Variation of Turbulence with Altitude to 70,000 ft

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The ratio of turbulent to total flight miles has been determined for altitudes up to 65,000 ft by comparing various turbulence data collection programs (e.g., ALLCAT, NASA, NATO, RAE, etc.). An evaluation was made of the criteria used to distinguish turbulence from smooth flight. Results can be used to update currently accepted models of turbulence variation with altitude. The percentage of flight miles with turbulence was found to be near 5% for the entire altitude range between 15,000 and 40,000 ft. Turbulence frequency increased below 15,000 ft, gradually down to 10,000 ft but markedly below 5,000 ft, and decreased above 40,000 ft, dropping to 1% near 65,000 ft. Terrain roughness had a pronounced effect on increasing both amount and intensity of turbulence at all altitudes. At low altitudes (below 1,000 ft) moderate or greater turbulence was up to 13 times more frequent over high mountains than over flat terrain and at least 3 times more frequent above 45,000 ft. The frequency of turbulence was re-evaluated for the HICAT program by careful examination of true gust velocity time histories. The ratio of turbulent to total flight miles was only 70% of the value previously arrived at in the HICAT program (only 33% for moderate and greater turbulence) when "smooth" and low-intensity portions of the turbulent encounters were properly identified.

I. Introduction

SPECIFICATIONS for turbulence parameters (e.g., military specifications for airplane strength and rigidity flight loads) are in need of updating, especially those relating to the ratio of turbulent to total flight miles. Despite comprehensive documentation on the role of turbulence in both design and operation of aircraft, an inconsistent representation of the atmosphere has resulted from inadequate efforts by various authors to compound the information from the numerous turbulence data collection programs. A goal of the present report is to establish appropriate values for parameters such as the proportion of flight distance in turbulence and turbulence exceedance and intensity statistics over the altitude range from near surface to 65,000 ft.

Particular reference is made to observations taken during routine flights of commerical and military aircraft which have been summarized in reports by organizations such as NASA, NATO, Royal Aircraft Establishment, National Research Council of Canada and various private industry and research groups. In addition, results from special research programs sponsored by the U. S. Air Force are included, namely, LO-LOCAT, MEDCAT, and HICAT. The proportion of flight distance in turbulence is established for various altitude bands up to 65,000 ft with special consideration of the criteria used to separate turbulent from smooth flight. Programs are carefully examined when their findings indicate considerable deviations from standard turbulence models such as the probability of flight distance in turbulence as specified by MIL-A-008861A.[1] Conclusions are weighted on the basis of relationships between turbulence and topographical and seasonal conditions.

II. Percentage of Flight Miles in Turbulence for Various Altitude Bands

A. Introduction

Figure 1 illustrates the variation in the ratio of turbulent to total flight miles by altitude for several turbulence measurement programs. The various programs are listed, along with pertinent statistics on turbulence, in Table 1. The general trend, exemplified by the Donely[6] turbine and U-2 data, is summarized as follows: Turbulence decreases rapidly in the first few thousand feet above the ground, leveling off at around 15,000 ft. A fairly constant turbulent/flight mile ratio of around 5% prevails from 15,000 to 40,000 ft. There is a gradual decrease from 5% to 1% between 40,000 and 65,000 ft.

Deviations from the preceding trend are accounted for by several factors including criteria used to distinguish turbulence from smooth flight, sample size, and selective sampling (e.g., by season, terrain, area prone to severe storms, etc.). The programs involved in the collection of data shown in Table 1 are discussed in the following section.

B. Turbulence Programs

Low Altitude (0–20,000 ft)

LO-LOCAT (Jones et al.[2]): In the LO-LOCAT program, eight predetermined legs (40-45 miles each) were flown at each base location. There were 5155 legs altogether but data were available for computation of turbulence percentages from only 25% of the total from flights at McConnell (Kansas), Edwards (California), and Peterson (Colorado) Air Force Bases. Criteria for turbulence were not specified and the predetermined locations and length of legs increased the probability of noncontinuous turbulence, that is, "turbulent" legs containing smooth portions. The legs were classified $\geq$ light turbulence 63% and $\geq$ moderate 33% of the time. Variations in percentages were very high from base to base, however. Edwards legs, some of which were flown over the ocean and in semiprotected valleys, were considered to be in turbulence $\geq$ light only 31% of the time and $\geq$ moderate only 5% as contrasted to 98% $\geq$ light and 67% $\geq$ moderate at Peterson where all legs were either over or on the lee of the Rocky Mountains. McConnell's sample was too small for any conclusions.

