C.P. No. 1248

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On the Nature of Large Clear Air Gusts Near Storm Tops

by

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LONDON: HER MAJESTY'S STATIONERY OFFICE

1973

PRICE *70p* NET

UDC 551.551 : 551.515.4

CP No.1248*
February 1972

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SUMMARY

Detailed analysis of a small patch of severe clear air turbulence recorded in a Canberra aircraft flying in the vicinity of storm tops, in Oklahoma, 1965, reveals the existence of a pattern in the variation of horizontal and vertical gust velocities. This pattern appears to arise from the presence of a complex system of equally-spaced vortex rolls, some with horizontal and some with tilted axes, embedded in turbulence of a more random nature. The largest gusts are found near the centres of the vortex rolls and are characterised by the sharpness of their gradients. The implications with respect to aircraft design loads of large gusts arising from such organised air motions is discussed with particular reference to the power spectral approach.

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* Replaces RAE Technical Report 72036 - ARC 33976

CONTENTS

1 INTRODUCTION

The proposals of the FAA to change their gust design load requirements based on the discrete gust, to requirements based on a power spectral approach has raised a number of interrelated problems. These concern both the validity of the power spectral approach for determining limit loads and its method of application in this field. Although considerable progress has been made to-date both in the USA and more recently in the United Kingdom towards narrowing these problem areas, diversity of opinion as to the advisability of a complete change-over still exists, one of its root causes being a deficiency of knowledge of the fundamental nature of the very large gust and of its statistical relationship with atmospheric turbulence of a more usual intensity. Experimental evidence on the detailed structure of large gusts is particularly difficult to acquire in any quantity and most data available are concerned with the magnitudes of vertical gusts derived from acceleration measurements. In studies concerned with this type of data, valuable contributions have been made by Taylor[1] on the statistical distribution of gust magnitudes with special reference to severe turbulence, and by King[2] on the relationship of the large gust to the size of the patch of turbulence in which it occurs. Despite these and other contributions in this field, the picture is still far from complete, particularly with respect to large gusts occurring in clear air turbulence not directly associated with convective activity. The cause of such turbulence has been the subject of much theoretical speculation[3,4,5], and of some illuminating laboratory experiments in hydrodynamics[6,7].

The object of the present Report is to contribute to this gap in our knowledge and in particular to highlight certain experimental observations which have a bearing on the specification of aircraft design loads. Although the main evidence presented here refers to a rather special situation where storm heads have penetrated into the stratosphere in the presence of strong winds, there are grounds for supposing that the phenomenon observed is associated with mesoscale wave motion, and hence may occur in other situations productive of such waves. Some evidence in support of this supposition is presented in Appendix A.

The report is mainly concerned with the analysis of a single patch of turbulence, brief reference only being made to other disturbances encountered in the same series of flight trials and to reported incidents of severe clear air turbulence. The structure of the larger gusts and their relation to the rest of the turbulence is examined in some detail and the observed features explained in terms of an encounter with a complex system of vortex rolls. The nature of these vortex rolls is not discussed, except very broadly, as it is to be the subject of a further report dealing more fully with the meteorological aspects. A study is made of the power spectra of the three components of turbulent air motion and of their probability distributions to see to what extent the special features of the turbulence are reflected in this type of statistical analysis. Finally the implications of gusts of design magnitude occurring in such vortex rolls are discussed with reference to the specification of aircraft design loads.

2 TEST FLYING AND OBSERVATIONS

2.1 General account of flight trials

In the summer of 1965 a Canberra aircraft instrumented to measure gust velocity along three axes took part in Project Roughrider, an investigation into various aspects of thunderstorms held annually in Oklahoma, USA. The main objective of the flight trials was to investigate atmospheric turbulence in the upper troposphere and lower stratosphere, in the vicinity of storms, such as might be encountered by a supersonic transport when circumnavigating the storms under radar guidance. Observations were made flying over and around storm tops, cruising in and around the anvil cloud, and skirting along the sides of lines of storms. Of 13½ hours spent in such flying, covering a distance of approximately 10000 km, some two-thirds was spent at altitudes between 40000 and 47000 ft, and it was this height band, the highest investigated, which proved the most productive of large gusts. Whereas little significant turbulence was encountered lower down despite a close approach to the sides of storms, moderate turbulence was not unusual in the 40000 to 47000ft height band; as shown by the experience of a second Canberra which encountered, on average, three derived gusts exceeding 10 ft/s per mile, while engaged in correlating turbulence and radar echoes in this height band. Even when the air felt smooth, pilots often commented on changes in Mach number and height which they attributed to atmospheric draughts. On three occasions unusual atmospheric disturbances were found associated with small patches of moderate turbulence, and on one occasion a severe disturbance in conjunction with a particularly intense patch of turbulence was encountered. It is this patch of turbulence which is the subject of the present Report. An earlier report by Harrold and Burns[8] suggests that it was associated with the deflection of the environmental wind over a barrier formed by the line of storms, a suggestion not incompatible with the phenomenon postulated in this Report. It is not, however, proposed to go into the nature and causes of the observed phenomenon in this Report, and a brief account only is given of the meteorological situation and flight conditions pertinent to its encounter. Additional information on the meteorological situation, and on the motions of the storms and flight path of the aircraft deduced from ground radar data, can be found in Refs.8 and 9.

