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AN IN-FLIGHT TECHNIQUE FOR WIND MEASUREMENT IN SUPPORT OF THE SPACE SHUTTLE PROGRAM

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Abstract

A technique to use an aircraft to measure wind profiles in the altitude range of 1,500 to 18,200 m has been demonstrated at NASA Ames-Dryden Flight Research Facility. This demonstration was initiated at the request of NASA Johnson Space Center to determine if an aircraft could measure wind profiles in support of space shuttle launches. The Jimsphere balloon is currently the device used to measure pre-launch wind profiles for the space shuttle. However, it takes approximately an hour for the Jimsphere to travel through the altitudes of interest. If these wind measurements could be taken with an aircraft closer to launch in a more timely manner and with the same accuracy as a Jimsphere balloon, some uncertainties in the measurements could be removed. The aircraft used for this investigation was an F-104G which is capable of flight above 18,000 m. It had conventional research instrumentation to provide air-data and flow angles along with a ring laser gyro inertial navigation system (INS) to provide inertial and Euler angle data. During the course of 17 flights, wind profiles were measured in 21 climbs and 18 descents. Preliminary comparisons between aircraft measured wind profiles and Jimsphere measured profiles show reasonable agreement (within 3 m/sec). Most large differences between the profiles can usually be explained by large spatial or time differences between the Jimsphere and aircraft measurements, the fact that the aircraft is not in a wings-level attitude, or INS shifts caused by aircraft maneuvering.

Nomenclature

AICS	airborne instrumentation computer system
EAFB	Edwards Air Force Base
FPS	fixed point station
H_p	pressure altitude, m
$\dot{h}$	rate of change of altitude, m/min
INS	inertial navigation system
LCD	liquid crystal display
M	Mach number
NACA	National Advisory Committee for Aeronautics
PCM	pulse code modulation
u	x-axis component of airspeed, m/sec positive forward
V	scalar airspeed, m/sec
V_{dn}	vertical component of airspeed, m/sec positive down
V_e	east component of airspeed, m/sec positive to east
V_G	scalar ground speed, m/sec
V_{G_e}	east component of ground speed, m/sec positive to east
V_{G_n}	north component of ground speed, m/sec positive to north
$V_{G_{up}}$	vertical component of ground speed, m/sec positive up
V_n	north component of airspeed, m/sec positive to north
v	y-axis component of airspeed, m/sec positive right
W	scalar wind speed, m/sec
W_e	east wind component, m/sec positive to east
W_n	north wind component, m/sec positive to north
W_{up}	vertical wind component, m/sec positive up
w	z-axis component of airspeed, m/sec positive down
Z	geometric altitude, m
α	angle of attack, deg
β	angle of sideslip, deg
γ	flightpath angle, deg
ΔW_e	Jimsphere minus aircraft east component, m/sec

ΔW_n	Jimsphere minus aircraft north component, m/sec
θ	Euler pitch angle, deg
ϕ	Euler roll angle, deg
ψ	Euler yaw angle, deg
ψ_{tr}	flight track angle, deg

Introduction

The most common method used to obtain atmospheric wind profiles is by tracking a rising balloon that moves with the winds, that is, Jimsphere or Rawinsonde. Balloon methods are adequate for many applications but some limitations exist. For example, it is impossible to control a balloon's flightpath once launched. In addition, the typical rise rate is approximately 5 m/sec so that about an hour is required to obtain a profile to 20,000 m. For certain applications, such as the space shuttle program, it would be desirable to obtain wind profiles quickly, on the order of 10–15 min. The preprogrammed launch trajectory for the space shuttle is based partially on an expected wind profile for a specific time of year. If winds are significantly different from the expected winds on the launch day, it is possible that certain structural load limits could be exceeded. Currently, day of launch winds are measured using a series of Jimsphere balloons with the last balloon used for loads assessment launched two hours prior to shuttle launch. After waiting approximately one hour for the Jimsphere to reach 20,000 m, the wind data is fed into a trajectory simulation and a loads prediction program. A wind persistence factor is also added to the calculations in an attempt to account for any wind changes over time and the possibility that the balloon may have been blown away from the launch path. Several studies, Hill (1986), Adlefang(1987), and Wilfong and Boyd (1989), have shown these changes to increase significantly when delays are longer than 2 hours or spatial separations are greater than 20 km. Depending on the results of the loads predictions, a go–no-go recommendation for launch is made.

To cut down the uncertainties in the pre-launch wind load assessment due to time and spatial variabilities in the winds measured by the Jimsphere, NASA Johnson Space Center requested NASA Ames-Dryden Flight Research Facility to perform a flight experiment. The objective was to determine the feasibility of using an instrumented high-performance aircraft to measure wind profiles. For this technique to be applicable to the space shuttle program, the following guidelines were suggested: 1) time to obtain profile to 18,000 m; 10–15 min, 2) aircraft profile area; within a 16-km radius circle and 3) accuracy of the measurement as good as the Jimsphere system. Aircraft have been used to obtain wind measurements previously, but most results have been obtained during steady level flight as discussed by Lenschow (1986), Ritter and others (1987), and Schänzer and others (1987). Basically, the wind speed is equal to the aircraft ground or inertial speed minus the airspeed. In steady level flight many simplifying assumptions can be made. However, in high speed or descending flight, as would be used to minimize time and spatial separation for a shuttle application, many of these assumptions are no longer valid. In addition, previous aircraft wind profile measurements have given little attention to the altitudes between 9,000 and 14,000 m where the aerodynamic forces on the space shuttle launch system are the greatest.

The aircraft used for this experiment was an F-104G, a single-engine, single-seat fighter. The F-104 airplane was instrumented with a National Advisory Committee for Aeronautics (NACA) type noseboom to obtain airspeed and flow angle information and accelerometers near the aircraft center of gravity. A ring laser gyro inertial navigation system (INS) was added to provide inertial speeds and angles as well as Euler angles and angular rates. An airborne instrumentation computer system (AICS) was also added to provide airdata information to the INS and to put the INS outputs on to the telemetered data stream. Radar tracking with ground based fixed point station (FPS-16) precision radar provided alternate inertial speed and angle measurements. After initial system checkout and airdata calibration flights, wind profile data were obtained during 21 climbs and 18 descents in both subsonic and supersonic flight. A maximum altitude of 20,400 m and a maximum Mach number of 2.0 were obtained in these flights. To assess the system accuracy, the aircraft wind profile data were compared with Jimsphere balloon profiles obtained during or within an hour of the flight data, knowing there would be time and spatial differences between the two measurements.

This paper describes the experiment and methods used to determine winds, presents selected wind profiles and their comparisons with Jimsphere, and discusses problems encountered during the experiment. This interim paper describes the overall flight experiment and the present status of data analysis.

Aircraft Description

The aircraft used for this experiment was a NASA F-104G. It is a single-seat, single-engine fighter type aircraft and is shown in Fig. 1. The F-104G airplane has a wing span of 6.68 m and an overall length of 16.69 m. The mean aerodynamic chord of the F-104G wing is 2.91 m. It is capable of flying at speeds up to Mach 2.2 and cruising at altitudes up to 18,500 m. Altitudes of more than 27,400 m are obtainable by using a zoom maneuver. At altitudes above 15,000 m the aircraft must remain supersonic in order to stay above its 1-g stall margin.

Instrumentation

Prior to this experiment, the F-104G airplane was instrumented for research aerodynamic experiments. This existing instrumentation included an airdata system, three axis accelerometers, rate gyros, and an uplink guidance system. To meet the requirements of this experiment, the following systems were added: 1) a ring laser gyro INS, 2) an AICS, and 3) a liquid crystal display (LCD) cockpit display. Each of the existing and new instrumentation systems will be briefly described in the following material.

Airdata System

The airdata system consists of a NACA type noseboom described 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 was mounted on the chin of the aircraft. The noseboom had two sets of static pressure ports; one of which was used for cockpit display and the other for research data. This arrangement was an attempt to minimize pressure lags in the system. There were separate pressure transducers for each set of static pressure ports and 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. Figure 2 shows the locations of the different components of the airdata system.

Accelerometers and Rate Gyros

A three axis accelerometer package was mounted in the electronics bay as indicated in Fig. 1. Pitch- and roll-rate gyros were also mounted in the electronics bay. All these measurements except normal acceleration were used as backups for this experiment. Normal acceleration was used to correct angle of attack for boom bending.

Uplink Guidance System

The uplink is a flight trajectory guidance system which uses an analog cockpit display that indicates deviations from desired flight conditions in real time. It was used to assist the pilot in obtaining accurate flight conditions for certain test points in a timely manner. As can be seen in Fig. 3, the way in which the cockpit display is mounted obscures the pilot's outside view and a chase aircraft is required when the system is installed. Therefore, the system was removed from the aircraft when chase aircraft support was not possible, such as during zoom climbs. The deviations for the following parameters were able to be displayed: M, α, β, H_p, Z, and $\dot{h}$. The uplink guidance system is discussed in detail by Meyer and Schneider (1983).

Inertial Navigation System

To obtain ground speeds and angles as well as Euler angles and rates, a ring laser gyro 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 airdata parameters must be input continuously. These parameters include Mach number, pressure altitude, calibrated and true airspeed, and ambient temperature.

Airborne Instrumentation Computer System

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

Liquid Crystal Display

In addition to the uplink guidance display, an LCD digital display was added to the cockpit. This display could be programmed to display any desired parameters and was updated approximately once every 2–3 sec. It was used to check the health of the INS and AICS as well as to provide the pilot with guidance information when the uplink was removed from the aircraft. This display could be folded back out of the way if necessary.

Radar Description

The radar values for both the Jimsphere and the F-104G aircraft were obtained using the FPS-16 radar facility. The Jimsphere was skin tracked and the aircraft was beacon tracked. The resulting time histories of range, elevation angle, and azimuth angle were converted to position and differentiated to give Earth-relative velocity. Under nominal conditions the Ames-Dryden FPS-16 radar facility is believed to be accurate to within 5 m in range and 0.001° in azimuth and elevation angles according to Whitmore and others, (1984).

Jimsphere Description

The Jimsphere wind measurement system consists of an aluminium coated mylar balloon which is skin tracked by an FPS-16 precision radar. The balloon, shown in Fig. 4, has conical protrusions in order to damp out any random motions of the balloon. The root mean square error of the radar tracking of the Jimsphere quoted by Hill (1986) is 0.5 m/sec for wind velocities averaged over 50 m intervals. Studies conducted by Hill (1986), Adlefang (1987), and Wilfong and Boyd (1989) show that the comparability of results from two Jimspheres is on the order of 2 to 3 m/sec if the time separation is 1 hour or the distance separation is 20 km.