Turbojets (Hunter,[3] Donely[6]): Derived gust velocity (U_{de}) turbulence data obtained from 2- and 3-engine turbojet transports indicate the turbulence environment to be more severe than that experienced by 4-engine turbojet transports. Hunter attributes this to sample size (fewer miles for the 2–3 engine aircraft), turbulence avoidance practices (assumed more frequent with the 4 engine jets) and turbulence environments. By environments, Hunter is probably referring to the flight track locations. The 2–3 engine jets generally flew over land and commonly over mountains while the longer range 4 engine jets had a significant percentage of flight miles over water where turbulence was less common.

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Table 1 Pertinent information on turbulence data including proportion of flight miles in turbulence (P) from various programs

Author	Aircraft	Location	Flight miles	Criteria	Altitude (ft)	P(%)
Jones et al.[2] (LO-LOCAT)	C-131 T-33	U.S.	191,000	≥ Light	250, 750	63
Hunter[3]	2-3 Engine Turbojets	U.S. Foreign	1.5 million	$U_{de} > 2$ fps	13,000 19,000	11.5 8.1
Hunter[4,5]	DC-8 Convair 880	East U.S. Oceans	3.6 million	$U_{de} > 2$ fps	0- 5,000 5-10,000 10-20,000 20-30,000 30-40,000 40-45,000	18.8 9.6 6.8 4.7 4.0 3.0
Donely[6]	2-4 Engine	World-Wide	15 million	$U_{de} > 2$ fps	0- 5,000 5-10,000 10-20,000 20-30,000 30-40,000 40-45,000	20.5 10.1 5.8 4.7 4.0 3.0
Endlich and Mancuso[7]	Commercial, Military	U.S.	10 million	≥ Light	20-30,000 30-40,000 40-45,000	4.7 4.7 2.2
Ryan et al.[8] (MEDCAT)	F-100, F-106	U.S.	210,000	Accel. >0.1 g	20-30,000 30-40,000	8.1 10.7
Estoque[9]	B-47	Eastern U.S.	55 Flights	Horiz. gust component ≥ 5 fps	30,000 35,000 40,000	23 17 3
Steiner[10]	U-2	World	820,000	$U_{de} > 2$ fps	40-50,000 50-60,000 60-70,000	2.5 2.0 0.6
Waco (HICAT)	U-2	World	500,000	Accel. >0.1 g	45-50,000 50-60,000 60-70,000	2.9 2.7 1.2
Wilson et al.[11]	XB-70	Western U.S.	94,000	Accel. $>.06$ g	40-50,000 50-60,000 60-70,000	6.3 6.8 5.5
MacPherson and Morrissey[12]	RB-57F	U.S., Panama, Atlantic	115,000	$U_{de} \geq 0.35$ g	45,000 50,000 55,000 60,000 65,000	0.6 0.8 0.3 0.4 0.1

General Aviation (Jewel[13]): Jewel summarizes several types of low-level operations where turbulence data were obtained from VGH recorders. Turbulence was defined using the NASA criterion of 1 U_{de} peak ≥ 2 fps in one minute of flight. The percent of time in turbulence varied from 21% for a jet-powered twin-engine executive airplane to 97% for an aircraft flown on pipeline patrol in commercial survey operations. Single-engine executive, personal, and instructional aircraft operations were in turbulence about 50 to 80% of their total flight time. The most severe gusts were experienced by instructional aircraft, likely maneuver generated.

Mid altitudes (20,000–40,000 ft)

MEDCAT (Ryan et al.[8]): Percentage of flight miles in turbulence was on the average about twice that of the turbojet operations described by Donely.[6] The large variation from one altitude band to the next (Fig. 1) is probably a reflection of the small sample size. Factors which may have contributed to the relatively high amount of rough air were, 1) effective turbulence search procedures, 2) lack of flight over water, 3) inclusion of significant amounts of smooth flight in the turbulence runs (a group of runs were combined if the distance between them was less than the shortest run) and 4) failure to distinguish spurious gusts from real turbulence. The relatively small fighter-type aircraft used in the MEDCAT program were more sensitive to gusts than the large turbojets and it is not obvious whether the differences were minimized in the conversion of accelerations to gust velocities.

