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HIGH ALTITUDE GUST ACCELERATION ENVIRONMENT AS EXPERIENCED BY A SUPERSONIC AIRPLANE

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16. Abstract

High altitude turbulence experienced at supersonic speeds is described in terms of gust accelerations measured on the YF-12A airplane. The data were obtained during 90 flights at altitudes above 12.2 kilometers (40,000 feet).

Subjective turbulence intensity ratings were obtained from air crew members. The air crew often rated given gust accelerations as being more intense during high altitude supersonic flight than during low altitude subsonic flight.

The portion of flight distance in turbulence ranged from 6 percent to 8 percent at altitudes between 12.2 kilometers and 16.8 kilometers (40,000 feet and 55,000 feet) to less than 1 percent at altitudes above 18.3 kilometers (60,000 feet). The amount of turbulence varied with season, increasing by a factor of 3 or more from summer to winter. Given values of gust acceleration were less frequent, on the basis of distance traveled, for supersonic flight of the YF-12A airplane at altitudes above 12.2 kilometers (40,000 feet) than for subsonic flight of a jet passenger airplane at altitudes below 12.2 kilometers (40,000 feet).

The median thickness of high altitude turbulence patches was less than 400 meters (1300 feet); the median length was less than 16 kilometers (10 miles). The distribution of the patch dimensions tended to be log normal.

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AS EXPERIENCED BY A SUPERSONIC AIRPLANE

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INTRODUCTION

The amount of turbulence supersonic aircraft can expect to encounter at high altitudes was previously described on the basis of data from special surveys made by subsonic aircraft (refs. 1 and 2). Since airplane acceleration response and passenger reactions to turbulence depend not only on the amount of turbulence but also on aircraft speed, structural flexibility, and configuration, the experience of supersonic aircraft at these altitudes is also of interest.

The amount of high altitude turbulence encountered by the XB-70 airplane at supersonic speeds and the structural response of the airplane are reported in references 3 and 4. Substantial additional data on turbulence encountered at high altitudes and supersonic speeds were acquired from flights made by the YF-12A airplane (fig. 1) during a NASA research program. This paper presents gust acceleration

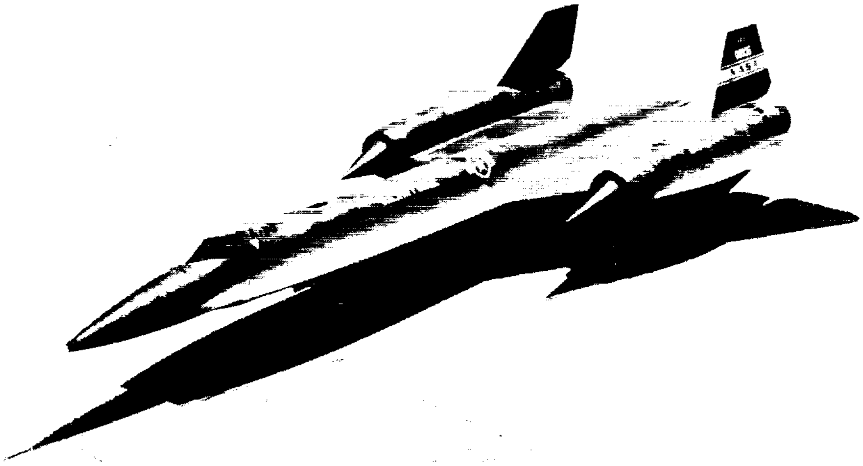


Figure 1. YF-12A airplane. *E-23129*

data acquired during these flights. The distribution of the gust acceleration magnitudes and the dimensions of the turbulence patches are discussed. Subjective ratings of turbulence intensity, the relative amount of turbulence encountered above 12.2 kilometers (40,000 feet), and seasonal tendencies are also reported.

The data were obtained during flights that were made from Edwards, California, and followed various flightpaths in the Western United States (fig. 2). Almost all the flights were conducted between midmorning and early afternoon. Flights were scheduled and routed without taking high altitude turbulence into consideration.

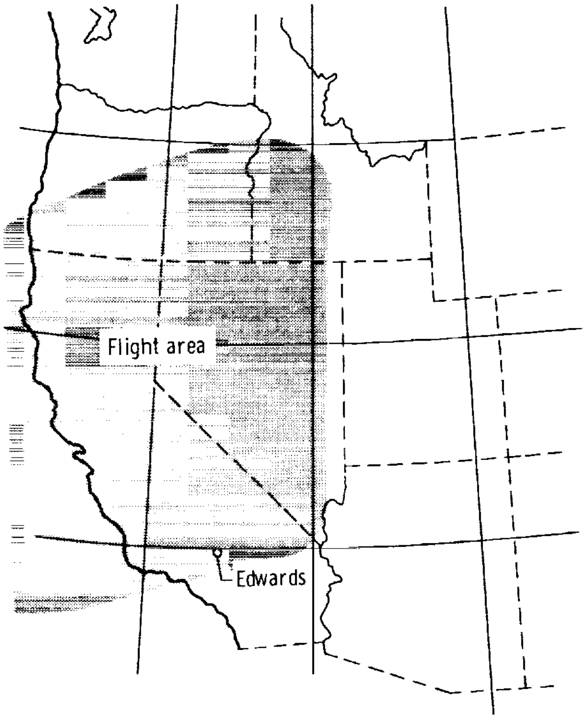


Figure 2. Flight test area for acquisition of YF-12A turbulence data.

Physical quantities are given in the International System of Units (SI) and parenthetically in U.S. Customary Units. Measurements were taken in U.S. Customary Units and converted with the factors given in reference 5.

AIRPLANE AND INSTRUMENTS

The YF-12A airplane is a high performance, two-place aircraft capable of flight at altitudes above 24 kilometers (80,000 feet) and speeds greater than Mach 3 (refs. 6 and 7). Its configuration incorporates a modified delta wing with chines extending from the nose cone to the wing. A turboramjet engine with a mixed compression inlet is mounted integral to each wing at approximately midsemispan. Twin rudders are on top of the engine nacelles, and there is a ventral fin on the aft fuselage that folds for takeoff and landing. The airplane's structure is described in detail in references 8 and 9.

The data reported herein were acquired with two YF-12A aircraft. Each airplane was equipped with a calibrated nose boom for obtaining air data (refs. 10 and 11) and accelerometers for monitoring gust response (fig. 3). The accelerometers were part of a NASA VGH recorder (ref. 12), which made time history traces of normal acceleration at the airplane's center of gravity and the pilot's station. The recorders used were identical to those that provided gust acceleration data for the XB-70 airplanes (refs. 3, 4, and 13).

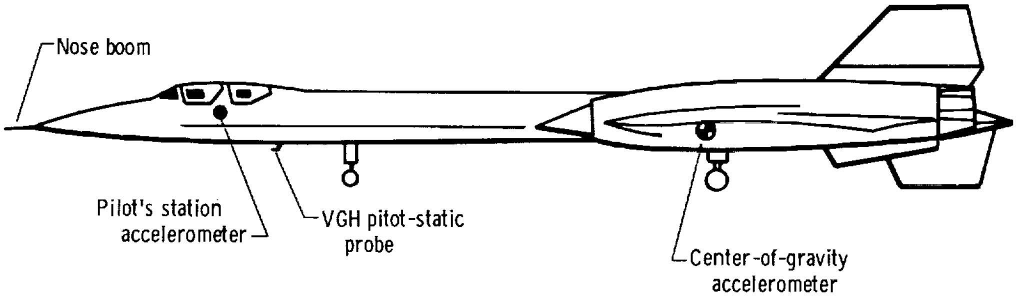


Figure 3. Instrument locations on the YF-12A airplane.

In addition to providing traces of normal acceleration, the VGH recorders provided time history traces of uncalibrated airspeed and pressure altitude. A pitot pressure probe mounted close to the recorder on each airplane provided the airspeed trace with rapid response capability. The recorder operated at a film speed of 0.68 centimeter per second (16 inches per minute) and ran continuously during flight at altitudes above 12.2 kilometers (40,000 feet).

A total temperature probe adjacent to the pitot probe provided the data necessary to convert flight Mach numbers to true airspeed. During the first flights, total temperature and basic air data parameters, including Mach number, equivalent airspeed, and altitude, were recorded by using a photopanel. These parameters were derived by an air data computer from nose boom measurements of total and static pressure. The air data computer also made corrections for the static-pressure position error (ref. 11). The computed values were displayed on the photopanel as well as on the cockpit instruments.

During the later flights, the air data, which were acquired from the air data sensors in analog format, were digitized by pulse code modulation and recorded by an onboard magnetic tape recorder. Mach number, altitude, and true airspeed were subsequently computed with ground-based data processing equipment.

DATA ANALYSIS METHOD

The presence of turbulence was indicated in the VGH records by characteristic random oscillations in the center-of-gravity normal acceleration trace and by rapid, irregular disturbances in the airspeed trace (fig. 4). The aircraft was considered to have encountered turbulence if the variation in the peak-to-peak center-of-gravity normal acceleration trace equaled or exceeded 0.10g at least once and if there were continuous, random fluctuations in the airspeed and normal acceleration traces. Since the structural response of the YF-12A airplane is lightly damped, a peak-to-peak variation of 0.10g in the normal acceleration trace is equivalent to a peak of approximately 0.05g on one side of the steady state value.

