NASA's B-57B Gust Gradient Program

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The B-57B Gust Gradient Program is a joint effort of NASA Headquarters, Marshall Space Flight Center, Dryden Flight Research Facility, Langley Research Center, and Ames Research Center. The primary program goal is to measure spanwise variations of turbulent gusts across an airflow. To this end, the NASA B-57B aircraft was equipped with three component gust probes on each wing tip and on the nose. Early results of flights done in conjunction with the Joint Airport Weather Studies (JAWS) project are described.

Introduction

THE idea of conducting a gust gradient program originated in discussions between John Enders (NASA Headquarters) and George Fichtl (NASA Marshall Space Flight Center) about 1973, relative to NASA's aeronautical program concerning the "Knowledge of Atmospheric Processes." The program was implemented due to the efforts of Dennis Camp and Harold Murrow. The first data to be collected for the program were obtained in conjunction with the Joint Airport Weather Studies (JAWS) Project.[1,2]

The objective of the gust gradient program is most easily explained by considering Fig. 1, here excerpted from an article by John Houbolt.[3] Houbolt describes the figure thusly: "The left side of Fig. 1 depicts the assumption commonly used in power spectral treatments of gust encounter, that is, the turbulence is considered random in flight directions but uniform in the spanwise direction. The right side of the figure depicts the more realistic situation wherein the turbulence is considered to be random in both the flight and spanwise directions." From Houbolt's figure and accompanying statement, it is easy to see that the assumption that an aircraft is completely imbedded in a single wind field (gust) is not really valid, especially when considering larger aircraft of the wide body category. Thus, the objective has been to obtain gust data for aircraft design and, also, for use in flight crew training in simulators. Specifically, the program requires that data on turbulence patchiness and spanwise gust gradients be obtained in a representative variety of atmospheric conditions from several sites (see Fig. 2) for aircraft design purposes and for safety of operations. Emphasis is placed on developing models applicable to approach and departure flight paths under conditions of strong wind-shear and profile-stability effects. The data collected from the various sites (Fig. 2) is in three segments. Segment 1 is from take-off to a height of approximately 1500 ft; segment 2 is from flight by a storm or turbulence area; and segment 3 is from approach to landing (approximately 1500 ft to touchdown or simulated touchdown). The aircraft used to obtain the gust gradient data is pictured in Fig. 3 and its nomenclature is given in Fig. 4. During the course of this 18-month program the B-57B will be used to obtain approximately 60 h of flight data.

The following sections contain requirements for obtaining data at the various sites as well as a brief discussion of data obtained during the JAWS project.

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Data Collection Sites

As shown in Fig. 2, there are plans to collect data at seven possible locations: at or in the vicinity of the Langley Research Center, Va., Kennedy Space Center, Fla. Marshall Space Flight Center, Ala.; Norman, Okla.; Denver, Colo.; Edwards Air Force Base, Calif., and Moffett Field, Calif. These sites were selected for various reasons; however, the main reasons are availability of support facilities at the sites and different topological features and climatologies.

Facilities desired at the various sites were: radar, weather towers, rawindsonde, meteorological networks, etc. Along with availability of facilities, it was also desirable for the output of the facilities to be readily available and in a format easily usable. It is believed these requirements will be met at the selected sites.

The sites chosen represent a cross section of U.S. topological features. Coastal, piedmont, mountainous, and desert areas are all included. In selecting these sites, it was believed that the topology would give rise to a variety of weather conditions. While only one of the locations has been used for data collection thus far, plans have been made for three locations to be utilized in the fall of 1982 and in 1983: Edwards Air Force Base, Norman, Okla., and the Marshall Space Flight Center. No comment can be made at this time relative to the other locations.

As indicated earlier, tha data to be presented here were obtained in conjunction with the JAWS Project (Denver, carried out in the Colorado area in July 1982). Eleven data collection flights (Table 1) were conducted during this one-month period. Shown in this table are the date, start and end time of each flight, and a general comment relative to the

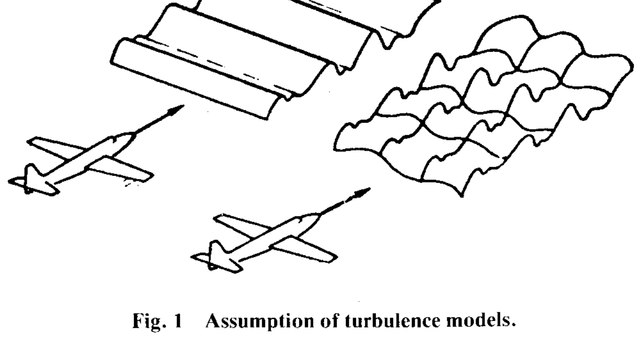


Fig. 1 Assumption of turbulence models.

flight data collected. Shown in Table 2 is the start/end time and run duration for five data cases. The locations of the two cases to be discussed (runs 10 and 12) are indicated in Fig. 5 by the corresponding black lines in the upper central part of the figure. These are the flight paths of the B-57B for the data runs. The arrows on these black lines show the direction of aircraft flight.