Project Jetstream (Estoque[9]): The very high-turbulence percentages have most likely resulted from rather selective sampling in location and time. The 1956-57 portion of the flights, 22 in number, were flown under conditions highly conducive to turbulence. The jet core speed averaged 140 knots and turbulence near the core exceeded 30% of the total flight time.[14]

Miscellaneous Programs: Endlich and Mancuso[7] have summarized numerous flights over the U. S. involving subjective pilot reports of turbulence ≥ light. The results agree remarkably with the 2–4 engine turbojets[6] despite differences between the two studies in criteria for designating turbulence. The NASA criterion, used in all their major programs involving turbulence data collection, specified that one minute of record contain at least one acceleration peak whose amplitude corresponded to $U_{de} \geq 2$ fps.[15] A rough equivalent to $U_{de} \geq 2$ fps would be an acceleration of slightly below 0.1 g.

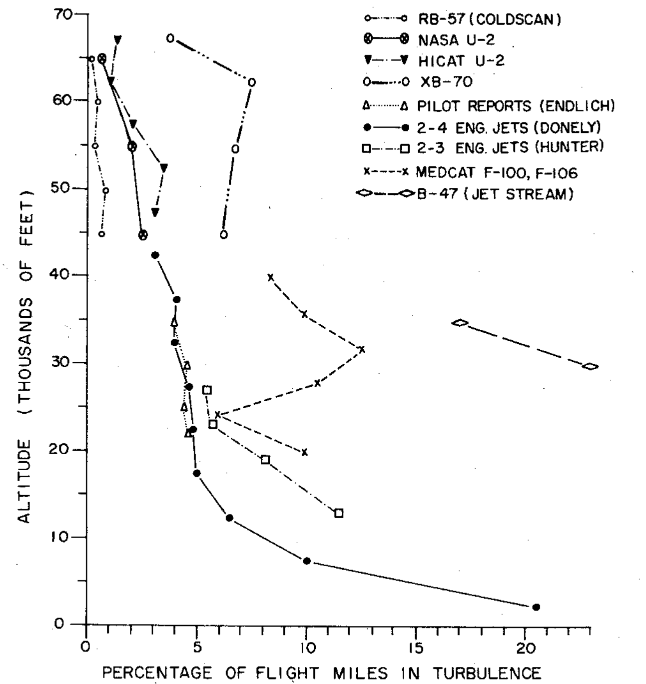

Fig. 1 Percentage of flight miles in turbulence up to 67,000 ft for various programs.

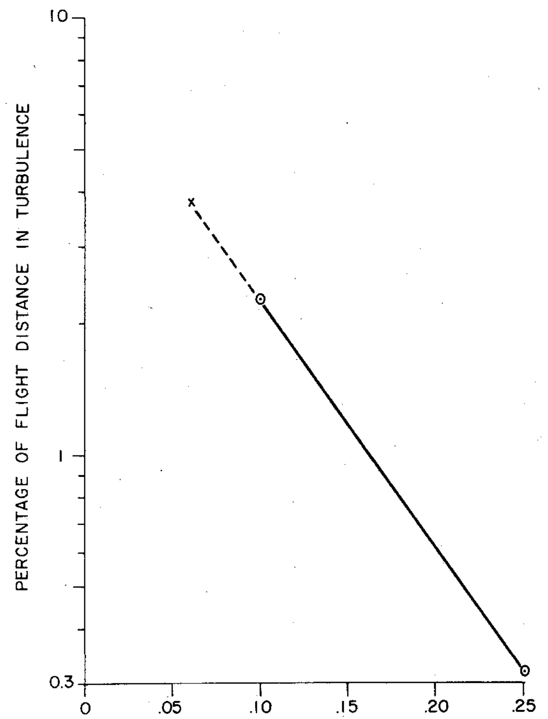

Fig. 2 Percentage of HICAT flight miles in turbulence as a function of the criteria used to classify the turbulence into various categories.

