ICAS Paper No. 68-36

MEASUREMENTS OF CLEAR AIR TURBULENCE USING AN INSTRUMENTED T-33 JET AIRCRAFT

by

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The Sixth Congress of the International Council of the Aeronautical Sciences

DEUTSCHES MUSEUM, MÜNCHEN, GERMANY/SEPTEMBER 9-13, 1968

Preis: DM 2.00

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I. Introduction

The National Aeronautical Establishment T-33 turbulence research aircraft was based in Denver, Colorado, during the month of February, 1968, participating in a joint mountain wave and turbulence measurement exercise. On two days (February 22 and 28), significant patches of clear air turbulence (CAT) were encountered. A description of the flight profiles and techniques used in these searches is given. Measurements of the wind and temperature fields as well as the three components of the turbulence were made in the patches. The time histories of the true gust velocities are analysed in terms of power spectra and speculations concerning the energetics of the turbulence processes are inferred from the shapes of the spectra.

II. The Instrumented Aircraft

The N.A.E. T-33 (Figure 1) is capable of measuring the three components of atmospheric turbulence (longitudinal, lateral, and vertical with respect to aircraft axes) in terms of true gust velocities. Sensor outputs, such as rates, attitudes, accelerations and flow-vane angles are recorded on a 14 channel F.M. magnetic-tape recorder.

A doppler navigational radar is installed on the T-33 in a pod mounted underneath the fuselage of the aircraft. Accurate drift and groundspeed outputs from this equipment, along with altitude, airspeed, total temperature and heading information permit fine scale measurements of the wind and temperature fields to be made in and around the turbulent areas. These parameters are time-multiplexed and recorded on one channel of the tape recorder. A voice channel permits suitable comments to be appended to the flight records as well as fixing the observations in time and space.

III. Data Analysis

The flight data tapes are played back into an analogue computer which computes the true gust

FIGURE 1. THE N.A.E. TURBULENCE RESEARCH AIRCRAFT

velocities. Reasonably homogeneous runs of turbulence are then recorded permanently as analogue records on magnetic tape. To obtain power spectra, auto- and cross-correlations, the analogue records are digitized, these and other statistics being computed by the usual digital methods.

IV. Flight Description

In the following, turbulence intensities will be defined as:

- Light - Turbulence in which peak gusts do not exceed 10 feet per second.
- Moderate - Peak gusts between 10 and 20 feet per second.
- Heavy - Peak gusts exceeding 20 feet per second.

The two CAT search flights of February 22 are depicted in Figure 2. All times on the figure are Greenwich Mean Time. The first flight originated in Denver. Before reaching Farmington an airliner report was received of CAT between Gunnison and Farmington at 27,000 feet. A descent to this altitude was made after passing Gunnison and light to moderate CAT was encountered between Gunnison and Farmington. A decision was made to stay in this area to study the patch, and a return run was made to Gunnison at 25,000 feet. Flight conditions at this altitude were smooth, so a climbing turn was executed, and another pass was flown through the area at 27,000 feet. No turbulence was experienced on this second run, the turbulence having drifted downwind or dissipated during the 50 minutes between traverses.

Approaching Farmington, reports of moderate to severe turbulence at 37,000 to 39,000 feet were received from airliners in the vicinity of Winslow. A climb was executed to 37,000 feet after passing Farmington. Moderate to heavy turbulence was encountered at this level. A sample of this turbulence measured south-west bound to Winslow is shown in Figure 3, Run 1. Course was reversed at 20:50Z and a return run through the turbulence was made. Two samples on this course were analysed, Run 2, and Run 3, Figure 3. Approaching Farmington, a meteorological sounding of the turbulent layer was taken by a slow ascent to 39,000 feet, followed by a descent to 35,000 feet, thence back to 36,000 feet. The turbulent layer had sharp boundaries at 35,500 and 38,500 feet. Shortage of fuel terminated the operation at this point, and a turn and a descent was commenced into Albuquerque.

After fueling at Albuquerque, the aircraft took off and climbed to 37,000 feet. Light turbulence was experienced at this level to Winslow, but flight conditions became smooth shortly after passing Winslow for Farmington. Again, a meteorological sounding was taken approaching Farmington, two hours and forty-five minutes having elapsed between the two soundings in the same area. At this time (00:00Z) the four thousand foot layer was absolutely calm. From over Farmington, the aircraft returned to Denver.