2.2 Flight conditions relating to encounter with patch of severe turbulence

On 27 May 1965, severe storms developed in the early afternoon a hundred miles south-west of Oklahoma City. By late afternoon when the Canberra was exploring the storms, they were well developed with occasional heads up to 55000 ft. The general level of storm tops and the top of the cirrus sheet lay at about 43000 ft. Upper winds were from west-south-west, $255^\circ/100$ kn at 38000 ft and $255^\circ/70$ kn at 45000 ft. The aircraft had been operating at a height of 45000-46000 ft, investigating conditions above the cirrus sheet near the south-west edge of a line of storms running approximately west-north-west/east-south-east. It was about to leave the region on a west-south-west heading, almost dead into wind, and was passing between two storm heads, about 30 km apart, when it encountered turbulence. At first the turbulence was light, and continued so for just under 3 minutes, covering a distance of 39 km (24 miles); there followed a few seconds of smooth air and then the severe patch. The severe turbulence, which was encountered for just under 1 minute, terminated abruptly and on emerging into smooth air the pilot reported a rapid and severe increase in airspeed. Recordings showed that this increase was attributable to wind shear and that it was accompanied by a sharp temperature gradient (see Fig.1). The aircraft continued to fly for several minutes on a westerly course and no more turbulence was encountered.

Flight conditions during the traverse of the patch of turbulence are given in Table 1 together with relevant characteristics of the Canberra aircraft and factors for deriving gust velocities from CG accelerations. Table 2 lists the acceleration levels exceeded.

3 INSTRUMENTATION AND DATA REDUCTION

These have been described fully elsewhere[10,11] and it is only proposed to mention certain features relevant to this Report. The aircraft was instrumented to measure gust velocities in three directions using a nose probe to detect airflow relative to the aircraft and accelerometers and gyroscopic instruments to measure aircraft motions. Simplified equations were used in the derivation of the three components of gust velocity from these measurements. Some discussion of these equations and of the accuracy of the methods of spectral analysis used can be found in Ref.12. The simplifications were aimed at increasing the accuracy at all but very long wavelengths (low frequencies), the inclusion of which would have required an accuracy beyond the capability of the accelerometers and gyroscopic instruments fitted in the Canberra. (The installation did not include a stabilised platform or elaborate gyroscopic instruments.)

Because of the doubtful accuracy of the long-wave information it was decided to filter out numerically all wavelengths greater than 3 km. The attenuation characteristics of the filter used are shown in Fig.2; virtually all information on wavelengths shorter than 2.2 km is retained and longer than 3 km rejected, with a varying degree of retention between. Prior to filtering, linear trends present in the variation of each component of gust velocity were removed and the zero gust datum equated to the arithmetic mean. These procedures result in most of the large scale motions of the atmosphere being removed, a point to be noted when considering the meteorological situation, but one which does not greatly affect loads in aircraft flying at current or currently proposed airspeeds.

Besides the gust measuring instrumentation, the Canberra was fitted with instrumentation for measuring more general parameters such as height, airspeed and temperature in order to provide background information. These parameters were recorded on a more compact timescale, than were the gust measurements, so that their variation cannot be studied in the same detail. Because of their compact timescale, however, these recordings proved particularly useful in detecting atmospheric disturbances of a non-turbulent nature.

4 ANALYSIS OF PATCH OF TURBULENCE

4.1 General discussion of gust velocities

Fig.3 shows the variation in the three components of gust velocity U_g, V_g and W_g plotted against distance along the flight path* - the timescale of the recording is converted to distance on the assumption of constant airspeed throughout the traverse. Gust velocities are evaluated every 1/20 second

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* As is usual with this type of analysis all distances relate to axes fixed in the ambient windstream on the assumption that the turbulence drifts with the windstream. If this is untrue, and the phenomenon is stationary relative to the ground, all distances including estimates of wavelengths and vortex spacing should be decreased by some 17%.

which at an average true airspeed of 421 kn corresponds to a spacing of just under 11 m. At first sight the turbulence of Fig.3 does not appear abnormal; a more careful examination however, reveals a periodicity in U_g, the fore-and-aft component of gust velocity at a wavelength of just over 1500 m (5000 ft). This periodicity is more easily perceived if the higher frequency content is removed by filtering (see Fig.4). A more careful examination also reveals a tendency for high velocity peaks in all three components to occur near the maxima of this periodic motion. All four peaks over 15 m/s (50 ft/s) and 85% of the 13 peaks over 12 m/s (40 ft/s) occur in these regions (see Table 3). Extracted and replotted, the parts of the V_g and W_g traces falling within these regions produce a pattern, consisting of the repetition at an equal spacing of what might be termed a 'key motif', somewhat reminiscent of the variation in circumferential velocity in a classical circular vortex (see Fig.4). This key motif appears five times in the trace of W_g and three times in that of V_g. It is masked to some extent by small scale turbulence and the second and third of the series in W_g are somewhat vestigial; in all cases, though, there is a tendency for left and right hand sides to be inverted mirror images of each other, suggesting rotary motion.

The central region of the key motif depicts a velocity variation which approximates to the rigid body rotation typical of the core of the classical circular vortex. Outside this region the depicted velocity at first falls off less steeply than in the classical vortex - in some cases it even tends to remain constant or increase before finally terminating in a sharp edge. A possible explanation for these differences is the presence of secondary contra-rotating vortices centred near the edges of the primaries as illustrated in Fig.5. Variation in the relative sizes of the secondary and primary vortices might be expected to produce various degrees of distortion, and an examination of Fig.3 indicates some such association between distortion and relative vortex size.

A probable explanation for the observations so far noted is that the aircraft is crossing a system of vortex rolls associated with wave motion. There is a wealth of theoretical backing for an explanation in these terms and it is proposed to continue the examination of the air motions observed, in the light of this hypothesis. Although many of the observations support this hypothesis, it is not possible to confirm it fully from evidence limited, as it is here, to a single traverse through what is essentially a three-dimensional phenomenon.