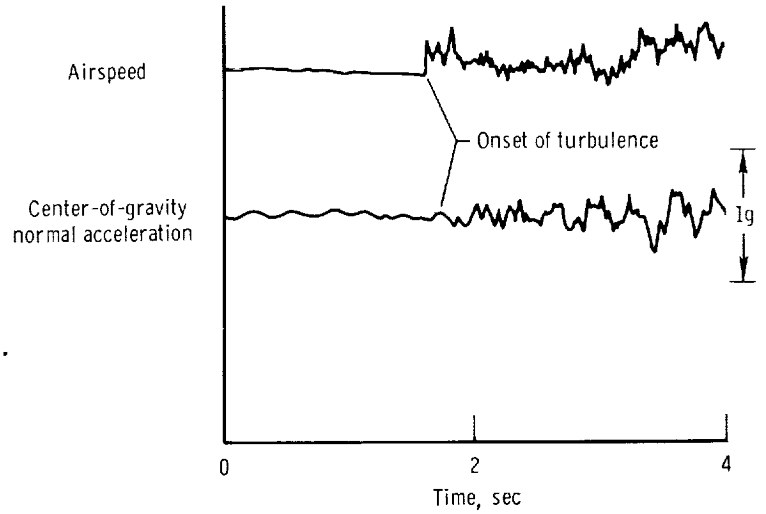


Figure 4. Typical time history of normal acceleration and airspeed for a YF-12A high altitude turbulence encounter.

The portion of overall flight distance in turbulence was determined by computing the total distance flown and the length of the turbulence patches encountered. The length of each turbulence patch was computed by multiplying its duration time by the average true airspeed for the encounter. The data were separated into 1.5-kilometer (5000-foot) altitude bands, and the distance flown in each altitude band was determined by multiplying the time spent in the altitude band by the average true airspeed. The relative amount of turbulence for each altitude band was determined by dividing the sum of the individual turbulence patch lengths by the total distance flown in each band.

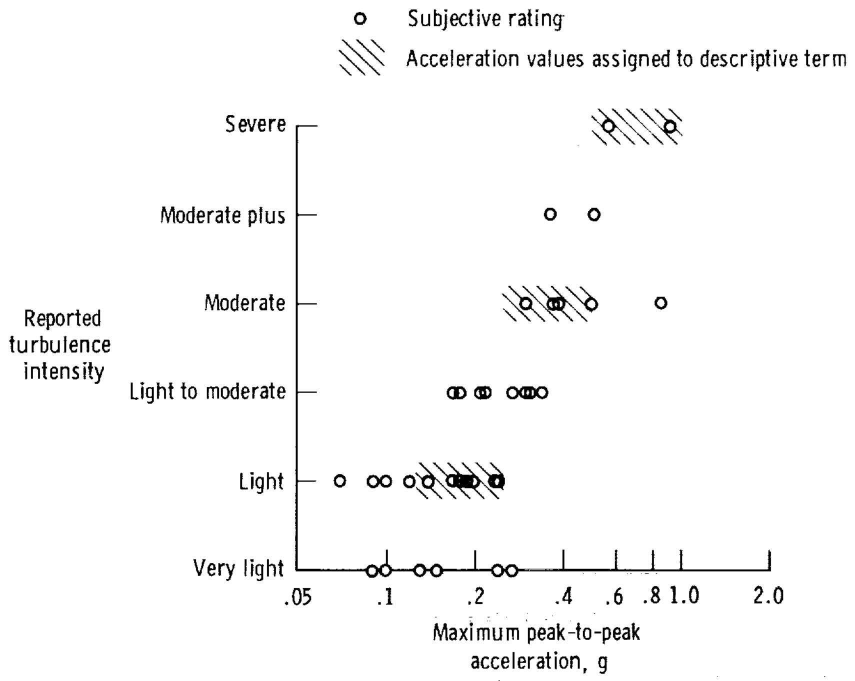
The accuracy of the measurement of the distance flown in each altitude band was estimated to be better than 1 percent, since the true airspeed was based on calibrated air data. It was more difficult to determine the duration of each turbulence encounter (and therefore the length of each turbulence patch), because the patches were usually short and the times of turbulence onset and termination were sometimes difficult to identify exactly. The duration of most of the rough air encounters could be determined within 1 second, but some encounters occurred while there were other sources of aircraft excitation or during periods when the quality of the recorder trace was poor. The determination of turbulence duration for these encounters is estimated to be accurate within 3 seconds. If it is assumed that there is an error of less than 1.5 seconds in the measurement of the duration of the average encounter, which is 18 seconds, the error that results in the computation of turbulence patch length is less than one-twelfth of the patch length. Since this error is random, it tends to cancel out when several patch lengths are added.

RESULTS AND DISCUSSION

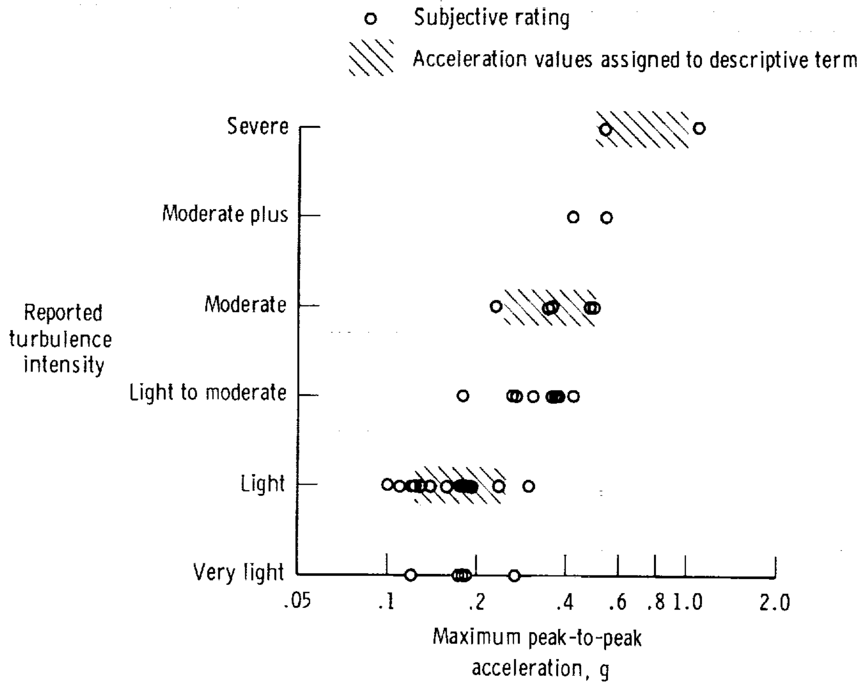
Subjective Intensity Ratings

During the test program, subjective pilot ratings of turbulence intensity were acquired for encounters with turbulence during supersonic flight at altitudes above 12.2 kilometers (40,000 feet). Ratings given by eight air crew members during the course of the survey were compared with values of the associated maximum peak-to-peak accelerations to describe an empirical relation between pilot-reported intensity and airplane gust response. Figure 5 is a plot of the resulting data for the center of gravity and the pilot's station, with a linear scale for the subjective intensity rating and a logarithmic scale for the gust accelerations. The subjective intensity ratings are grouped within reasonably well-defined ranges of acceleration magnitude for ratings greater than light. The grouping is especially pronounced for the ratings for the pilot's station. This demonstrates that the air crew members were able to make rather fine distinctions between the various turbulence intensities encountered during high altitude supersonic flight. Consequently, it was relatively easy to assign gust acceleration amplitude intervals to the descriptive terms, as shown in figure 5. The acceleration values selected to correspond to the descriptive terms are as follows:

	Maximum peak-to-peak acceleration, g
Light	<0.25
Moderate	0.25 to 0.50
Severe	≥0.50



(a) *Center of gravity.*



(b) *Pilot's station.*

Figure 5. Normal acceleration versus air crew turbulence intensity ratings during supersonic flight at high altitude (above 12.2 kilometers (40,000 feet)).

The subjective intensity ratings and the pilot's station accelerations for turbulence encountered by the YF-12A airplane during subsonic flight at altitudes below 12.2 kilometers (40,000 feet) are shown in figure 6. The ratings are not as well grouped as the ratings for the higher altitudes. The lack of definition is especially noticeable for the light and light-to-moderate ratings, which were given to higher accelerations and over a wider range of values than at the higher altitudes during supersonic flight.

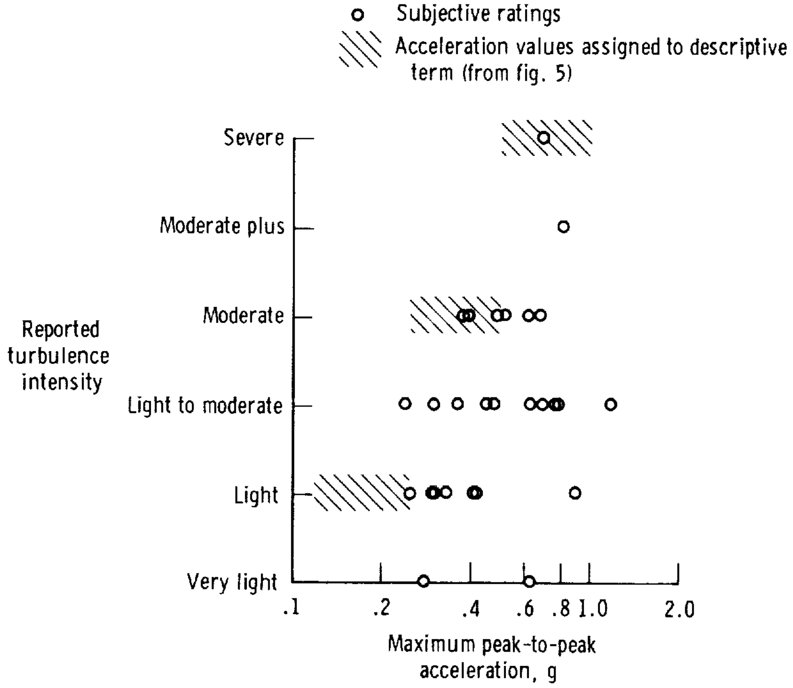


Figure 6. Normal acceleration at the pilot's station versus air crew turbulence intensity ratings during subsonic flight below 12.2 kilometers (40,000 feet).