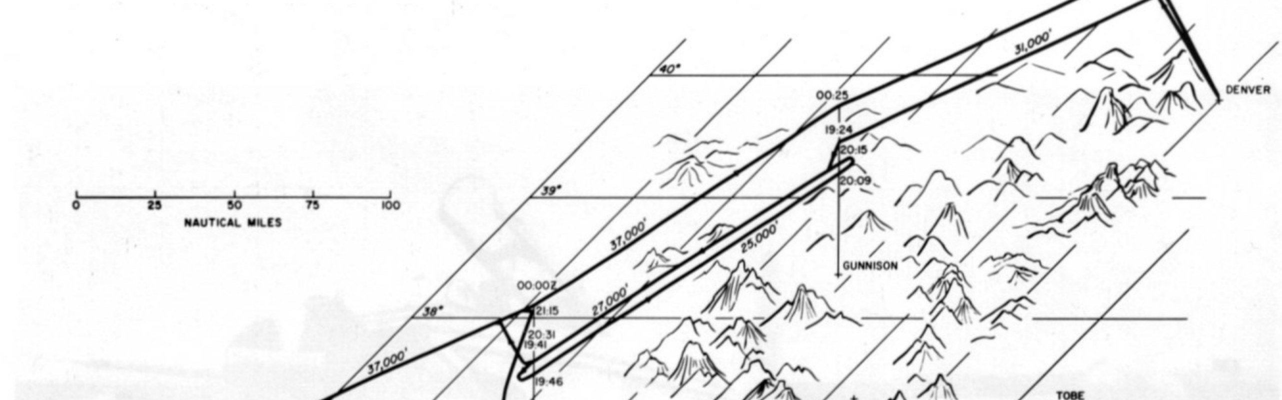

FIGURE 2. FLIGHT PROFILE - 22 FEB. 1968

On February 28, a similar search pattern was carried out. Turbulence had been reported in the Winslow area at 37,000 feet. Only light turbulence was experienced, so a decision was made to return to Denver via Farmington, Alamosa and Tobe. Just west of Alamosa (at 37,000 feet), moderate, occasionally heavy turbulence was encountered and persisted until descent was commenced into Denver. Three time histories of turbulence experienced between the initial encounter and Tobe are shown in Run 4, 5, and 6 in Figure 3. A meteorological sounding was executed over Tobe, up to 39,000 feet, down to 35,000 feet and back to 37,000 feet. The thickness of the turbulence layer was again well defined, smooth air existing below 36,000 and above 38,500 feet. After turning towards Denver from over Tobe, another sample of turbulence was taken before descending. The time-history of this record is shown in Run 7, Figure 3.

V. Results

Power Spectra

Figure 4 shows the power spectra obtained from the seven turbulence runs. Here, u_g is the spectrum of the longitudinal component of turbulence, v_g the lateral and w_g the vertical (with respect to aircraft axes). The root-mean-square (r.m.s.) intensities, σ', are truncated over a wavelength range from 12,000 to 100 feet, and therefore correspond to the square root of the areas under the spectra shown in the plots. These spectra have been smoothed, the three components superimposed, and re-plotted in Figure 5, to reveal some of the more salient features of the spectra.

At the shorter wavelengths (1000-100 feet) all spectra conform well to a -5/3 slope, a result predicted by Kolomogorov over a range of wavelengths called the inertial subrange, where no production or dissipation of turbulent energy takes place. To determine the degree of isotropy in this wavelength region, truncated r.m.s. gust intensities were computed between 1000 and 100 feet, and are listed in Table 1.

For isotropic turbulence in the inertial subrange:

$$\frac{\sigma_w''}{\sigma_v''} = 1, \qquad \frac{\sigma_u''}{\sigma_v''} = \sqrt{\frac{3}{4}} = 0.87 \qquad (1)$$

The ratios of the intensities from Table 1, except for one or two cases, do not conform well to the values in (1) suggesting that, for clear air turbulence, the isotropic range is approached at wavelengths of less than 1000 feet. At longer wavelengths the spectra show a marked dependence on the orientation of the aircraft with respect to the wind direction when the measurements were taken. The tendency is for the longitudinal spectra to lie above the lateral spectra at the longer wavelengths as the aircraft is turned more parallel to the flow, indicating that the horizontal component of turbulence over this wavelength range is more intense along the jet-stream axis than across it. This characteristic was also observed to occur in the measurements of clear air turbulence made during Project Topcat[1]. An exception to this tendency is Run 7, in which the lateral turbulence component lies above the longitudinal with the aircraft flying at an angle of 35 degrees to the wind direction. Truncated (12,000 - 100 feet)

Run	σ_u'' (ft/sec)	σ_v'' (ft/sec)	σ_w'' (ft/sec)	σ_u''/σ_v''	σ_w''/σ_v''
1	.71	.88	.77	.81	.87
2	.60	.93	.84	.65	.90
3	.74	.83	.79	.89	.95
4	.32	.55	.36	.57	.65
5	.47	.67	.44	.70	.66
6	.49	.64	.54	.77	.84
7	.60	.89	.62	.67	.70

TABLE 1. TRUNCATED R.M.S. INTENSITIES: 1000 - 100 feet.