On probability one would not expect the path of the aircraft to pass through the axes of the rolls or to be precisely normal to them. The appearance of the key motif initially in the vertical component of airflow indicates that the axes of the first series of rolls lie in a horizontal plane. According to whether the traverse passes above or below the axes one would expect the head-on airflow to show a temporary decrease or increase as each roll is crossed, in order to comply with the direction of rotation indicated by the vertical air motion (this is consistent with negative wind shear). A general increase is indeed evident as each roll is crossed but it is not clear to what extent this is due to vorticity rather than wave motion. The large positive peaks in U_g, denoting head-on gusts - in one case negative - near the centres of the cores are, however, strong evidence that the flight path lies slightly below the axes - in one case slightly above. Obliquity of the flight path to the axes might be expected to produce a similar temporary increase or decrease in lateral gust velocity as each roll is crossed, together with some asymmetric gust loading on the wings. The lateral gust velocity shows no such systematic variation, but the rapid application of aileron to raise the starboard wing as the cores of the three strongest horizontal rolls are crossed, indicates at least some degree of obliquity in the flight path such that the starboard wing is leading. The fact that the aircraft course was almost identical with the direction of the ambient wind as given by the nearest relevant sounding, probably accounts for the obliquity not being larger.

Towards the end of the traverse the appearance of the key motif in V_g centred near the sharp upwind extremities of the W_g key motifs, suggests the presence of a second system of rolls with their axes orientated diagonally. In physical terms, rolls classed as secondary horizontal rolls, further downwind, have their axes tilted towards the vertical and become the dominant system as the upwind edge of the patch of turbulence is approached. Although double systems of vortex rolls feature in two-dimensional theories[13], three-dimensional treatment appropriate to the case in hand has not yet been developed - to the best of the author's knowledge. Possibly the three-dimensional nature of the observed phenomenon is associated with vector wind shear (change in wind direction, as well as speed, with height). The nearest meteorological soundings do not show any significant change of wind direction in the relevant height-band but, according to Roaches' studies[14], local airflow associated with the nearby storm heads would appear capable of producing lateral deflection of the windstream.

The series of tilted vortex rolls is too short and variable, consisting as it does of only three vortex rolls, for detailed analysis of the sort made in the case of the horizontal rolls. The best defined of these rolls, namely the second, appears to have its axis tilted at an angle of roughly 20° to the vertical.

4.2 Statistical analysis of patch of turbulence

Since the turbulence contains elements of organized air motion associated with the vortex rolls it might be argued that statistical analysis, such as that used in power spectral methods, with its underlying concept of randomness, is not strictly admissible. Nevertheless such an analysis has been carried out, in order to ascertain the extent to which the results reflect the properties peculiar to the organised motion, particularly those of import with regard to aircraft loads.

Curves of spectral density calculated for the three components of velocity are shown in Fig.6 and appear to be quite usual in shape in spite of the element of orderliness present in the turbulence. For wavelengths less than 100 m the turbulence tends to be isotropic in that $\sigma_w^2 \simeq \sigma_v^2 \simeq \frac{4}{3}\sigma_u^2$. At larger scales the spectral density of the vertical component compared with that of the other two components is overlarge for isotropy, a reflection, probably, of the high vertical velocities in the vortex rolls. The slopes of the spectra at the shorter wavelengths approximate to the $-5/3$ law; at the longer wavelengths they show only a slight tendency to flatten, so that the scale length cannot be determined with certainty. Best fit of the transverse Von Karman spectrum to the experimental vertical estimates, indicates a scale length near 200 m; it may well be that this very low scale length is genuine and reflects the dimensions of the vortex rolls. The truncated rms value of 4.25 m/s (13.9 ft/s) obtained for the vertical component is high for clear air turbulence, and is more in line with that given by Houbolt *et al.*[15] as typical of storm turbulence; a comparison of these and other rms values and of spectra for various conditions is given in Fig.7.

4.3 Normalcy of distributions

Non-normalcy of the probability distribution of the turbulent velocities at extreme values is known to be a common feature of individual patches of severe turbulence. It is, therefore, not proposed to dwell on its occurrence in the present case, except to note that it is associated with the large positive longitudinal and vertical peaks which occur in the vortex rolls. The corresponding lateral peaks are not so outstandingly large, and the fit of the distribution to the Gaussian line is correspondingly better (see Fig.8). The probability distribution of velocity derivatives, in the form of slopes or gradients, has, on the other hand, not been so widely investigated; although it might be expected to have an almost equally important effect on aircraft loads. This matter is therefore treated in rather more detail.

The probability distribution of slopes cannot be obtained directly from data digitised at discrete intervals as in the present case. Nor would such true slopes necessarily be meaningful in the context considered here since they would be highly dependent on the amount of high frequency filtering employed. Instead the distributions of average gradients over various fixed distances are considered. That over the shortest distance, 11 m (35 ft), can be regarded as an approximate slope of relevance to the problem in hand; particularly since, as discussed below, no trends are observable in the variation of the distribution with gradient distance. Gradient distances have been varied in steps of 11 m up to 54 m (35 ft up to 180 ft). Fig.9a, b and c show the probability distributions obtained for gradients of U_g, V_g and W_g respectively. Except for extreme values the distributions relating to the different gradient distances collapse onto one curve. Extreme values show some scatter tending towards higher probabilities but no particular trend with gradient distance can be observed. Those for gradients of W_g and V_g show a far greater departure from the Gaussian line than in the case of U_g. The reason appears to lie in the sharp gradients which occur in V_g and W_g at the centres of the vortex cores. Such sharp transitions do not occur in the fore-and-aft component of air motion, being essentially a feature of vortex motion sensed transverse to a line of penetration, regardless of its orientation. The collapse of the probability distributions for different gradient distances onto one curve, together with the fact that the rms values tend to vary inversely as the cube root of gradient distance squared (see Table 4) is not surprising in virtue of the tendency of the spectra to conform with the -5/3 law. This law according to Weizsacker[16] leads to a variation of velocity change with the cube root of gradient distance, a relation implicit in the above experimental results. The probability of the sharpest measured gradient, a change of vertical gust velocity of 31 m/s (102 ft/s) over a distance of 54 m (180 ft), occurring in a Gaussian process with the same standard deviation is extremely low, of the order of 1 in 10^7, a result which emphasises the need to take account of the non-normalcy of the gradients, should further evidence of the importance of this type of turbulence warrant its inclusion in gust design.