Wind Equations

In simple terms, the wind is equal to the ground speed minus the airspeed. However, both velocity measurements must be in the same axis system. To accomplish this, the scalar airspeed is transformed to the aircraft body-axis system by using the following equation:

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = V \begin{bmatrix} \dfrac{1}{\sqrt{1 + \tan^2 \alpha + \tan^2 \beta}} \\ \dfrac{\tan \beta}{\sqrt{1 + \tan^2 \alpha + \tan^2 \beta}} \\ \dfrac{\tan \alpha}{\sqrt{1 + \tan^2 \alpha + \tan^2 \beta}} \end{bmatrix}$$

All of the inputs to this equation (velocity, angle of attack, and angle of sideslip) were obtained from the airdata system. The velocity has been corrected for position error and the flow angles have been corrected for vane offsets, angular rates, boom bending, shock interaction, and up- and sidewash effects.

To transform the body-axis velocity components into inertial-axis velocity components, the classic Euler angle transformation matrix is used

$$\begin{bmatrix} V_n \\ V_e \\ V_{dn} \end{bmatrix} = \begin{bmatrix} \cos\theta\cos\psi & \sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi & \cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi \\ \cos\theta\sin\psi & \sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi & \cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi \\ -\sin\theta & \sin\phi\cos\theta & \cos\phi\cos\theta \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix}$$

The Euler angles used as inputs to this equation were obtained from the onboard INS.

To transform the scalar ground speed into the inertial-axis system, the following matrix equation was used

$$\begin{bmatrix} V_{G_n} \\ V_{G_e} \\ V_{G_{up}} \end{bmatrix} = V_g \begin{bmatrix} \cos\psi_{tr} \\ \sin\psi_{tr} \\ \tan\gamma \end{bmatrix}$$

The inputs to this set of equations (ground speed, ground track angle, and flightpath angle), were either obtained from the onboard INS or from FPS-16 precision radar tracking.

Finally, the inertial axis components of the wind are obtained by simple subtraction as shown in the following equation

$$\begin{bmatrix} W_n \\ W_e \\ W_{up} \end{bmatrix} = \begin{bmatrix} V_{G_n} - V_n \\ V_{G_e} - V_e \\ V_{G_{up}} + V_{dn} \end{bmatrix}$$

which yields the following

$$W_n = V_{G_n} - \frac{V}{\sqrt{1 + \tan^2\alpha + \tan^2\beta}} [\cos\theta\cos\psi + \tan\beta \times (\sin\phi\sin\theta\cos\psi - \cos\phi\sin\psi) + \tan\alpha(\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi)]$$

$$W_e = V_{G_e} - \frac{V}{\sqrt{(1 + \tan^2\alpha + \tan^2\beta}} [\cos\theta\sin\psi + \tan\beta \times (\sin\phi\sin\theta\sin\psi + \cos\phi\cos\psi) + \tan\alpha(\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi)]$$

$$W_{up} = V_{G_{up}} + \frac{V}{\sqrt{1 + \tan^2\alpha + \tan^2\beta}} [-\sin\theta + \tan\beta\sin\phi\cos\theta + \tan\alpha\cos\phi\cos\theta]$$

Results and Discussion

Over the course of 17 flights, wind profile data was obtained with the F-104G airplane during 21 climbs and 18 descents. Table 1 presents a summary of these profiles. Most of these climbs and descents were subsonic (M = 0.9) and low altitude ($Z \leq$ 12,000 m). To attain altitudes above 14,000 m, a portion of the profile had to be supersonic. These profiles were broken into subsonic and supersonic segments as shown in Fig. 5. Both shuttle program area guidelines and restricted supersonic airspace at Edwards Air Force Base (EAFB) dictated this arrangement.

Wind profiles obtained with the aircraft were calculated by subtracting the airspeed from the ground speed as discussed previously. Two different wind calculations were made; one using the aircraft INS as the source for ground speed, track angle, and flightpath angle, the other using the ground based radar as the source for the same information. These aircraft results were compared with Jimsphere results that were obtained as close as possible to the flight time. It was not possible to attain perfectly ideal comparisons because the aircraft and Jimsphere measurements were not taken at the exact place and time.

In this paper, data for selected profiles (indicated in Table 1) will be presented. The actual profiles, along with Mach number and rate of climb, will be shown as well as the aircraft ground track for the profile. Differences between Jimsphere and both INS and radar calculated aircraft wind profiles will also be discussed to show the type of agreement obtained and to identify the problems encountered.

Aircraft Profiles

Selected INS calculated aircraft profiles are shown in Figs. 6 through 12. Several of these profiles were selected to illustrate problems encountered; others are examples of the best profiles obtained in terms of comparison to Jimsphere, which will be discussed in a later section. In addition to the wind profiles, the Mach number and rate of climb are presented as a function of altitude. Both the aircraft and Jimsphere ground tracks are shown.

Profile 1, Fig. 6 was a subsonic climb to 11,500 m. The average rate of climb was 1,300 m/min (Table 1) with a maximum of approximately 2,900 m/min (Fig. 6(d)). The wind blew to the south on this flight while the aircraft traveled north, resulting in a large distance separation between the Jimsphere and the aircraft (Fig. 6(e)).

Profiles 2 and 3 (Figs. 7 and 8) were both obtained during the same flight. Profile 2 was a descent and profile 3 was a climb. They both covered an altitude range between approximately 3,000 and 12,000 m. The average descent rate was 3,100 m/min and the average climb rate was 2,600 m/min (Table 1).

Profile 4 (Fig. 9) was a supersonic descent from 19,300 m to 7,800 m. It was performed on the first flight where a profile to maximum altitude was attempted. The descent was aborted at 7,800 m because of fuel limitations. For this partial profile, the average descent rate was 5,800 m/min (Table 1) with a maximum descent rate of almost 12,000 m/min (Fig. 9(d)). In order to stay within the restricted supersonic airspace at EAFB, the profile was flown while turning (Fig. 9(c)).

Profiles 5 (Fig. 10) and 6 (Fig. 11) were a climb and a descent on the same flight. The maximum altitude was 18,700 m and both the climb and descent were performed in both subsonic and supersonic segments. These segments were separated by turns or accelerating dives. The climb required space positioning between segments to line up with the EAFB supersonic corridor and to accelerate to M = 1.9. The two segments of the descent were done on opposite headings in order to minimize the space used. The time required to perform the climb (including maneuvering and acceleration) was 14.1 min and the descent was accomplished in 7.1 min (Table 1). The subsonic and supersonic segments for both the climb and descent overlapped in altitude. The climb covered an area of approximately 125 km by 55 km (Fig. 10(c)), much too large for any shuttle application. However, the descent covered a much smaller area (Fig. 11(c)) and came very close to staying within the area guidelines recommended by the shuttle program. These results were encouraging because they showed that an aircraft could stay fairly close to the launch area. This may not be the case when a Jimsphere is used. Depending on the wind speed and direction, a Jimsphere could travel well away from the launch area.

Profile Comparisons

From a study of the available literature on wind profile comparisons made with Jimspheres separated either by time or space, it was determined that as a general rule an indication of a satisfactory comparison between components from Jimsphere and aircraft profiles was a difference of up to 3 m/sec. This was due to the knowledge that the Jimsphere and aircraft measurements would be separated by both time and space and therefore perfect comparisons could not be expected. The 3 m/sec criteria is primarily a guideline value since atmospheric variability is not constrained to any finite limit. Differences between Jimsphere and aircraft wind components for each profile discussed previously are presented in Figs. 12 through 17. A difference is presented for each source of aircraft ground speed.

Three causes for less than ideal comparisons ($\Delta W \geq$ 3 m/sec) have been identified so far: extreme spatial separation between Jimsphere and aircraft, excessive roll angle ($\phi \geq \pm 10°$) during the profile, and aircraft maneuvering between profiles or profile segments. Examples of these problems and examples of the best comparisons are discussed in the following paragraphs.

Figure 11 (profile 1) is an example where extreme spatial separation can cause large differences in the comparison of Jimsphere to aircraft. Most of the differences are within 3 m/sec but there are larger differences between 6,000 and 7,000 m for the east component and above 11,000 m for both components. As shown in Fig. 6(c), the balloon and aircraft traveled in opposite directions during this flight. At 6,400 m the separation was approximately 75 km and grew to 200 km at 11,500 m.

The differences between aircraft and Jimsphere wind profiles for profiles 2 and 3 are presented in Figs. 13 and 14 respectively. As discussed previously, these profiles were flown at a fairly constant heading. Differences between Jimsphere and aircraft remain less than 3 m/sec over most of the profile. These are examples of some of the best comparisons obtained during this flight experiment, however they only extend to 12,000 m.

Large differences between aircraft and Jimsphere wind profiles were observed when large roll angles occurred during the profile. This is shown in the comparisons for profile 4 (Fig. 15). This profile was the first attempt at a supersonic descent. The aircraft was turning and therefore in a bank throughout most of the descent as shown in Fig. 15(c). It was expected that the equations used for calculating the winds would account for roll angle. The largest errors appear when not only roll angle is large, but also when angle of attack is high and the heading is perpendicular to the wind component in question (that is, an E–W heading for the north component). It is believed that these errors may be due to angle-of-attack measurement errors. In wings level flight, angle of attack has less influence on the horizontal wind components than angle of sideslip. Therefore more emphasis was put on the angle of sideslip calibrations. However, when the bank angle is large, angle of attack enters into the horizontal component and any errors in the measurement affect the wind measurement.