Figure 6 is a time altitude trace for two data collection runs. The figure also shows the aircraft airspeed plot for the respective data runs. Run 10 is for "level" flight near the storm and run 12 is for a simulated approach and departure flight.

The lower left hand corner of Fig. 3 illustrates the flight path procedure for data collection. When a storm enters the desired test area (an airport or open area having a possible 20 mi radius where simulated approaches can be made), a flight test will begin. The diagram at the bottom of Fig. 6 shows the segments for data collection, namely, a 3-deg glide slope approach and departure along with a straight and level portion by the storm cell.

Table 1 Gust gradient flights during JAWS 1982

Flight	Date	Start	End	Comments
1	7/7	15:41:38	15:59:39	Landmark familiarization flight
2	7/8	14:49:11	16:40:35	Light to moderate turbulence
3	7/9	13:17:10	15:42:34	Light to moderate turbulence with data correlation with JAWS 02 and 30
4	7/11	14:46:07	17:02:44	Moderate turbulence and lightning
5	7/13	15:20:18	16:44:56	ILS approaches to Stapleton in light turbulence
6	7/14	13:41:13	15:55:21	Severe turbulence and outflows visible on radar
7	7/15	14:08:13	16:26:20	Outflows, severe turbulence, and ILS approaches
8	7/17	15:49:35	17:17:56	Rain with light to moderate turbulence
9	7/20	15:59:30	18:35:52	Light to moderate turbulence with some ILS approaches
10	7/21	16:05:05	18:04:40	Good downburst with moderate to severe turbulence
11	7/22	13:36:09	15:24:45	Light and moderate turbulence

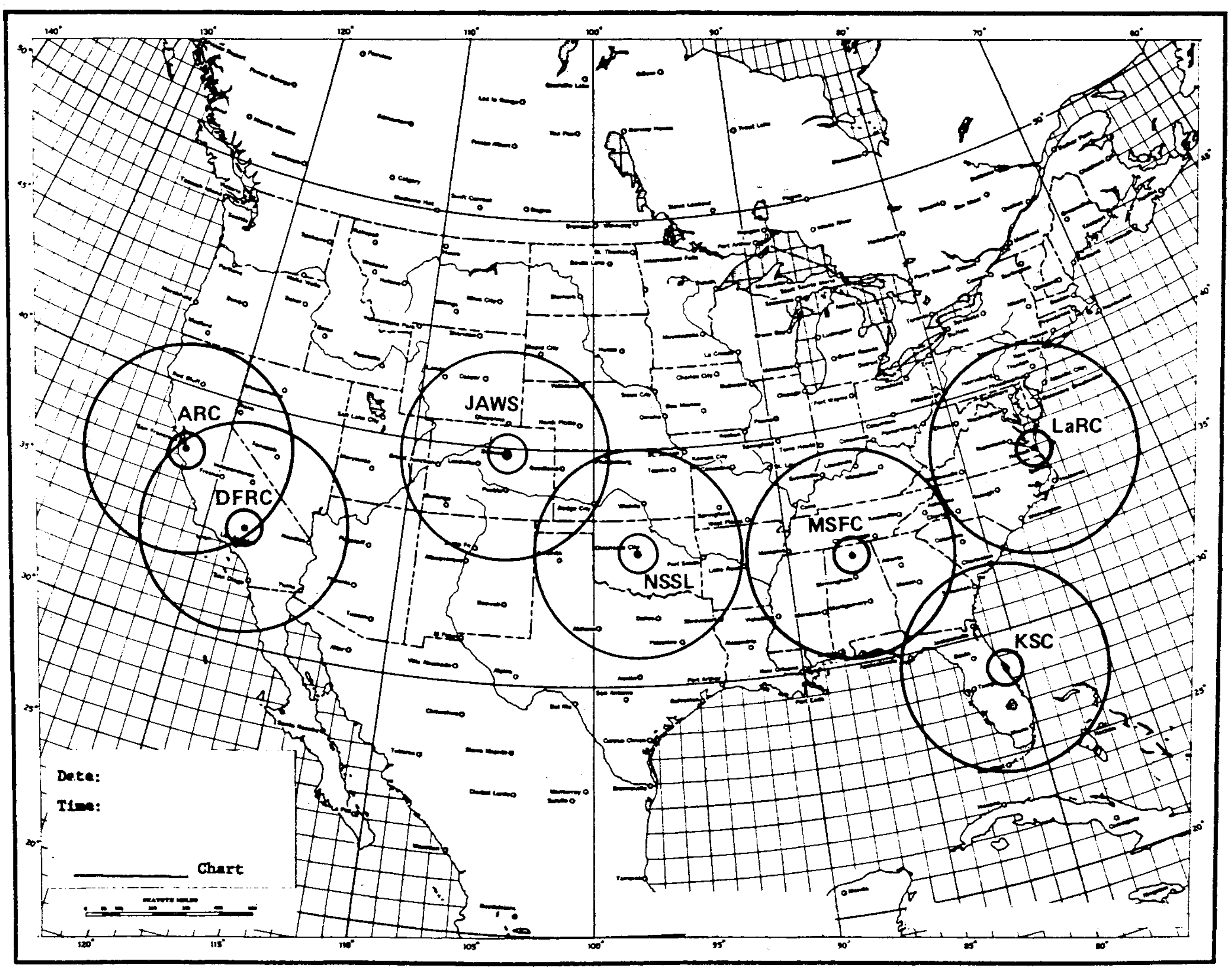


Fig. 2 Suggested B-57B gust gradient data collection sites.