Run	σ_u' (ft/sec)	σ_v' (ft/sec)	σ_w' (ft/sec)	σ_u'/σ_v'	Angle between wind direction & aircraft heading (degrees)
1	4.05	5.35	2.82	0.76	90
2	4.41	3.53	2.56	1.25	60
3	5.10	4.74	3.47	1.08	65
4	3.05	3.33	2.59	.92	135
5	3.72	3.28	2.79	1.13	135
6	3.77	3.51	2.46	1.07	155
7	2.54	3.84	1.82	0.66	35

TABLE 2. TRUNCATED R.M.S. INTENSITIES: 12,000 - 100 feet.

r.m.s. gust velocities are compared to the angle between the wind and the aircraft heading in Table 2.

The vertical spectra (w_g) obtained when flying at an angle to the flow exhibit an S-shaped curvature (Figure 5, Run 1) which diminishes as the aircraft is flown closer to wind direction. This cubic curvature was also observed in the cross-wind vertical spectra obtained during the Topcat exercise (Figure 6).

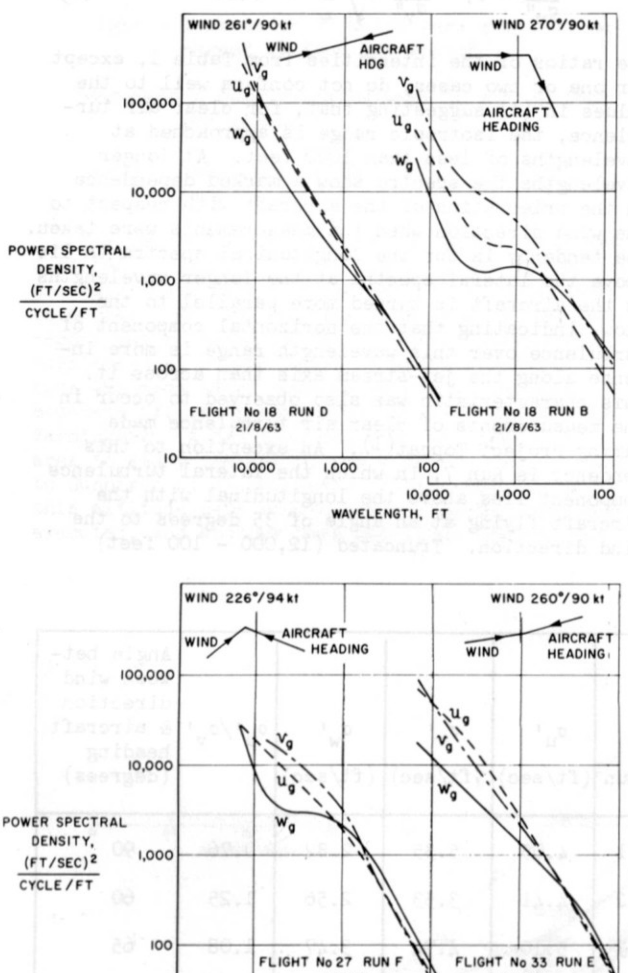

FIGURE 6. POWER SPECTRA FROM PROJECT TOPCAT (from Reference 1).

In discussing the CAT spectra with Karl Doetsch of the N.A.E., the author was led to examine results from boundary-layer studies, particularly the experimental measurements of Klebanoff, Tidstrom and Sargent (2). If the flow during boundary-layer transition to turbulence is visualized in spectral terms, similarities appear between the boundary-layer observations thus visualized and the characteristics of the clear air turbulence spectra, suggesting that perhaps some of the mechanisms responsible for boundary-layer breakdown also contributed to the formation of clear air turbulence. With this in mind, three main features observed during transition from laminar flow to turbulence in the boundary-layer experiments are listed. The evidence that such parallel phenomena occur in clear air turbulence generation is qualitatively discussed.

Primary Wave. Sufficiently large oscillations (crests normal to the flow direction) introduced into the boundary layer rapidly become unstable, leading to breakdown of the laminar flow. This process is illustrated in Figure 7 from Reference 2.

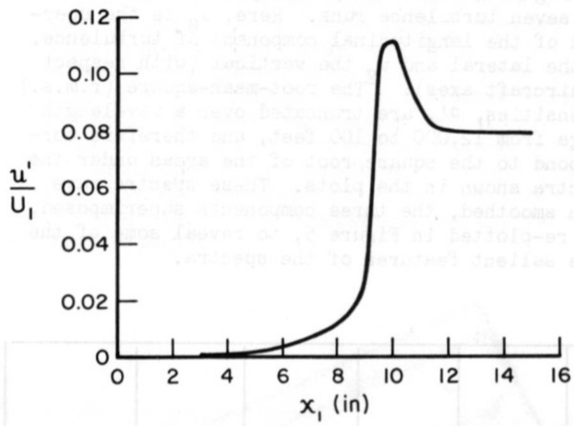

FIGURE 7. GROWTH IN INTENSITY OF u - FLUCTUATION (from Reference 2)