To avoid errors due to angle of attack when the bank angle was large, subsequent profiles were flown wings level at a constant heading. This constraint then forced the profiles of over 18,000 m to be flown in segments as discussed previously. In order to minimize the space used to fly the profile, some maneuvering was required between segments. As can be seen in Figs. 16 and 17, this maneuvering sometimes caused a shift in the INS data. These figures present the differences between Jimsphere and aircraft measurements for profiles 5 and 6. Profile 5 was a climb from 1,400 to 18,700 m done in two segments. Between the two segments, some maneuvering was performed to accelerate to supersonic speeds. Figure 16 shows larger differences between the comparisons using radar ground speed and INS ground speed for the subsonic segment than for the supersonic segment. Similar results are seen in the comparisons for profile 6. Profile 6 was a descent from 18,000 m to 2,000 m and the supersonic and subsonic segments were broken up by a 180° turn at approximately 13,500 m. Both the INS calculated and radar calculated comparisons with Jimsphere are similar above the turn altitude, however there is an approximate 3-m/sec shift in the INS calculated comparison in the east component below the turn altitude (Fig. 17(b)). When the radar is used as the ground speed source, good comparisons are obtained throughout both profiles. There was excellent agreement of the aircraft derived winds for the climb and descent, in addition to good comparisons between aircraft and Jimsphere derived winds for profiles 5 and 6. This is illustrated in Fig. 18. This agreement is consistent throughout the altitude and speed range of the profiles. There are differences in the INS calculated east component below 13,500 m. Again, this is attributed to some type of shift in the INS data as previously discussed. Due to the shifts in INS data observed during this flight demonstration, aircraft derived winds using radar tracking as the ground speed source yielded the best results.

Concluding Remarks

A flight technique has been described which uses a high-performance aircraft to measure wind profiles to 18,000 m. It was desired that these wind profiles be measured in 10–15 min while staying within an area defined by a 16.1-km radius circle. These time and spatial guidelines were defined in order to use this technique to obtain pre-launch wind measurements for the space shuttle.

Preliminary results indicate that it is feasible to use an aircraft to measure winds during climbs and descents. During the experiment, aircraft wind profiles were obtained from 21 climbs and 18 descents. Average rates ranged from 500 m/min to 12,000 m/min. Descent rates ranged from 1,600 m/min to 10,000 m/min. At high roll angles, angle-of-attack errors seem to have an adverse effect on the aircraft wind measurements. A wings-level descent profile performed in segments could be obtained in 7 min over 39-km distance. Because of space positioning required to set up the supersonic zoom maneuver, climb profiles used significantly more space, on the order of 120 km and 14 min from 1,500 to 18,200 m. Some aircraft maneuvering must be performed in order to satisfy spatial constraints and this was observed to cause errors in the INS inertial information. Although Jimsphere and aircraft measurements could never be taken at exactly the same location in space or in time, most comparisons were satisfactory, which was deemed to be on the order of 3 m/sec. This was especially true when the ground speed was obtained from radar tracking information.

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Table 1. Flight profile summary.

		Climb				Descent		
Flight number	Climb number	Altitude range, km	Time, min	average $\dot{h}$, m/min	Descent number	Altitude range, km	Time, min	average $\dot{h}$, m/min
1206	---	---	---	---	1	9.0–1.4	6.8	−1,100
1207	1	3.2–12.0	12.4	700	1	12.0–3.5	11.2	−800
	2	3.1–8.0	4.8	1,000	2	11.8–3.2	4.3	−900
	3	8.0–12.0	1.3	3,100	---	---	---	---
1208	1[a]	1.2–11.5	8.1	1,300	---	---	---	---
1210	1	3.2–11.9	3.8	2,300	1[b]	11.8–3.1	2.8	−3,100
	2[c]	3.2–12.1	3.4	2,600	2	11.9–3.0	3.3	−2,700
1211	1	2.0–10.0	3.3	2,400	1	9.5–5.5	2.4	−1,700
1212	1	2.0–10.0	3.1	2,600	1	9.5–4.0	3.5	−1,600
1214	1	3.2–11.0	2.9	2,700	1	11.0–3.7	1.8	−4,100
	2	3.0–11.0	2.3	3,500	2	11.0–3.7	1.8	−4,100
	3	3.0–11.0	1.3	6,200	3	11.0–4.0	3.7	−1,900
1227	1				1[d]			
Overall		3.7–19.0	12.9	1,200		19.3–7.8	2.0	−5,800
Subsonic segment		3.7–13.7	8.5	1,200		---	---	---
Supersonic segment		10.0–19.0	4.4	2,000		19.3–7.8	2.0	−5,800
1228	1				---			
Overall		3.5–12.5	7.5	1,200		---	---	---
Subsonic segment		3.5–12.5	7.5	1,200		---	---	---
Supersonic segment		---	---	---		---	---	---
1229	1				---			
Overall		3.0–13.2	6.5	1,600		---	---	---
Subsonic segment		3.0–11.0	4.6	1,700		---	---	---
Supersonic segment		10.2–13.2	1.9	1,600		---	---	---
1230	1				1			
Overall		3.0–14.0	4.6	2,400		10.5–2.0	2.8	−3,000
Subsonic segment		3.0–14.0	4.6	2,400		10.5–2.0	2.8	−3,000
Supersonic segment		---	---	---		---	---	---
1231	1				1			
Overall		3.2–18.7	17.5	1,200		18.7–3.1	6.5	−3,100
Subsonic segment		3.0–13.8	11.1	1,000		9.6–3.1	2.5	−2,600
Supersonic segment		10.8–18.7	1.4	5600		18.7–9.8	2.6	−3,400
1232	1				1			
Overall		1.5–18.1	16.1	1,400		17.4–1.5	6.1	−4,800
Subsonic segment		1.5–13.7	8.1	2,000		9.1–1.5	2.0	−3,800
Supersonic segment		10.7–18.1	3.7	2,000		17.4–9.1	1.3	−6,400
1235	1[e]				1[f]			
Overall		1.4–18.7	14.1	2,000		18.7–2.3	7.1	−4,400
Subsonic segment		1.4–13.9	7.3	1,600		12.7–2.1	2.4	−4,500
Supersonic segment		11.2–18.7	1.3	5,800		18.3–11.7	1.3	−4,500
1239	1				1			
Overall		1.8–15.2	10.5	1,900		15.2–3.0	4.8	−4,500
Subsonic segment		1.8–13.7	5.4	2,200		12.2–3.0	2.0	−4,600
Supersonic segment		7.5–15.2	1.5	5,100		15.2–12.2	0.7	−4,300
1283	1				1			
Overall		3.0–20.4	15.5	2,600		20.4–2.4	6.8	−7,800
Subsonic segment		3.0–13.7	5.3	2,000		11.0–2.4	1.2	−7,200
Supersonic segment		12.2–20.4	1.3	6,300		20.4–12.2	1.1	−7,400
1284	1				1			
Overall		1.8–20.4	14.0	2,700		19.8–2.1	6.7	−7,100
Subsonic segment		1.8–13.4	5.8	2,000		11.6–2.1	1.8	−5,300
Supersonic segment		9.8–20.4	1.2	8,800		19.8–11.6	0.7	−11,700

[a]Profile 1; [b]Profile 2; [c]Profile 3; [d]Profile 4; [e]Profile 5; [f]Profile 6

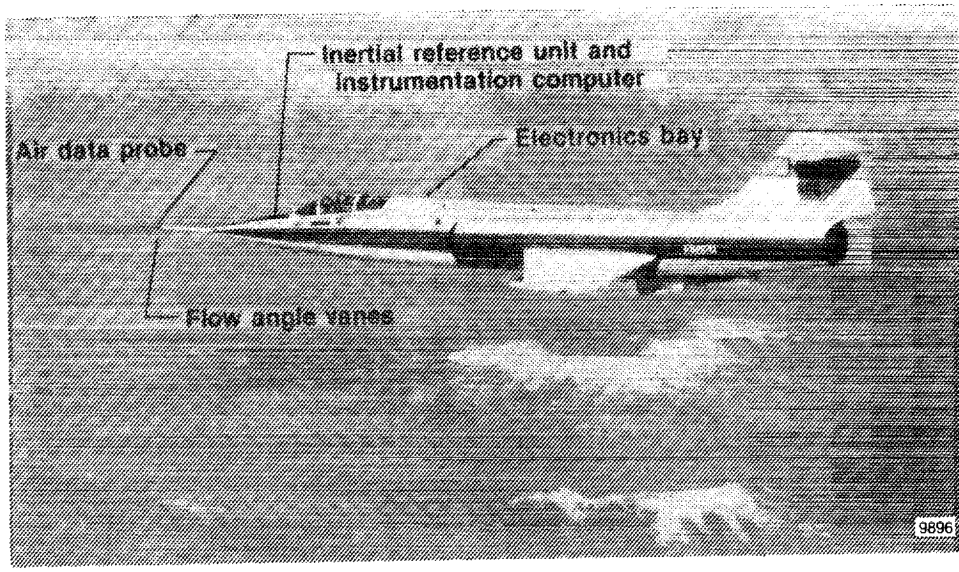

Fig. 1 F-104 aircraft.

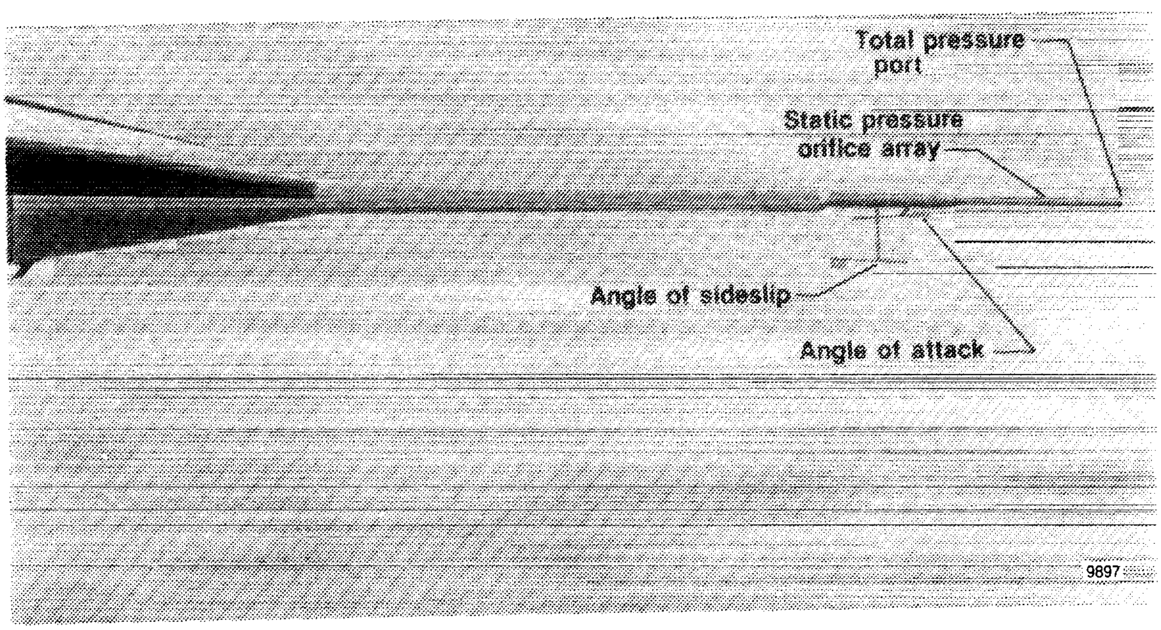

Fig. 2 Details of airdata system.