Data Presentation

During the JAWS project, 11 data collection flights were made. Table 1 summarizes the data collected during this period. Of the 11 flights, 3 included severe turbulence encounters. The data analysis is currently concentrated on these 3 flights (Flights 6, 7, and 10). Flight 3 is of more than average interest because the B-57B flew some intercomparison flights with both the University of Wyoming King Air and Royal Aircraft Establishment (UK) HS-125 aircraft. The King Air is instrumented for cloud physics studies and the HS-125 has a forward looking LIDAR being tested for giving advanced warning of wind-shear events.

During the time the B-57B was at Denver, many wind-shear and severe weather events occurred. Figure 7 shows a sequence of a funnel cloud development near CP-2 on July 14. The cloud persisted for about five minutes and photos clearly show the decay. On another day the operations center at CP-2 was bombarded by centimeter-size hail whose noise disrupted aircraft communications. With support data provided by triple Doppler radar, a network of surface weather stations, and many other sources, and with the cooperation of the weather, the Gust Gradient Program had good success in the Denver area.

Table 2 JAWS Flight 7, 7/15/82

Run	Start time	Stop time	Duration, s
9	15:12:15	15:14:13	118
*10	15:14:55	15:17:30	155
*11	15:18:42	15:21:07	145
*12	15:22:50	15:25:10	140
*13	15:27:20	15:33:43	151
*14	15:31:20	15:33:43	143
15	15:35:48	15:41:23	335
16	15:44:00	15:45:45	105
17	15:49:30	15:51:49	139
18	15:54:10	15:58:18	248
19	16:00:14	16:04:09	235
20	16:06:02	16:10:09	247
21	16:14:25	16:17:30	185
22	16:18:14	16:22:54	280
23	16:25:53	16:27:27	94

The B-57B gust gradient data was digitally recorded on a data recorder carried in the B-57B cargo compartment. A single tape, holding as much as an hour of flight data, was then shipped to the Langley Research Center (LaRC) at Hampton, Va. for conversion to engineering units (m/s, rad/s, etc.). The resultant data were then transmitted to Marshall Space Institute at Tullahoma, Tenn. for analysis. The engineering unit tape contained 58 channels of data. They are summarized in Table 3.

Figure 8 is the data analysis flow chart for work done at MSFC. The raw data tape from LaRC is in 60 bit word, CDC compatible form. A translation routine allows selection of desired data channels for translation. The selected channels are converted to 32 bit form and written into a magnetic tape file. The resulting file can be plotted with raw data plot routines, correlated and/or spectrally analyzed, or processed for probability densities.

The results presented in this section were taken from two runs (10 and 12) during Flight 7 on July 15, 1982. Flight 7 was selected because the B-57B encountered severe turbulence during runs 10-14. Of these runs, 10 and 12 were selected because they are examples of one level flight and one simulated ILS approach/departure case, respectively.

Turbulent velocity plots for the left, center, and right booms are presented on the left side of Figs. 9 and 10. The plots on the right side are the differences between velocities measured at the left wingtip and those measured at the right wingtip. The turbulent velocity plots vary little from wingtip to wingtip in large scale features. The features that catch the eye are mostly low-frequency features with a length scale much larger than the 19.5 m (60 ft) wingspan of the B-57B. The only differences between the u component measured at

