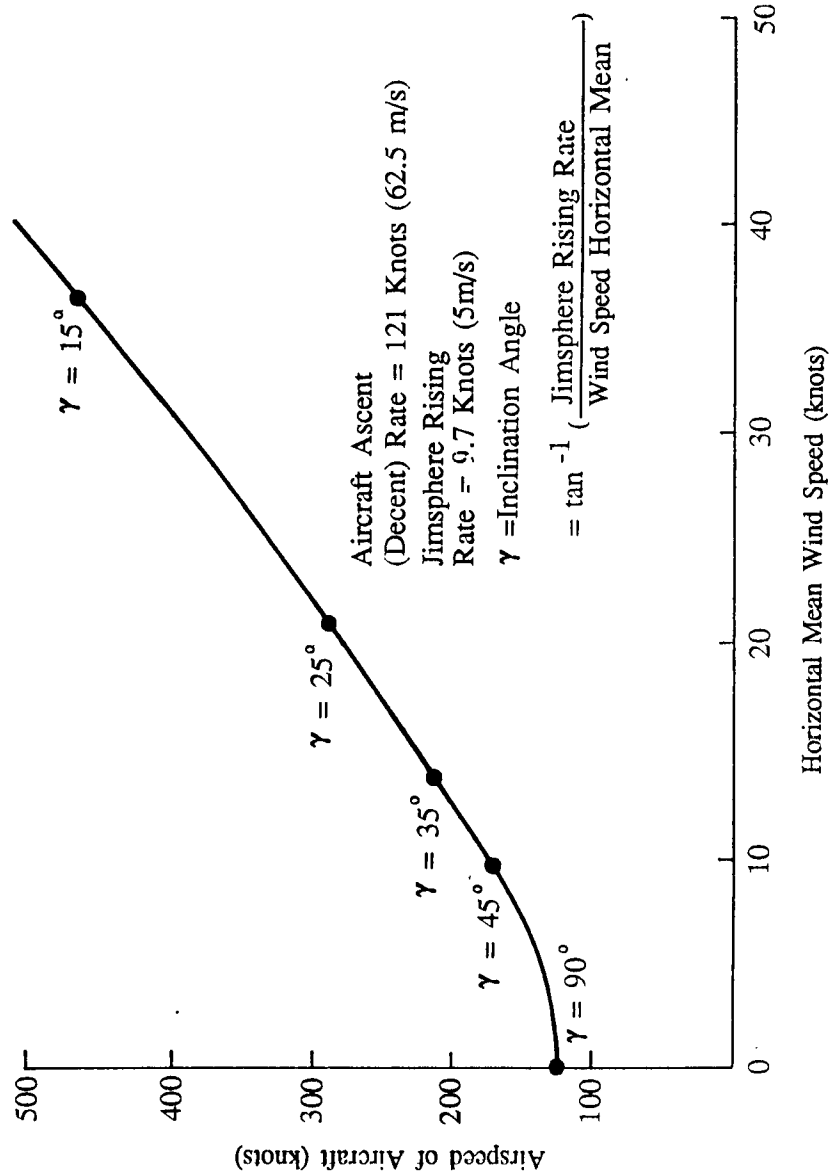


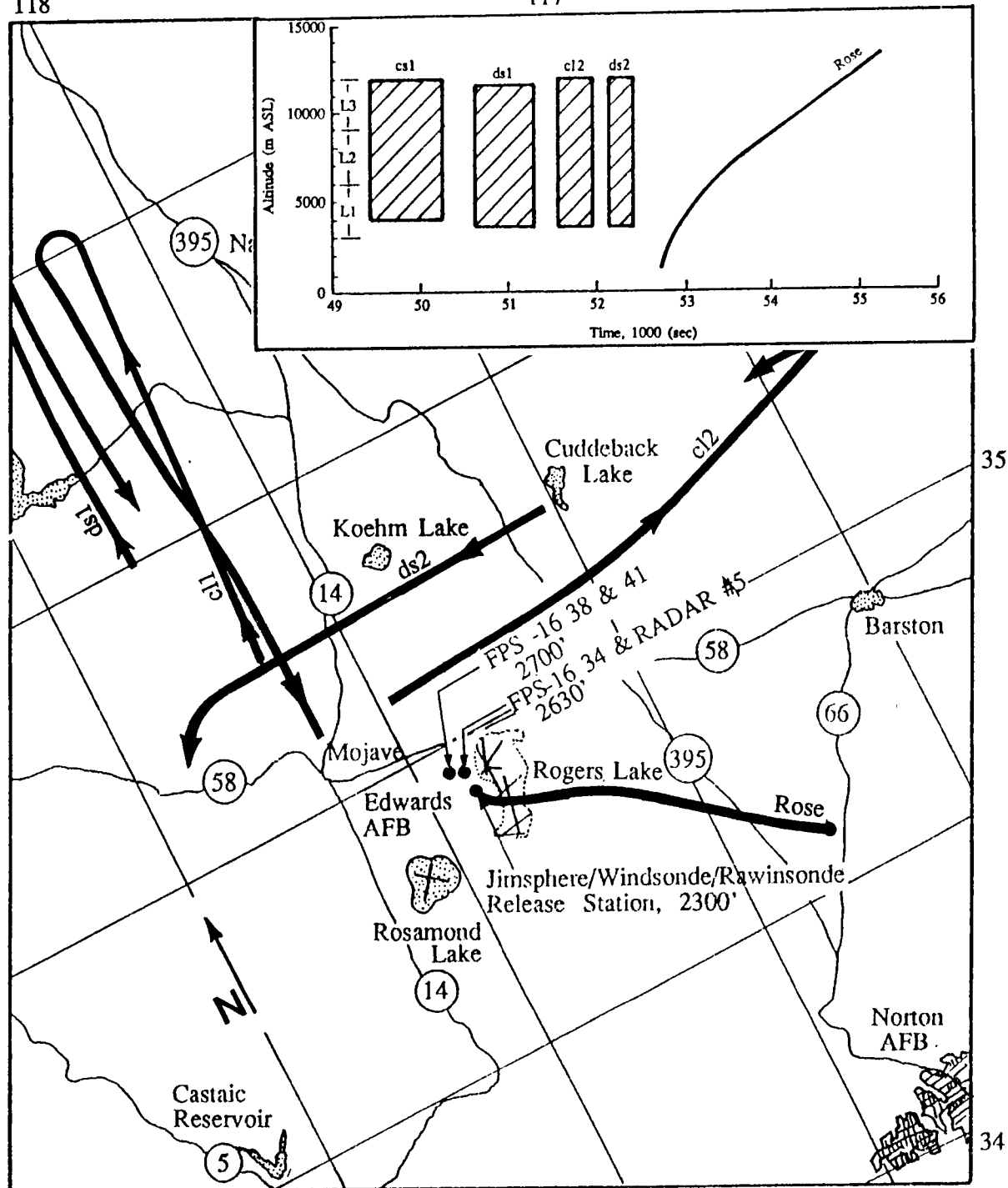
Figure 3.20 Essential Airspeed and Flight Path Angle for Aircraft to Fly Parallel to the Mean Jimsphere Trajectory.

4.0 COMPARISON OF JIMSPHERE AND AIRCRAFT MEASURED WIND PROFILES

4.1 Experiment

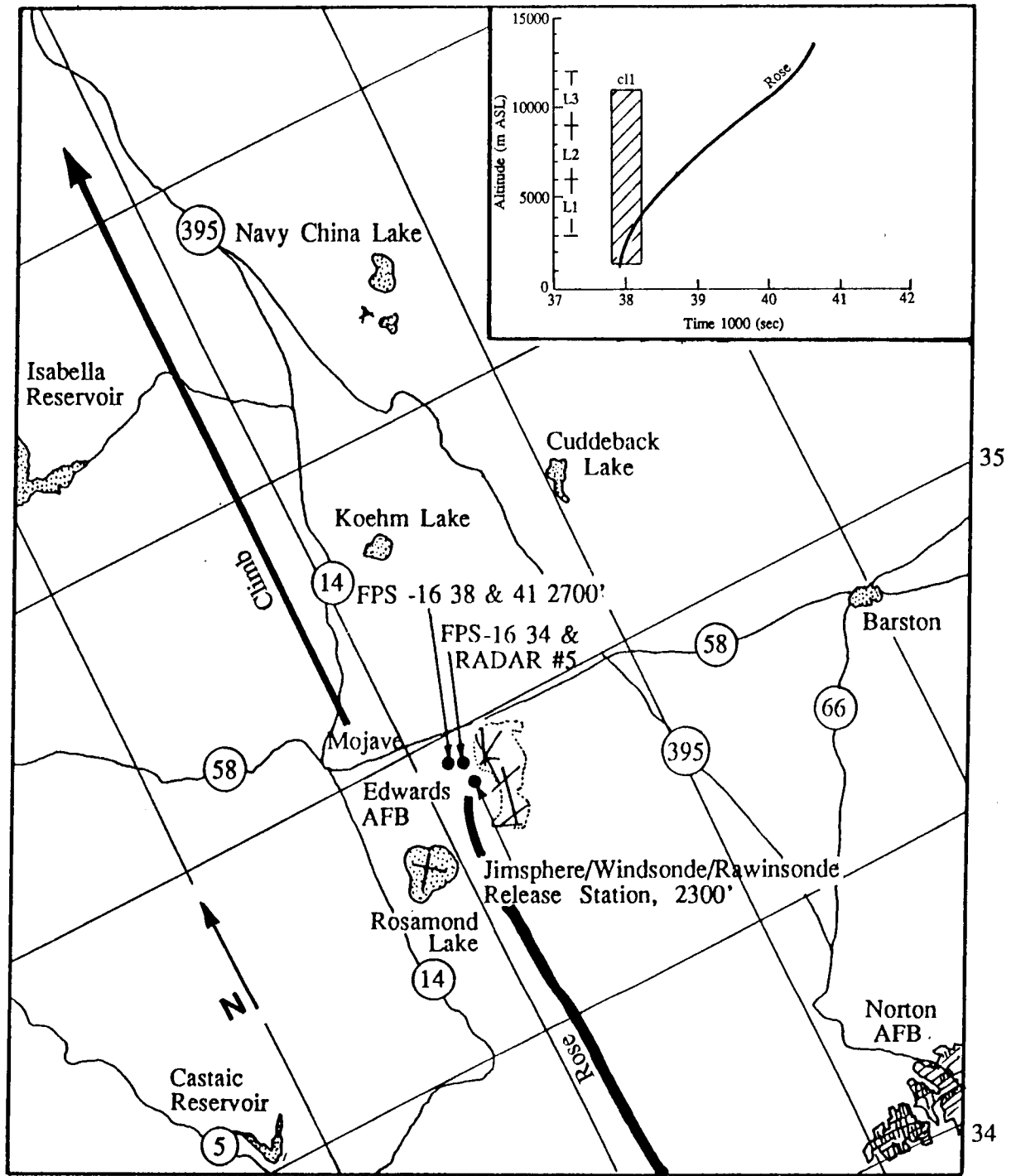
Four flights were carried out: Flights 1207, 1208, 1210, and 1214 on 12/21/87, 1/19/88, 1/28/88, and 4/4/88, respectively. The flight experiments were broken down into individual flight paths corresponding to climbs and descents of the aircraft. The overall experiment consisted of 8 climbs and 7 descents. This portion of the experiment was designed to verify the low altitude subsonic measurement capabilities and all flights were below 40,000 feet altitude.