Port[16] described results of a 29,000-flight mile operation of Spitfire aircraft between 20,000- and 40,000-ft altitudes. The fraction of flight time in turbulence above 0.2 g was 4.3% (0.2 g is equivalent to U_{de} gusts of approximately 4-5 fps.). Frequency of gusts > 2 fps would be much higher, of course. Besides the small sample size and selective flight locations, the increased sensitivity of the aircraft to gusts (as in the MEDCAT F-100 and F-106 flights) probably contributed to the high amount of turbulence relative to the large turbojets. Project TOPCAT in Australia[17] has results nearly identical to the Spitfire flights. The turbulence criteria ($\geq$0.2g) and altitude regime were the same and proportion of flight miles in rough air (5%) was slightly higher. Flights were in winter and spring only. Consequently, average wind speeds were quite high (120 knots in the jet core) which undoubtedly contributed to the relatively high turbulence frequency.

Weber[18] discussed results from 320,000 miles of Boeing 707 flights along the North Atlantic route. Turbulence $\geq$0.05 g (equivalent to very light) occurred only 6% of the time which probably reflects lower probability of encountering turbulence over water.

High Altitudes (40,000 to 65,000 ft)

Four major programs have been involved in the collection of turbulence probability data above 40,000 ft: HICAT and NASA U-2 flights, NASA XB-70 flights, and Operation Coldscan RB-57 flights. Turbulence statistics for the two U-2 programs are in reasonable agreement (Fig. 1) although the criteria for turbulence differ. Steiner[10] used the NASA criterion of U_{de} peaks $\geq$2 fps for evaluating the NASA U-2 data. The HICAT program[19] specified turbulence $\geq$ light existed if there were repeated disturbances on the accelerometer trace $\geq$0.1 g ($U_{de}\sim$2.5 fps). HICAT turbulence percentages originally compiled by Crooks et al.[20] were adjusted downward by Ashburn et al.[21] to account for bias when HICAT search aircraft made repeated passes in regions known to be turbulent. Several HICAT turbulence runs were rather lengthy and contained large sections of flight with accelerations <0.1 g. When these "smoother" patches were eliminated the amount of turbulence $\geq$ light was reduced an additional 30% (see next section). The HICAT data in Fig. 1 are the Ashburn et al.[21] figures reduced by 30%. The average turbulence for the 45,000- to 65,000-ft altitude band after these reductions was 2.9%, 40% higher than the 1.6% for the NASA U-2. The turbulence criterion for the HICAT U-2 appeared to be slightly more stringent which suggests that the differences are even greater between the two programs. Direction of HICAT flights to areas thought to have a high probability of turbulence resulted in a relatively large percentage of flights over high mountains and may have been the strongest factor contributing to the differences.

The ratio of turbulent to total flight miles for the XB-70 (6.1%)[11] was nearly 3 times that of the HICAT U-2. If an exponential relationship is assumed for the acceleration level exceedances as a function of turbulence percentage exceedances for HICAT $\geq$ light and $\geq$ moderate turbulence (Fig. 2), extrapolation suggests that 1.6 times more turbulence would be experienced with a cutoff of 0.06 g (the criteria used for XB-70 flights) than with a 0.1-g cutoff. Also, considering the lengthy XB-70 encounters (5% over 40 miles and a maximum of 450 miles) it is probable that these turbulence runs contained either significant patches of smooth data or long wave motions that would not ordinarily be detected as turbulence by the slower flying U-2. When adjustments are made for the lower cutoff level used in designating turbulence for XB-70 flights, it may be better to compare the XB-70 data (3.8% when adjusted) with the Ashburn et al.[21] U-2 data (3.0%) which included smooth patches within turbulent regions. The XB-70 commonly flew along the lee of the Sierra Nevada and Cascade ranges in the western U. S., parallel to the ridge, which would be an additional factor in increasing both the probability of turbulence and the length of runs.

Only 0.5% of the RB-57 flight miles were in turbulence.[12] However, the criterion for turbulence (one spike>0.35 g or $U_{de}\sim$8 fps) was roughly equivalent to that for moderate turbulence in the HICAT program. Only 0.3% of HICAT flight miles were in moderate turbulence after "smooth" patches of the runs were eliminated and 0.8% before elimination (see following section). It appears, then, that there is a fair amount of agreement between the HICAT U-2 and RB-57 results.