Here x_1 is the distance from the leading edge of the flat plate, and u'/U_1 is the ratio of the r.m.s. value of the longitudinal fluctuations to the free-stream velocity. To seek a corresponding wave occurrence in CAT, it was necessary to examine recorded fluctuations in dynamic pressure (airspeed) as the aircraft was either entering or leaving the upwind edge of a significant patch of CAT on a heading parallel to the flow. In our research so far, only three such cases have been encountered. These are shown in Figure 8. The top trace (a) is a time-history of the airspeed fluctuations experienced prior to and after entering the turbulence of February 28, just west of Alamosa. An oscillation with a wavelength of about 30,000 feet can be seen which suddenly increases in magnitude just before the onset of turbulence. The oscillation reoccurs further downstream just before a second and more intense burst of turbulence. In (b) of Figure 8, a wave of about 24,000 feet was detected at the leading edge of some moderate turbulence.

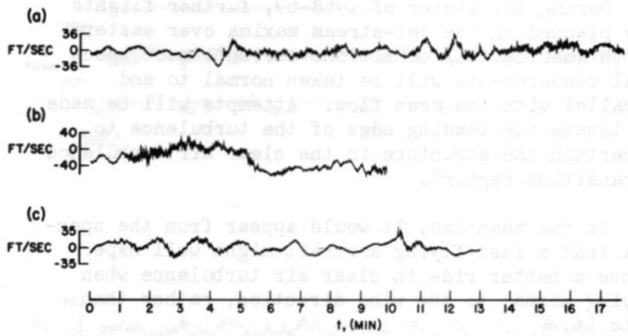

FIGURE 8. TIME HISTORIES OF u (AIRSPEED) FLUCTUATIONS

Both (a) and (b) were measured over mountainous terrain. Trace (c) shows waves experienced over the flat prairies of the mid-western United States. A wavelength of about 50,000 feet occurs in light turbulence at the beginning of this record. Both the turbulence and the wave damp out until towards the end of the trace, where amplification takes place coupled with a sudden burst of turbulence. It is possible that these records are slightly contaminated with aircraft motions, but since constant pressure altitudes were carefully maintained in all traverses, it is unlikely that the observed waves can be attributed to natural aircraft frequencies such as the phugoid.

It would appear from the limited evidence presented that a "primary wave" structure does exist, at least in some cases of CAT generation. The wave, on entering an atmospheric layer whose characteristics (such as shear and temperature profile) promote instability, breaks down into clear air turbulence.

Longitudinal Vortices. As the primary wave in the boundary layer grew, three dimensional aspects of the flow were observed, characterized by the formation of longitudinal vortices with axes paralleling the flow. As the three dimensionality of the flow became dominant, these longitudinal eddies developed a cross-flow wavelength of one half the primary wavelength, a result consistent with Benny's detailed analysis(3).

For evidence of a longitudinal vortex structure in clear air turbulence, examine the spectra in Figure 5. Such a structure would have a nominal wavelength of, say, 15,000 feet (half the primary wavelength). Some evidence of longitudinal eddies, if they exist would probably just be detected at the long wavelength end of the vertical spectra, and would be most readily observed in measurements taken when the aircraft was cutting across the flow. Run 2 (Figure 5) is a traverse in a reciprocal course through the same area from which Run 1 was sampled. In Run 2 the aircraft heading is thirty degrees closer to the wind direction than in Run 1. Although the intensities of the u_g and v_g spectra at long wavelengths have switched positions between the two runs, the resultant power of the horizontal turbulence around $\lambda = 10,000$ feet is approximately the same. However, the vertical power at 10,000 feet drops significantly between Run 1 and Run 2.

Consider Run 5 and Run 6. In Run 5, the angle between the aircraft heading and the wind direction is 135 degrees. When the aircraft is angled twenty degrees closer to the flow direction (Run 6), the power at 10,000 feet in the vertical spectra drops considerably, whereas the power in u_g and v_g at the longer wavelengths remains relatively constant in the two runs.

Another source of evidence for a longitudinal eddy structure can be found in an interpretation of the initial steep slope of the cross-wind vertical spectra. This characteristic, also found in the Topcat data (Figure 6) suggests the existence of a "buoyant subrange", proposed by Bolgiano(4 & 5). Under stable conditions, a range of eddy sizes may exist that are small enough to be uninfluenced by the shear, yet large enough to lose energy working against the negative buoyancy of a stable atmosphere. For clarity, consider the equation for the conservation of turbulent kinetic energy:

$$\frac{\partial(\frac{1}{2}\overline{u_i' u_i'})}{\partial t} = -\overline{u'w'}\,\frac{d\bar{u}}{dz} - u_j\,\frac{\partial\,\overline{(\frac{1}{2}u_i' u_i' + p')}}{\partial x_j} - \frac{g}{\rho_o}\,\overline{w'\rho'} - \epsilon \qquad (2)$$

(from Reference 5)