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5 CONCEPT OF THE SHEAR-BOUNDED PATCH OF TURBULENCE

Other characteristics of the air motions, besides those within the turbulent patch, merit discussion in that they affect aircraft loads. As previously remarked the Canberra aircraft encountered a sharp wind shear and temperature gradient on emerging from the patch of turbulence into seemingly smooth air (see Fig.1). The wind shear was sensed as an increase in airspeed; the difference in wind speed across the shear layer probably exceeded the 50 kn change registered in airspeed (TAS) since the pilot was attempting to keep the airspeed below the limiting Mach number by raising the nose of the aircraft (the angle of pitch was increased by a maximum of 8^{o}). This bounding of a small patch of severe clear air turbulence by a strong wind shear and temperature gradient is by no means unique. Other cases of a less severe nature, one on the same day, were recorded during the flight trials in Oklahoma, the original A13 records for which are reproduced in Fig.10. A point of interest is that in all four cases an increase of airspeed (EAS) was experienced, a fact which suggests that increases and decreases are not equally likely. A possible explanation lies in the fact that when a stratified shear layer is distorted by wave motion, at a wavelength long in comparison with the depth of the layer, instability in shear occurs at the troughs or crests of the wave according to whether the shear is negative or positive[17]. In the lower stratosphere, where these instances occur, one would expect the shear to be predominantly negative (wind decreasing with height) and hence instability to occur at the troughs. It follows that the shear layer on the upwind side of the instability would be tilted downwards in the direction of flow. As shown in Fig.11, no matter which way this layer is crossed an increase in airspeed is always experienced. The argument refers to traverses made only in near horizontal flight; in steep climbs or descents the shear layer may be crossed differently.

If this explanation is correct one would expect an aircraft crossing a shear-bounded patch of turbulence of this nature in the middle troposphere, where the wind shear associated with polar and sub-tropical jet streams is predominantly positive, to experience a decrease of airspeed. Experimental evidence on this point has not been forthcoming but it is not hard to find reports of incidents during operational flying in the tropopause, which indicate the existence of a sharp wind shear bounding a patch of severe clear air turbulence without specifying its effect on airspeed. Reports of three such incidents are given in Appendix A.

5.1 Pattern displayed in the arrangement of the shear boundary and adjacent patches of turbulence

Not only does the concept of a shear-bounded patch of turbulence begin to emerge, but as discussed in Appendix A a general pattern can be traced in the orientation, with respect to wind direction, of the shear boundary and of the surrounding areas of smooth and turbulent air. The shear is found on the upwind side of the severe patch; further upwind the air is smooth - as sensed by a subsonic aircraft - in contrast to the downwind side where a second discrete patch of more extensive but less severe turbulence is likely to be found. This pattern is consistent with the cyclical breakdown (cyclical in time) of a stratified shear layer into turbulence by a triggering mechanism which is stationary, or slow-moving relative to the wind stream. Such a broad-term explanation accounts for the presence of wind shear only on the upwind edge of the turbulence; further downwind its laminar interface is destroyed in the turbulence itself - possibly to reform at different levels. It also accounts for the presence of a second patch of less severe turbulence downwind: this was originally a severe patch of turbulence, generated at the triggering source, which has drifted downwind, decaying as the turbulence diffuses into the surrounding air. Other even less severe and more diffused patches might be expected further downwind. The extent to which the incidents of Appendix A and the Canberra incident conform to this general pattern is summarised in Table 5.

6 IMPLICATIONS WITH RESPECT TO AIRCRAFT DESIGN LOADS

It is now proposed to consider the implications of associating aircraft loads of design magnitude with a phenomenon of the type encountered by the Canberra. The fact that this matter is the subject of discussion should in no way be taken as implying, except inasmuch as particular evidence is produced - that the loads caused by this phenomenon are necessarily of sufficient magnitude and frequency to be included in the gust design case. The proposition that violent clear air motions are associated with the breakdown of waves into vortex rolls under shear, has been the subject of theoretical speculation, but more experimental evidence in support of that presented here is required before the proposition can be considered to be substantiated.

Characteristics, both of the environmental atmospheric conditions and of the air motions within the vortex rolls can produce loading effects of potential severity and these two aspects are discussed separately - except insofar as they interact.

6.1 Effects arising from air motions adjacent to the patch of turbulence

On the assumption that the air motions follow the pattern defined in Table 5 and Appendix A three effects are noteworthy; the first concerns the degree of warning available to the pilot, so that he can reduce airspeed if desirable before encountering the largest gusts. Because of the smooth air upwind, an aircraft flying on a predominantly downwind track is likely to run into extreme turbulence without any immediate advance warning from the presence of less severe turbulence. Moreover, the patch itself is too small and the severe gusts distributed throughout it too evenly to provide such warning itself. Flying upwind, the situation is slightly more favourable and encounters with nearby patches of less intensive turbulence should provide some warning,albeit rather short.