During each of the experiments, at least one Jimsphere was released. It was generally intended for the Jimsphere flight to overlap the aircraft flights in time. However, in some cases the aircraft flight occurred before or after the Jimsphere release. Figures 4.1 through 4.4 show a projection of the flight paths for the aircraft climbs and descents and for the Jimsphere on an areal map of the NASA Dryden flight test area. The insert on the upper righthand side of the figure indicates the altitude and time profile of the Jimsphere, as well as, a box indicating the approximate position and time of the aircraft during the climbs and descents. In each case, it is evident that the measurements of wind along the aircraft flight trajectories were not coincident in space or in time with the Jimsphere release. For this reason it was necessary to compare the wind measurements from the different systems using statistical analysis techniques.



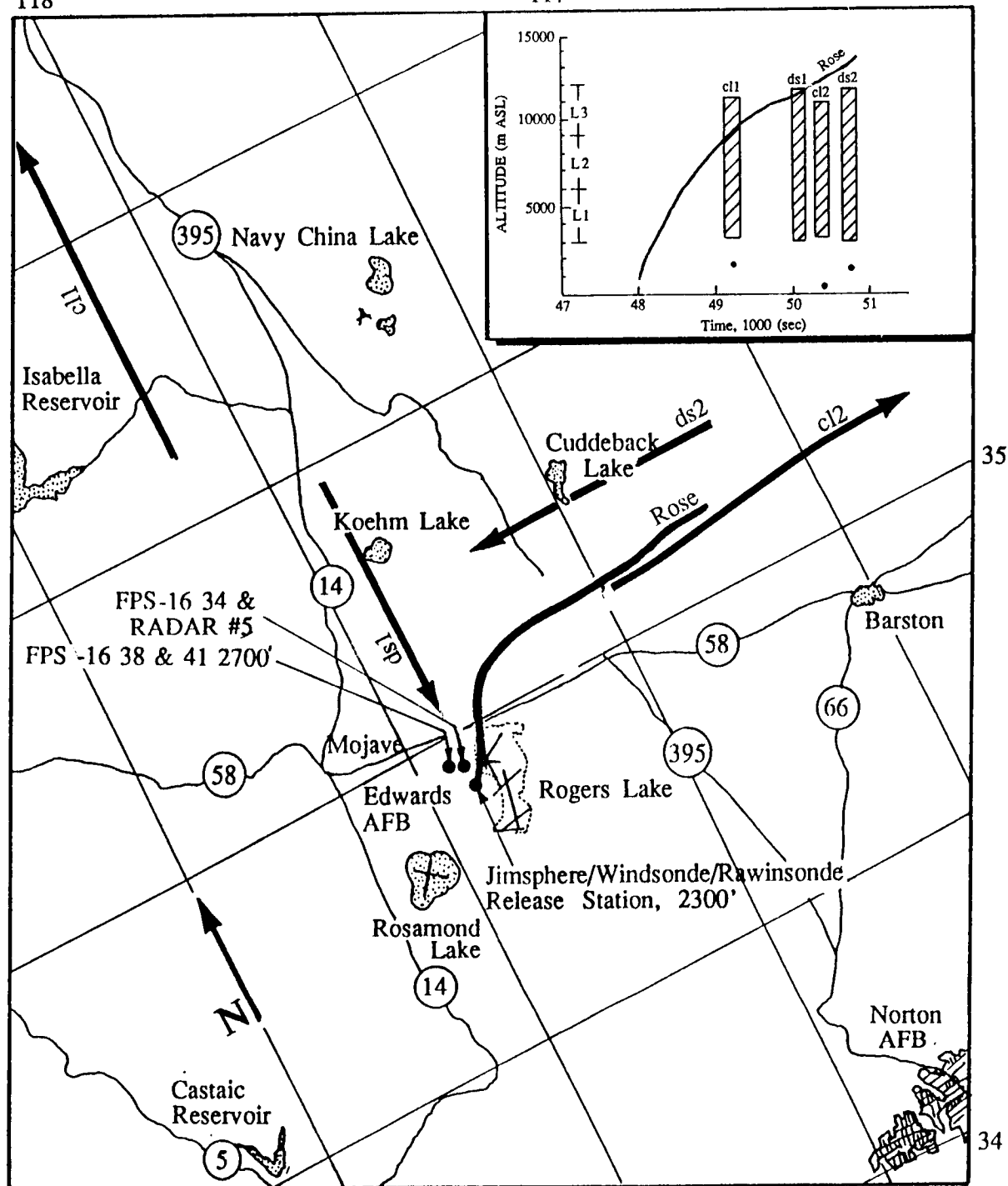
At 35° Latitude; 1° Longitude = 91.290 km, 1° Latitude = 110.938 km

Figure 4.1 Flight 1207 Jimsphere and Aircraft Paths.



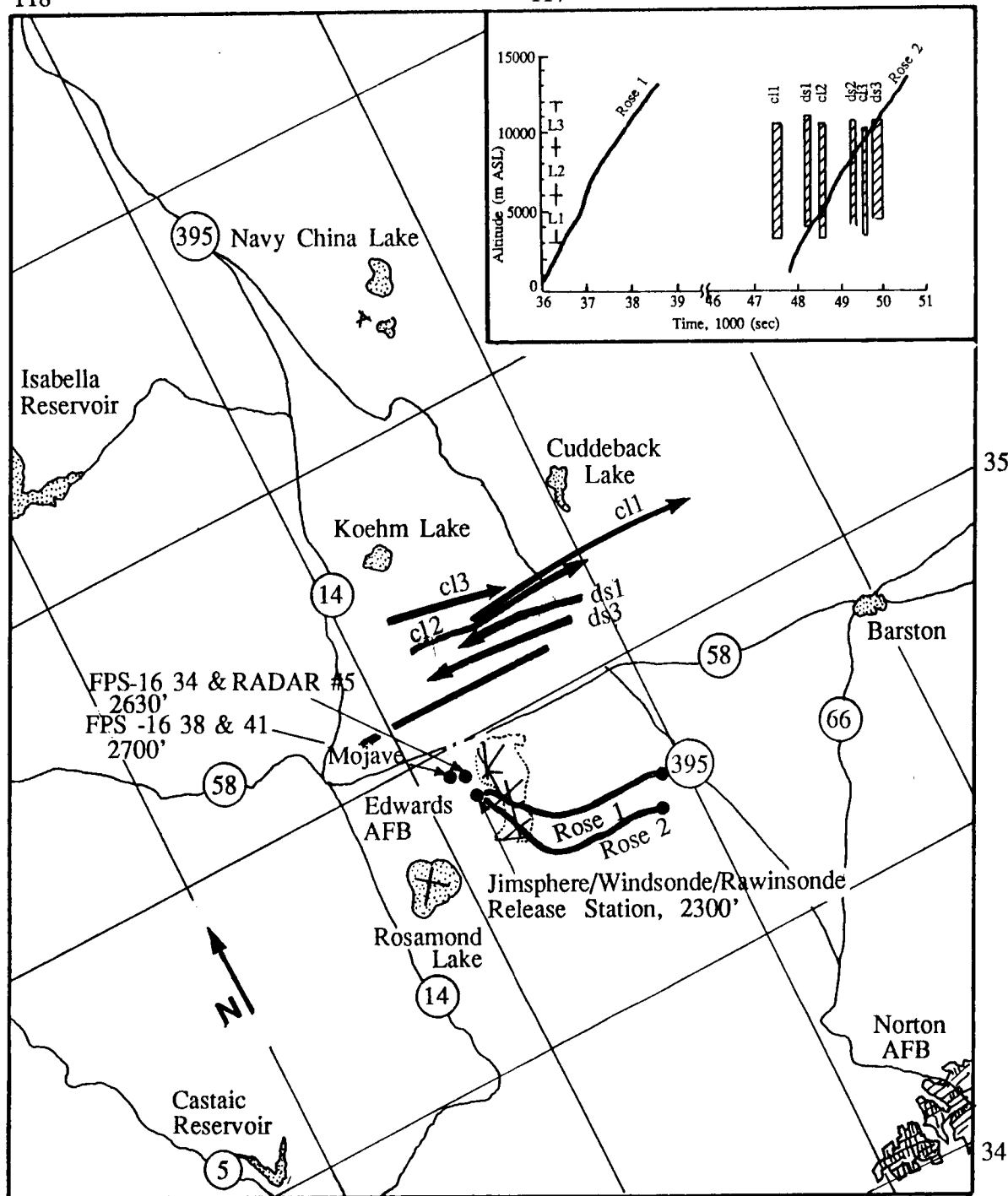
At 35° Latitude; 1° Longitude = 91.290 km, 1° Latitude = 110.938 km

Figure 4.2 Flight 1208 Jimsphere and Aircraft Paths.