The first term on the right-hand side of this equation describes the production of turbulent energy, the second serves to re-distribute this energy among the various turbulence components, but neither adds nor subtracts energy from $\frac{1}{2}\overline{u_i' u_i'}$. The third term (omitted in boundary-layer considerations) will either add energy (unstable atmosphere) or in a stable atmosphere, subtract kinetic energy by the working of the vertical fluctuations against negative buoyancy. The fourth term is viscous dissipation, and is always negative. Bolgiano, through dimensional analysis reasoned that, if such a "buoyant subrange" were to exist in turbulence in a stably-stratified fluid, the energy spectra would be characterized by a -11/5 slope. The initial portion of the vertical spectra of Run 1 approximates a -11/5 slope, whereas the slopes of the vertical spectra of Run 4 and 5 appear steeper than Bolgiano's theory predicts. Evidence of a buoyant subrange appears in some of the vertical spectra obtained on traverses angling across the flow, indicating a structure to the turbulence that has a longitudinal orientation with respect to the flow.

Hairpin Eddies. At breakdown in the boundary-layer experiments, a system of "hairpin eddies" were observed forming, which appeared to stretch as they propagated downstream in the flow. The frequency of these eddies was observed at onset, and averaged about one tenth the frequency of the primary wave. If such a mechanism is also present in generating clear air turbulence, the primary wave observed upwind of the turbulence of February 28 at breakdown would produce "hairpin eddies" of wavelengths of around 3,000 feet, providing an energy input into the turbulence spectra. Since these "hairpin eddies" are elongated downstream, this energy would be shown most clearly in the vertical spectra measured while flying across the flow, although humps should appear in the other spectra around the 3000 foot wavelength as well. Run 4, Figure 5, shows an increase in spectral power in all three components due to an energy input around λ = 3-4,000 feet. Again if the vertical spectrum in Run 1, Figure 5, was to receive no additional energy input after the energy loss in the "buoyant subrange", the remainder of the spectrum at the shorter wavelengths would lie considerably below the v_g and u_g spectra. The hump in the spectra around λ = 3000 feet indicates an energy input into the spectrum. This perhaps characteristic hump in the cross-wind measurements of vertical spectra in clear air turbulence also appeared in the Topcat data (Figure 6).

In summary then, observations have shown that growing two-dimensional waves introduced into the boundary layer rapidly give rise to non-linear, three-dimensional wave motions characterized by longitudinal vortices superimposed on the primary wave. The longitudinal eddies develop a wavelength of half the primary wave as the three-dimensionality becomes dominant. At breakdown, "hairpin eddies" of about one tenth the frequency of the primary wave are observed. These appear to stretch along the mean flow as they propagate downstream.

In these clear air turbulence measurements, some evidence of an unstable primary wave was found (Figure 8). A qualitative analysis of the spectra indicates that the existence of a longitudinal structure to the turbulence and of an energy input around one tenth the wavelength of the primary wave ("hairpin eddies") is not inconsistent with the observed behaviour of the spectra. Although the analogy between boundary-layer instability and clear air turbulence is rather speculative, the similarities observed in this analysis are sufficiently striking to warrant further investigations.

Work of a more quantitative nature is proceeding at N.A.E. Temperature profiles and wind shears through the turbulence layers are being examined. Cross-correlations of the turbulence components are being computed to study the energy exchanges over the measured wavelengths.

During the winter of 1968-69, further flights are planned in the jet-stream maxima over eastern North America. If conditions warrant, most spectral measurements will be taken normal to and parallel with the mean flow. Attempts will be made to locate the leading edge of the turbulence to ascertain the structure in the clear air turbulence "transition region".

In the meantime, it would appear from the spectra that a fast-flying aircraft might well experience a better ride in clear air turbulence when flying normal to the wind direction, rather than into it.