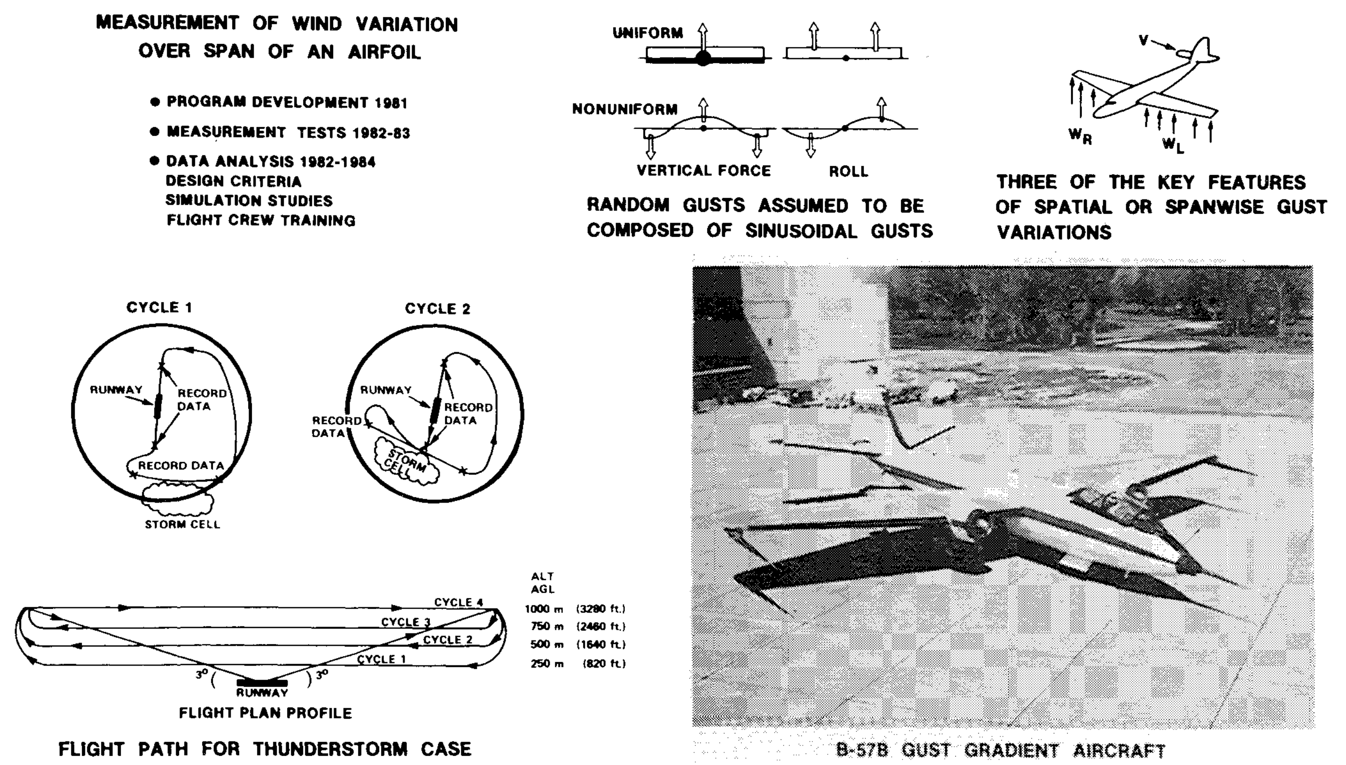
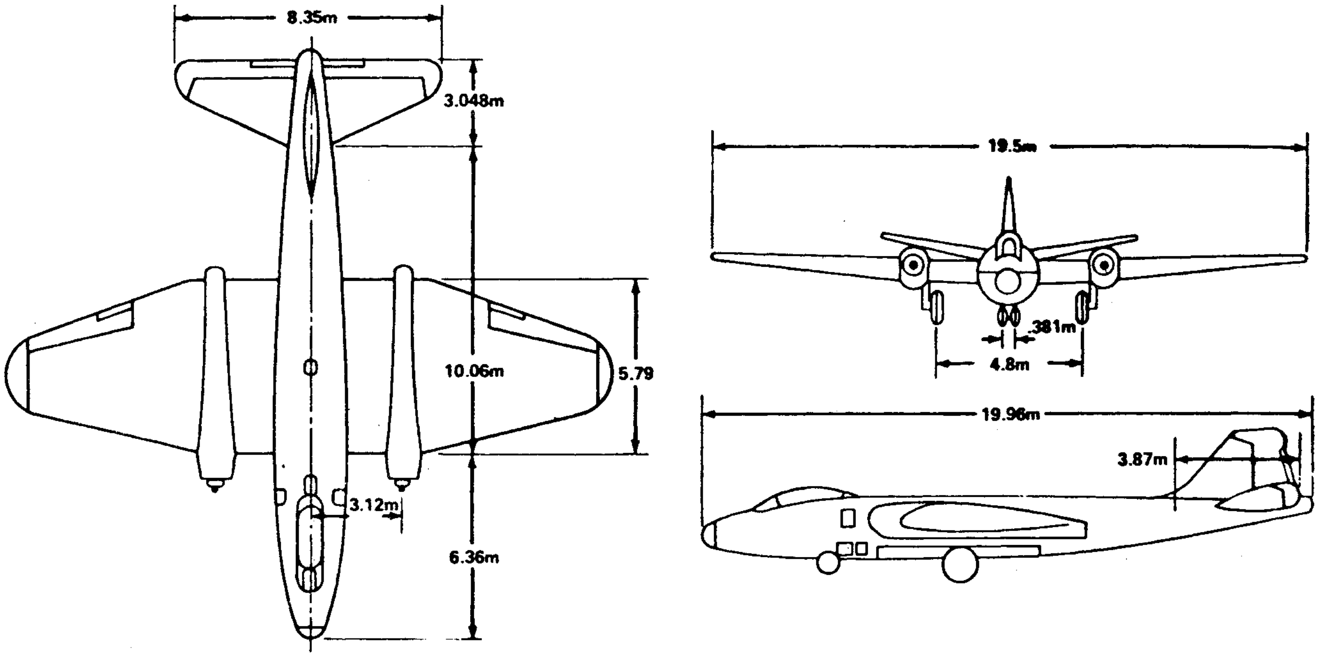


Fig. 3 NASA's B-57B Gust Gradient Program.