At 35° Latitude; 1° Longitude = 91.290 km, 1° Latitude = 110.938 km

Figure 4.3 Flight 1210 Jimsphere and Aircraft Paths.



At 35° Latitude; 1° Longitude = 91.290 km, 1° Latitude = 110.938 km

Figure 4.4 Flight 1214 Jimsphere and Aircraft Paths.

4.2 Data Analysis

Aircraft measured data in engineering units, along with Jimsphere TAER (time, range, azimuth, elevation) data were received from NASA Dryden on magnetic tape. Table 3-1 lists the variables provided and Figure 4.5 illustrates the data flow for computing winds from the aircraft measurements. The output of the analysis based on the system of equations described in Chapter 3.0 are the north (W_N), east (W_E), vertical (W_Z) wind components, and altitude (h). These values were later converted to wind magnitude, W_H , and wind direction, θ . The data were smoothed to spatial increments, Δh , of 25 meters. Appendix A describes the smoothing procedure. This smoothing was carried out to make the aircraft data consistent in spatial averaging with the Jimsphere data which are used conventionally on government meteorological ranges.

Figure 4.6 illustrates the flow of the Jimsphere data. Two algorithms were investigated. One was developed by Lockheed (Hill 1984) and the other by The University of Dayton Research Institute (1956). The latter is called the ROSE Code. The output from both codes is the north-east wind components balloon rise rate and altitude. The two codes gave virtually the same results and therefore the ROSE Code which is the standard used on all meteorological ranges was thus used for all Jimsphere results reported in this study.

The resulting wind profiles and the differences in wind speeds at a common altitude were initially plotted and visually inspected. Example data from Flight 1208 is presented in Figures 4.7 through 4.10. All data from the F-104 flight exper-

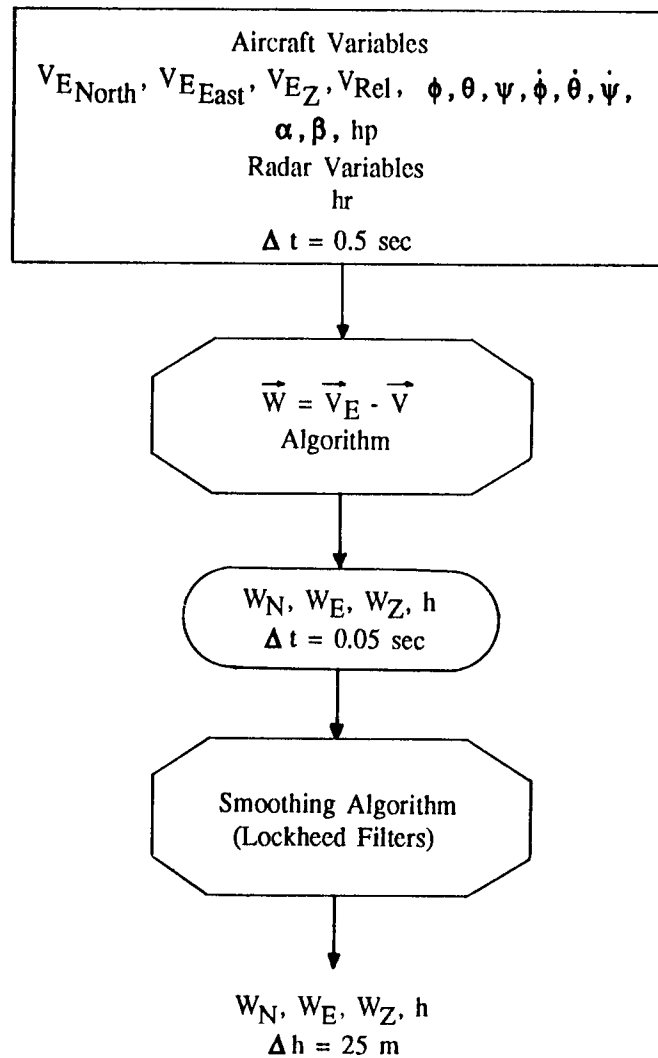


Figure 4.5 Aircraft Data Flow Chart.

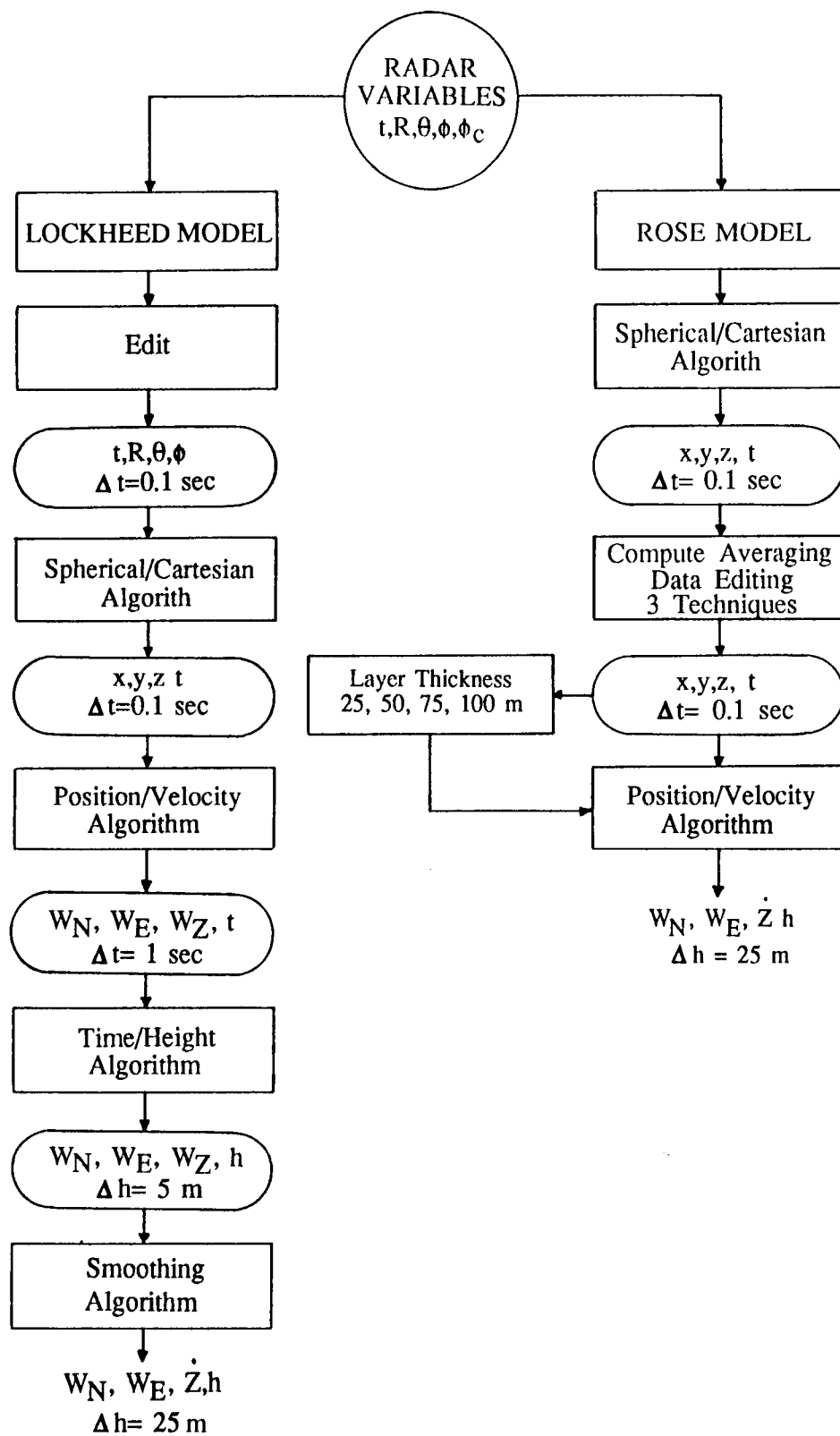


Figure 4.6 Radar Data Flow Chart.