VI. References

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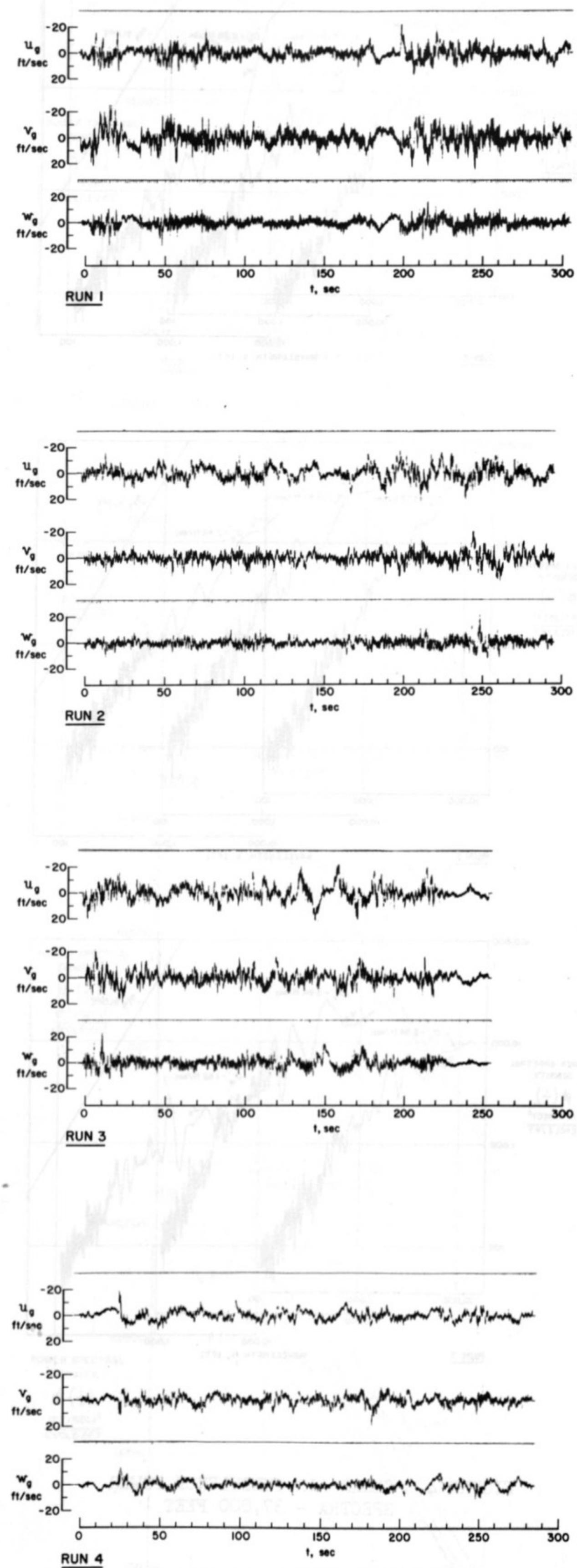