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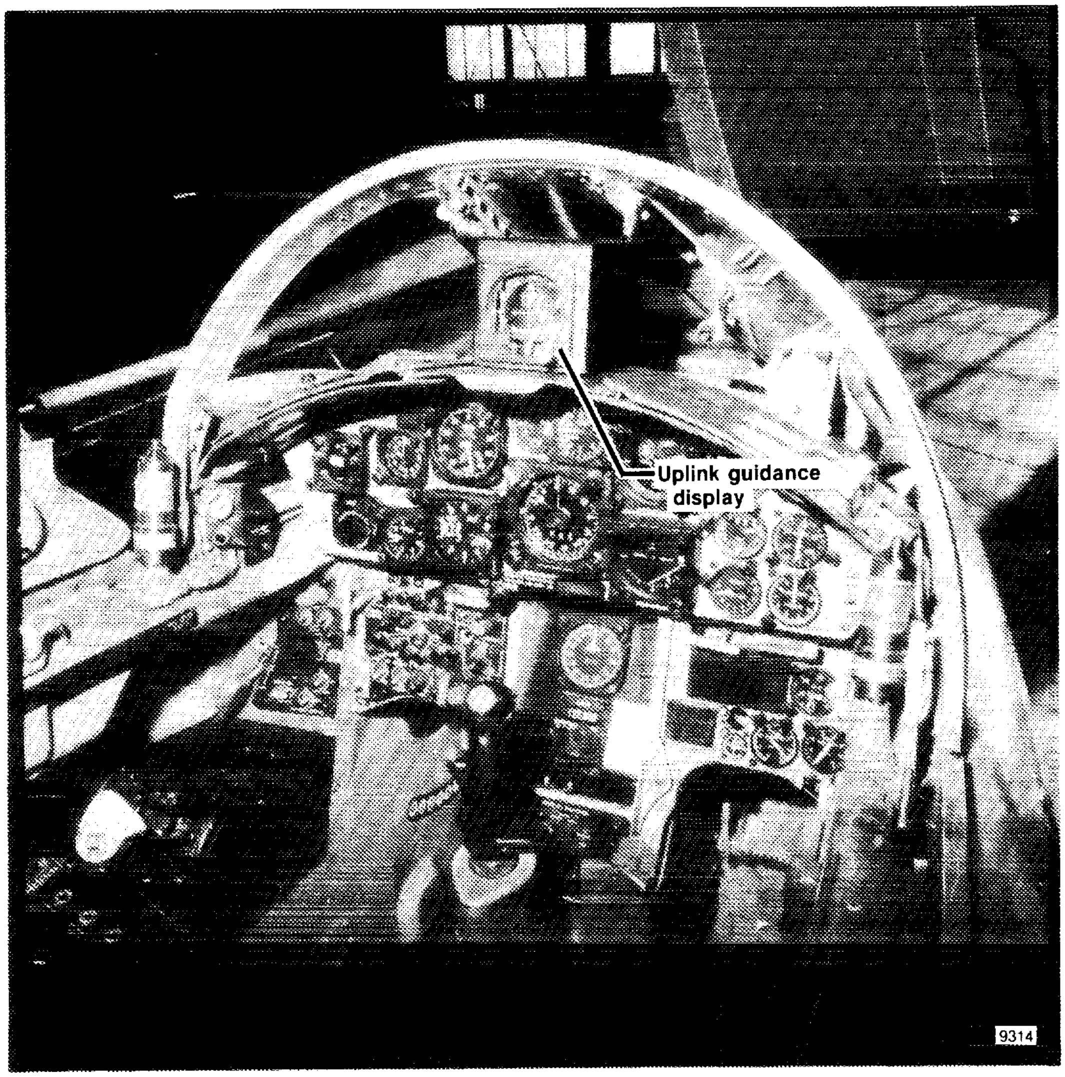
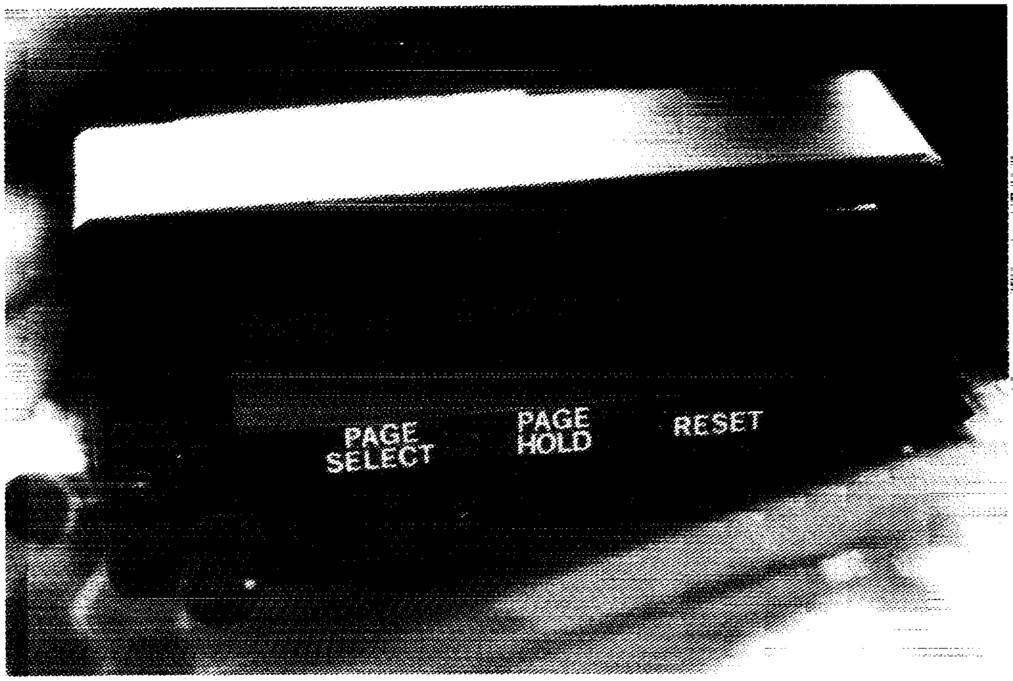


(a) Uplink guidance system display.

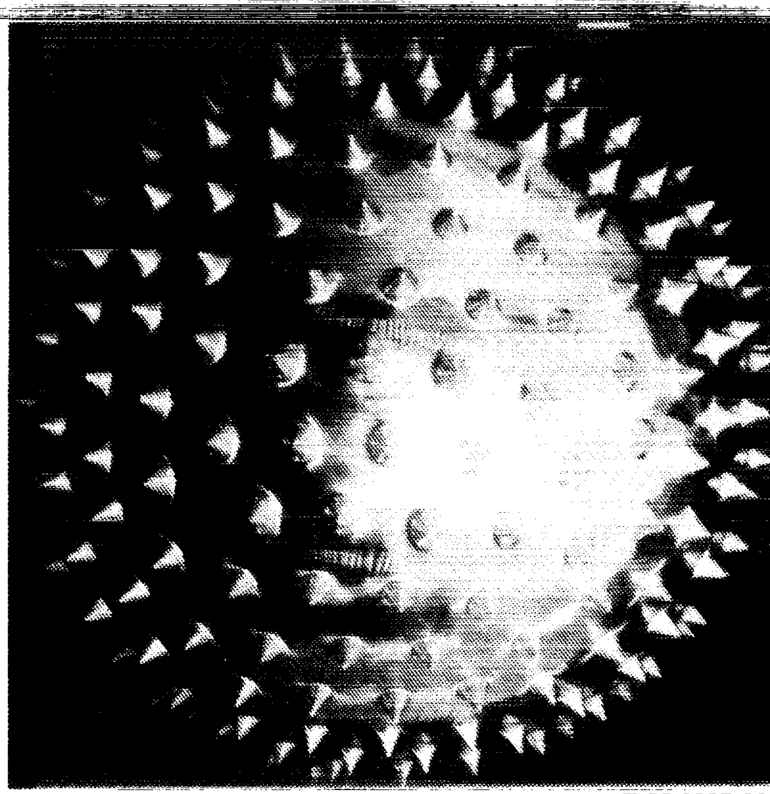
Fig. 3 Cockpit displays used for pilot guidance.



EC 89 0169-001

(b) Cockpit LCD.

Fig. 3 Concluded.



E 89 0227-001

Fig. 4 Jimsphere balloon.

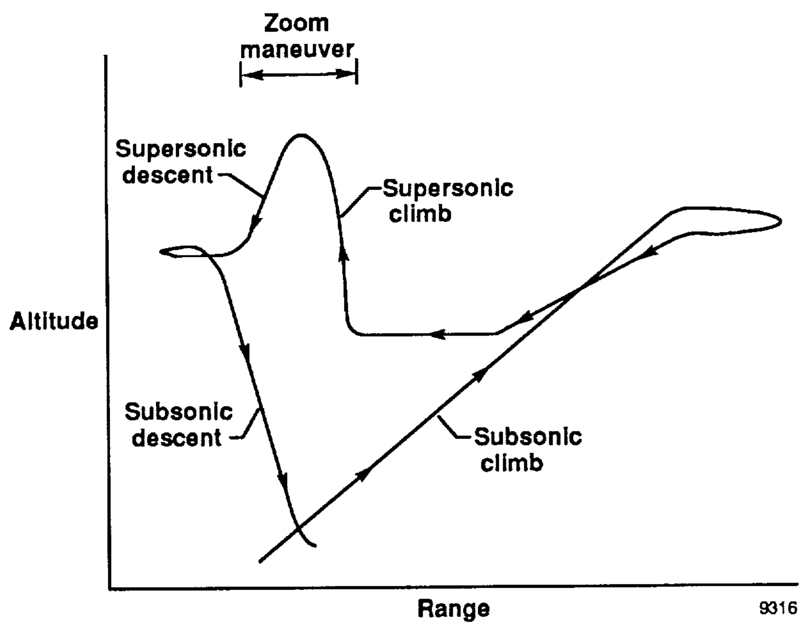
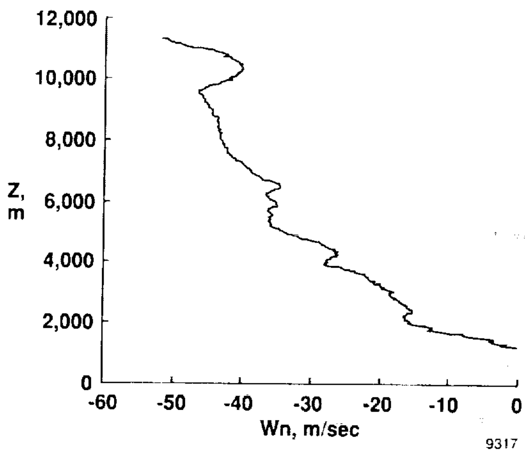
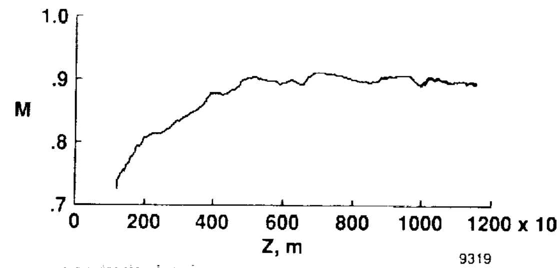