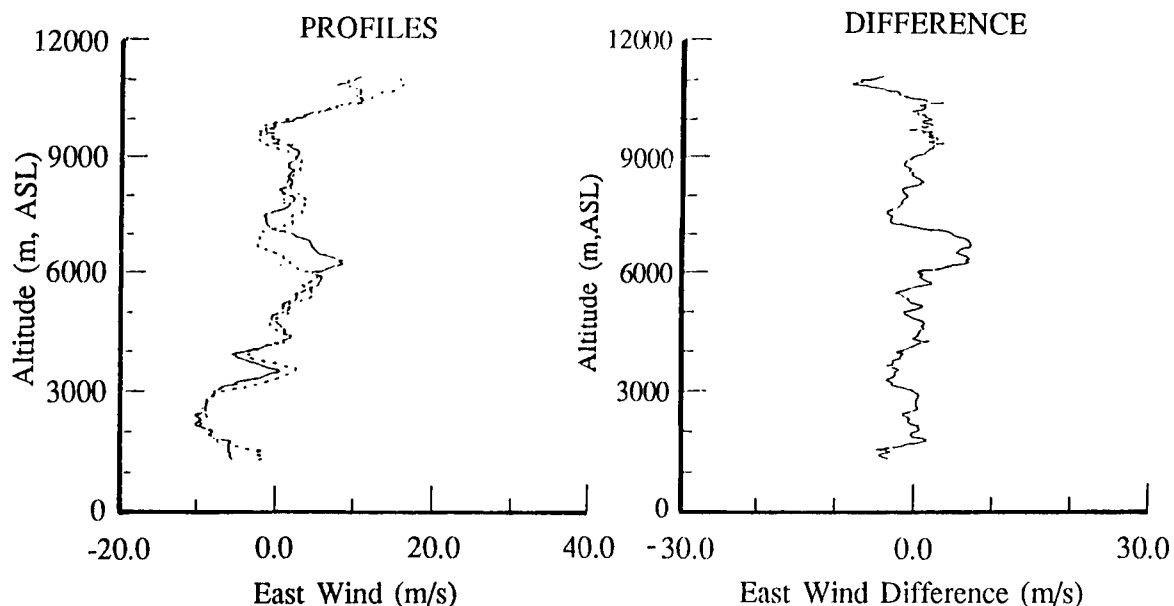


Figure 4.7 East Wind: Flight 1208 Reduced with Lockheed Technique. Jimsphere Wind is Solid Line. Aircraft Wind is Dotted Line.

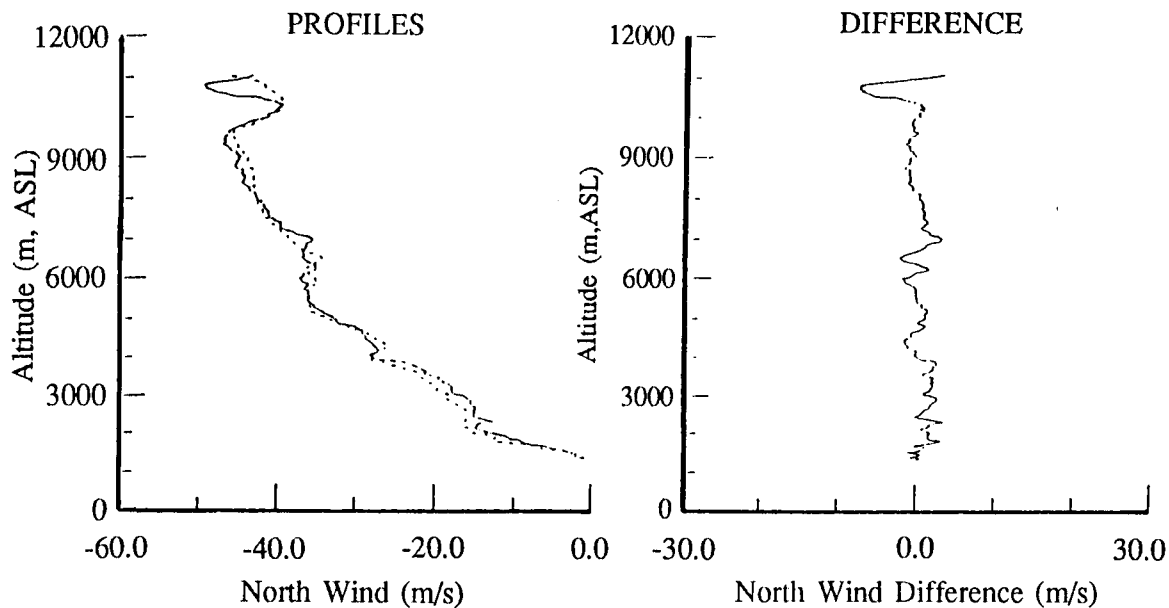


Figure 4.8 North Wind: Flight 1208 Reduced with Lockheed Technique. Jimsphere Wind is Solid Line. Aircraft Wind is Dotted Line.

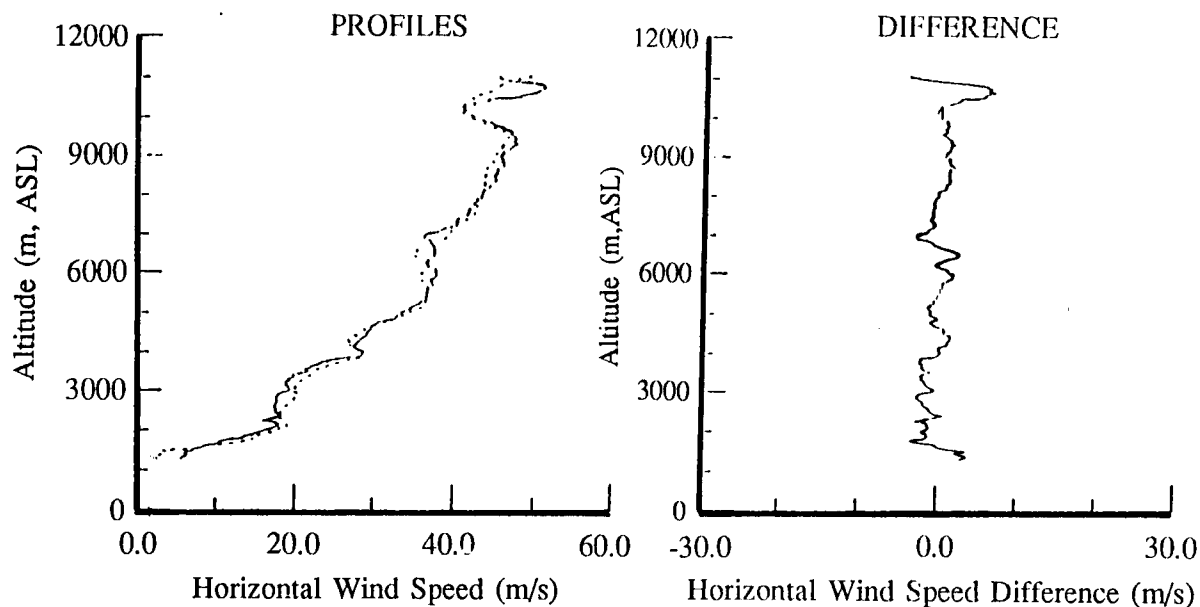


Figure 4.9 Horizontal Wind Speed: Flight 1208 Reduced with Lockheed Technique. Jimsphere Wind is Solid Line. Aircraft Wind is Dotted Line.

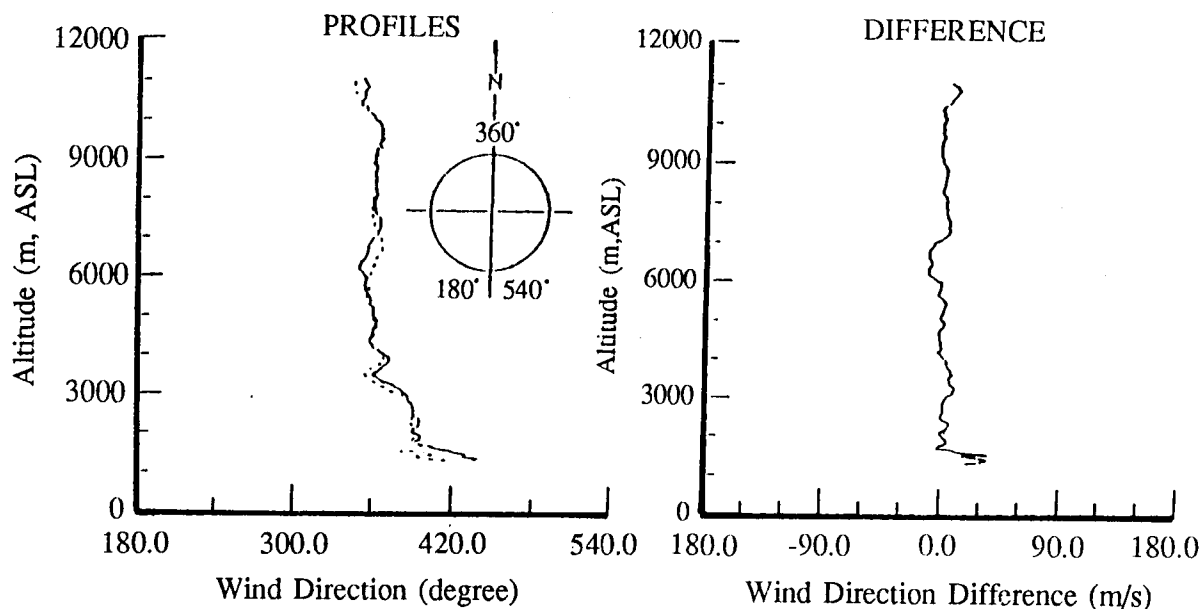


Figure 4.10 Wind Direction: Flight 1208 Reduced with Lockheed Technique. Jimsphere Wind is Solid Line. Aircraft Wind is Dotted Line.