It should also be noted that the accelerations for each rating given by YF-12A air crew members for high altitude, supersonic flight are considerably lower than those specified by the Supplementary Information on Turbulence Reporting Criteria Table (Subcommittee on Aviation Meteorological Services, U.S. Dept. of Commerce) for subsonic aircraft. Figure 7 shows the acceleration amplitudes for the various subjective intensity ratings for the subsonic aircraft criteria, the YF-12A air crew, and the XB-70 air crew (ref. 14). In the XB-70 data, too, the accelerations for each subjective turbulence rating were relatively low during high altitude supersonic flight. The fact that the subsonic aircraft criteria are in terms of peak acceleration values (on one side of the steady state value) as opposed to the YF-12A and XB-70 data, which are in terms of peak-to-peak values, further emphasizes the differences in acceleration magnitude shown. These differences are believed to be due to the increased awareness of the air crew to disturbances at high altitudes and Mach numbers as well as to the increased rapidity with which strong gust accelerations are experienced when updraft-downdraft patterns are encountered at high speeds.

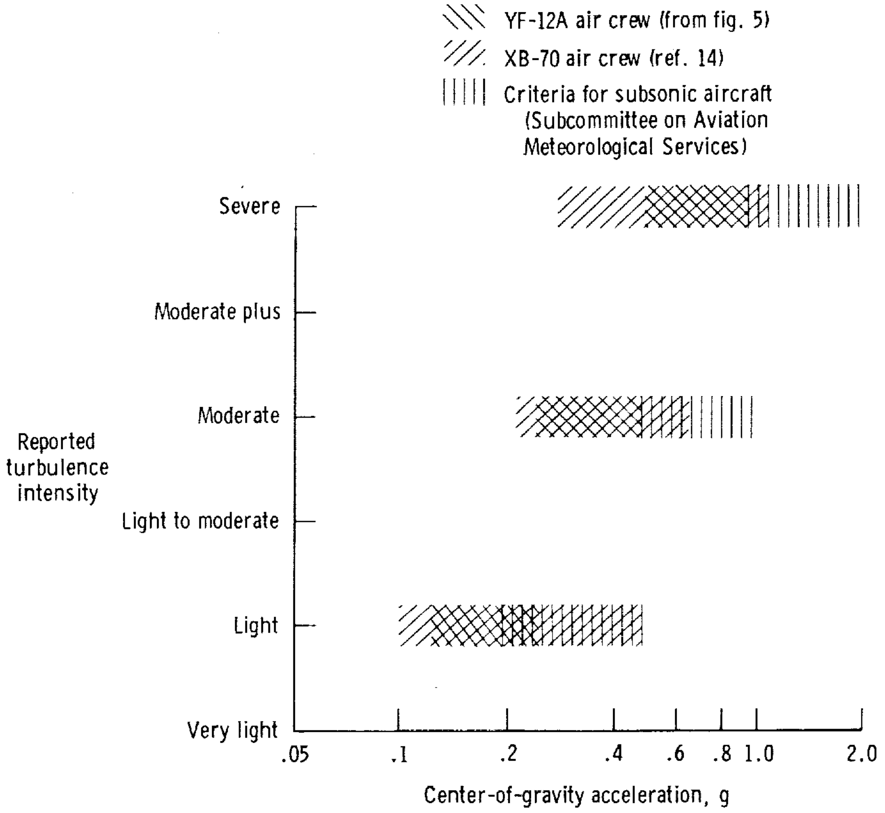


Figure 7. Normal accelerations for subjective turbulence intensity ratings from high altitude supersonic flight compared with rating criteria for conventional subsonic aircraft.

Relative Amount of High Altitude Turbulence

The portion of flight distance during which the YF-12A airplane experienced turbulence based on the 0.10g peak-to-peak acceleration threshold varied greatly with altitude. The data obtained from 90 flights for altitudes above 12.2 kilometers (40,000 feet) are summarized in table 1. At altitudes between 12.2 kilometers and 16.8 kilometers (40,000 feet and 55,000 feet), 6 to 8 percent of the flight distance was turbulent, in contrast to less than 1 percent of the distance at altitudes above 18.3 kilometers (60,000 feet).

The variation of the percentage of distance in turbulence with altitude is compared with the results of previous surveys in figure 8. Since survey results depend on such factors as speed, aircraft structural characteristics, the turbulence threshold definition used, topography, and atmospheric conditions, the agreement of the results of surveys based on measured accelerations is not expected to be close. However, the reference 4 data for the XB-70 airplane for altitudes below 16.8 kilometers (55,000 feet), which were acquired with the same VGH recorders and similar threshold criteria as for the YF-12A airplane, agree closely with the YF-12A data. The lower amount of turbulence indicated by the subsonic U-2 airplane data (refs. 1 and 15) may be primarily the result of the threshold definitions used. A derived

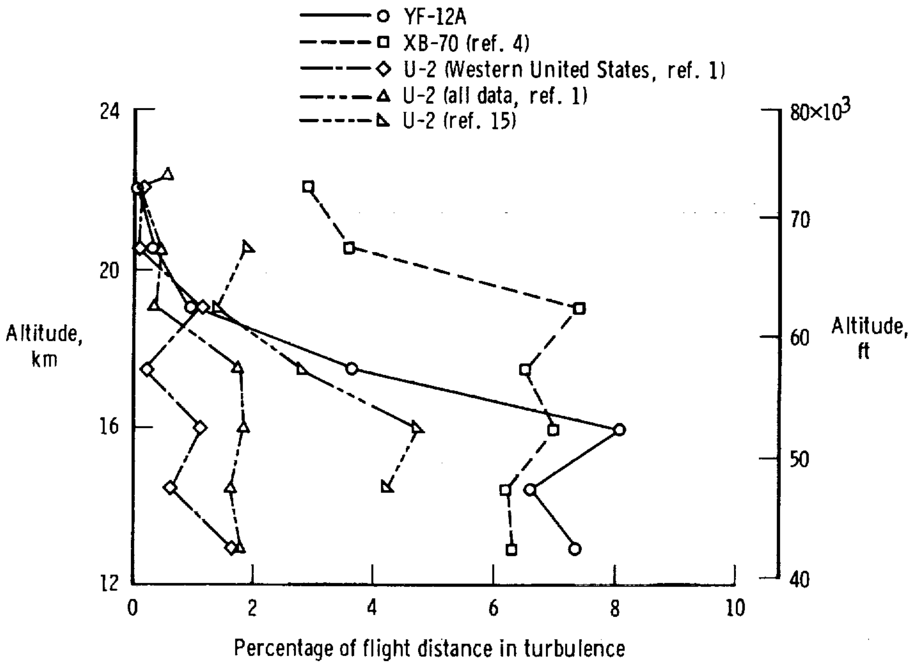


Figure 8. Amount of turbulence versus altitude.

equivalent gust velocity of 0.6 meter per second (2 feet per second) was used as the threshold in reference 1, and continuous, rapid center-of-gravity normal acceleration disturbances with peak amplitudes in excess of ±0.10g were used as the threshold criteria in reference 15. The differences between the reference 1 and the reference 15 results may be due in part to differences in the flight scheduling and routing procedures, which for much of the reference 15 data called for sampling areas of forecast turbulence.

Another way to assess high altitude gust accelerations is illustrated by figure 9, in which the logarithmic ordinate scale gives the cumulative frequency with which the peak acceleration amplitudes specified on the abscissa are exceeded per kilometer (nautical mile) of flight. The gust acceleration amplitude distribution for a subsonic passenger jet transport operating at altitudes below 12.2 kilometers (40,000 feet) (ref. 16) is compared with YF-12A data for altitudes above 12.2 kilometers (40,000 feet). (Half-amplitude, or peak, YF-12A acceleration values are shown instead of full peak-to-peak amplitudes for consistency with the ref. 16 data.) The transport airplane experienced given acceleration levels five to 10 times more frequently than the YF-12A airplane operating at altitudes between 12.2 kilometers and 18.3 kilometers (40,000 feet and 60,000 feet) and nearly two orders of magnitude more frequently than the YF-12A airplane operating at altitudes between 18.3 kilometers and 19.8 kilometers (60,000 feet and 65,000 feet). Above 19.8 kilometers (65,000 feet), the YF-12A airplane experienced no gust accelerations with half amplitudes greater than 0.10g during this survey. These relatively mild gust accelerations suggest that on the basis of distance traveled the influence of gust accelerations on fatigue life and ride quality is less for high altitude supersonic aircraft than it is for subsonic transports operating at lower altitudes.