The second effect also concerns the control of airspeed. In downwind flight the wind shear bounding the patch of extreme turbulence introduces a large inadvertent change in airspeed just before entering the turbulence. Either an increase or decrease of airspeed may be experienced according to the tilt of the shear layer as discussed in section 5, the former being more likely in the lower stratosphere. At subsonic speeds an increase leads to a direct increase in gust loads. Both increases and decreases of speed can have adverse effects on control and stability[18], and although a jet upset is unlikely in clear air, recovery manoeuvres from an incipient upset can lead to an adverse combination of manoeuvre and gust loads. The situation may be aggravated by other hazards such as engine compressor stall on subsonic aircraft, and malfunctioning of engine air intakes on supersonic aircraft due to the temperature changes associated with the shear[19].

The third effect concerns the excitation of rigid body oscillations of the aircraft. These may be excited by the abrupt shear on the boundary or by wave motion adjacent to, or within the patch itself (see trace U_g of Fig.4). On their own these oscillations are not likely to produce serious loads, unless a resonance occurs; but if insufficiently damped, they may produce loads additive to those of the gust loading. Because the characteristic reversal of gust loading across the vortex core produces peak structural loads in both directions within a time interval short in comparison with the periodic time of the oscillation, an adverse combination is likely in one direction or the other. In the case of the Canberra, rolling and yawing oscillations of $\pm 8^{\circ}$ and $\pm 6^{\circ}$ respectively occurred almost continuously within the patch, and must have contributed to the severity of the structural loads. The effect of the rolling oscillation is to be the subject of a separate analysis.

Not all cases of severe clear air turbulence will conform to the general pattern of air motions assumed in the above discussion, since different mechanisms will be involved. Nor will all aircraft encounter turbulence of this pattern while flying on a predominantly up or downwind track. However, the cases quoted in Appendix A provide some evidence that the pattern does recur, and moreover that it occurs in conjunction with severe turbulence. King's findings from CAADRP are of interest in this context: in his study of severe gust loads[2] he comments on the small extent of the patches of turbulence containing the largest derived gusts, and on the lack of warning as evidenced by the failure of the pilot to reduce speed before encountering the patches containing the largest gusts. Nearly half of the most severe gusts occurred in patches of less than 15 seconds duration, or 2300 m (7500 ft) extent, and for 80% of these there was no warning - the situation as regards warning for the remaining 20% was indeterminate. Thus both King's investigations and that of the present report point to the conclusion that the designer cannot rely on aircraft being flown at the recommended rough airspeed when the largest gusts are encountered.

6.2 Effects arising from organised motion within the turbulence

Batchelor[20], in discussing the changes of velocity of turbulent motion in fluids for which the Reynolds number is large, has remarked on the tendency for a small number of large disturbances to form rather than small disturbances distributed throughout the fluid. The gradients found in the vortex rolls of this Report are striking examples of this tendency: moreover, they appear to be associated with gusts of a magnitude comparable with that of the design case. The present military design case appropriate to the altitude in question stipulates a true vertical gust velocity of 60 ft/s with a gradient distance of 100 ft, almost identical in magnitude and gradient to the largest gust which would have been encountered had the aircraft been flying in the reverse direction*. The need to take account of these gradients has already been commented upon with reference to their non-normalcy. The introduction of eigenfunctions, as proposed by Lumley[21], to provide a realistic representation of the large loads has interesting possibilities in this respect. Dutton[22,23] has commented on the close relation between the eigenfunction method and the spectral approach - he has shown the former to be a generalization of the latter - thus opening the way to a joint method with eigenfunction representation for large gust velocities of an organised nature, and spectral representation for the more random gusts of all sizes.

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* The design gusts appropriate to the altitude were not critical in the case of the Canberra.

Deterministic representation of this sort, whether by eigenfunctions, or some form of discrete gust[24,25], has the obvious attraction of allowing direct treatment of the complex loading actions arising from the rapid reversal of gust velocity from one extreme to the other across the vortex cores. This feature of the turbulence can lead to the pilot's (or autopilot's) efforts to counteract the effects of the first gust peak resulting in an amplification of the structural loads from the following reverse peak owing to pilot reaction time and lag in aircraft response. Moreover, the adverse effects from the pilot's action may be superimposed on unusually large dynamic loads, also arising from the rapid reversal of gust loading from one extreme to another. Loads measured in the Canberra during the traverse of the first vortex roll exemplify these points. Despite a second gust peak considerably smaller than the first, -41.5 ft/s compared with +60.4 ft/s (true); the second CG acceleration peak was larger than the first, -1.11 g compared with +0.94 g, by a ratio of -1.18:1. Calculated rigid body response, excluding pitch, to the same gust history slightly idealised, gives a corresponding ratio of -1.04:1 leaving a difference of some 13% to be accounted for. The pilot's elevator movement certainly contributed to this difference which from the records appears to be largely due to adverse pitch (for further details see Ref.8). The corresponding measured wing root bending moments were -1.44 and +1.08 times the quasi-static-bending moment per g appropriate to the height and speed. These figures indicate dynamic overloads of 30% and 15% at the second and first peaks respectively, over and above any dynamic contribution contained in the CG acceleration. The overload of 30% demonstrates the unusually large dynamic effects associated with the second peak.