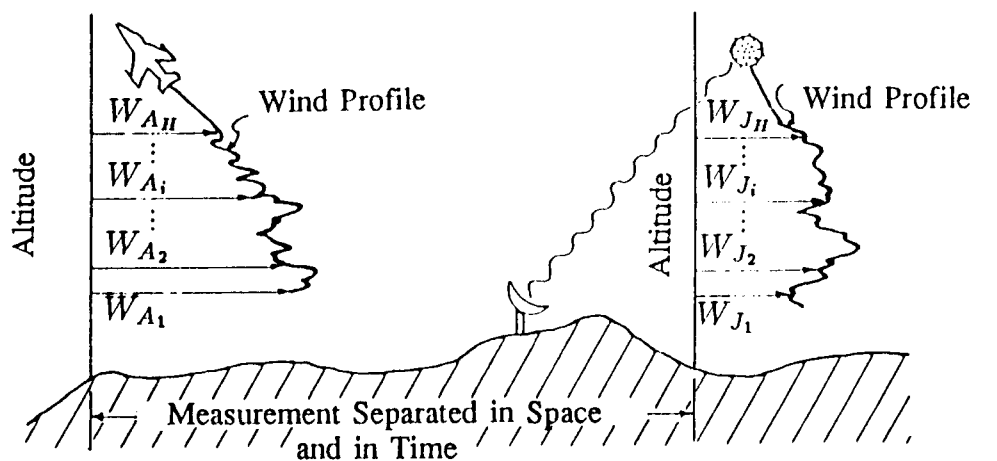
iment will be compiled in a final document reporting the results of the overall flight program. Because of the very large numbers of wind profile plots, only example results are presented here.

Flight 1208 consisted of a climb from 1,300 to 11,050 m (4,300 to 36,300 ft) over the time period of 37,820-38,220 seconds. The corresponding Jimsphere flight path occurred during the period of 37,931-40,680 seconds. Thus, the time of flights overlap with the exception of approximately the initial 110 seconds.

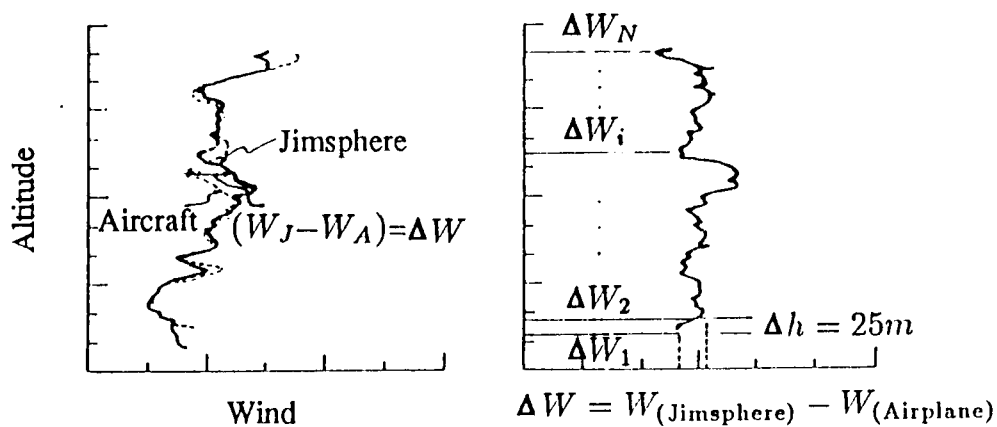
Inspection of the figures show the aircraft wind measurements agree very well with the Jimsphere measurements both in magnitude and in contour. The differences shown on the plots correspond to simply subtracting the aircraft measurement from the Jimsphere measurement at a common elevation or altitude. Note, however, that the difference shown is between winds that are occurring at different times and at different spatial positions.

4.3 Comparison Criteria

Figure 4.11a illustrates schematically that, as noted earlier, measurements by the Jimsphere and the aircraft cannot be made simultaneously in space or in time. Thus, natural, random variability of the atmosphere must be accounted for when comparing measured winds from the two systems. Figure 4.11b illustrates schematically the approach used to make this comparison. The difference in wind speeds measured by the aircraft versus that of the Jimsphere at a common altitude is first computed. Note however, these winds are at different horizontal spatial locations and at different times albeit at the same altitude. The plotted differences in



(a) Measurement cannot be made simultaneously in space or time.



(b) Compute difference in wind speeds at a common altitude.

Figure 4.11 Schematic of Statistical Analysis of Data.

winds at a common altitude are then analyzed on a statistical basis. The mean of the difference, $\overline{\Delta W}$, the root mean square of difference, $RMS \Delta W$, and standard deviation of the difference, $SD \Delta W$, are given by:

- Mean of Difference

$$\overline{\Delta W} = \frac{1}{N} \sum_{i=1}^N \Delta W_i$$

- RMS of Difference

$$RMS \Delta W = \sqrt{\frac{1}{N} \sum_{i=1}^N (\Delta W_i)^2}$$

- Standard Deviation of Difference from Mean

$$SD \Delta W = \sqrt{(RMS \Delta W)^2 - (\overline{\Delta W})^2}$$

The mean difference is simply a measurement of the difference in the wind measured by the two systems. In principle, it should be zero. The RMS of the difference represents the scatter between the Jimsphere measurement and the aircraft measurement (always a positive quantity). The standard deviation is also a measure of the scatter, but, with the mean wind subtracted out.

The primary statistical parameter used to compare the wind profiles in this study is the $RMS \Delta W$ parameter. It was determined that the RMS values of differences between Jimsphere measured wind profiles and aircraft measured wind at common heights should not exceed 2.5 m/s (4.7 kts) for the total profiles (from surface to maximum altitude) and 3.0 m/s (5.8 kts) for separate layers of three kilometer thickness. These values should not be construed to represent the absolute

accuracy with which the aircraft measures the wind speed, but the statistical limits within which the computed difference parameters can be expected to lie when comparing random winds measured at different spatial locations and at different times with different or even the same instruments. The selection of the RMS criteria was based on extensive studies of the literature and of current ongoing experiments which reported similar comparisons of wind profiles; that is, wind profiles measured with different or the same systems separated spatially and in time. Results of these studies are summarized in Table 4-1. Table 4-1 shows reported RMS differences of measured wind speeds made with a variety of wind profiling systems. The first value in Table 4-1 (0.5 m/s) is the generally accepted accuracy of the Jimsphere measured winds which is based on a single Jimsphere balloon being tracked by two independent radars.

The reported 0.5 m/s absolute accuracy is believed by this author to actually represent the accuracy with which two radars can track the same balloon. It is in truth not the true wind speed. As discussed in Section 2.0, errors associated with the fidelity of the balloon to follow the wind, the rate of spirial, etc., introduce uncertainty in the measurement which cannot be resolved quantitatively.

In turn, the wind speed measured by the Jimsphere is a spatial average over the balloon as contrasted to a more nearly point measurement, as measured with the aircraft instrumentation. Thus, comparison of the wind measurements must be made carefully. The measure of statistical "goodness" in this study is that the RMS ΔW values are less than 2.5 m/s (4.7 kts) for the full wind profile and less than 3.0

TABLE 4-1 RMS DIFFERENCES OF MEASURED WIND SPEEDS.

Difference between windspeed measured by:	RMS Difference (m/s)	Comments
Jimsphere tracked by 2 independent radars	0.5	Radar noise component in Jimsphere winds. 20 pairs/winter 86-87
Two radiosondes suspended beneath same balloon	3.1	NOAA radiosonde precision. 50 weekly flights/1978
Jimsphere and Windsonde-Mss system	1.9	Balloons launched within 15 mins of each other. 10 pairs/Jan 1986
Two Jimspheres separated by ~ 20 km	1.9	CCAFS and KSC Wx Stns for launch points. 17 pairs/Dec 87-Feb 88
Two pilot balloons with METRAC trackers separated by		0-5 km altitudes near Minneapolis
4 km	1.4	Oct. 1978
21 km	2.2	60 pairs
Two Jimspheres separated in time by		33 KSC Winter "Triplicates"
2 hrs	3.5	
3.5 hrs	5.1	
Aircraft and Jimsphere 1 climb/1 descent	1.5-2.2	Aircraft and Jimsphere spatial separation 10-20 miles with overlapping times. Altitude 9,400-12,400 meters.
Jimsphere and Windsonde/MSS pre-launch Shuttle Mission # 51-D Jimsphere/FPS-16, Two 50 MHz Doppler radars	1.2	22 pairs/March-April 85 released at the same location, separated in time by 10 minutes
Jimsphere and Radiosonde/SOUSY KSC	2.9	Radian/SOUSY wind at 150 m intervals 2-20 km
Jimsphere and NASA/NOAA profilers systems KSC	4.9	NASA/NOAA wind at 290 m intervals from 2-9.8 km; 870 m intervals from 5.5-17.7 km
Aircraft and lidar	0.6-2.5	Aircraft flight path is approximately aligned with the lidar beam positioned at a 4.5 degree elevation angle

m/s (5.8 kts) for each 3 km (985 ft) layers. If the data meet this criteria, the two systems are considered to measure equivalent winds.

4.4 Statistical Results

Table 4-2 is a comparison of the mean, the standard deviation and the RMS values, for the total wind profile using the ground speeds measured with the INS system. Results are given for the east and north wind components, as well as, for the horizontal wind speed and direction. It should be noted that a negative value of the mean difference indicates a larger aircraft measured wind than the Jimsphere measured wind. Table 4-3 shows a comparison of the RMS values when the wind profile is broken down into 3 km layers. Again, these results are calculated using the INS measured ground speeds.

Comparison tests reported for this study are based primarily on the RMS values for the horizontal wind, W_H , (i.e., the magnitude of the wind speed). These values are indicated with the heavy lined boxes in the tables. Based on the established criteria of statistical "goodness", the RMS values should be less than 3 meters per second. Inspection of the RMS example clearly illustrates that 92% of the RMS ΔW_H datum points fall within the 3.0 m/s (5.8 kts) criteria. In fact, 56% are less than 2.0 m/s (3.9 kts).