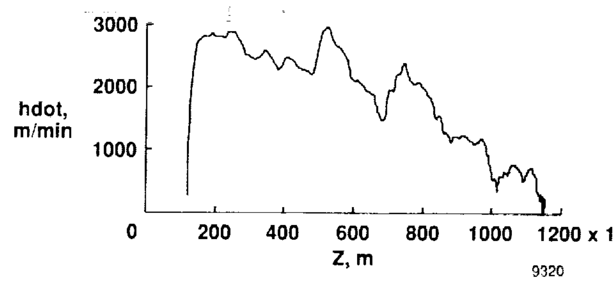
Fig. 5 Flightpath required to obtain profile to 18,200 m.



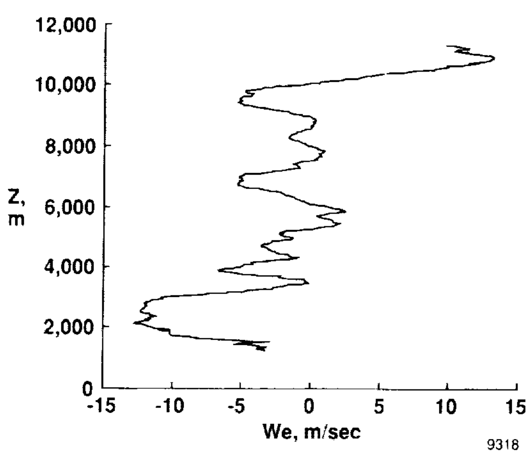
(a) INS calculated north component.



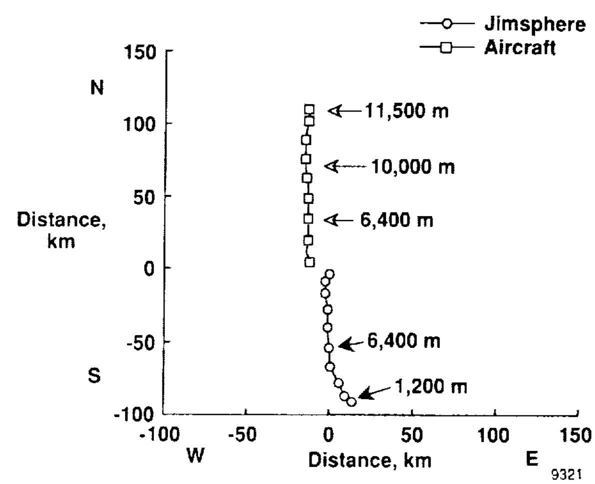
(c) Mach number for profile 1.



(d) Climb rate for profile 1.

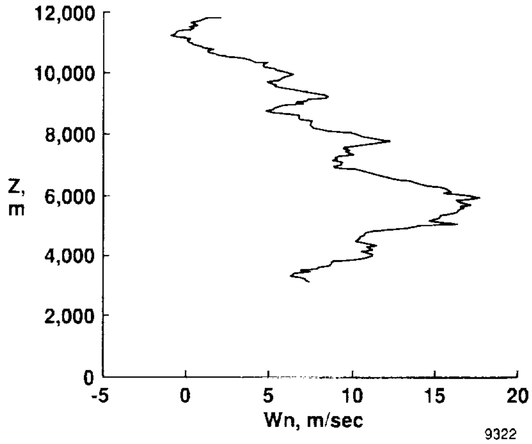


(b) INS calculated east component.

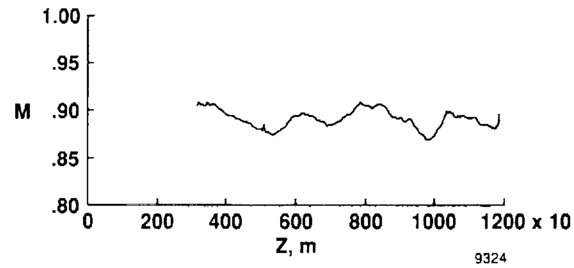


(e) Jimsphere and aircraft ground track.

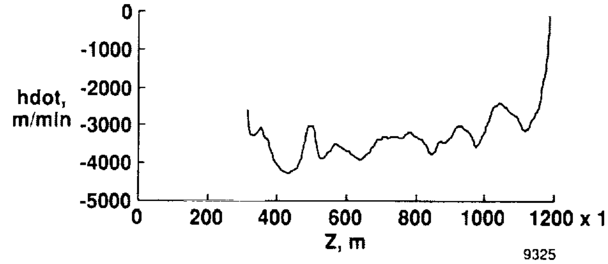
Fig. 6 Aircraft derived winds and profile information for profile 1.



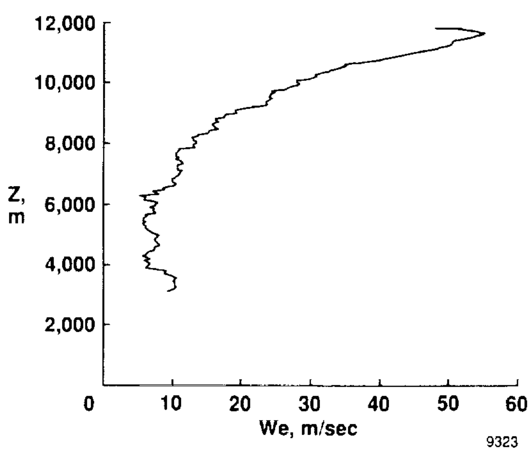
(a) INS calculated north component.



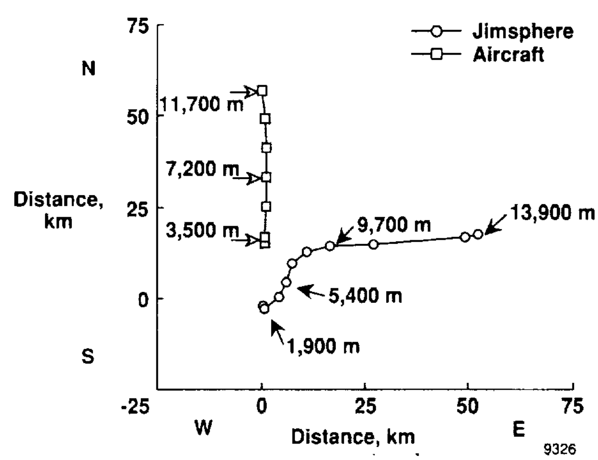
(c) Mach number for profile 2.



(d) Rate of climb for profile 2.

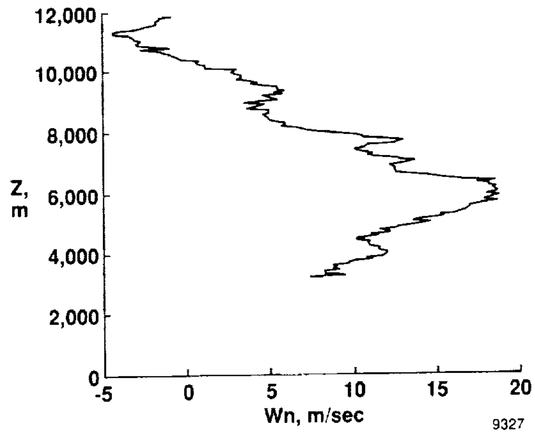


(b) INS calculated east component.

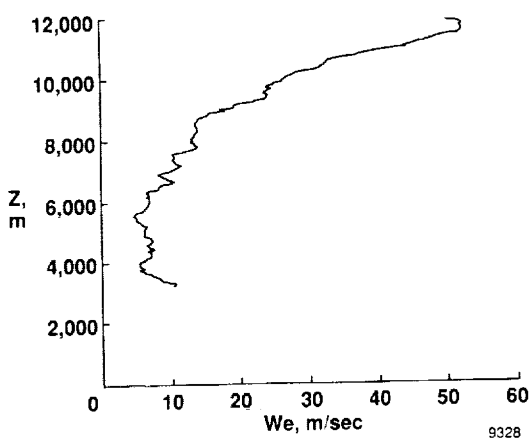


(e) Jimsphere and aircraft ground tracks.

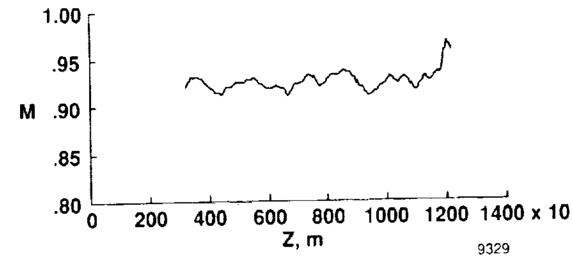
Fig. 7 Aircraft derived winds and profile information for profile 2.



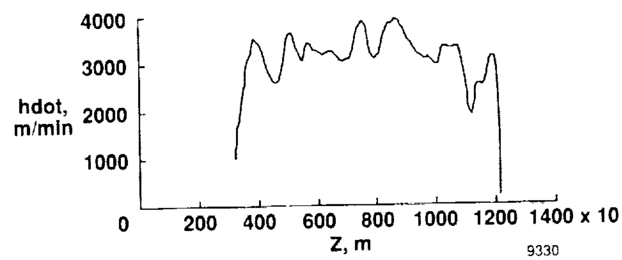
(a) INS calculated north component.