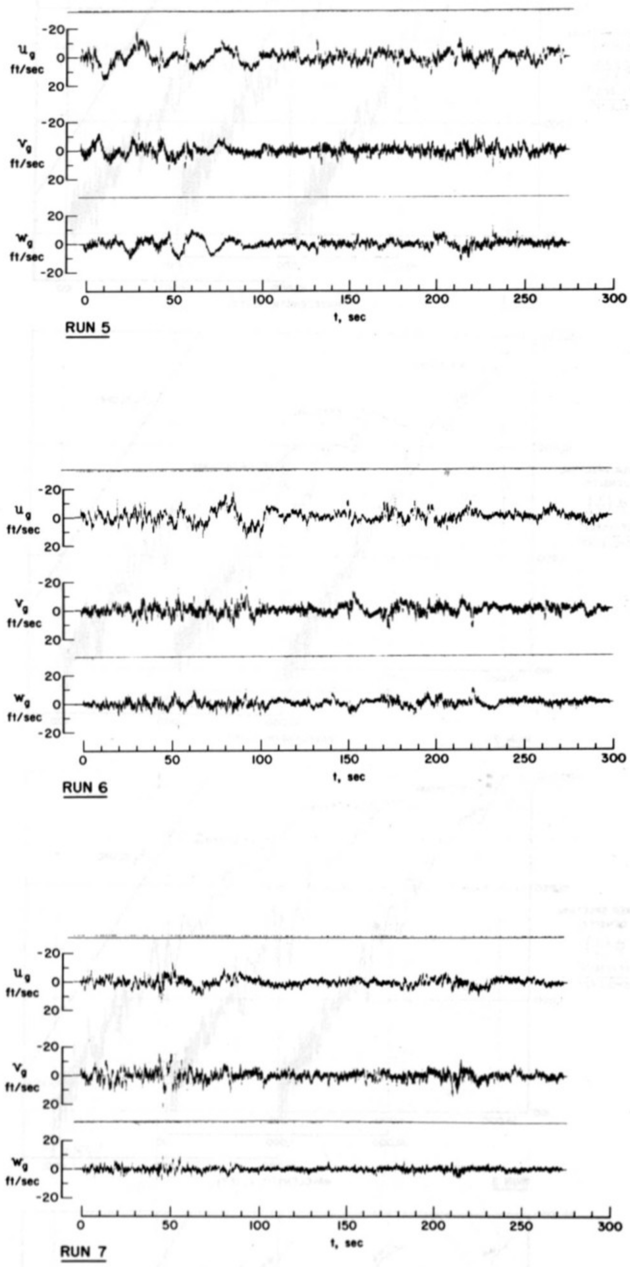
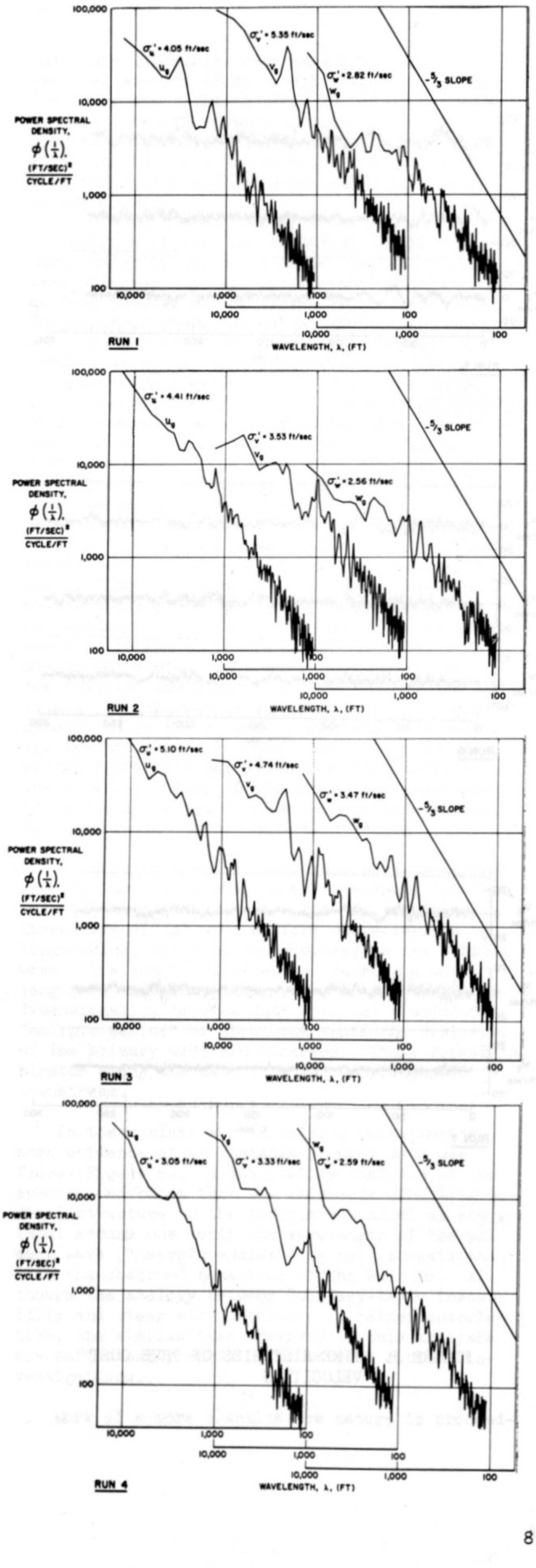