6.3 Asymmetric and lateral loads

Loading aspects have so far been discussed mainly in general terms without reference to the type of loading or part of the aircraft under load. It is now proposed to consider some special aspects of asymmetric and lateral loading since experience from past incidents and accidents in clear air turbulence points to the importance of these types, particularly of the latter. Since an aircraft is likely to traverse a vortex roll, whose axis is horizontal at an oblique angle, some degree of asymmetry in the wing loading may be expected. In an extreme case the rolling loads could be both severe and prolonged if the flight path happens to lie almost along one of the roll axes; an extremely unlikely event but one which may possibly have been the cause of a Canberra aircraft being turned onto its back in clear air turbulence, associated with a jet stream over UK, in the late fifties. In the more realistic case the wing will be subjected to a combination of symmetric and anti-symmetric gust loading coupled with loads arising from the rapid usage of the ailerons. The other extreme case is that of pure symmetric loading; it is an interesting point that in virtue of the lateral extent of the vortex roll, no alleviation due to spanwise variation of gust velocity can be expected. The case of virtually pure symmetric loading is likely to be more common than that of virtually pure antisymmetric loading since it does not require such a critical positioning of the flight path.

Diagonal gust loading of the same typical vortex pattern produced by vortex rolls with their axes tilted, will give rise to loads in the fin and rudder which may be superimposed on those arising from motion in the Dutch roll, excited in one of the ways discussed previously. The prevalence of Dutch roll, despite autostabilization in yaw, should not be underestimated. An additive effect is likely in one direction or the other since the load reversal in the vortex is rapid compared with periodic times typical of the Dutch roll. In the case of the T-tail, the diagonal gust loading acts both on the tail surfaces and those of the fin and rudder. Obliquity of the flight path to the horizontal component of the axes of the vortex rolls results in asymmetry of load across the tail just as in the case of the wing, producing a bending moment at the fin root which, if the obliquity is in the right sense, is additive to that produced by direct gust loading on the fin. Further effects such as increase in airspeed and lag in response to corrective movements of the aileron and rudder may aggravate the loads produced.

Diagonal loading is not usually specified in design load requirements and the designer has to make his own assumptions when problems involving such loading arise. Usual practice in UK is to adopt the concept of the "round-the-clock" gust, a gust of constant magnitude acting in any direction. It is interesting to note, however, that in the case of the patch of turbulence under consideration, the distribution of the larger peaks of transverse gust velocity, show a tendency to bunch on the diagonals; for example, all but one of the seven transverse gust peaks exceeding 13.5 m/s (45 ft/s) fall into a diagonal class as opposed to a horizontal or vertical class, when grouped according to eight classes of direction. This suggests that the concept of the "round-the-clock" gust, with its underlying assumption of homogeneity, may not be valid for certain types of clear air turbulence. More evidence is required, however, before coming to any conclusions on this point.

7 CONCLUSIONS

A patch of clear air turbulence has been encountered in the lower stratosphere near storm tops in which the largest gusts appear to be associated with organised air motions embedded in turbulence of a more general nature. The organised air motions are consistent with the presence of two series of equi-spaced vortex rolls, one of five rolls (two rather vestigial) with near horizontal axes, overlapping one of three rolls with tilted axes. The diameters of the rolls are of the order of 500 m and their spacing does not exceed 1500 m.

The rotational motion near the centres of the vortex rolls is similar to that of the classical circular vortex. It produces sharp reversals of severe vertical and lateral gust loading coupled with unidirectional longitudinal gust loading.

The curves of power spectral density of the three components of air motion, considered individually, do not exhibit any unusual features. Considered in relation to each other, they indicate the turbulence to be anisotropic above wavelengths of about 200 m, due to an excess of vertical energy. The intensity of the vertical component is comparable with that of storm turbulence, but the scale length appears to be considerably smaller, probably reflecting the scale of the vortex rolls.

The probability distributions of the turbulent velocities show the usual tendency to exceed the Gaussian distribution at extreme values. Those of the gradients show even more marked departures, particularly in the case of V_g and W_g, probably due to the sharp gradients in the vortex cores which are absent in U_g. Inclusion of this type of turbulence for design purposes would entail consideration being given to the non-normalcy of its gradients.

A pattern is apparent in the Canberra and other incidents of severe clear air turbulence involving the air motions upwind and downwind of the severe patch. Characteristics of this pattern, and of the organised motions within the vortex rolls, lead to particular loading actions which could be of importance with regard to gust design should the seriousness of this type of loading be confirmed. These effects and their implications are as follows:-

(i) Gusts of design magnitude are likely to be encountered, when flying downwind, without warning from less intensive nearby turbulence. (the aircraft may even experience an increase of airspeed just before the gusts are encountered). Hence, unless other methods of warning are available, the designer cannot rely on the attainment of the rough air speed to alleviate the gust loads. This conclusion is in agreement with the more general findings of CAADRP studies.

(ii) The rapid reversal of gust loading from one extreme to another across the vortex cores, leads to a potentially complex loading situation in which the induced loads are likely to be aggravated by:-

(a) Pilot or autopilot's control movements,
(b) Unusually large dynamic effects,
(c) Rigid body oscillations.

(iii) The above remarks include the rapid reversal of lateral loading on the fin which occurs when the axes of the vortex rolls are tilted. In this situation T-tails are particularly susceptible to adverse combinations of loading from diagonal gusts; furthermore, it may be characteristic of the turbulence that diagonal gusts are larger than vertical or horizontal gusts.

Realistic representation of the gust loading by means of eigenfunctions or other semi-discrete or discrete representation, would have the advantage of allowing a direct treatment of the above effects. A further advantage of the eigenfunction method is its affinity with the spectral approach which would facilitate the joint use of the two methods.