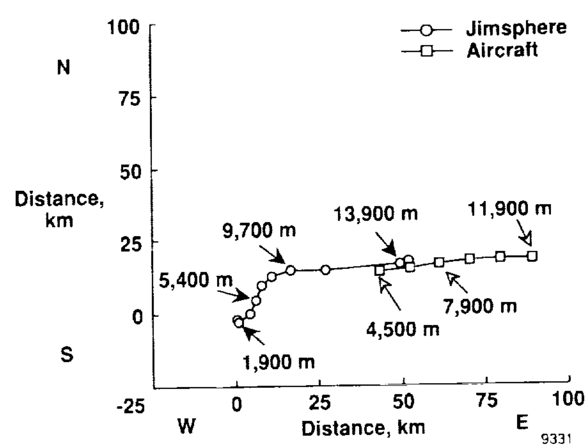
(b) INS calculated east component.



(c) Mach number for profile 3.

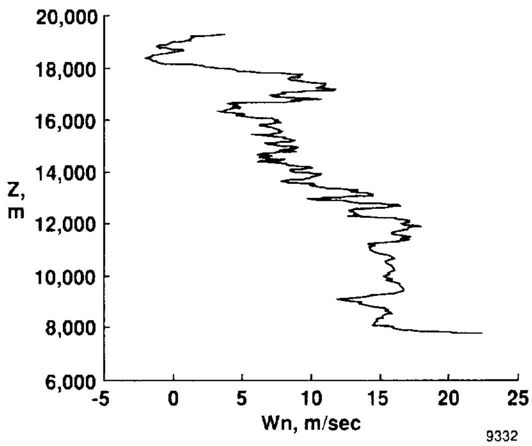


(d) Rate of climb for profile 3.

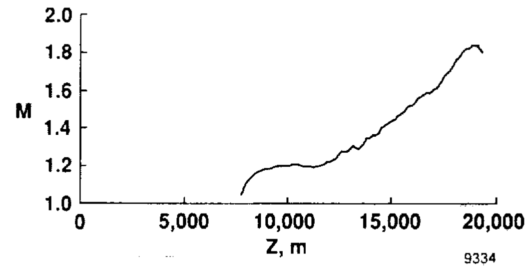


(e) Jimsphere and aircraft ground track.

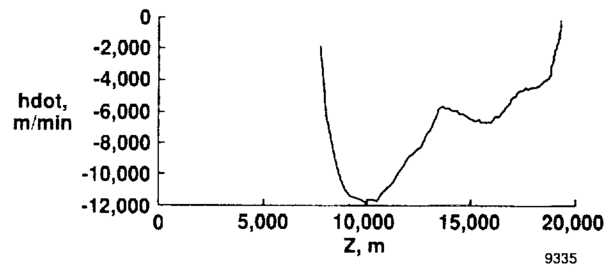
Fig. 8 Aircraft derived winds and profile information for profile 3.



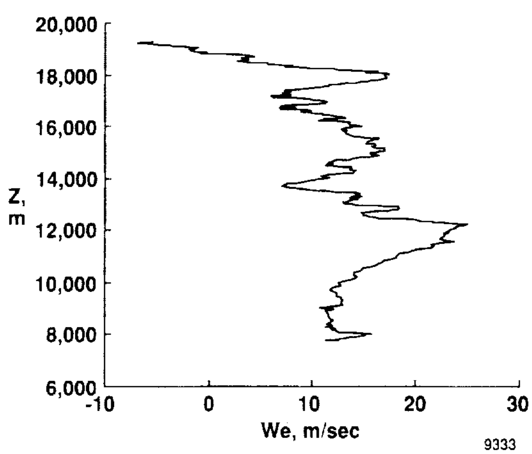
(a) INS calculated north component.



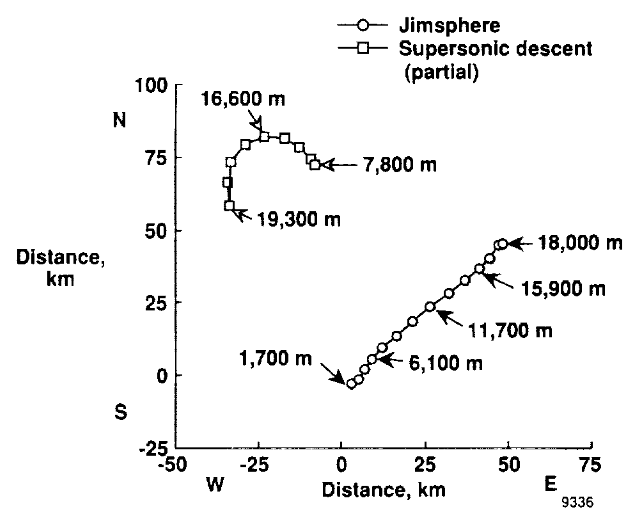
(c) Mach number for profile 4.



(d) Rate of climb for profile 4.

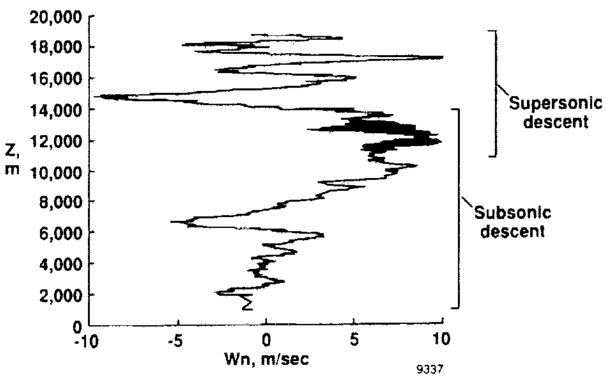


(b) INS calculated east component.



(e) Jimsphere and aircraft ground tracks.

Fig. 9 Aircraft derived winds and profile information for profile 4.



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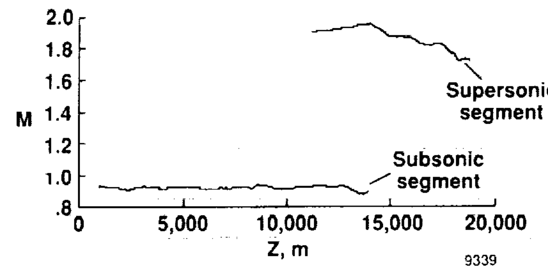
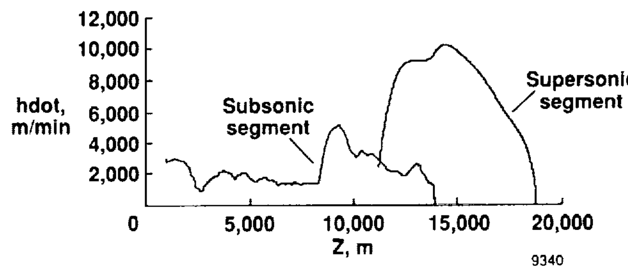
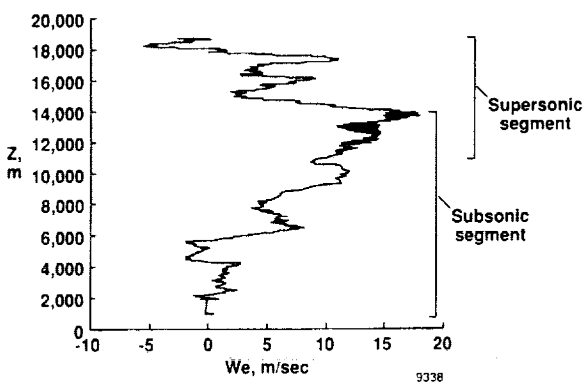


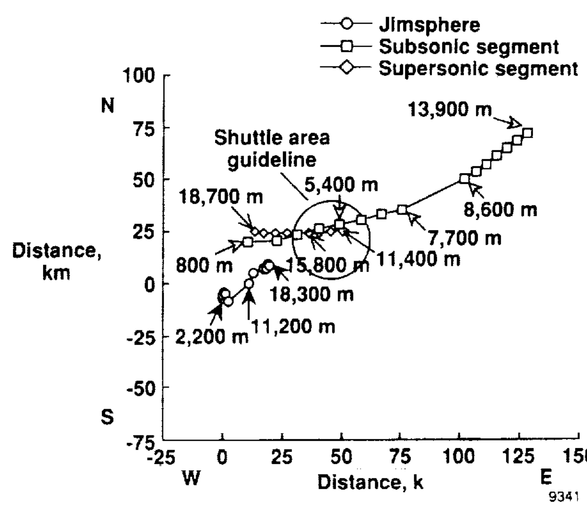
(c) Mach number for profile 5.



(d) Rate of climb for profile 5.

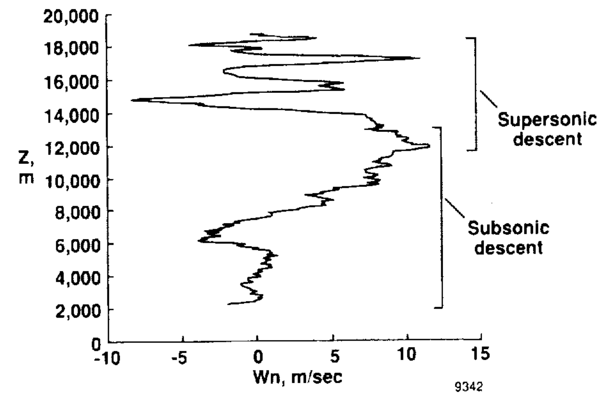


(b) INS calculated east component.

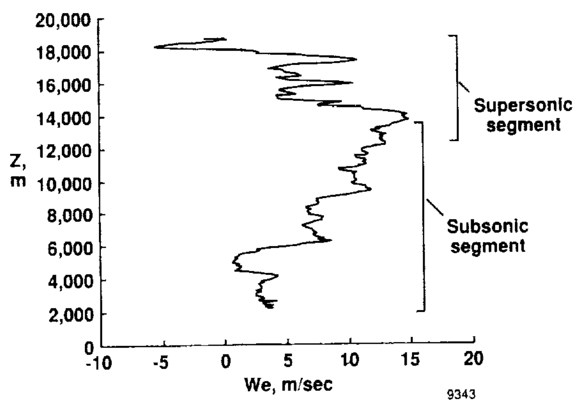


(e) Jimsphere and aircraft ground track.