FIGURE 3. TIME HISTORIES OF TRUE GUST VELOCITIES



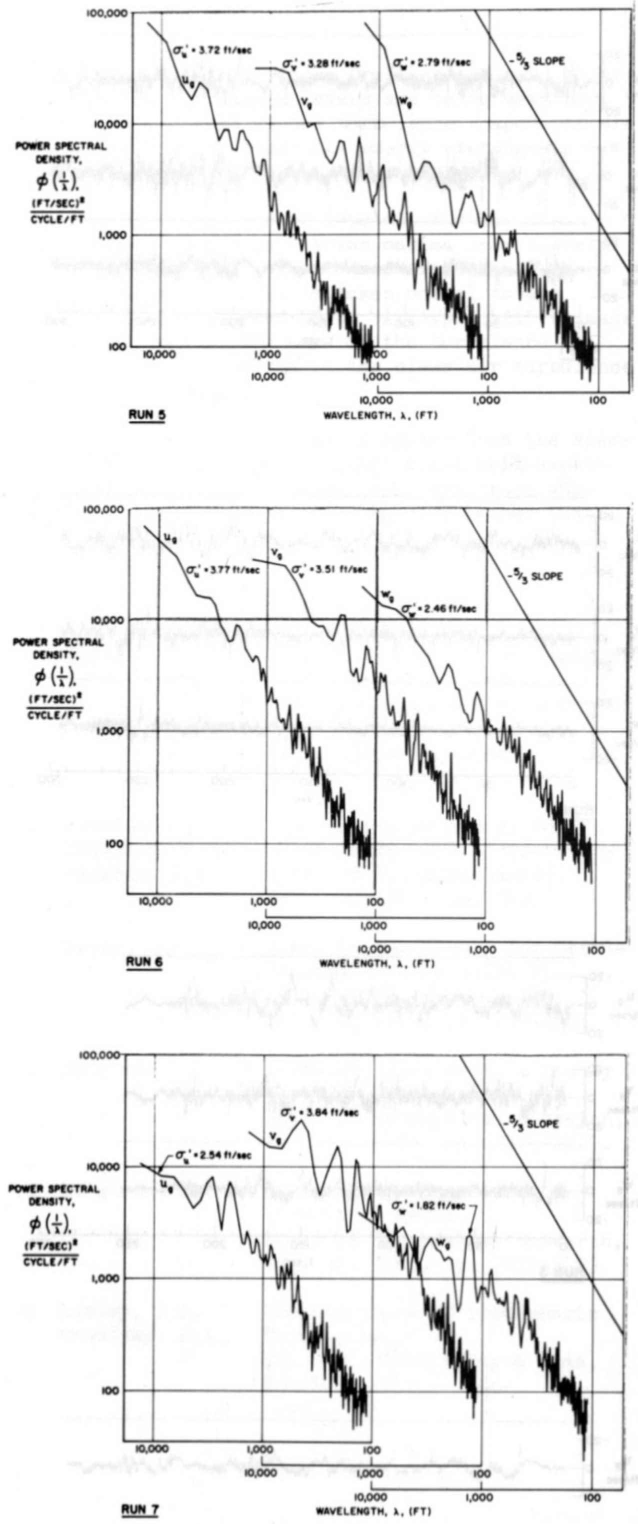


FIGURE 4. CLEAR AIR TURBULENCE POWER SPECTRA - 37,000 FEET

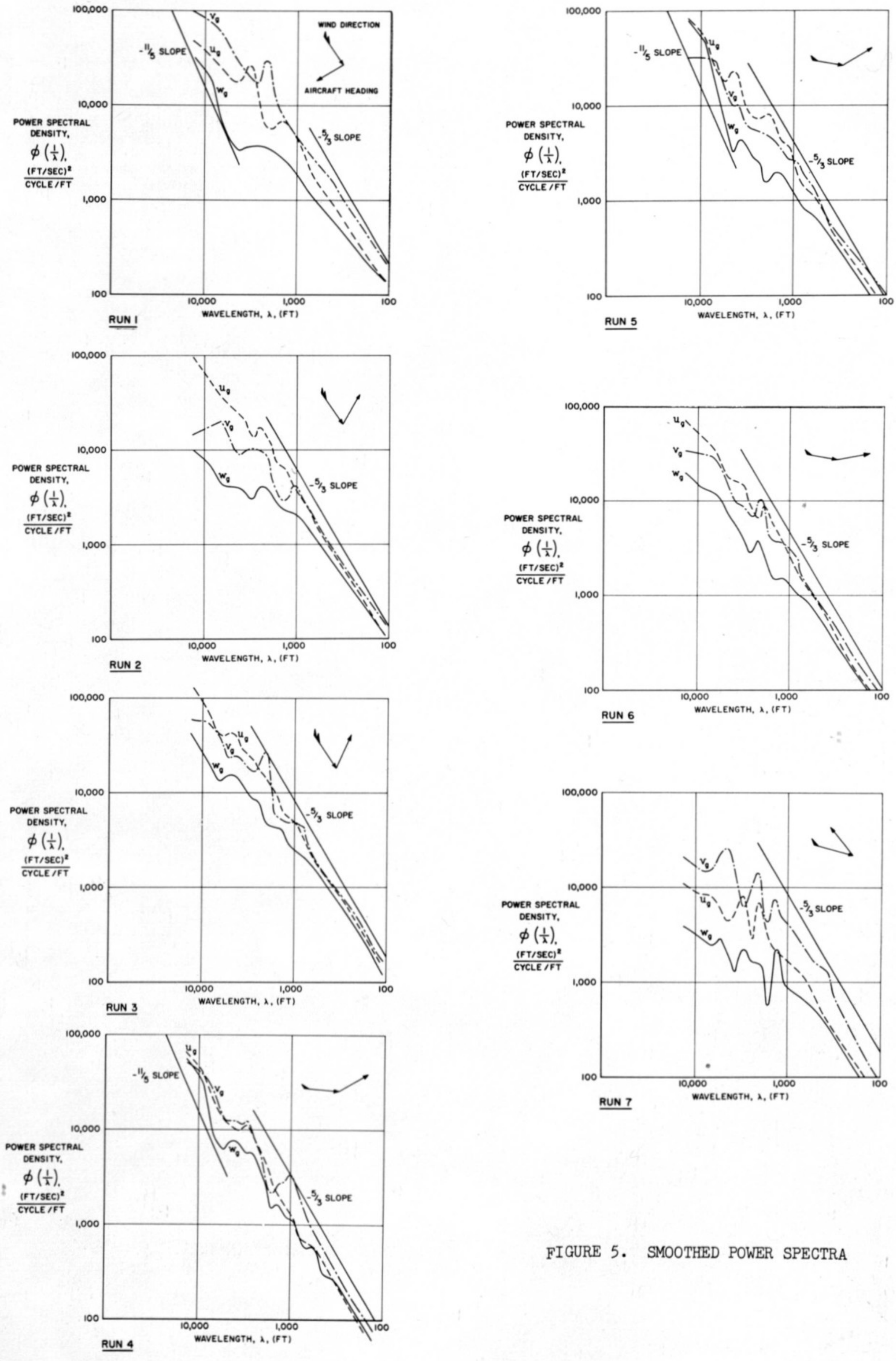


FIGURE 5. SMOOTHED POWER SPECTRA