Appendix A

REPORTS OF INCIDENTS INDICATING THE PRESENCE OF SHEAR-BONDED PATCHES OF CLEAR AIR TURBULENCE

Reports of incidents in which aircraft have encountered severe clear air turbulence, in some cases suffering structural damage, can be found which can be interpreted as indicating the presence of an abrupt wind shear, bounding the severe turbulence. The shear appears to be sensed by the aircraft as an acceleration, not necessarily vertical, and features in the pilots' report as a large acceleration,bump or gust, distinct from those of the turbulence adjacent to it. In one case the pilot even refers to "an unreported shear". Three examples, mostly quoted verbatim from their sources, follow:-

A.1 Incident to Boeing 707 on 10 January 1964 over Colorado[28]

This was the same day that an Air Force experimental B52 lost its fin while investigating turbulence in the lee of the Sangre de Cristo Mountains. The Boeing was flying considerably higher than the B52, at an altitude of 28000 ft, and further north, some 38 n miles west of Denver, when it encountered severe turbulence. Mountain waves had not been reported but had been anticipated after the headwind component of this westborne flight increased to 80 kn. The aeroplane shook violently and then encountered a terrific bump - turbo compressors became inoperative, the aircraft lost 1000 ft of altitude. The pilot felt that "an unreported wind shear existed on the west side of the mountain wave which caused the extreme violence found there".

A.2 Incident to Boeing 707 on 18 January 1964 over Colorado[28]

On 18 January 1964, a day on which there were numerous reports of clear air turbulence associated with mountain wave, the pilot of a Boeing 707 at 27000 ft over La Vita, Colorado reported "heavy side gust from left - then felt as though a bulldog had hold of the nose and was shaking it violently - lasted 70 seconds then smooth for 70 seconds, then followed by slightly lesser turbulence for another 70 seconds". The aircraft recorder on this downwind flight showed normal accelerations ranging from +3.33 to -0.35 g. The aircraft suffered structural damage and seven passengers were injured.

The heavy side gust from the left suggests a wind shear with a strong horizontal component. This pattern of heavy shear followed by a short patch of severe turbulence, followed by smooth air, then by less severe turbulence is remarkably similar to that which the Canberra would have experienced had it been flying in the reverse direction.

A.3 Incident to Comet 2 on 3 January 1964 over Italy

As a final example a report of an incident follows which occurred when a RAF Mk.2 Comet was on transit from UK to El Adem over Italy at an altitude of 37000 ft. The wind was 020^{o} 86 kn and there was no forecast of clear air turbulence. Suddenly the aircraft experienced severe turbulence. Flying on autopilot, without warning a violent positive acceleration was felt followed by a period of severe turbulence lasting about 3 seconds (700 m). Speed was reduced by which time the aircraft was in smooth air. However, one minute later a further period of clear air turbulence was encountered. The aircraft suffered Category III damage (structural damage repairable on site).

In this case the wind shear was felt as a 'violent positive acceleration' prior to the turbulence. Again the same pattern of alternating smooth air and turbulence is apparent as in the Canberra incident; it can be summarised in the following sequence:

(i) extensive smooth air
(ii) an abrupt shear in airflow leading immediately into:-
(iii) a small patch of severe turbulence
(iv) a short interval of smooth air
(v) a further patch of less intense turbulence.

The pattern may of course be encountered in the reverse order and all elements may not be present. Further investigation reveals an orientation with respect to the general wind direction such that the abrupt shear lies on the upwind side of the patch of turbulence. This orientation holds for both the Boeing incidents and for the Canberra incident. The heading of the Comet at the time of the incident over Italy is not known but if it was overflying Malta on the usual RAF track to El Adem, the wind would have had a tail component so that the orientation would hold for the Comet too. In all these cases the wind was strong - of the order of 80 kn, although not unduly strong for these altitudes. Of the three less severe instances of shear-bounded turbulence encountered by the Canberra, that on the same day as the main incident has the sharper shear on the upwind side of the turbulence. Winds for the other two cases were light and variable so that the orientation cannot be checked. In these three instances the shear tends to appear on both boundaries but is sharper on one.

The similarity in the general pattern of the air motions in the three incidents reported above to that in the Canberra incident suggests that they are all examples of the same phenomenon. There is no direct evidence, however, of the presence of systems of vortex rolls in the three reported incidents. In the case of the two Boeing aircraft, both reports speak of violent shaking, in one case it is described in terms of a bulldog shaking the nose of the aircraft. Analysis of the Canberra records shows a tendency for several load reversals to occur on each side of the primary vortices, attributable to contra-rotating vortices (see Fig.5), and this could account for the above rather unusual description. On the other hand it may simply be that response in lightly damped structural modes is responsible for the particular effect of shaking experienced in this type of aircraft.

The point as to whether the same phenomenon is involved in the three incidents reported above as in the Canberra incident has been stressed since it has a bearing on the generality of the findings. Wave conditions are more frequently met and less easily avoided than storm heads and the three reported incidents are either associated directly, or likely to be associated, with wave. In this context it is relevant to note that the Canberra incident itself was attributed, prior to the finding of traces of vortex rolls in the records, to deflection of the wind over the barrier formed by a line of storms, a very wavelike situation[8].