WING SPAN	19.5 m
MEAN AERODYNAMIC CHORD	(4.57m)
ROOT CHORD	(5.79m)
TIP CHORD	(2.38m)
LENGTH, FUSELAGE	(19.97m)
OVERALL	(20.20m)
HEIGHT	(4.75m)
TRACK	(4.70m)
TAIL PLANE SPAN	(8.35m)
ROOT CHORD	(3.44m)
TIP CHORD	(1.23m)

FIN AND RUDDER CHORD, ROOT	(3.87m)
TIP	(1.54m)
FUSELAGE GROUND CLEARANCE, NORMAL	(0.81m)
WING AREA, GROSS	(89.1m^2)
ASPECT RATIO	4.3
THICKNESS/CHORD RATIO, ROOT	12%
TIP	9%

MAIN PLANE INCIDENCE	2°
DIHEDRAL, INNER PLANE	2°
OUTER PLANE	4° 21′
TAIL PLANE AND ELEVATOR AREA, CROSS	(15.9 m^2)
INCIDENCE, NORMAL	+1°
MAX.	+1° 52′
MIN.	−3° 52′
FIN AND RUDDER AREA, GROSS	(6.6m^2)
MASS =	25,900 kg

Fig. 4 Nomenclature of B-57B.

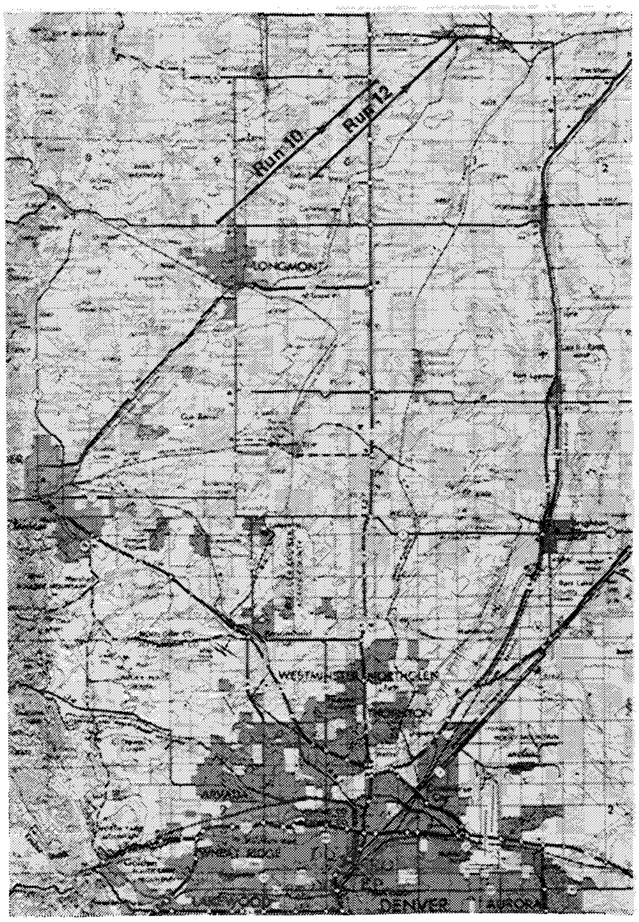


Fig. 5 Data collection area (Jaws Project, Denver, Colo).

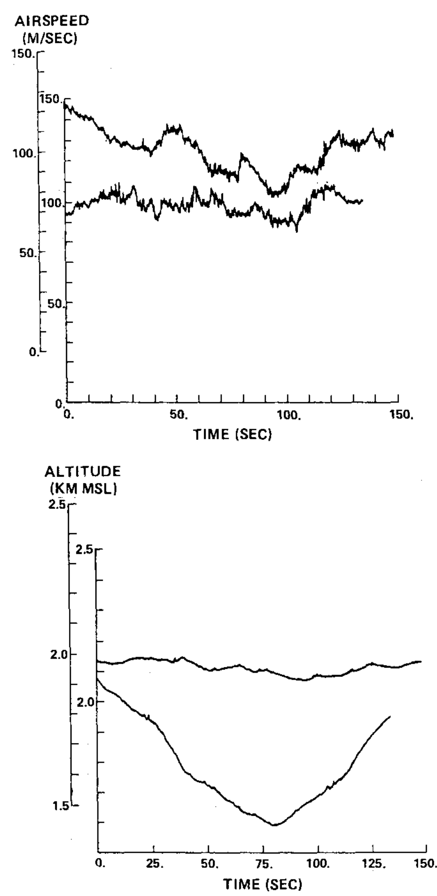


Fig. 6 B-57B flight altitude and airspeed traces for two test runs from the JAWS-7 flight.