Larger RMS values than the 3.0 m/s limits are observed for those flight paths listed in Table 4-4. These large values can be justified based on explainable experimental inaccuracies.

Inspection of Flight 1207 shows that Climb 1 and Descent 1 had excessively

TABLE 4-2 COMPARISON OF THE MEAN, STANDARD DEVIATION, AND RMS VALUES OF THE TOTAL WIND PROFILES USING INS MEASURED G.S.

		Flt 1207				Flt 1210				Flt 1214							
		Rose VS.				Rose VS.				Rose 2 VS.							
		cl1	ds1	cl2	ds2	cl1	ds1	cl2	ds2	cl1	ds1	cl2	ds2	cl3	ds3		
Total Profile	MEAN	ΔW_E	-3.5	-3.2	-3.0	-3.0	0.13	1.6	-1.0	-0.42	0.97	-0.13	-5.4	-2.7	-2.8	-1.7	
		ΔW_N	0.76	-2.0	-1.4	-2.2	-0.05	0.16	0.82	-0.14	0.77	-1.9	-0.48	-0.17	-0.80	1.5	
		ΔW_H	-3.7	-2.3	-2.2	-2.0	0.16	1.8	0.00	-0.44	1.2	0.70	-4.1	-2.0	-1.7	-2.1	
		$\Delta \theta$	3.3	8.4	7.8	9.1	1.6	0.09	-5.4	-2.8	-2.1	5.4	10.2	10.8	5.9	9.2	-1.3
Total Profile	SD	ΔW_E	4.4	2.5	1.9	0.90	2.7	2.6	1.3	1.4	1.6	1.2	1.2	1.4	1.1	1.7	1.5
		ΔW_N	2.7	2.0	1.6	1.7	1.9	1.4	1.5	1.6	1.4	2.1	1.7	1.9	1.8	2.0	2.2
		ΔW_H	3.8	2.6	1.7	0.84	1.8	2.4	1.2	1.6	1.7	1.6	1.8	2.2	1.6	1.9	1.9
		$\Delta \theta$	2.2	4.9	4.2	4.4	6.8	5.9	6.4	2.8	3.8	9.2	8.7	8.1	6.3	5.8	7.6
Total Profile	RMS	ΔW_E	5.6	4.1	3.6	3.2	2.7	3.0	1.7	1.4	1.9	1.3	5.6	5.7	2.9	3.3	2.3
		ΔW_N	2.8	2.8	2.1	2.8	1.9	1.4	1.7	1.6	1.6	2.8	1.8	1.9	1.8	2.1	2.7
		ΔW_H	5.3	3.5	2.8	2.2	1.8	3.0	1.2	1.7	2.1	1.8	4.5	4.6	2.6	2.6	2.8
		$\Delta \theta$	22.3	9.8	8.2	10.1	7.0	5.9	8.4	4.0	4.3	10.7	13.4	13.6	8.7	10.9	7.7

NOTE: Negative Mean of Difference ($-\Delta W$) Indicates Larger Aircraft Winds Than Jimsphere Winds

TABLE 4-3 COMPARISON OF THE RMS VALUES 3000 METER LAYERS OF THE WIND
PROFILES USING INS MEASURED G.S.

Flt. 1207				Flt. 1208		Flt. 1210				Flt. 1214							
Rose VS.				Rose VS.		Rose VS.				Rose 2 VS.							
Layer 3	RSM	ΔWE	cl1	ds1	cl2	ds2	cl1	ds1	cl2	ds2	cl1	ds1	cl2	ds2	cl3	ds3	
		ΔWN	4.1	2.2	1.8	2.8	1.9	1.2	2.2	1.3	0.90	1.3	4.9	5.0	2.7	3.3	1.4
		ΔWH	2.6	3.4	3.2	3.4	1.6	0.89	1.2	1.3	0.69	1.9	1.4	1.6	1.9	2.4	2.2
		Δθ	3.4	2.0	1.6	2.2	1.8	1.1	0.73	1.5	0.57	2.1	3.0	3.2	2.3	2.1	2.3
		30.1	12.7	11.0	12.9	10.2	4.8	10.8	3.7	4.7	3.6	14.2	15.2	8.7	13.1	4.6	
Layer 2	RSM	ΔWE	7.4	6.1	2.9	3.4	3.6	1.8	1.7	1.3	1.7	1.3	6.1	6.6	3.4	3.8	2.9
		ΔWN	3.8	2.7	1.7	3.0	1.2	2.1	2.4	1.5	1.6	3.7	1.9	2.1	1.9	1.4	2.5
		ΔWH	7.6	5.2	2.3	2.1	1.2	1.6	1.7	1.7	2.1	1.7	4.7	5.6	2.9	3.2	3.5
		Δθ	7.2	9.5	5.5	9.5	5.5	8.6	9.2	3.6	3.7	15.8	16.2	15.1	10.3	9.7	6.3
Layer 1	RSM	ΔWE	4.3	2.4	4.9	3.3	2.5	4.9	1.0	1.8	2.9	1.2	5.3	4.8	2.3	1.4	1.7
		ΔWN	1.6	2.2	1.4	1.5	2.6	0.84	1.1	2.1	2.3	2.1	1.9	2.0	1.5	2.8	3.4
		ΔWH	2.8	1.8	3.7	2.2	2.2	4.9	0.89	1.8	3.1	1.2	5.4	4.9	2.4	1.7	2.0
		Δθ	25.7	6.4	8.1	6.7	3.5	1.6	2.6	4.7	4.7	7.0	5.3	4.7	8.5	11.5	

**TABLE 4-4 FLIGHT PATHS WHERE RMS VALUES EXCEED EXPECTED
VALUE OF 3.0 m/s (5.8 kts)**

FLT. 1207

- C11 ~ TURN MID-LAYER
- Ds1 ~ TURN MID-LAYER
- C12 ~ TURN UPPER LAYER

FLT. 1210

- C11 ~ SPATIALLY SEPARATED
(≈ 140 km)

FLT 1214

- Ds1 ~ INS DRIFT
- C12 ~ INS DRIFT

large RMS values in the mid-layer and Climb 2 had an excessively large value in the upper layer. Examination of Figure 4.1 suggests that these effects are associated with sharp aircraft turns. For example, Climb 1 had a 180° turn which occurred within the middle 3 km (985 ft) increment. In turn, Decent 1, although off the graph, had a similar 180° turn. Correspondingly, Climb 2 had a very sharp turn in the upper level prior to discontinuation of the climb. Although a quantitative justification for why the instrumentation gives large errors during sharp turns of the aircraft is not readily available, it is concluded from the above observations that while measuring wind profiles straight flight paths should be maintained.

Inspection of Table 4-3 for Flight 1210 indicates that during Climb 1 an RMS of 4.9 m/s (9.5 kts) was encountered in the upper level. For this particular climb, Figure 4.3 shows that the flight path was over 140 kilometers from the Jimsphere flight path. The high value of RMS for this flight is attributed to the large separation distance between the two measurements.

Finally, inspection of data for Flight 1214 shows very large discrepancies in the data for Descent 1 and Climb 2. These departures from "goodness" of fit are associated with the Schuler drift in the INS ground speed measurements. This is apparent from inspection of Table 4-5 which is a calculation of the RMS wind speeds for Flight 1214 using radar measured ground speeds. Unfortunately, the radar data are not good for Climb 3 and Descent 3. The RMS values shown in the table demonstrate that Descent 1 and Climb 2 now comply with the expected RMS values, with the exception of Layers 1 and 2 of Descent 1 and Layer 2 of Climb 2.

TABLE 4-5 COMPARISON OF THE RMS VALUES FOR 3000 METER LAYERS
OF THE PROFILES USING RADAR MEASURED G.S.

		Radar G.S.							Radar G.S., Aero. Corr. Included						
		Rose 2 VS. Aircraft							Rose 2 VS. Aircraft						
Layer 3	RMS	ΔW_E	cl1	ds1	cl2	ds2	cl3	ds3	cl1	ds1	cl2	ds2	cl3	ds3	
		ΔW_N	1.2	2.4	3.0	0.82		1.8	1.6	1.4	2.8	0.82			
		ΔW_H	1.8	1.2	1.4	1.9		2.2	1.7	1.2	1.5	1.9			
		$\Delta \theta$	1.8	1.9	2.3	2.0		2.4	1.7	1.6	2.1	2.0			
Layer 2	RMS	ΔW_E	2.2	4.0	4.5	1.6			2.8	2.9	4.3	2.0			
		ΔW_N	4.1	1.8	2.2	2.1			4.0	1.9	2.2	1.9			
		ΔW_H	1.6	3.4	3.9	1.9			1.7	2.7	3.7	2.2			
		$\Delta \theta$	18.7	10.7	12.0	7.5			18.9	8.4	11.8	6.9			
Layer 1	RMS	ΔW_E	1.9	3.4	2.2	0.76	0.68	1.3	2.5	2.9	1.6	1.1			
		ΔW_N	2.6	2.1	2.2	1.4	2.9	3.7	2.2	2.2	2.2	1.3			
		ΔW_H	2.0	3.4	2.3	0.64	0.84	1.6	2.6	2.9	1.7	1.1			
		$\Delta \theta$	8.5	7.0	6.7	5.6	9.6	12.6	6.9	7.8	7.0	4.7			

Table 4-5 also shows the RMS results when aerodynamic corrections are applied to the aircraft instrumentation for vane geometric distortion and subsonic Mach number effects. With the appropriate corrections, all but the Climb 2 Layer 2 RMS values fit within the expected statistical "goodness" criteria. There is no explanation of this large RMS other than Figure 4.4 shows the wind as measured by the Jimsphere makes a relatively sharp (approximately 90°) turn at that particular level. It is physically reasonable that this turning layer was changing position with time during the experiment, due to natural atmospheric variability, resulting in an actual difference in winds between the aircraft measured values and the Jimsphere measured values.