Table 2 Ratio of turbulent to total flight miles for XB-70 and U-2 flights by terrain (total flight miles are in parenthesis)

	Flatland and low mountains	High mountains	Ratio: high mountains / Flatland and low mountains
XB-70	3.3%(19,000 miles)	8.0%(29,000 miles)	2.4
U-2	2.0%(30,000 miles)	4.8%(28,000 miles)	2.4

C. High-Intensity Turbulence

Statistics on moderate or greater turbulence are not as plentiful as those for turbulence of lesser intensity. Criteria used in distinguishing moderate from light turbulence are generally quite vague. Both the MEDCAT and HICAT programs used acceleration levels of 0.25 g. The ratio of ≥ moderate to ≥ light turbulence was 1:5 for MEDCAT, 1:4 for HICAT without removal of below threshold patches of turbulence, and 1:7 for HICAT after removal. Endlich and Mancuso[7] found the moderate to light ratio for commercial and military aircraft pilot reports of turbulence to be 1:4 while Colson[22] as well as Pchelko and Vasil'yeva[23] found 1:3. The Colson and Pchelko-Vasil'yeva reports were based on frequency of encounters in given areas (e.g., 5-degree squares) and not flight distance in turbulence. Since the turbulence intensity designated was that of the most severe part of the encounter, it may be assumed that the frequency of moderate or greater turbulence has been overestimated when compared to the MEDCAT and HICAT amounts.

Gust exceedance data infer that when the magnitude of gusts is doubled, there is a decrease of around one order of magnitude in the cumulative frequency of gusts (see, for example Peckham,[24] Hunter,[3] and Hunter and Fetner[5]). The criteria for designating moderate turbulence denoted in most programs specifies gusts that are generally about 250% larger in magnitude than for light turbulence. It appears that the ratio of ≥ moderate to ≥ light turbulence is critically dependent on the specifications that affect the length of the average run and unfortunately from a statistical standpoint, the lengths of the runs are commonly the result of subjective editing. If the average run length is as small as the wavelength of the average gust, the frequency of ≥ moderate turbulence, as specified by most criteria, would be only a fraction of the turbulence ≥ light.

D. Terrain Effects on Turbulence

The increase in turbulence over rough terrain is well-documented. Differences in turbulence frequencies for LO-LOCAT flights from Edwards AFB, which included legs over valleys and ocean, and Peterson AFB (high mountain or lee flights only) have already been illustrated. The increase in the proportion of turbulent to smooth legs from Edwards to Peterson was three times for ≥ light and 13 times for ≥ moderate. Data in a report by Bullen[25] summarizing 170,000 flight miles over North Africa at 200-ft altitude were analyzed and it was found that 17 times more U_{de} gusts ≥ 10 fps and 30 times more gusts ≥ 20 fps occurred over land than sea. From the same report a small sample of flights over hilly desert at midday showed gust frequencies ≥ 10 fps 150 times higher than over water.

Mid altitude (20,000–40,000 ft) commerical and military pilot reports of turbulence over the U. S. have shown a frequency of turbulence 1.2 times higher for mountain flights than for flights over all terrain (1.6 times higher along the lee of mountains). MEDCAT aircraft experienced turbulence 1.7 times more often when relief differences were > 2000 ft than when < 2000 ft.[8]

Vinnichenko et al.[26] reported that USSR supersonic flights at altitudes between 9 and 18 km (30,000–60,000 ft) had a mean maximum gust acceleration for turbulence encounters over mountains of ±0.37 g or 3 times the average for flights over plains. Coldscan RB-57 flights[12] had 5 moderate or greater turbulence occurrences per 10,000 n.mi. over mountains and only 1.5 occurrences over water and flat terrain.

The XB-70 flight tracks published by Ehrenberger[27] and Wilson et al.[11] were used to compile terrain-related statistics on turbulence. The same criteria were designated to distinguish mountains from flatland as in the HICAT program.[28] The proportion of flight miles in turbulence for XB-70 and HICAT U-2 flights over the western U. S. is shown in Table 2 for combined flatland and low mountain flights (relief < 7000 ft) and for high mountains (> 7000 ft).

The mean flight altitude of both programs was within 1000 ft of 56,000 ft. The differences in turbulence percentages between the XB-70 and U-2 stem largely from the less stringent requirement for designating turbulence used in the XB-70 program. The ratio of high mountain to flatland–low mountain turbulence (2.4) is remarkably similar for both programs, however.