Fig. 10 Aircraft derived winds and profile information for profile 5.



(a) INS calculated north component.



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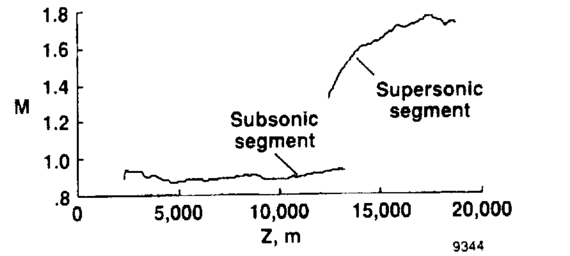
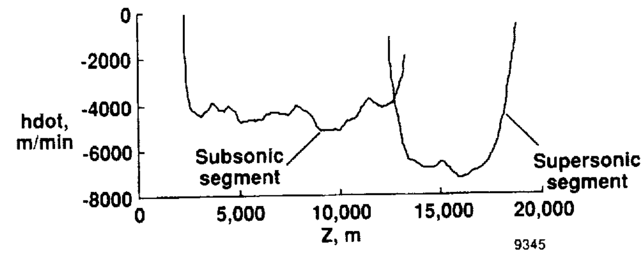
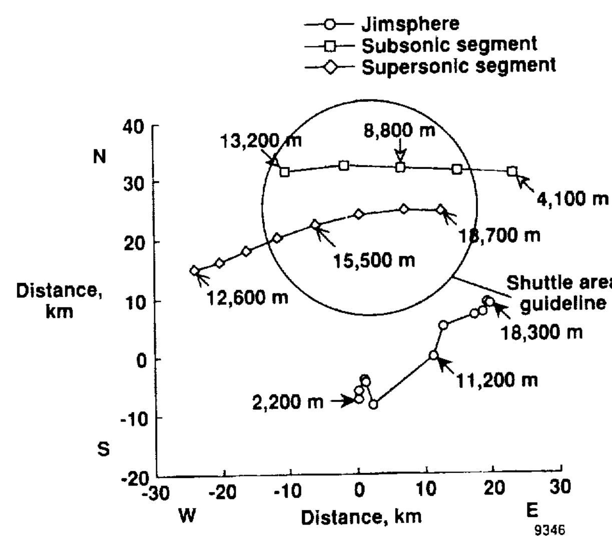


(c) Mach number for profile 6.

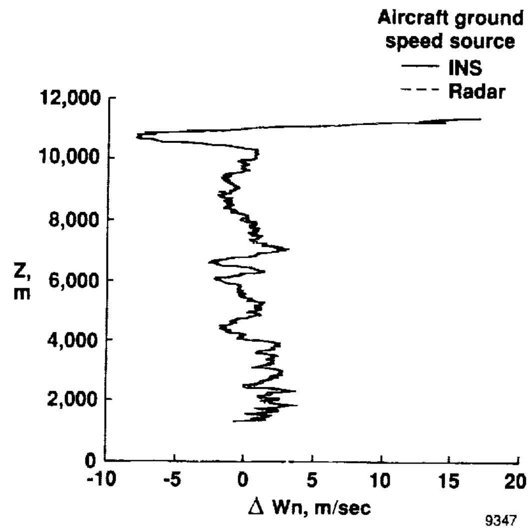


(d) Rate of climb for profile 6.

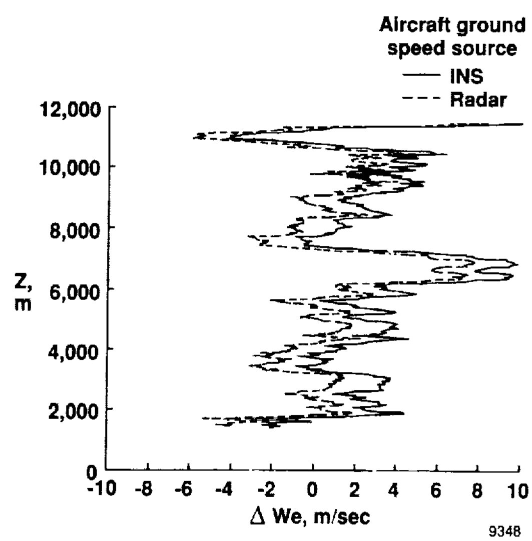


(e) Jimsphere and aircraft ground tracks.

Fig. 11 Aircraft derived winds and profile information for profile 6.

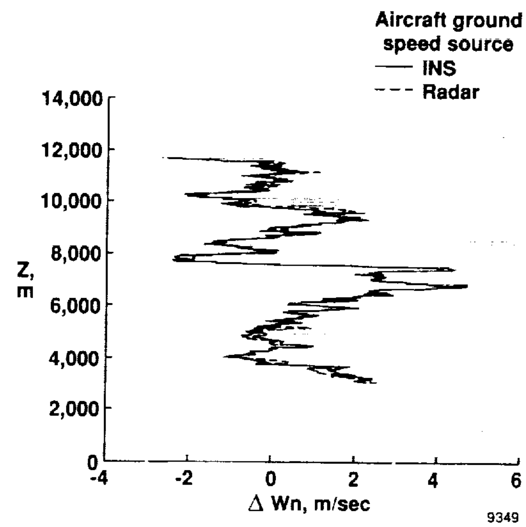


(a) North component.



(b) East component.

Fig. 12 Differences between Jimsphere and aircraft derived winds for profile 1.



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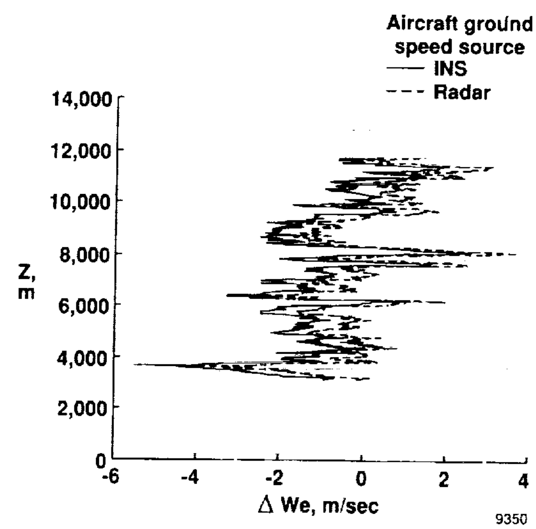
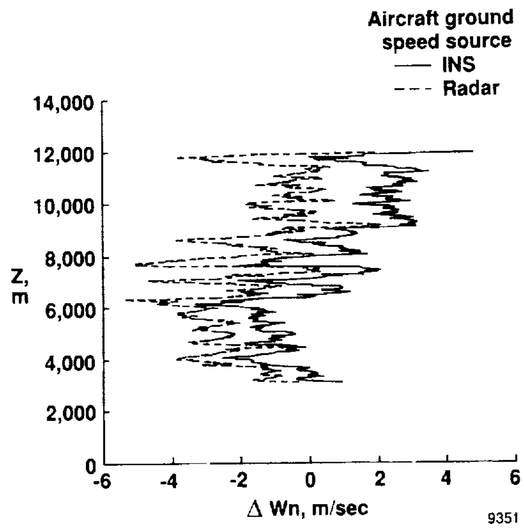


(b) East component.

Fig. 13 Differences between Jimsphere and aircraft derived winds for profile 2.



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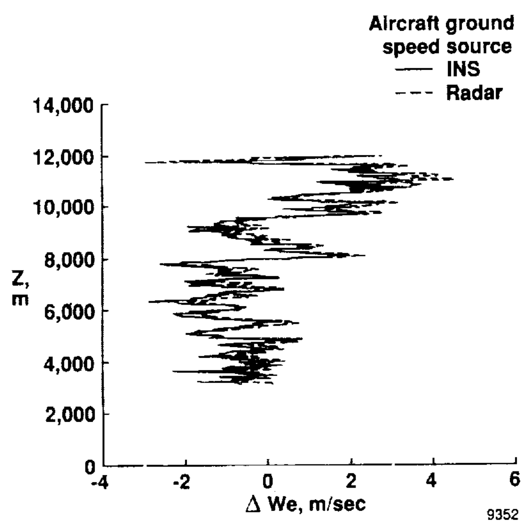
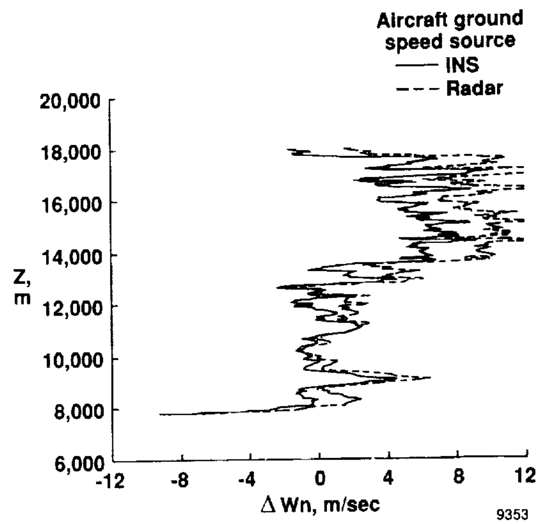
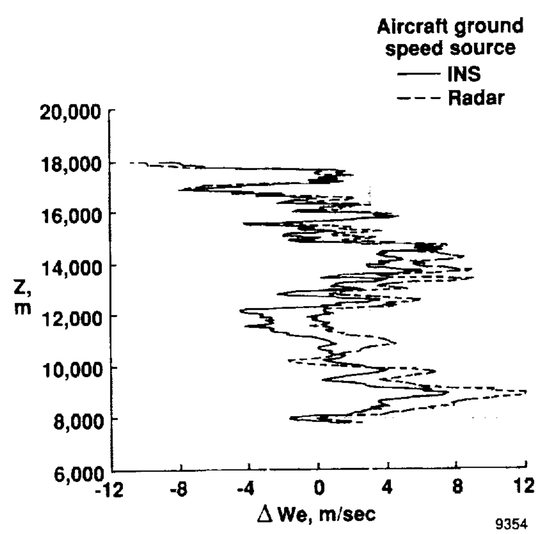


(b) East component.

Fig. 14 Differences between Jimsphere and aircraft derived winds for profile 3.