TABLE 1.—FLIGHT DISTANCE, DISTANCE IN TURBULENCE, AND PERCENTAGE

Altitude band, km (ft)	Flight distances	January	February	March	April	May
12.2 to 13.7 (40,000 to 45,000)	Total distance flown, km (n. mi.)	476 (257)	513 (277)	1,323 (714)	1,769 (955)	1,864 (1,006)
	Distance in turbulence, km (n. mi.)	67.4 (36.4)	23.0 (12.4)	127.8 (69.0)	105.4 (56.9)	78.1 (42.1)
	Distance in turbulence, percent	14.2	4.5	9.7	6.0	4.2
13.7 to 15.2 (45,000 to 50,000)	Total distance flown, km (n. mi.)	468 (253)	463 (250)	1,371 (740)	1,361 (735)	2,202 (1,189)
	Distance in turbulence, km (n. mi.)	10.4 (5.6)	25.1 (13.6)	169.1 (91.3)	23.8 (12.9)	8.0 (4.3)
	Distance in turbulence, percent	2.2	5.4	12.3	1.8	0.4
15.2 to 16.8 (50,000 to 55,000)	Total distance flown, km (n. mi.)	1,347 (727)	750 (405)	1,698 (917)	1,706 (921)	808 (436)
	Distance in turbulence, km (n. mi.)	26.5 (14.3)	57.1 (30.8)	152.8 (82.5)	59.4 (32.1)	16.1 (8.7)
	Distance in turbulence, percent	2.0	7.6	9.0	3.5	2.0
16.8 to 18.3 (55,000 to 60,000)	Total distance flown, km (n. mi.)	913 (493)	830 (448)	2,208 (1,192)	4,012 (2,166)	1,613 (871)
	Distance in turbulence, km (n. mi.)	112.4 (60.7)	13.7 (7.4)	157.9 (85.2)	105.2 (56.8)	6.1 (3.3)
	Distance in turbulence, percent	12.3	1.6	7.2	2.6	0.38
18.3 to 19.8 (60,000 to 65,000)	Total distance flown, km (n. mi.)	1,672 (903)	1,329 (718)	1,664 (899)	5,110 (2,759)	2,636 (1,423)
	Distance in turbulence, km (n. mi.)	9.3 (5.0)	56.8 (30.7)	11.5 (6.2)	60.7 (32.8)	0 (0)
	Distance in turbulence, percent	0.6	4.3	0.7	1.2	0
19.8 to 21.3 (65,000 to 70,000)	Total distance flown, km (n. mi.)	3,259 (1,760)	3,156 (1,704)	3,624 (1,957)	4,556 (2,460)	2,746 (1,482)
	Distance in turbulence, km (n. mi.)	0 (0)	5.0 (2.7)	54.7 (29.5)	13.4 (7.2)	0 (0)
	Distance in turbulence, percent	0	0.2	1.5	0.3	0
≥21.3 (≥70,000)	Total distance flown, km (n. mi.)	1,332 (719)	3,669 (1,981)	9,102 (4,915)	6,134 (3,312)	4,600 (2,484)
	Distance in turbulence, km (n. mi.)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	Distance in turbulence, percent	0	0	0	0	0

OF DISTANCE IN TURBULENCE BY ALTITUDE BAND AND MONTH

June	July	August	September	October	November	December	Total
640 (346)	341 (184)	343 (185)	274 (148)	531 (287)	1,001 (541)	404 (218)	9,479 (5,118)
52.9 (28.6)	1.6 (0.9)	13.3 (7.2)	7.6 (4.1)	64.2 (34.7)	88.3 (47.7)	67.4 (36.4)	697.0 (376.4)
8.3	0.5	3.9	2.8	12.1	8.8	16.7	7.35
636 (343)	612 (330)	399 (216)	539 (291)	549 (296)	1,009 (545)	412 (223)	10,021 (5,411)
18.7 (10.1)	11.1 (6.0)	52.3 (28.2)	3.0 (1.6)	42.0 (22.7)	244.3 (131.9)	53.2 (28.7)	661.0 (356.9)
2.9	1.8	13.1	0.5	7.7	24.2	12.9	6.60
914 (494)	399 (216)	525 (283)	587 (317)	626 (338)	2,148 (1,160)	534 (288)	12,042 (6,502)
11.4 (6.2)	69.1 (37.3)	0 (0)	37.3 (20.2)	118.6 (64.0)	221.3 (119.5)	204.7 (110.5)	974.3 (526.1)
1.2	17.3	0	6.4	18.9	10.3	38.3	8.09
4,171 (2,252)	1,032 (557)	748 (404)	880 (475)	924 (499)	1,477 (798)	866 (468)	19,674 (10,623)
4.3 (2.3)	2.2 (1.2)	9.6 (5.2)	12.1 (6.5)	31.2 (16.9)	81.6 (44.1)	180.6 (97.5)	716.9 (387.1)
0.10	0.2	1.3	1.4	3.4	5.5	20.9	3.64
2,704 (1,460)	2,491 (1,345)	1,154 (623)	1,156 (624)	887 (479)	2,366 (1,277)	1,239 (669)	24,408 (13,179)
0 (0)	47.2 (25.5)	0 (0)	0 (0)	6.1 (3.3)	33.8 (18.2)	7.0 (3.8)	232.4 (125.5)
0	1.9	0	0	0.7	1.4	0.6	0.95
3,245 (1,752)	2,654 (1,433)	2,626 (1,418)	901 (487)	877 (474)	4,688 (2,531)	1,698 (917)	34,030 (18,375)
0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	11.1 (6.0)	20.1 (10.9)	104.3 (56.3)
0	0	0	0	0	0.2	1.2	0.31
2,311 (1,248)	306 (165)	4,838 (2,612)	2,876 (1,553)	4,279 (2,311)	9,542 (5,152)	5,393 (2,912)	54,382 (29,364)
0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	43.5 (23.5)	43.5 (23.5)
0	0	0	0	0	0	0.8	0.08

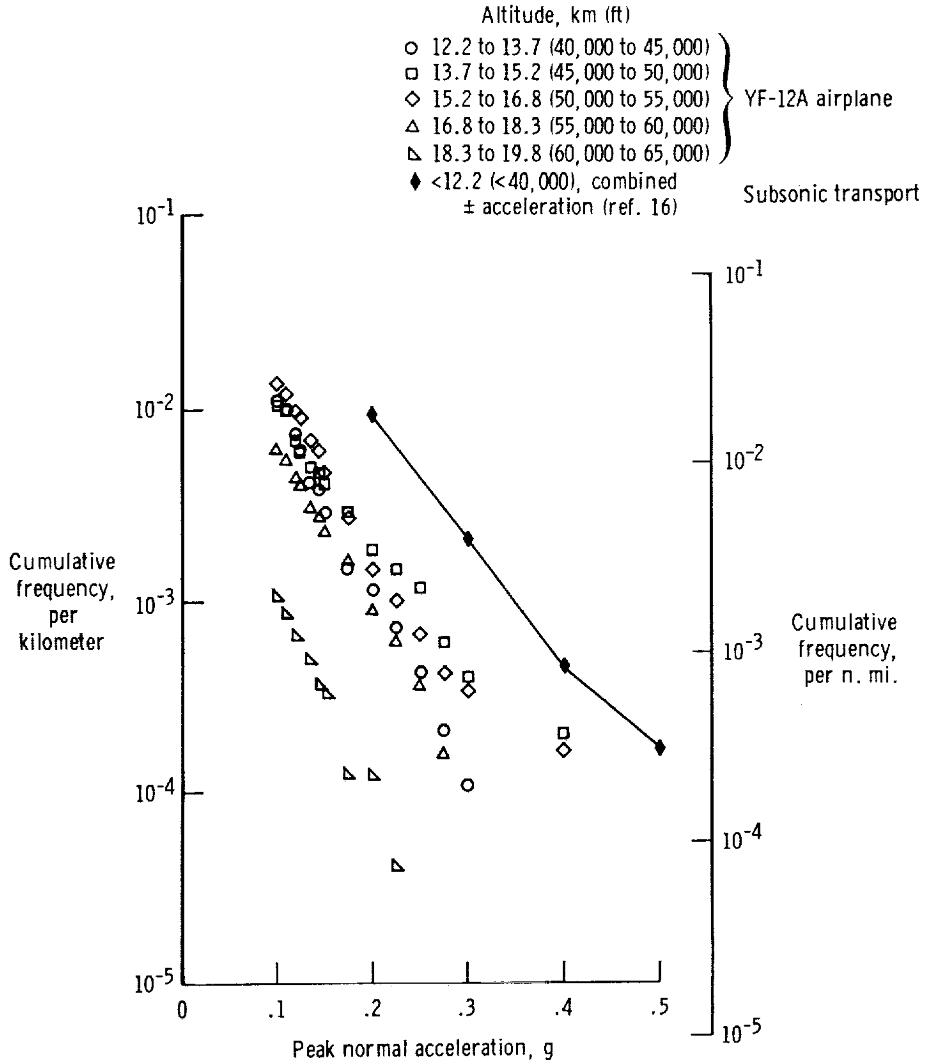
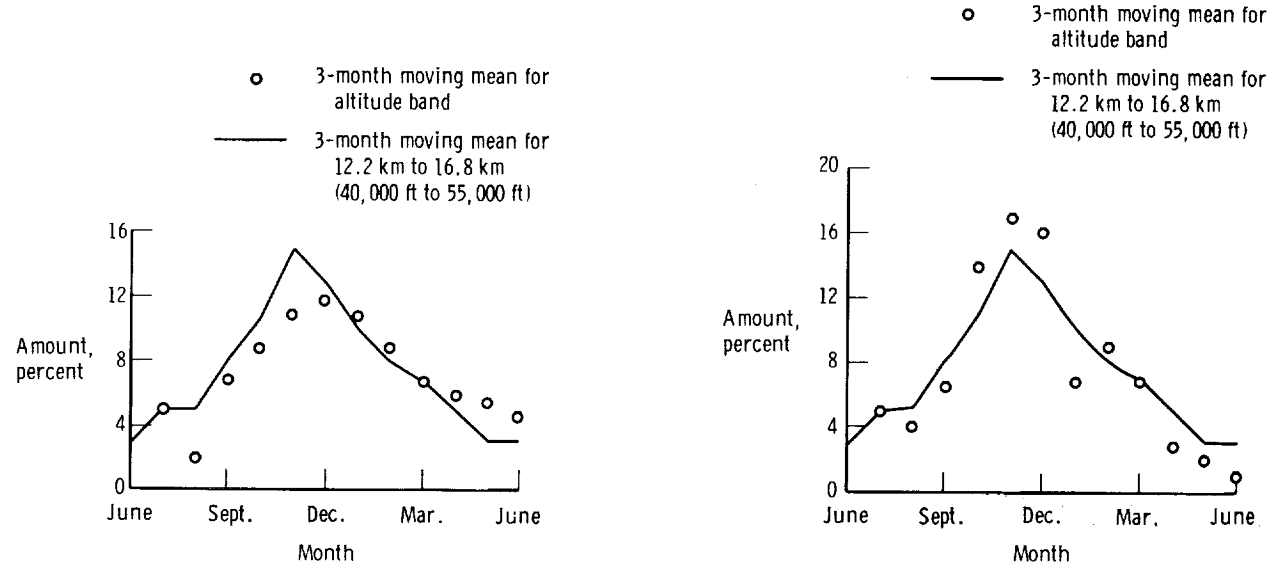