Further indication of the effect of the Schuler drift on Flight 1214 is shown in Figures 4.12 and 4.13. Figure 4.12 is a plot of the mean of the difference in wind speed as a function of time. If a Schuler drift effect influences the measurements, it will have an approximate 84 minute period. Schuler oscillation would result in a bias between the measured winds and the aircraft winds which would vary with the approximate same 84 minute period. It is clear from the plot that the data corresponds roughly to this anticipated sinusoid variation.

Additionally, one can see from Figure 4.13 that when the wind profiles computed from data using INS ground speeds versus those using radar ground speeds are compared; Climb 1, Climb 3 and Descent 3 lie almost on top of one another; whereas Descent 1, Climb 2 and Descent 2 show an increasing and decreasing bias with time. This displacement of the curves suggesting a sinusoidal varying bias in

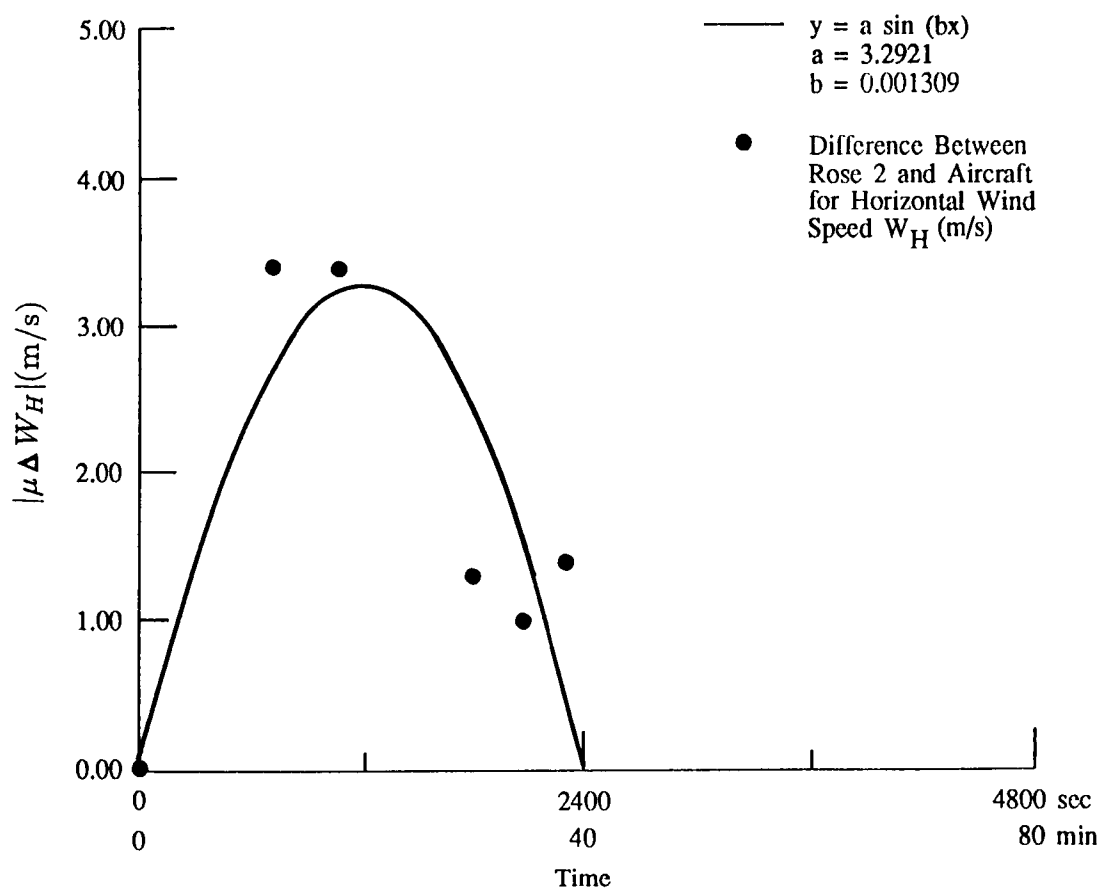


Figure 4.12 Sinusoidal Curve-fit of Absolute Values of Mean of Difference of Horizontal Wind Speed for Flight 1214 (3C/3D) Relative to the Lowest Value.

the wind measurement by the aircraft. The bias begins with Descent 1, becomes larger with Climb 2, and then decreases during Descent 2. The visual observation of a bias in the wind speeds is consistent with the sinusoidal plot in Figure 4.12.

5.0 CONCLUSIONS

Based on the results of the statistical analysis, it is concluded that the aircraft measured wind profiles up to 40,000 ft are the same quality as the Jimsphere measured winds. This conclusion is based on the statistical parameters which include the mean of the wind difference at a common altitude, the RMS of the wind difference at a common altitude, for both the total profiles and for 3,000 m segmented layers.

Based on the data presented, no definite conclusion on the need for radar measured ground speeds versus INS measured ground speeds has been reached. The data are insufficient at the present time; however, the limit data suggests there is a problem of INS drift and that an alternate method of providing ground speed will be required for operations.

Other observations from the data analysis are that larger RMS values, or poor agreement with the data occur for flights in which the aircraft undergoes relatively sharp turns. It is therefore recommended that all operational flights should be carried out along straight climb and descent profiles. It is also observed that large spatial separations cause larger values of the RMS or poor agreement between the two measurement systems. However, it is also observed that flights which do not overlap in time with the Jimsphere flights give poorer agreement than those separated spatially but which do overlap in time. Thus, a departure in time seems more significant than a departure in space when making comparisons between wind

profiles measured with two systems at different positions and times.

It is recommended that additional flights be carried out to higher altitudes to provide assurance that equivalent winds can be measured to the required 18 km (60,000 ft) altitude for STS operational wind profile measurements.

APPENDIX

DATA REDUCTION PROCESS

The aircraft data is reduced to wind data and then filtered with a technique similar to the smoothing process described by Hill (1984). A flowchart of the smoothing process to obtain winds at 25 m intervals is given in Figure A.1. The numerical smoothing technique is a low-pass filter designed by Graham (1963). The filter or gain function is defined in the frequency domain, where frequency (f) is the independent variable and gains of frequencies ($G(f)$) is the dependent variable. Wind data are analyzed in the time domain, thus requiring transformation of the gain function in the frequency domain to a weight function in the time domain.

A simple low-pass gain function in the frequency domain is:

$$G(f) = \begin{cases} 1; & f < f_c \text{ (cutoff frequency)} \\ 1/2 [\cos(\frac{f-f_c}{f_t-f_c}\pi) + 1]; & f_c < f < f_t \text{ (termination frequency)} \\ 0; & f > f_t \end{cases} \quad (A-1)$$

The weight function in the time domain is the inverse Fourier transformation given by:

$$h(t) = \frac{\sin(2\pi f_t t) + \sin(2\pi f_c t)}{2\pi t[1 - 4t^2(f_t - f_c)^2]} \quad (A-2)$$

This is the basic functional form from which numerical smoothing weights are defined. To obtain weights at distinct points, a sum must be substituted for the integral in the Fourier equation. The response function of $2N+1$ weights is:

$$\hat{G}(f) = h_o + 2 \sum_{i=1}^N h_i \cos(2\pi f i \Delta t) \quad (A-3)$$

The comparison between the digitized gain function and the original gain function shows the precision of the output filter. Figure A.2 shows the response characteristics of the 55- point weights used to obtain smoothed 1-second wind velocity

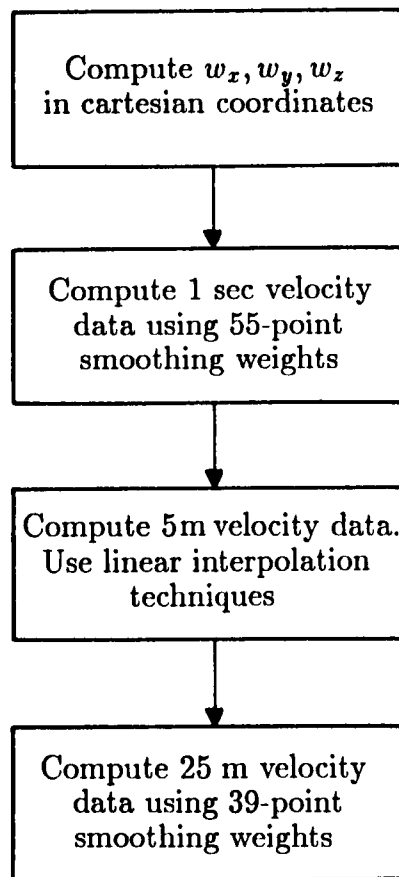


Figure A.1 Flowchart of the Smoothing Procedures for Aircraft-Measured Wind Profiles.