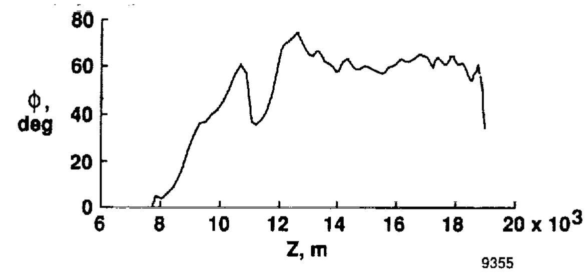


(a) North component.

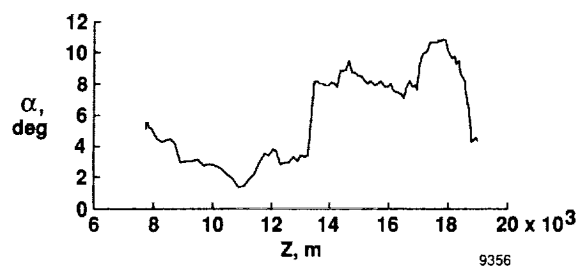


(b) East component.

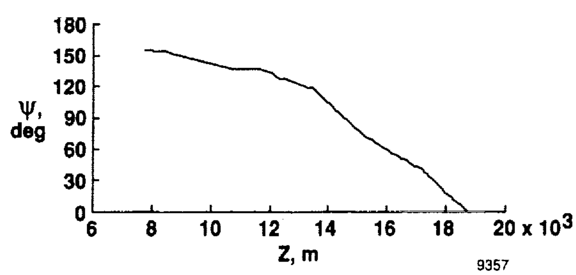
Fig. 15 Differences between Jimsphere and aircraft derived winds for profile 4.



(c) Roll angle during descent.

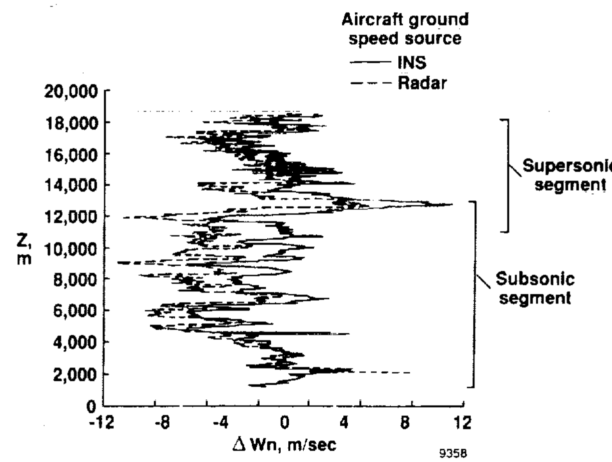


(d) Angle of attack during descent.

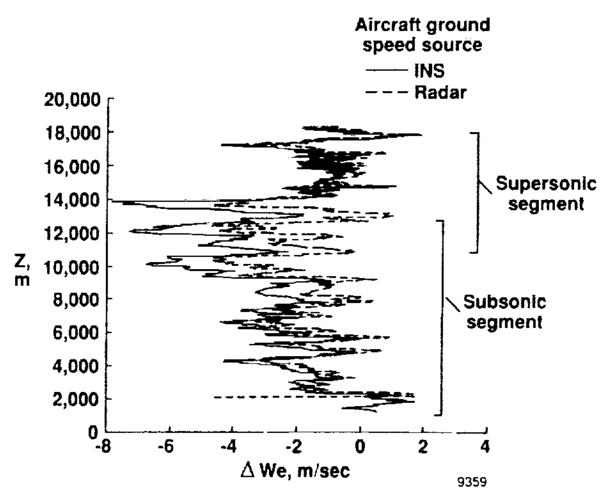


(e) Heading angle during descent.

Fig. 15 Concluded.

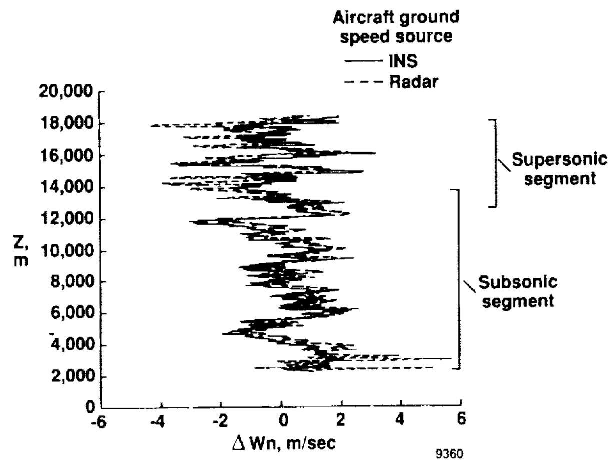


(a) North component.

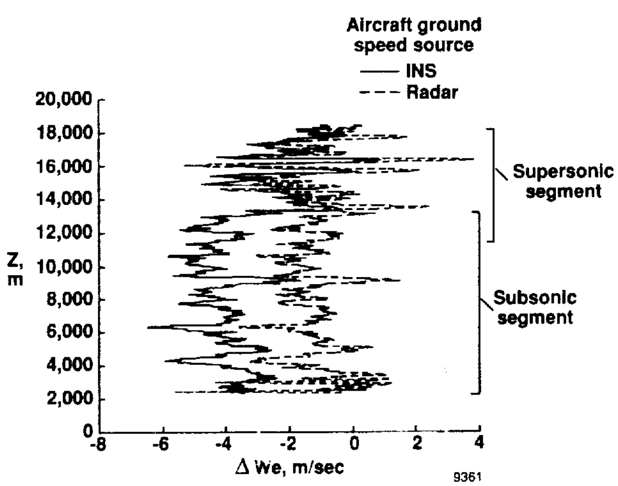


(b) East component.

Fig. 16 Differences between Jimsphere and aircraft derived winds for profile 5.

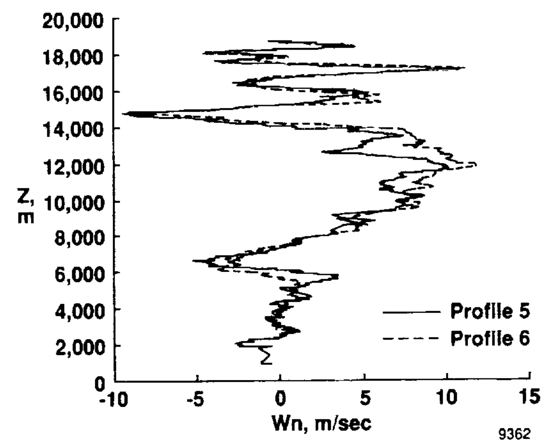


(a) North component.

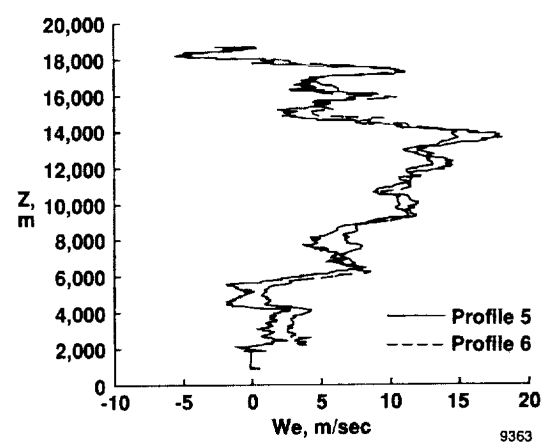


(b) East component.

Fig. 17 Differences between Jimsphere and aircraft derived winds for profile 6.

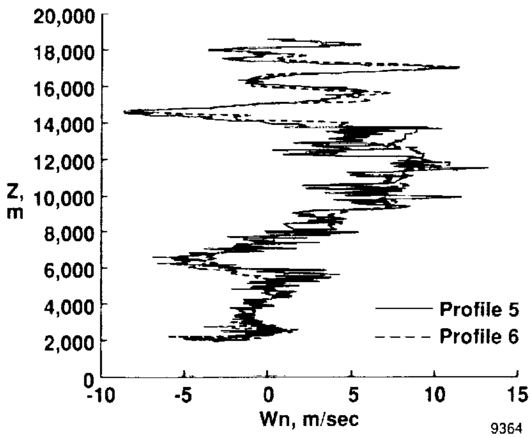


(a) INS calculated north component.

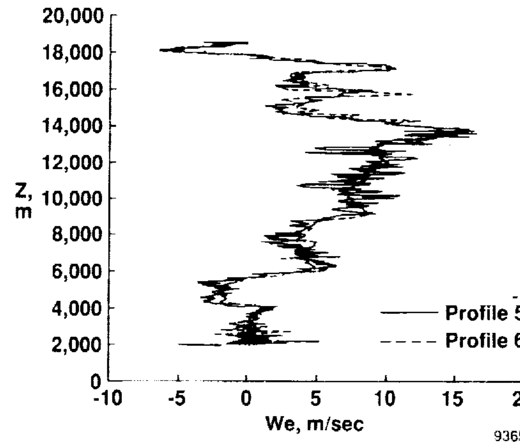


(b) INS calculated east component.

Fig. 18 Comparisons of aircraft derived winds for two profiles from the same flight.



(c) Radar calculated north component.



(d) Radar calculated east component.

Fig. 18 Concluded.

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16. Abstract

A technique to use an aircraft to measure wind profiles in the altitude range of 1,500 to 18,200 m has been demonstrated at NASA Ames-Dryden Flight Research Facility. This demonstration was initiated at the request of NASA Johnson Space Center to determine if an aircraft could measure wind profiles in support of space shuttle launches. The Jimsphere balloon is currently the device used to measure pre-launch wind profiles for the space shuttle. However, it takes approximately an hour for the Jimsphere to travel through the altitudes of interest. If these wind measurements could be taken with an aircraft closer to launch in a more timely manner and with the same accuracy as a Jimsphere balloon, some uncertainties in the measurements could be removed. The aircraft used for this investigation was an F-104G which is capable of flight above 18,000 m. It had conventional research instrumentation to provide airdata and flow angles along with a ring laser gyro inertial navigation system (INS) to provide inertial and Euler angle data. During the course of 17 flights, wind profiles were measured in 21 climbs and 18 descents. Preliminary comparisons between aircraft measured wind profiles and Jimsphere measured profiles show reasonable agreement (within 3 m/sec). Most large differences between the profiles can usually be explained by large spatial or time differences between the Jimsphere and aircraft measurements, the fact that the aircraft is not in a wings-level attitude, or INS shifts caused by aircraft maneuvering.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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