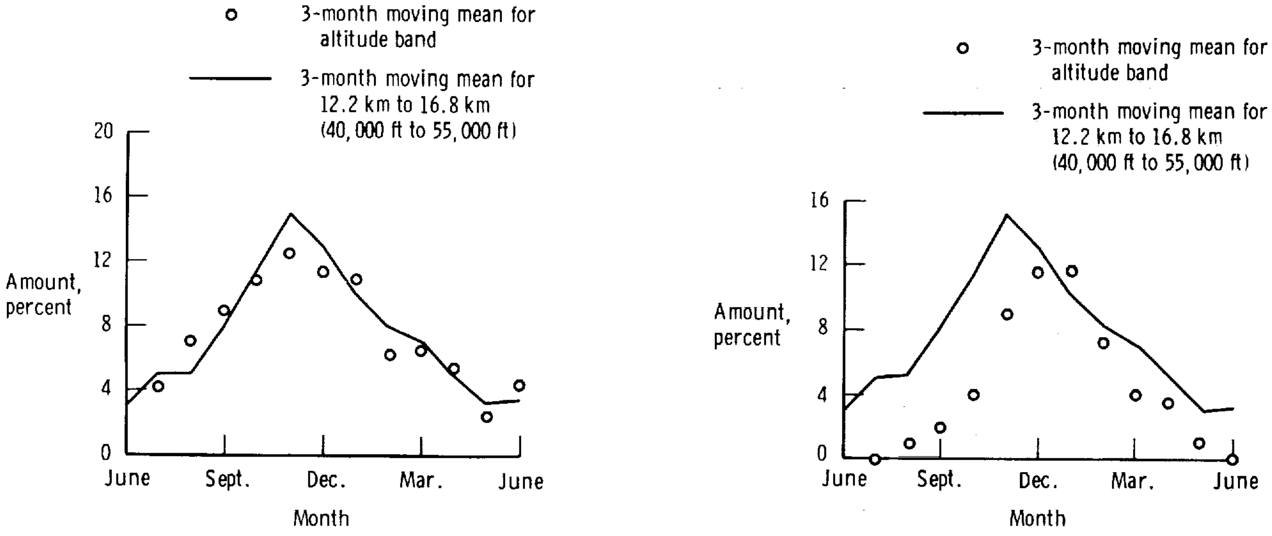
Figure 9. Comparison of cumulative frequency distributions of peak accelerations due to turbulence.

The variation of turbulence with season was examined on the basis of the monthly data also presented in table 1. Included in the table for each altitude band are the total distance flown, the distance flown in turbulence, and the percentage of the total distance that was flown in turbulence. The irregular month-to-month variation of the data for the altitude bands indicates that the sample, which consists of 90 flights made on 86 days, is smaller than desirable. Therefore, the variations were smoothed by using 3-month moving means for the distance flown and the distance flown in turbulence, which resulted in the relative amounts of turbulence shown in figure 10. There is a seasonal trend for altitudes below 18.3 kilometers (60,000 feet), where turbulence was more prevalent; however, month-to-month variation is still noticeable, particularly for altitudes below 16.8 kilometers (55,000 feet). The solid curve



(a) 12.2 km to 13.7 km (40,000 ft to 45,000 ft).

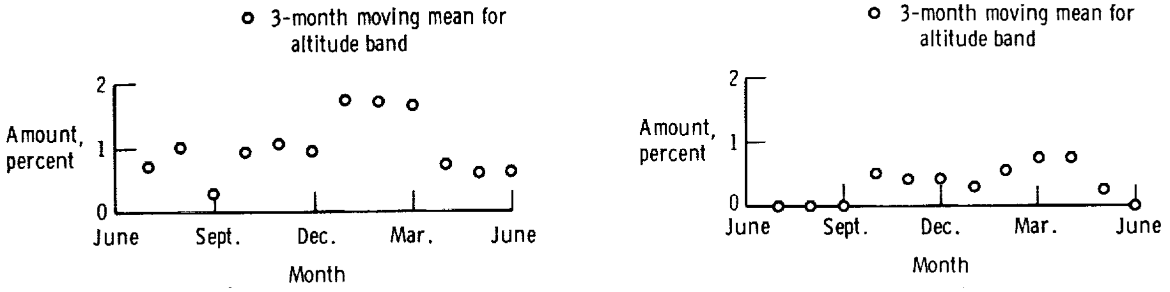
(b) 13.7 km to 15.2 km (45,000 ft to 50,000 ft).



(c) 15.2 km to 16.8 km (50,000 ft to 55,000 ft).

(d) 16.8 km to 18.3 km (55,000 ft to 60,000 ft).

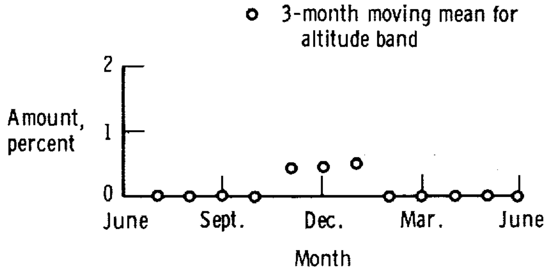
Figure 10. Seasonal variation (smoothed) of the relative amount of turbulence in percent of flight distance by altitude band and month.



(e) 18.3 km to 19.8 km (60,000 ft to 65,000 ft).

(f) 19.8 km to 21.3 km (65,000 ft to 70,000 ft).

in figure 10 shows the variation of the combined data for the three altitude bands between 12.2 kilometers and 16.8 kilometers (40,000 feet and 55,000 feet), which experienced similar amounts of turbulence. At altitudes above 18.3 kilometers (60,000 feet) the relative amount of turbulence remains at 1 percent or less except during winter and early spring in the band between 18.3 kilometers and 19.8 kilometers (60,000 feet and 65,000 feet), when it approaches 2 percent. For the altitude bands between 12.2 kilometers and 16.8 kilometers (40,000 feet and 55,000 feet), the relative amount of turbulence increases by a factor of 3 or more from summer to winter, rising from between 1 percent and 5 percent in summer to between 6 percent and 16 percent in winter.



(g) ≥21.3 km (≥70,000 ft).

Figure 10. Concluded.

The variation of turbulence with season can also be analyzed in terms of the percentage of flight days on which turbulence was encountered. The data presented herein were separated into seasons, and the number of days flown in each altitude band and the number of days turbulence was encountered in each altitude band were tabulated (table 2). The percentage of days turbulence was encountered was greatest during the winter for all altitude bands, and it was least at altitudes above 18.3 kilometers (60,000 feet) for all seasons.

Turbulence Patch Dimensions

Turbulence patches at high altitude tend to be flat and somewhat elongated in shape because of the general stratification of atmospheric properties. Therefore, the length and thickness of a patch of turbulence experienced by an aircraft depend on the airplane's flightpath. Aircraft flying at steep flightpath angles tend to enter and exit the upper and lower boundaries of the turbulence, whereas at shallow flightpath angles they tend to cross the sides. For intermediate flightpath angles, these effects are mixed. As a result, the dimensions of a turbulence patch experienced by an aircraft generally differ from the real dimensions of the turbulence patch.

TABLE 2.— FLIGHT DAYS AND FREQUENCY OF TURBULENCE ENCOUNTERS BY SEASON[1] AND ALTITUDE BAND

(a) Number of flight days

Altitude interval, km (ft)	Winter	Spring	Summer	Fall	Total
12.2 to 13.7 (40,000 to 45,000)	14	37	15	20	86
13.7 to 15.2 (45,000 to 50,000)	14	36	15	20	85
15.2 to 16.8 (50,000 to 55,000)	14	34	15	19	82
16.8 to 18.3 (55,000 to 60,000)	14	33	15	19	81
18.3 to 19.8 (60,000 to 65,000)	13	32	14	17	76
19.8 to 21.3 (65,000 to 70,000)	13	26	13	16	68
≥21.3 (≥70,000)	10	23	10	16	59

(b) Number of days turbulence was encountered

Altitude interval, km (ft)	Winter	Spring	Summer	Fall	Total
12.2 to 13.7 (40,000 to 45,000)	10	14	6	10	40
13.7 to 15.2 (45,000 to 50,000)	8	12	8	10	38
15.2 to 16.8 (50,000 to 55,000)	12	13	5	8	38
16.8 to 18.3 (55,000 to 60,000)	8	12	3	7	30
18.3 to 19.8 (60,000 to 65,000)	6	9	1	2	18
19.8 to 21.3 (65,000 to 70,000)	3	4	0	2	9
≥21.3 (≥70,000)	3	0	0	0	3