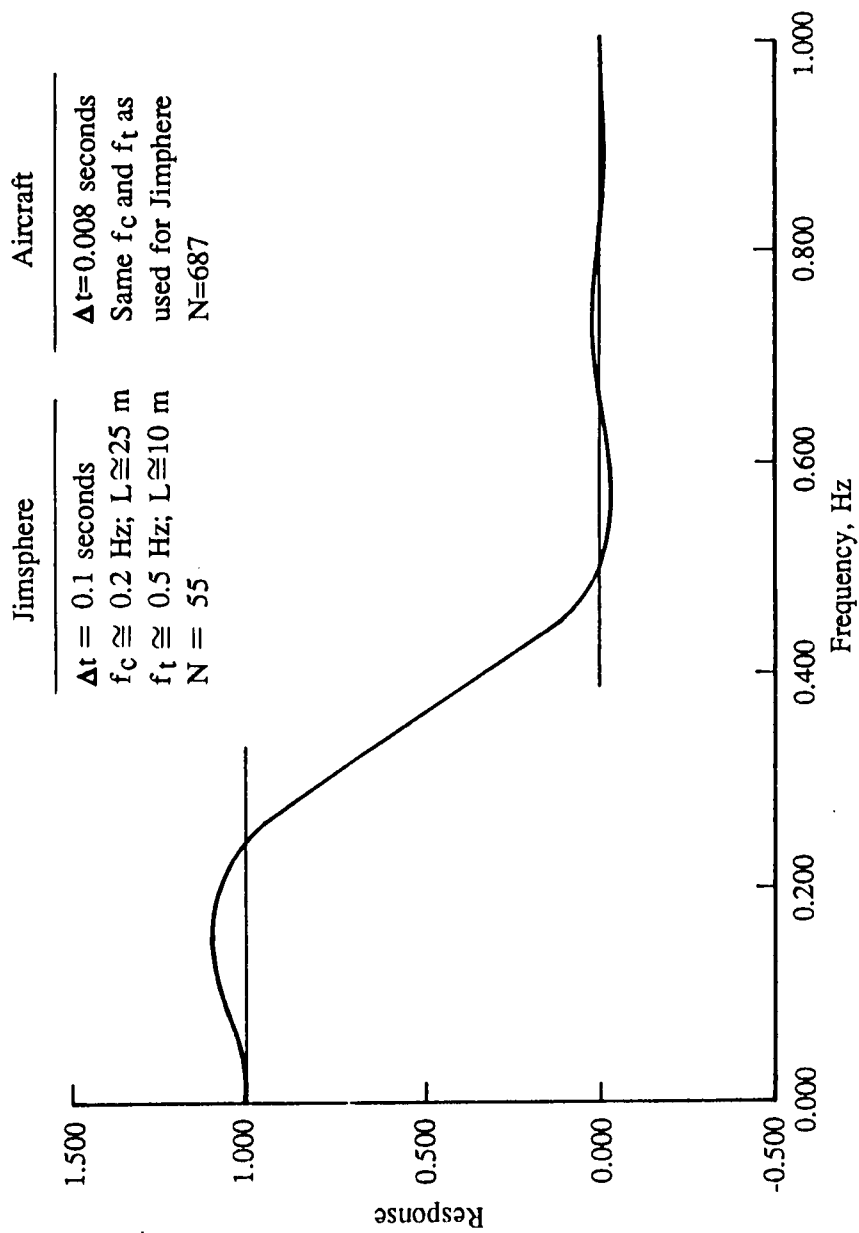


**Figure A.2 Response Characteristics of the 55-Point Weights (A Martin-Graham Low-Pass Filter)
Used to Obtain Smoothed 1-Second Velocity Data From 0.1 Second Data.**

data. The response characteristics of the 39-point weights for obtaining 25 m wind data is shown in Figure A.3. The 55-point weights and 39-point weights used to reduce aircraft measured winds are given in Tables A-1 and A-2 respectively. These weights were chosen since they provide a desirable frequency response.

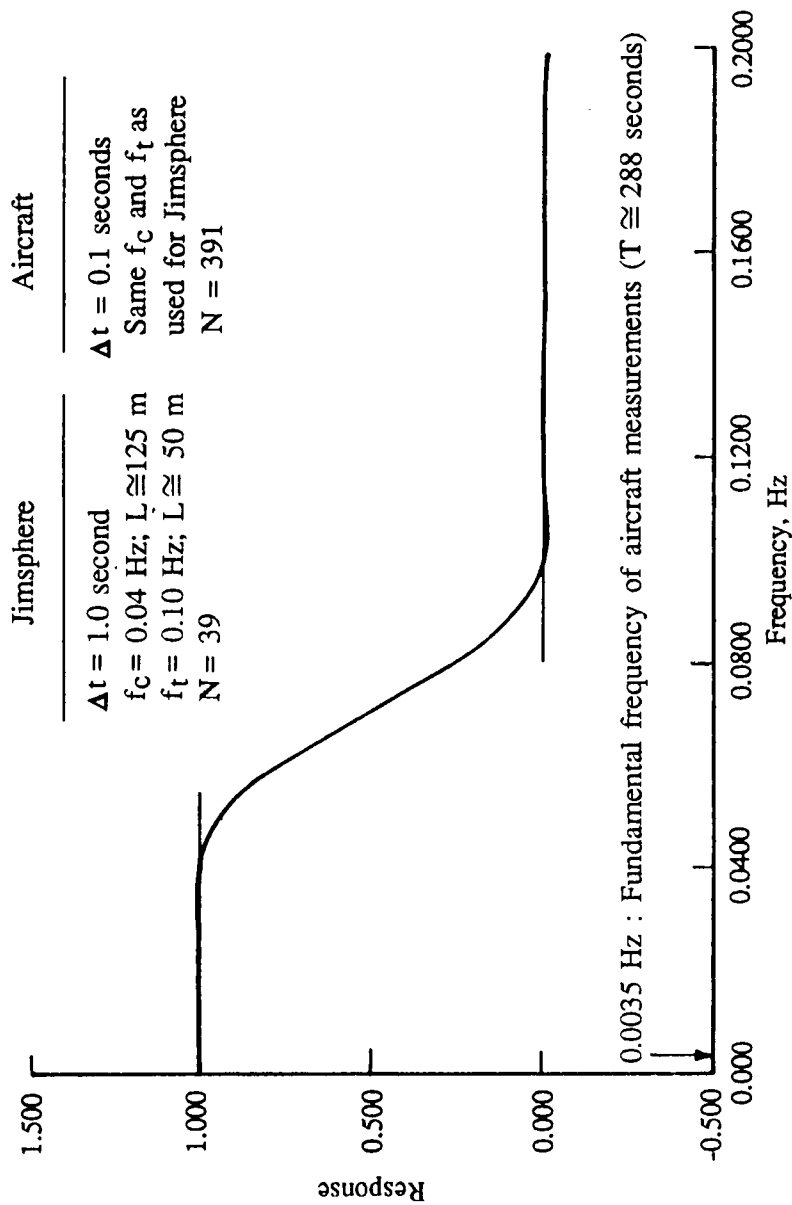


Figure A.3 Response Characteristic of the 39-Point Weights (A Martin-Graham Filter) Used to Obtain Smoothed 25 m Velocity Data From 5 m Data.

**TABLE A-1 WEIGHTS USED TO OBTAIN SMOOTHED 1-SECOND
VELOCITY DATA**

Points	Weight	Points	Weight
(1.55)	-0.00170115	(15.41)	0.00536330
(2.54)	-0.00335008	(16.40)	0.01109891
(3.53)	-0.00509943	(17.39)	0.01746935
(4.52)	-0.00685550	(18.38)	0.02431932
(5.51)	-0.00850874	(19.37)	0.03146420
(6.50)	-0.00993790	(20.36)	0.03869666
(7.49)	-0.01101528	(21.35)	0.04579480
(8.48)	-0.01161294	(22.34)	0.05253129
(9.47)	-0.01160935	(23.33)	0.05868300
(10.46)	-0.01089632	(24.32)	0.06404076
(11.45)	-0.00938586	(25.31)	0.06841865
(12.44)	-0.00701636	(26.30)	0.07166239
(13.43)	-0.00375300	(27.29)	0.07365641
(14.42)	0.00038329	(28.28)	0.07432916

**TABLE A-2 WEIGHTS USED OVER A 39-POINT INTERVAL TO
COMPUTE 25 m VELOCITY DATA**

Points	Weight	Points	Weight
(1.39)	0.31609500E -02	(11.29)	-0.19400450E -01
(2.38)	0.46590200E -02	(12.28)	-0.11719670E -01
(3.37)	0.54903200E -02	(13.27)	0.24096200E -02
(4.36)	0.50246700E -02	(14.26)	0.22573790E -01
(5.35)	0.27815200E -02	(15.25)	0.47256220E -01
(6.34)	-0.13689400E -02	(16.24)	0.73969890E -01
(7.33)	-0.70447600E -02	(17.23)	0.99595700E -01
(8.32)	-0.13284600E -01	(18.22)	0.12087210E -00
(9.31)	-0.18611820E -01	(19.21)	0.13494444E 00
(10.30)	-0.21240690E -01	(20.20)	0.13986549E 00

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VITA

Charles Kelly Hill was born in Lafayette County, Oxford, Mississippi on December 26, 1938. He is the son of James Howell Hill and the former Lillian Gladys Livingston. He has one brother, James William Hill and one sister, Mrs. Lillian Joanne Klenk. He received his high school education at Millington Central High School in Millington, Tennessee, graduating in June 1957. In 1957 he entered the University of Tennessee, Martin, transferring in 1959 to Florida State University in Tallahassee where he received his Bachelor of Science degree in Meteorology in 1962 from the Department of Meteorology. He did post-graduate work at the University of Alabama in Huntsville from 1963 to 1973. In December 1984 he was awarded the Master of Science degree in Engineering Science from the University of Tennessee Space Institute.

After graduating from Florida State University in June 1962 he was employed by the U.S. Weather Bureau (now National Weather Service). Since October 1962 he has been employed by the National Aeronautics and Space Administration, Marshall Space Flight Center; Huntsville, Alabama, as an Aerospace Engineer and a Space Scientist.