NASA U-2 turbulence data are not broken down into terrain classes. The western U. S. flights of the NASA U-2's encountered turbulence during only 0.9% of the 56,000 flight miles.[29] The difference in turbulence frequencies between NASA and HICAT U-2 flights is much greater in the western U. S. than for the total programs. The relatively small sample represented by the western U. S. flights may be largely responsible. The ratio of turbulent to flight miles was greater than 3% for NASA U-2 flights in Japan, primarily the result of one flight over the Japanese Alps where 151 miles of turbulence was experienced. During this encounter (representing only 0.5% of the program's 315,000 flight miles up to 1960) 88% of the U_{de} gusts > 8 fps occurred. The difficulty in establishing firm statistics on turbulence from a limited sample is rather apparent from this observation.

III. Estimating the Proportion of Flight Distance in Turbulence for HICAT Flights

The proportion of flight distance in turbulence (P), i.e., the ratio of miles in turbulence to total flight miles, was originally determined for the HICAT flights by Crooks et al.[20] from cg normal acceleration data. The figures were later revised by Ashburn et al.[28] to account for bias due to repeated flight patterns, and classification by terrain was added. The values of P depended in part on the subjectivity used in the sampling and analyzing of flight data. In general, the determination of P included reference to: 1) The cutoff point between turbulence and smooth flight. 2) Criteria for minimum and maximum lengths of turbulence runs. 3) Range in frequency of the measurements.

Selection of beginning and end points of turbulence runs was affected by stipulating a limitation on the total number of runs (which usually resulted in combining separate encounters) and by difficulties arising due to the sporadic nature of turbulence. These shortcomings led to the inclusion in the records of "smooth" data and patches of turbulence with intensity below that assigned to the overall run resulting in various degrees of nonstationarity.

An example of nonstationarity in HICAT gust velocity time histories is illustrated in Fig. 3. The top trace shows a fairly stationary run of moderate turbulence with a vertical gust velocity rms (λ_{max} = 2000 ft) of 2.26 fps. The middle trace, containing turbulence of variable intensity, was rated severe and had an rms of 3.07 fps. Notable in the bottom trace are

Table 3 a) Ratio of P's obtained by editing true gust velocity time histories to P's listed in Ashburn et al.[28] b) comparison of Ashburn P's to edited time history P's

	a)			b)			
	Ratio: Time history *P* to Ashburn *P*			Ashburn *P*'s (%)		Time history *P*'s (%)	
	≥L	≥*M*	≥MS	≥L	≥M	≥L	≥M
Water	0.66	0.27	a	2.7	0.5	1.8	0.1
Flatland	0.66	0.18	0.11	2.7	0.5	1.8	0.1
Low mountains	0.75	0.30	a	3.6	1.5	2.7	0.5
High mountains	0.72	0.46	0.32	4.9	1.8	3.5	0.8
All terrain	0.70	0.33	0.29	3.1	0.8	2.2	0.3

[a] Less than 1% of turbulent miles in this category.

Table 4 Recommended values of proportion of flight distance in turbulence (in percent) for altitude bands up to 70,000 ft

	Turbulence	
Altitude (ft)	≥Light	≥Moderate
0–5,000	20%	5%
5–10,000	9%	2%
10–20,000	6%	1%
20–30,000	5%	0.6%
30–40,000	5%	0.6%
40–50,000	3%	0.4%
50–60,000	2%	0.2%
60–70,000	1%	0.1%

the patches of "smooth" data. This run was classified as severe[20] despite an rms of only 2.12 fps.

An effort was made to recalculate *P* by analyzing time histories of true gust velocities for 277 HICAT runs (27% of the turbulence encounters from which Crooks et al.[20] and Ashburn et al.[28] were able to determine *P* from cg accelerations). Table 3 lists (by intensity) the comparison of *P*'s as determined by editing out the smooth portions of time histories (as outlined in the following) to the cg-derived *P*'s. In the *P*'s derived from time histories that portion of a time history was considered as light or light-moderate turbulence when any of the three gust velocity components had recurring changes between 8 fps and 20 fps. If the changes exceeded 20 fps the turbulence was classified as moderate and severe for changes greater than 35 fps. "Smooth" flight was implied if there were no recurring changes of 8 fps.