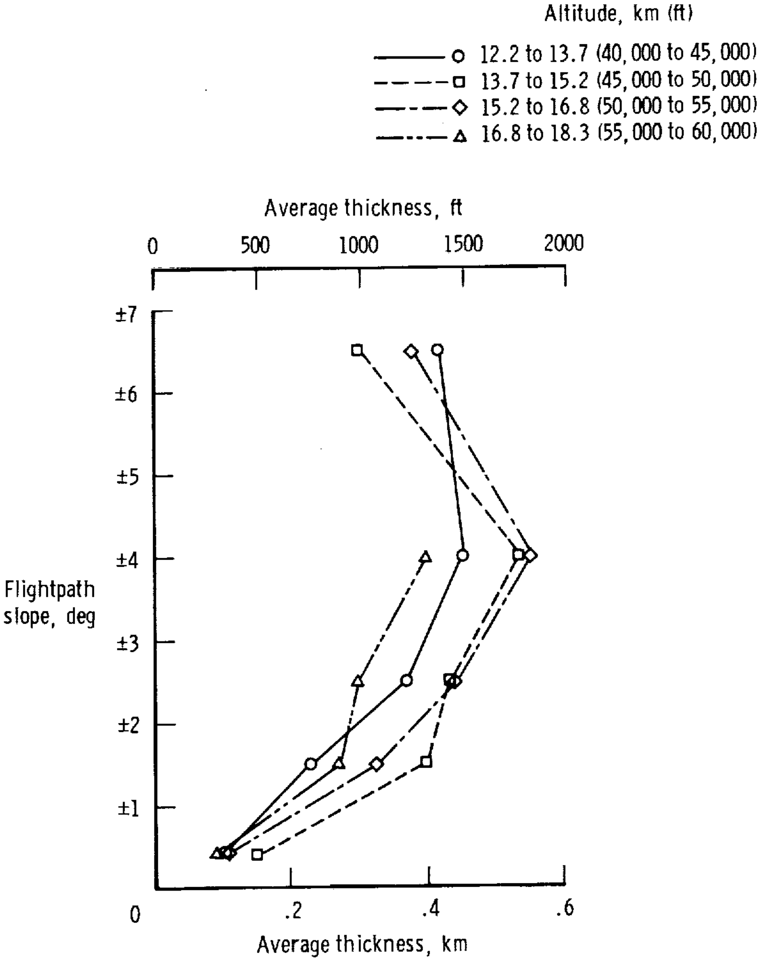
(c) Percentage of days turbulence was encountered[2]

Altitude interval, km (ft)	Winter	Spring	Summer	Fall	Total
12.2 to 13.7 (40,000 to 45,000)	71	38	40	50	46
13.7 to 15.2 (45,000 to 50,000)	57	33	53	50	45
15.2 to 16.8 (50,000 to 55,000)	80	38	33	42	46
16.8 to 18.3 (55,000 to 60,000)	57	36	20	37	38
18.3 to 19.8 (60,000 to 65,000)	46	28	7	12	24
19.8 to 21.3 (65,000 to 70,000)	23	15	0	12	13
≥21.3 (≥70,000)	30	0	0	0	5

[1] Seasons are as follows: winter, December to February; spring, March to May; summer, June to August; and fall, September to November.

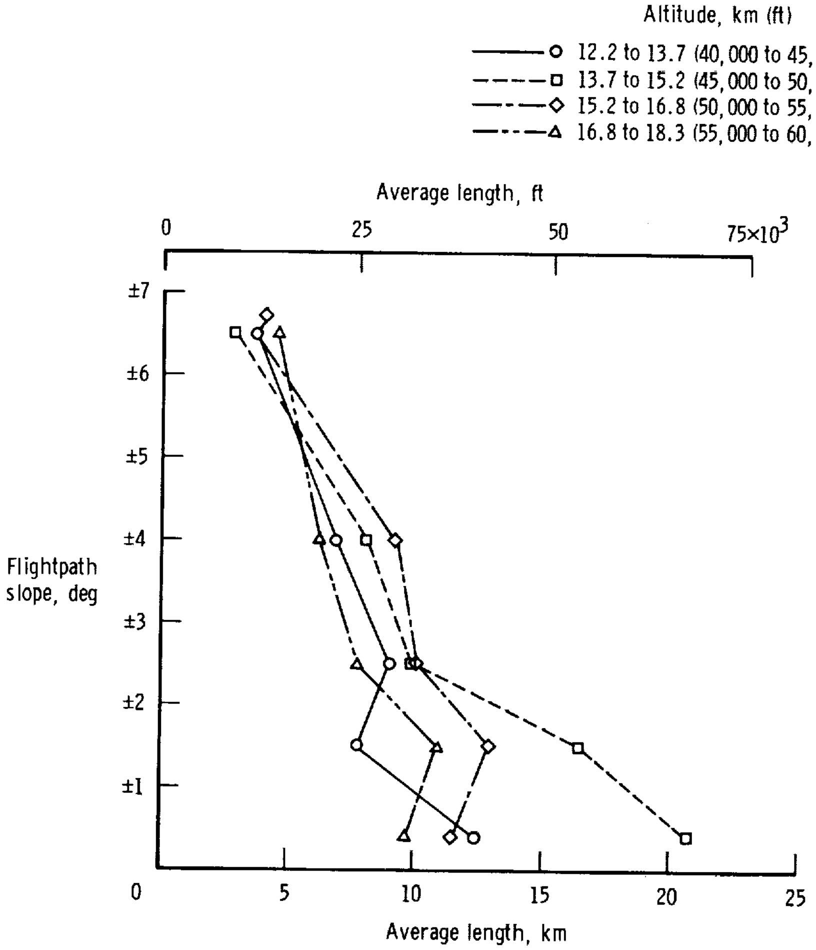
[2] Percentage based on number of flight days in altitude interval.

The YF-12A airplane encountered high altitude turbulence while flying at flightpath slopes (γ, which is the arc sine of altitude change divided by distance traveled) that ranged from 0° to steeper than ±7°. This relatively wide range enabled an examination of the effects of flightpath slope on the measurement of turbulence patch dimensions to be made. The average measurements of turbulence patch thickness and length are presented as a function of flightpath slope in figures 11(a) and 11(b), respectively. The thickness experienced by the YF-12A airplane increased consistently with flightpath slope up to $|\gamma| = 3°$ in each altitude band between 12.2 kilometers and 18.3 kilometers (40,000 feet and 60,000 feet). Conversely, the length experienced decreased consistently with flightpath slope at slopes steeper than ±2°. Since the greatest thicknesses and lengths along the flightpath were experienced at flightpath angles steeper than ±3° and shallower than ±2°, respectively, the data for flightpath angles steeper than ±3° were used to estimate the distribution of the patch thicknesses, and the data for flightpath angles shallower than ±2° were used to estimate the distribution of the patch lengths.



(a) Thickness.

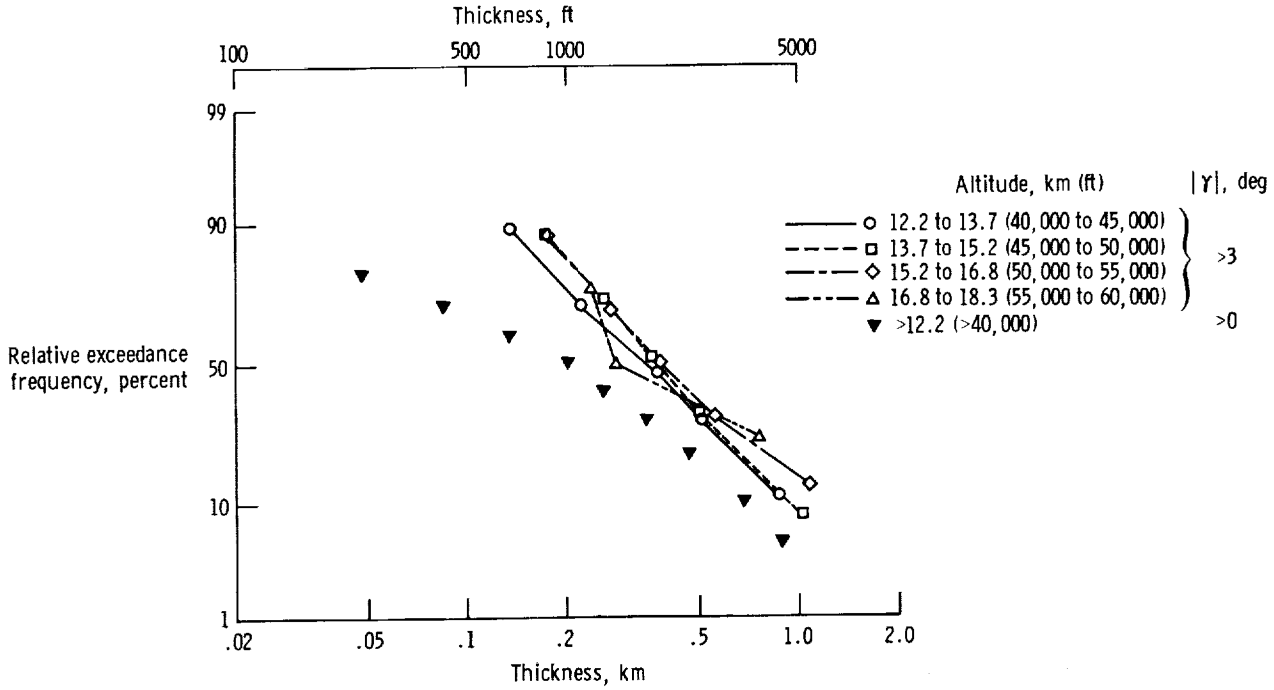
Figure 11. Turbulence patch thickness and length versus flightpath slope.