Fig. 7 Sequence of a funnel cloud development.

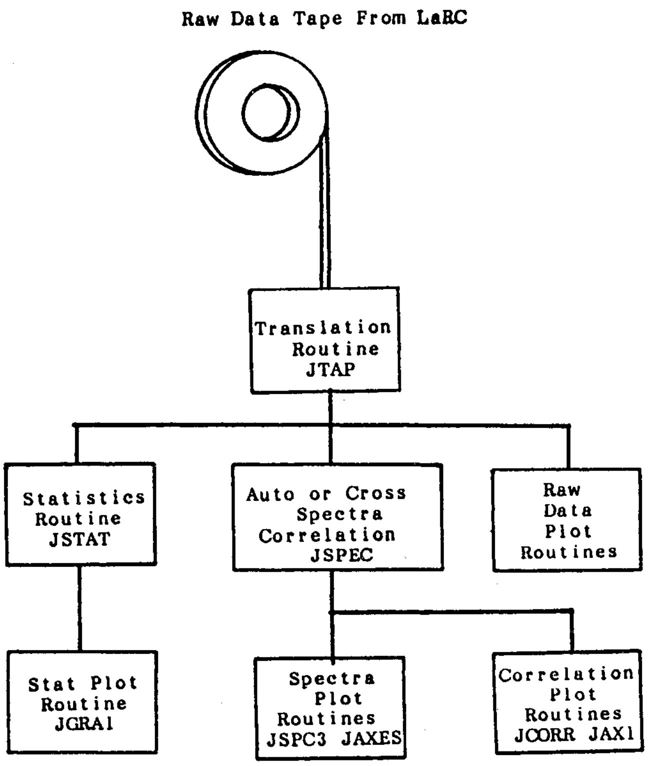


Fig. 8 Gust gradient data analysis.

one wingtip and the u component measured at the other wingtip occur at higher frequencies. Intuitively, this situation is exactly what one would expect. The similarity of the velocity traces increases confidence in the instruments and measurements.

The limited spatial variation of the turbulence velocities raises the question of whether spanwise gust variation is significant. Reference to the right side of Figs. 9 and 10 indicates that the variation is significant. Velocity differences are as large as 10 m/s (20 knots). At a 100 m/s (200 knot) airspeed, this is a 10% variation in velocity across an airfoil, which is quite large. Differing velocities performs efficient high-pass filtering. The large scale trends are removed. This

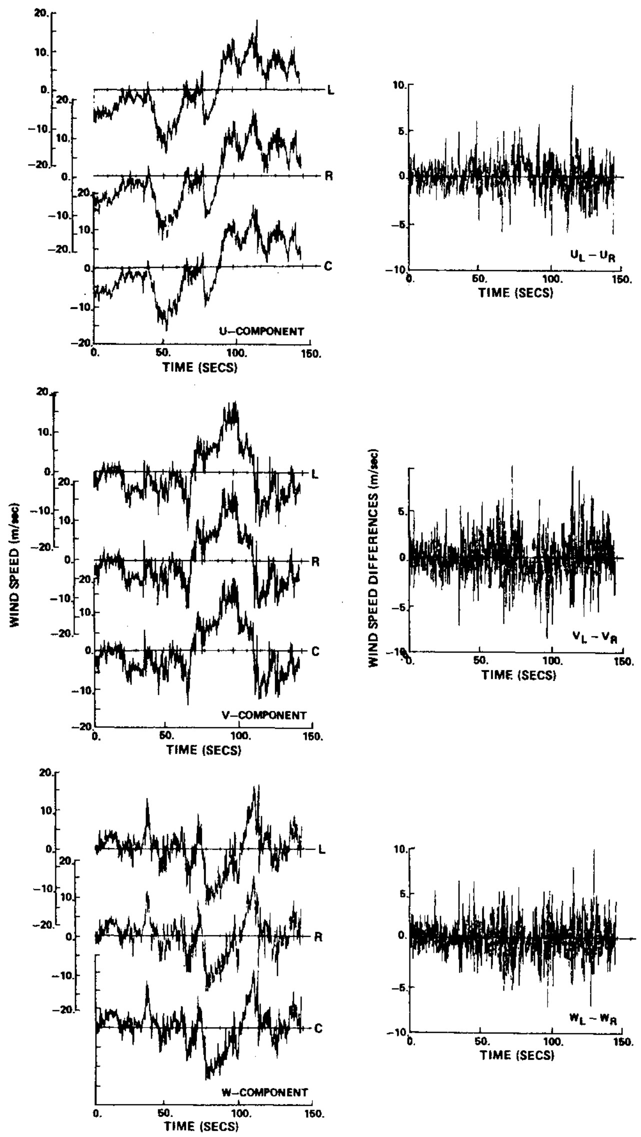


Fig. 9 JAWS-7/run 10 component wind speeds and wind speed differences.