The amount of turbulence experienced by the U-2 is shown in Table 3 to be considerably less when "smooth" or low-intensity portions of runs are edited out. The cg peak method of classifying turbulence tended to represent the intensity of most runs by that of the most intense portion. In the time history evaluation method, time in turbulence ≥ light has been reduced 30% and moderate or greater turbulence 70%.

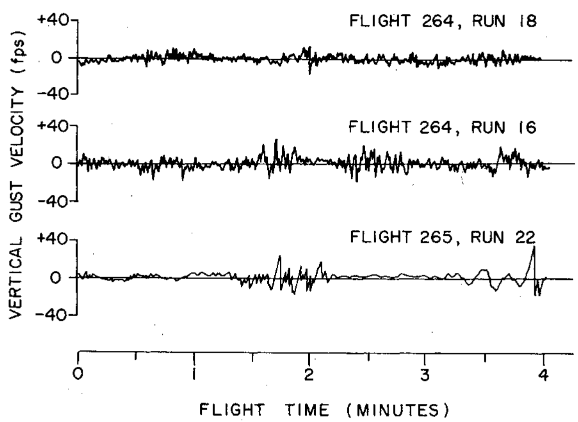

Fig. 3 Time histories of vertical gust velocities for three HICAT runs.

Values of *P* were computed for all HICAT flights by reducing the figures indicated by Ashburn et al.[28] by the amounts determined in observing the true gust velocity time histories. Comparison of *P*'s derived from the cg acceleration measurements of Ashburn et al. and those from time history evaluations are listed by terrain in Table 3. Both sets of values could be too low because turbulence durations of 10 sec or less were not included in the original processing of the data by Crooks et al.[19] However, several factors contributed towards possibly increasing turbulence time above what would be expected from a series of flights based on routine or random rather than search procedures. These are as follows: 1) Experienced meteorologists directed many HICAT flights towards regions of expected turbulence, especially mountains. 2) Pilots commonly would search over wide-altitude ranges until turbulence was found. 3) Flights over high mountains were most frequent in winter, a season with maximum storms. 4) Around four times as many miles were flown over mountains than would be expected if the flights had been randomly distributed throughout the world.[21]

IV. Summary and Conclusions

Turbulent motions in the atmosphere have been observed at scales down to the smallest measurable eddies. Generally, programs that collect turbulence data have been limited in their instrumentation capabilities which has resulted in low signal to noise ratios for small-scale turbulence measurements. Consequently, it has become necessary in all programs to specify turbulence in terms of atmospheric motions larger than particular values. The critical boundary between turbulence and smooth flight is reflected in the variable definitions of turbulence.

This article has been an attempt to establish reasonable concordance between the turbulence programs in order to present a complete picture of turbulence variation with altitude. For this purpose of producing meaningful data on the proportion of flight miles in turbulence, the following definition of turbulence has been adopted: Turbulence exists when the accelerometer trace shows repeated excursions of 0.08 g (equivalent to derived gust velocities of 2 fps). Any portion of the record 15 seconds or longer not containing gust velocities of 2 fps is classified as smooth flight. The moderate turbulence criterion is accelerations ≥0.25 g ($U_{de} \sim 6$ fps).

When the preceding criteria are applied to NASA turbulence data some flight segments previously classified as turbulent (i.e., one gust > 2 fps in one minute of flight) would now be designated as smooth flight. The moderate turbulence requirements are slightly more stringent than those adopted by HICAT and MEDCAT programs. Considering that portions of the moderate turbulence measured in these programs would be redesignated to lesser intensities, the general ratio of moderate to light turbulence is estimated as 1:8 for altitudes above 20,000 ft. Gust exceedance statistics suggest that moderate turbulence tends to occur a higher proportion of time below 20,000 ft relative to light turbulence. Hence, the ratio of moderate to light is designated as 1:6 for the 10,000- to 20,000-ft altitude band and 1:4 for below 10,000 ft.

The recommended values for proportion of flight distance in light and moderate turbulence are listed in Table 4 for altitude bands up to 70,000 ft. These figures have been derived by applying the definition of turbulence suggested in the preceding to turbulence statistical data summarized in the present report. In future work an error analysis should be performed on the data. Fewer flights above 40,000 ft suggest that less confidence in the turbulence statistics would be expected at these altitudes.

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