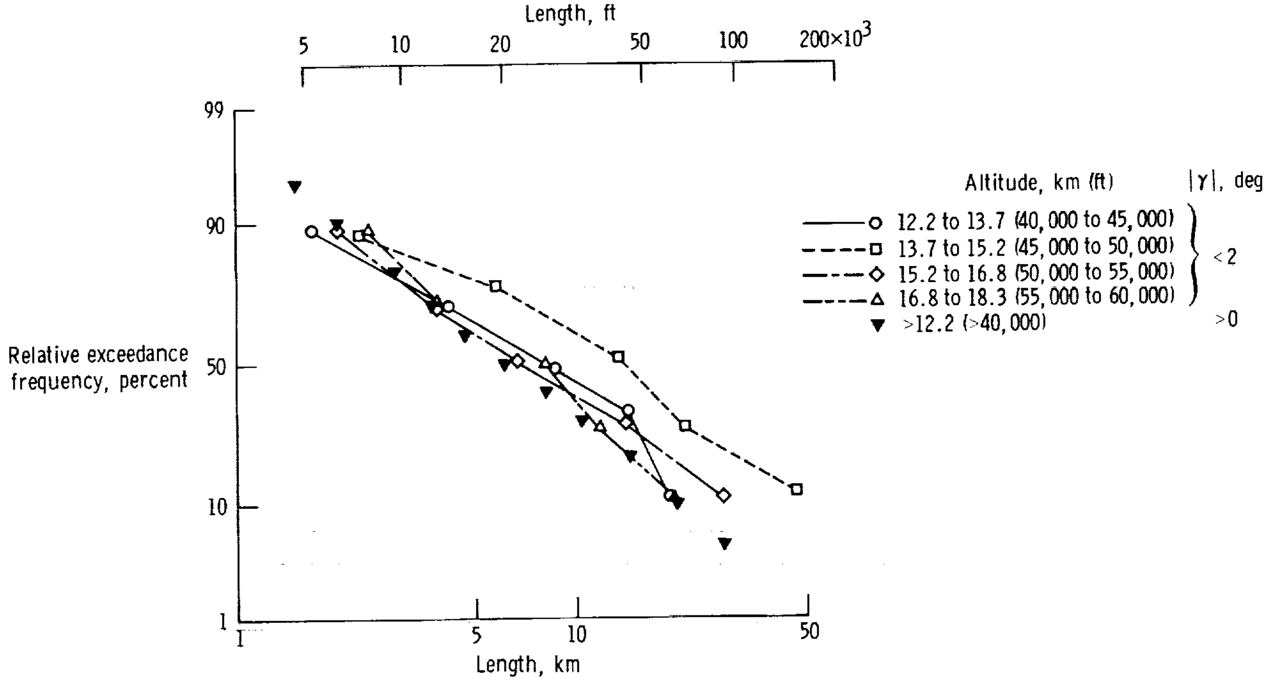
(b) Length.

Figure 11. Concluded.

As shown in figures 12(a) and 12(b), these data indicate that the distribution of the patch dimensions is approximately log normal. The distribution of the thickness and length data was similar for all altitude bands between 12.2 kilometers and 18.3 kilometers (40,000 feet and 60,000 feet). An exception is the tendency for greater patch lengths for the altitude band between 13.7 kilometers and 15.2 kilometers (45,000 feet and 50,000 feet). The experience of the YF-12A airplane over all flightpath slopes above 12.2 kilometers (40,000 feet)(solid symbols) indicates that aircraft operating over a wide range of flightpath slopes experience less than the full patch dimensions, especially in the case of thickness. In any case, typical patch dimensions are relatively small, with median values of less than 400 meters (1300 feet) in thickness and 16 kilometers (52,500 feet) in length.



(a) Thickness.



(b) Length.

Figure 12. Distribution of turbulence patch thickness and length as experienced by the YF-12A airplane.

Figure 13 shows that the slope of the thickness distribution of the data obtained with the YF-12A airplane at flightpath angles steeper than ±3° agrees closely with thickness distribution slopes of data obtained with radiosonde balloons ascending over the U.S.S.R. (ref. 17) and parachutes descending over the United States (ref. 18). The YF-12A data are for altitudes between 12.2 kilometers and 18.3 kilometers (40,000 feet and 60,000 feet), the balloon data for Moscow are for the altitude band from 16 kilometers to 20 kilometers (52,500 feet to 65,600 feet), and the parachute data are for altitudes between 3.0 kilometers and 18.3 kilometers (10,000 feet and 60,000 feet). The slopes of these log-normal distributions are parallel even though the thickness and intensity threshold criteria applied to the data differed. For example, the minimum observable thickness for the radiosonde data was approximately 50 meters (164 feet), whereas for the parachute data it was somewhat less and for the YF-12A airplane it depended on both speed and rate of climb. Intensity thresholds also differed.

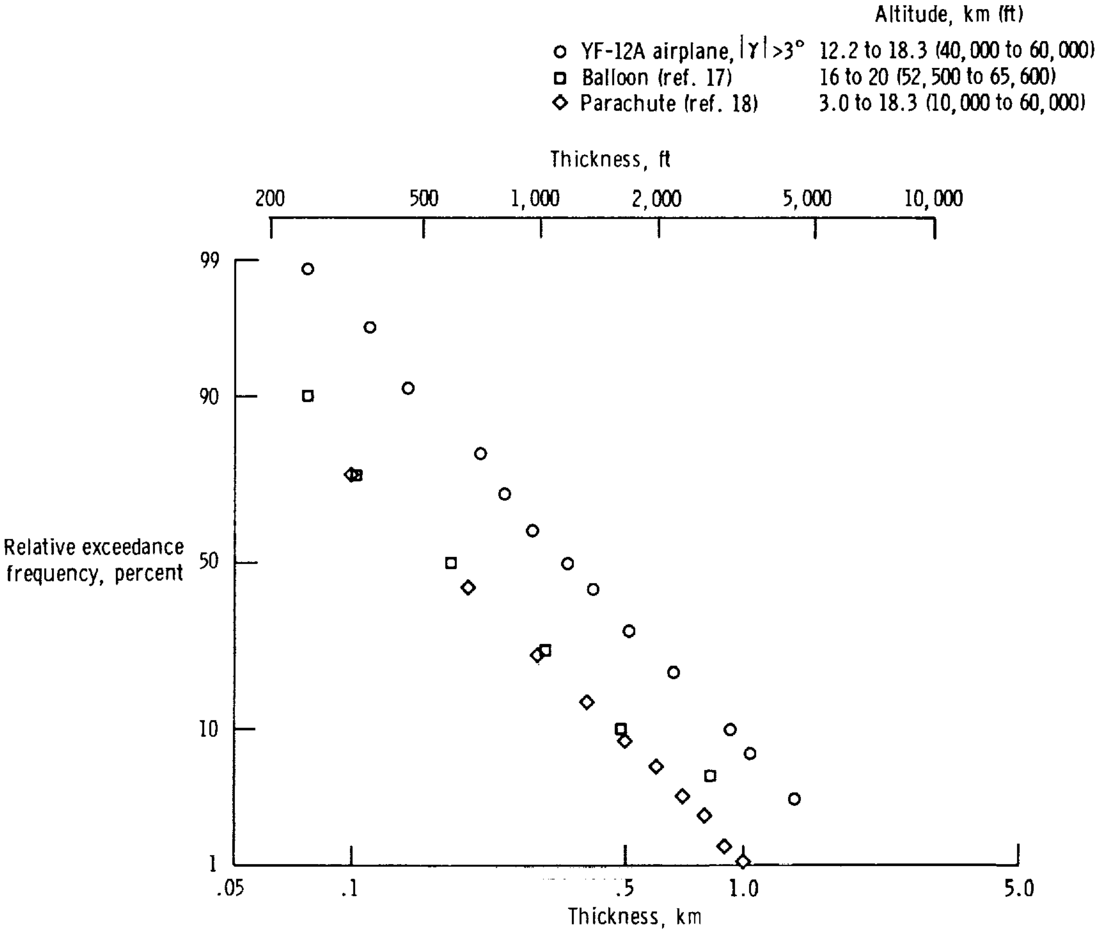


Figure 13. Turbulence patch thickness distributions from three sources.

The distribution for turbulence patch lengths experienced by the YF-12A airplane at flightpath slopes shallower than ±2° is compared with previously acquired data in figure 14. This figure includes data from the XB-70 airplane for altitudes above 12.2 kilometers (40,000 feet) (ref. 4), from the U-2 airplane for altitudes between 6.1 kilometers and 22.9 kilometers (20,000 feet and 75,000 feet) (ref. 1), and from the U-2 airplane during Phase II of the high altitude clear air turbulence (HICAT) program for altitudes between 14.0 kilometers and 19.8 kilometers (46,000 feet and 65,000 feet) (ref. 19). The distribution shapes for the various data sources are similar but not identical. The length distributions are influenced not only by threshold intensity and duration; they are also affected by the criteria used to decide whether to continue or break a patch when turbulence intensity diminishes. Because of differences in vehicle characteristics and data acquisition equipment, editing procedures have not been uniform for all survey programs.