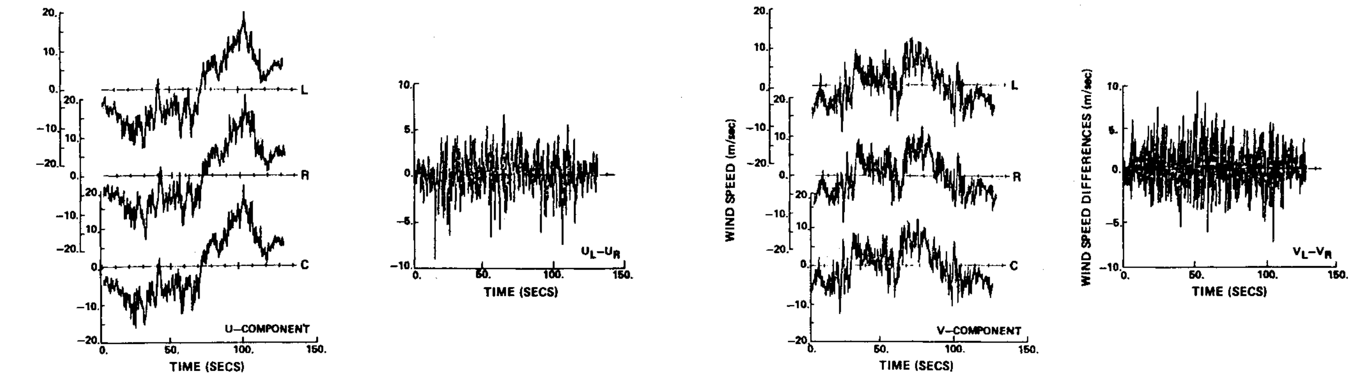
has a smoothing effect on the probability densities. Figure 11 shows turbulent velocity probability densities. Because of the large trends in the data, the probability densities are quite rough with more than one mode. This roughness does not occur for the velocity differences which are not shown. The densities of the differences are smooth and uninodal and modeling these with a normal distribution is not unreasonable.

Figure 9 indicates a phenomenon which requires some explanation. The u component of turbulent velocity seems less "noisy" that the v and w components. This is due to the fact the longitudinal velocity components are filtered at LaRC. The filtering can be seen in the raw data plots, but is more apparent in the spectra.

Flight altitudes for runs 10 and 12 are shown in Fig. 6. The vertical axis begins at 1.5 km above sea level, which in the Denver area is roughly ground level. In run 12 the minimum altitude of about 100 m (328 ft) is achieved at about 80 s into the run. Just after 25 s into the run, the aircraft experienced a significant drop in altitude, falling 50 m (165 ft) below the glideslope. At that point on the true airspeed curve, the B-57B encountered an increase of 10 m/s (20 knots over a period of approximately 25. The fall occurs over a period of approximately 15 s after which time the pilot was able to return

Table 3 B-57B data channels

CH	Quantity	Range	Resolution
1	Time, s		0.01 s
2	Roll velocity (rad/s)	1 rad/s	0.02
3	Normal acceleration at the CG (G units)	+5 −3 G	0.004
4	Pitch velocity (rad/s)	1 rad/s	0.002
5	Pitch attitude (rad)	15 deg	0.03
6	Roll attitude (rad)	"	"
7	Heading relative to true north (deg)	0-360 deg	0.14 arc/s
8	Heading relative to time zero HDG (deg)	"	"
9	HDG relative to true north, diff range (deg)	"	"
10	Diff Range HDG relative to time zero HDG (deg)		"
11	Normal acceleration at left wingtip (G units)	+5, −3G	0.004
12	Normal accelaration at right wingtip (G units)	"	"
13	X acceleration at the CG (G units)	1 G	0.002
14	Y acceleration at the CG (G units)	1 G	"
15	Angle of attack at the nose boom (rad)	15 deg	0.03
16	Angle of sideslip at the nose boom (rad)	"	"
17	Temperature of the INS pallet (deg, F)		0.1
18	Temp of the instrument pallet (deg, F)		"
19	Z accel INS (G units)	+ OR − 1G	0.04
20	Angle of attack at right boom (rad)	+ -15 deg	0.03
21	Sideslip angle at right boom (rad)	"	"
22	Angle of attack at left boom (rad)	"	"
23	Sideslip angle at left boom (rad)	"	"
24	Yaw rate (rad/s)	1 rad/s	0.002
25	Total temperature (deg, C)		0.1
26	Impact pressure at the left boom (psid)	0-3 psi	0.0004
27	Impact pressure at the center boom (psid)	"	"
28	Impact pressure at the rightr boom (psid)	"	"
29	Static pressure at the center boom (psia)	0-15 psia	"
30	Temp from IR radiometer (deg, C)		
31	Large distance (word overflow)		
32	Bearing to destination (deg)	0-360	0.14 arc/s
33	Longitude (deg)	+ -90 deg	"
34	Latitude (deg)	+ -180 deg	"
35	Track angle (deg)	0-360 deg	"
36	Heading (rad)	"	"
37	Airplane east-west inertial vel (m/s)	+ -1200 m/s	0.0003 m/s
38	Airplane north-south inertial vel (m/s)	"	"
39	Altitude (km)		
40	Computed free air temp (deg, C)	+ 35-65 deg, C	0.1
41	East-west wind speed (knots)		
42	North-south wind speed (knots)		
43	Wind speed (knots)		
44	Wind direction (deg)		
45	Airspeed R (m/s)	1200 m/s	0.0003 m/s
46	Airspeed C (m/s)	"	"
47	Airspeed L (m/s)	"	"
48	Alt change from start of run (m)		
49	Inertial displacement (m)		
50	UG R (m/s)		0.3 m/s
51	UG C (m/s)		"
52	UG L (m/s)		"
53	VG R (m/s)		"
54	VG C (m/s)		"
55	VG L (m/s)		"
56	WG R (m/s)		"
57	WG C (m/s)		"
58	WG L (m/s)		"