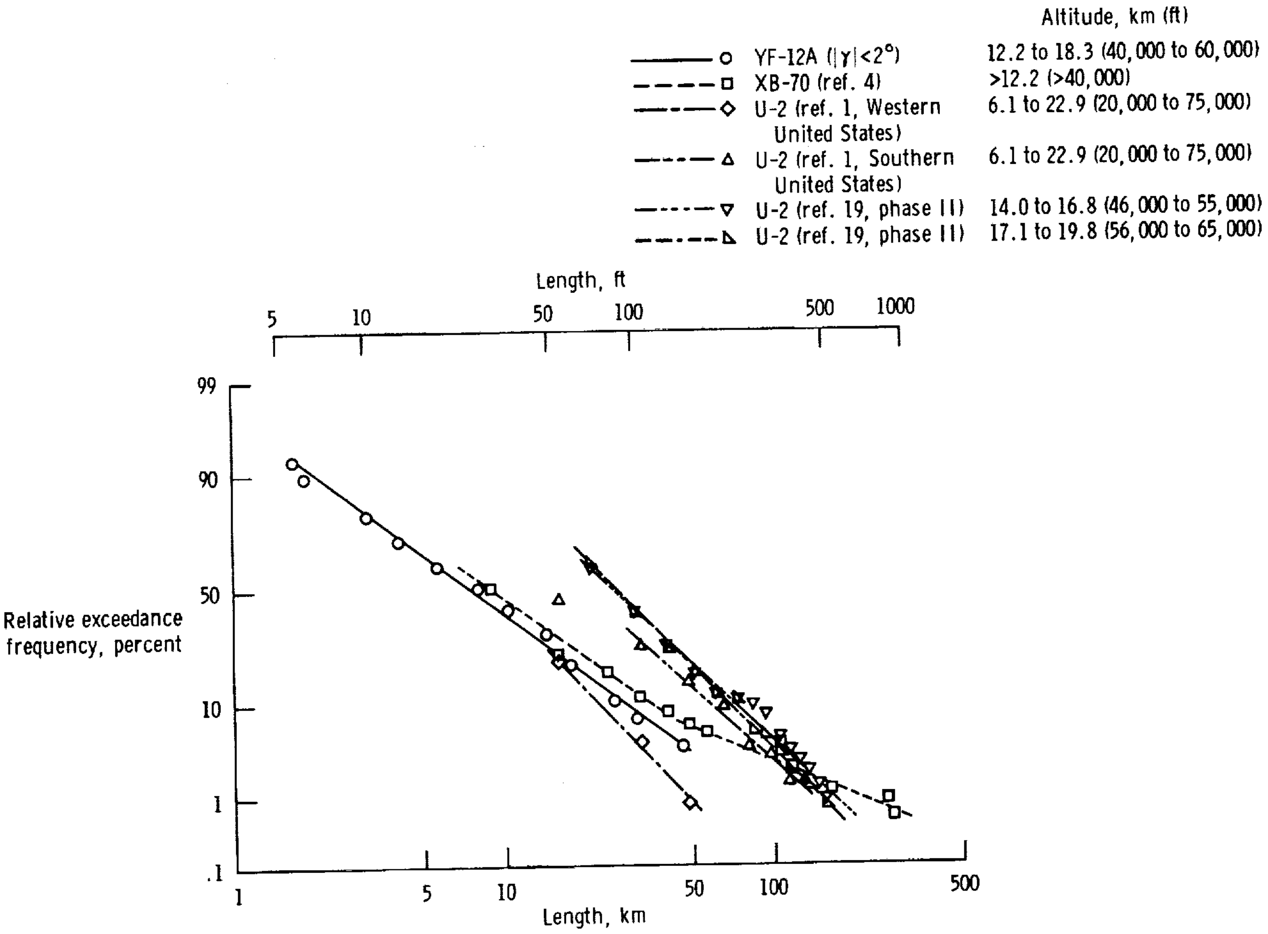
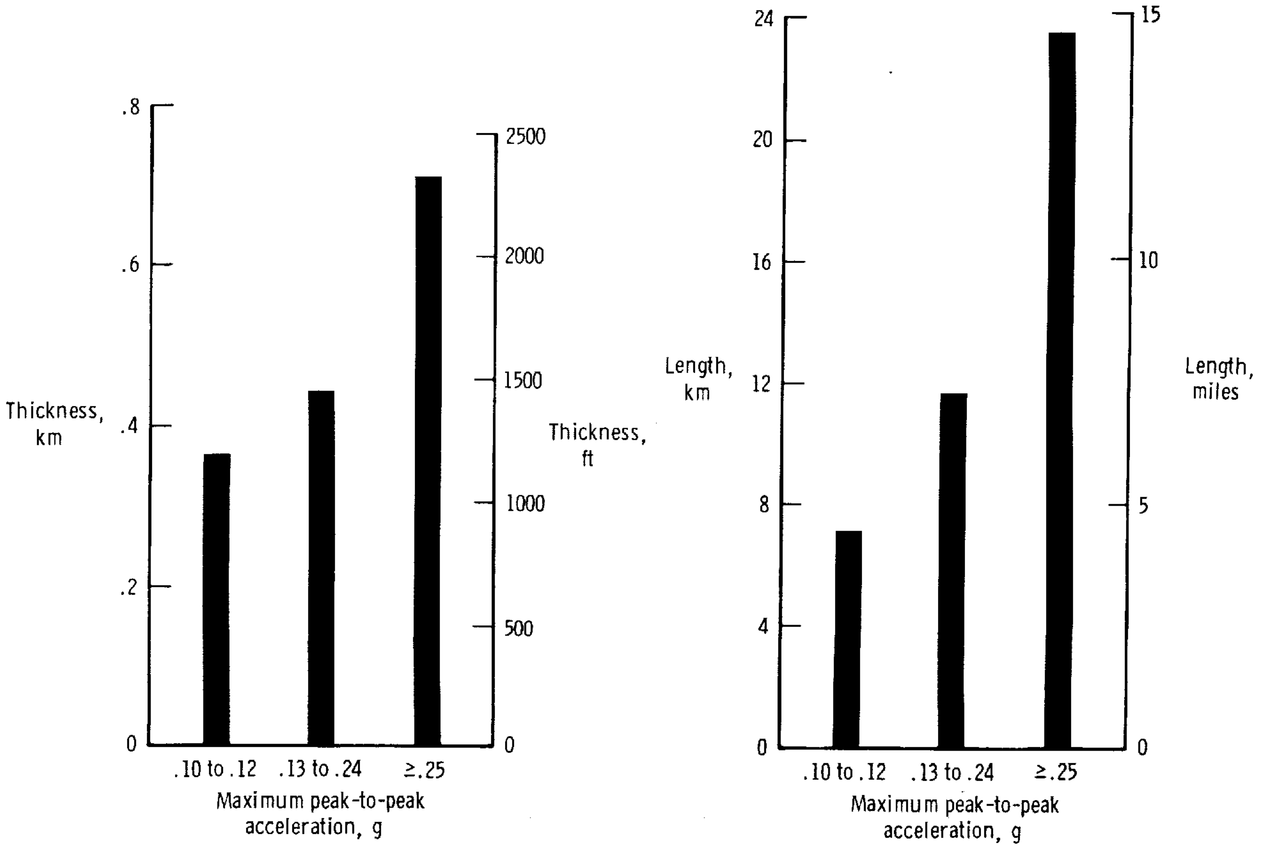


Figure 14. *Comparison of turbulence patch length distributions from various sources.*

The relationship between turbulence intensity and patch dimensions was examined by separating the YF-12A data according to the maximum peak-to-peak normal acceleration experienced in each patch. The average length and thickness of the patches increased with peak acceleration, as shown in figure 15. Although stronger turbulence is expected to encompass larger volumes than weaker turbulence, the maximum acceleration experienced is also related statistically to the duration of exposure to turbulence. Because of both of these effects, it is assumed that for the thickness distribution data more intense turbulence was required to exceed the YF-12A threshold than the balloon and parachute thresholds (fig. 13). Similarly, for the length distribution data (fig. 14), the exceedance of the YF-12A threshold is believed to have been caused by turbulence that was less intense than the turbulence that caused the U-2 thresholds used in references 1 and 19 to be exceeded.



(a) Thickness, $|\gamma| > 3°$.

(b) Length, $|\gamma| < 2°$.

Figure 15. Average turbulence patch thickness and length as a function of maximum acceleration.

In addition to being affected by flightpath angle and editing criteria, measurements of turbulence patch dimensions may be affected by the changes in atmospheric structure that occur with altitude and with changes in weather patterns. Because of the variety of factors that influences the measurement of gust patch dimensions, the data used to estimate turbulence patch shapes should be acquired with controlled sampling procedures and sensors. The YF-12A turbulence patch dimension data satisfy this requirement, since both thickness and length measurements were acquired with the same measurement platform and threshold criteria.

CONCLUDING REMARKS

The high altitude turbulence environment of a supersonic airplane was described on the basis of gust acceleration data from the YF-12A airplane. Above 12.2 kilometers (40,000 feet), the gust acceleration magnitudes were mild compared with those experienced by one type of passenger jet operating below 12.2 kilometers (40,000 feet). However, subjective intensity reports indicated that air crew members were more sensitive to gust accelerations during supersonic flight at altitudes above 12.2 kilometers (40,000 feet) than during subsonic flight at lower altitudes.

The percentage of the total flight distance during which turbulence was encountered decreased markedly from an altitude of 16.8 kilometers to 18.3 kilometers (55,000 feet to 60,000 feet). Between 12.2 kilometers and 16.8 kilometers (40,000 feet and 55,000 feet), approximately 6 percent to 8 percent of the distance traveled was in turbulence, and this decreased to less than 1 percent at altitudes above 18.3 kilometers (60,000 feet). The amount of high altitude turbulence varied with season, increasing by a factor of 3 or more from summer to winter.

Typical high altitude turbulence patch dimensions were relatively small, with median thicknesses of less than 400 meters (1300 feet) and median lengths of less than 16 kilometers (52,500 feet). The distributions of turbulence patch dimensions, both thickness and length, tend to be log normal. It was shown that the measurements of the dimensions are influenced by threshold definition and editing criteria, so estimates of turbulence patch shape should be based on uniform measurement techniques and sampling procedures.

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National Aeronautics and Space Administration
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