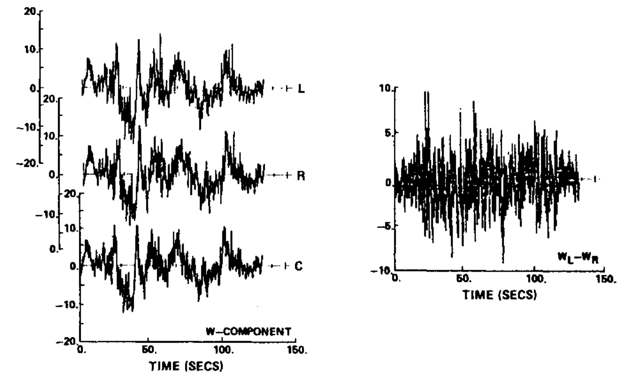


Fig. 10 JAWS-7/run 12 component wind speeds and wind speed differences.

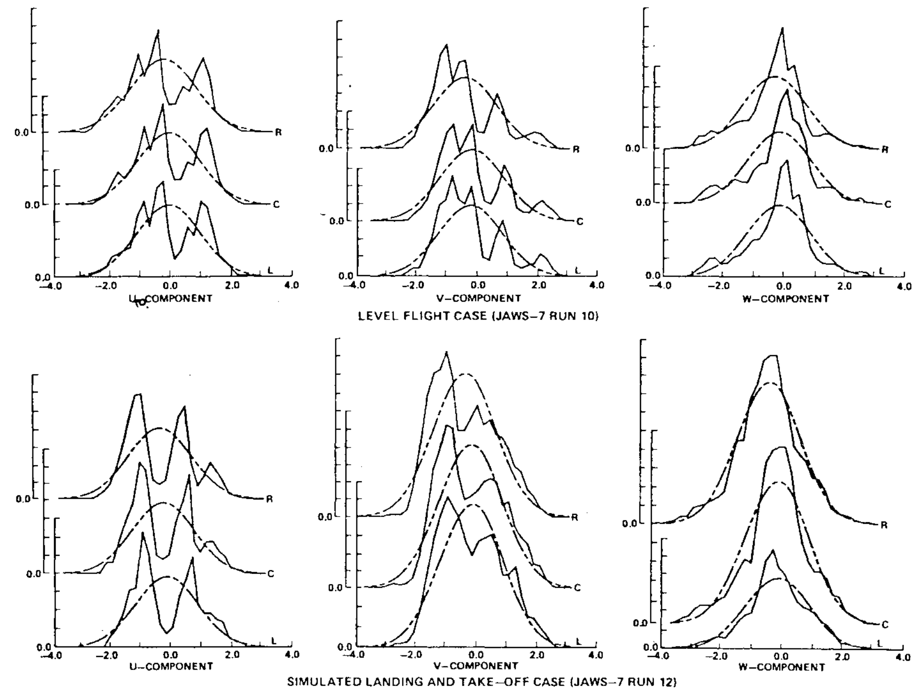


Fig. 11 Probability densities for two selected data runs.

to the nominal 3 deg glide slope. Because the approach was simulated over an open field, the pilot had no way of returning to the original approach path and he continued the 3 deg glide slope at the lower altitude.

Several conclusions can be drawn from the preliminary data analysis. Gust gradients in moderate to severe turbulence are significant, even over the 19.5 m (60 ft) windspan of the B-57B. Gust differences on the order of 10 m/s (20 knots) from wingtip to wingtip were encountered. This velocity difference was observed in all three components (U_L-U_R, V_L-V_R, W_L-W_R) of velocity. The difference in the vertical components (W_L-W_R) generates a roll moment. This roll moment resulted in roll attitudes of ± 12 deg in the two runs presented. These roll moments are especially significant in light of the high skill level of the research pilot for the B-57B. For wide bodied aircraft with large wingspans, the effects of roll moments on aircraft performance may be even more pronounced.

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