Table 1

CONVERSION FACTORS AND RELEVANT DATA

	Imperial	Metric
ICAN height	45830 ft	13970 m
Mach number	0.76	-
True airspeed	421 kn	780 km/h
All-up-weight	37500 lb	17000 kg
Span	64 ft	19.51 m
Mean chord	15 ft	4.57 m
Gross wing area	960 ft^2	89.19 m^2
Slope of lift curve, $\frac{dC_L}{d\alpha}$, relevant to height	4.4 per radian	4.4 per radian
Duration of patch*	64 seconds	64 seconds
Extent of patch along flight path*	7.5 n miles	13.9 km

* Includes region of shear on boundary

Method of derivation	Conversion factors			
	ft/s (equivalent)/g	m/s (equivalent)/g	ft/s (true)/g	m/s (true)/g
Zbrozek[26]	26.3	8.02	61.0	18.58
Kaynes[27]	43.7	13.33	101.3	30.9

Table 2

EXCEEDANCES OF NORMAL CG ACCELERATION IN PATCH OF TURBULENCE 27 MAY 1965

	Acceleration increments - g																					Fall-back between repeat counts at any one level
	-1.2	-1.1	-1.0	-0.9	-0.8	-0.7	-0.6	-0.5	-0.4	-0.3	-0.2	-0.1	Zero crossings	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	
Number of exceedances	1	2	2	2	2	6	7	9	16	24	33	47	76	52	37	29	21	13	11	7	4	2	Return to zero
	1	2	2	2	2	6	7	10	19	28	43	59	76	56	42	34	25	15	12	7	4	2	½ level

Table 3

LIST OF GUSTS EXCEEDING ±35 ft/s (±10.7 m/s) (TRUE) IN PATCH OF TURBULENCE 27 MAY 1965

Time from start of Fig.2 s	Magnitude of gust peak velocity			Whether peak occurs in region postulated as a vortex roll
	U_g ft/s (m/s)	V_g ft/s (m/s)	W_g ft/s (m/s)	
8.75		-39.5 (-12.0)		No
9.5			40.8 (12.4)	No
13.65			60.4 (18.4)	Yes - vortex 1 of system 1
13.7	57.7 (17.6)	44.2 (13.5)		
13.9			-41.5 (-12.6)	
21.0	41.6 (12.7)			Yes - vortex 2 of system 1
21.6			-36.0 (11.0)	
21.9	35.4 (10.8)			
35.35			44.1 (13.4)	Yes - vortex 4 of system 1
36.65	46.9 (14.3)			
37.4			-43.3 (13.2)	
39.25	-42.9 (-13.1)			No
42.0			51.3 (15.6)	Yes - vortex 5 of system 1
42.6	55.1 (16.8)			
43.75			-39.9 (12.2)	
43.7		-35.1 (-10.7)		Yes - vortex 2 of system 2
44.0		37.2 (11.3)		
45.35	-35.7 (-10.9)			No
48.45		-39.2 (11.9)		Yes - vortex 3 of system 2
49.15	37.9 (11.6)			
49.75		40.6 (12.4)		
52.15		39.9 (12.2)		No - edge of turbulence
Total	8	7	8	
Total in vortex rolls	6	5	7	

Gust velocity (true) ft/s	35	40	45	50	55	60
Number of exceedances	23	13	5	4	3	1
Proportion in vortex rolls	78%	85%	100%	100%	100%	100%

NOTE:- Where a cluster of peaks occur, not separated by a zero crossing, only the largest is listed.

Table 4

PRODUCT OF (RMS GUST GRADIENT) × $(\text{GRADIENT DISTANCE})^{\frac{2}{3}}$

Gradient distance d	Product		
	P_u $m^{\frac{2}{3}}/s$	P_v $m^{\frac{2}{3}}/s$	P_w $m^{\frac{2}{3}}/s$
10.8	0.79	0.84	0.92
21.7	0.83	0.90	1.01
32.5	0.83	0.90	1.03
43.4	0.82	0.92	1.07
54.2	0.82	0.92	1.07

For rms values see Figs.9a, b, c

NOTE:- This product is constant if change in gust velocity is proportional to the cube root of the gradient distance.

Table 5

SIMILARITIES IN AIR MOTIONS ADJACENT TO PATCH OF SEVERE CLEAR AIR TURBULENCE FOR FOUR INCIDENTS

Date	Aircraft	Height	Wind	Direction of flight	Characteristics of air motion				
					← upwind of patch →			← downwind →	
					Smooth air	Abrupt shear	Small patch of severe turbulence	Small region of smooth air	Further patch of turbulence
10.1.64	Boeing 707	28000	80 kn westerly	Into wind	Conditions not reported	Yes - terrific bump	Yes	Conditions not reported	Conditions not reported
18.1.64	Boeing 707	27000	85 kn slightly S of W	Down-wind	Conditions not reported	Yes - heavy side gust	Yes - lasted 70 seconds	Yes - 70 seconds	Yes - slightly less severe. Lasted 70 seconds
3.1.64	Comet Mk 2	37000	86 kn NE	Probably a downwind component	Yes - extensive	Yes - violent positive acceleration	Yes lasted 3 seconds	Yes under 1 minute	Yes - severity not reported
27.5.65	Canberra B2	46000	70 kn WSW	Into wind	Yes - extensive	Yes - shear recorded as rapid change in airspeed	Yes - lasted 56 seconds	Yes - 10 seconds	Yes - less severe

SYMBOLS

U_g	component of true incremental velocity of air motion along longitudinal axis of aircraft - head-on gust positive
V_g	component of true incremental velocity of air motion along lateral axis of aircraft - gust from starboard positive
W_g	component of true incremental velocity of air motion along vertical axis of aircraft - up-gust positive
ΔU_g, ΔV_g, ΔW_g	change in value of U_g, V_g, W_g over distance d
d	distance along flight path over which gust gradient is measured
V_A	true airspeed of aircraft
V_W	true windspeed
P_u, P_v, P_w	product of ΔU_g, ΔV_g, ΔW_g and $d^{\frac{2}{3}}$ respectively = quotient of gust gradient and $d^{\frac{1}{3}}$
σ_u, σ_v, σ_w	truncated rms values of U_g, V_g and W_g

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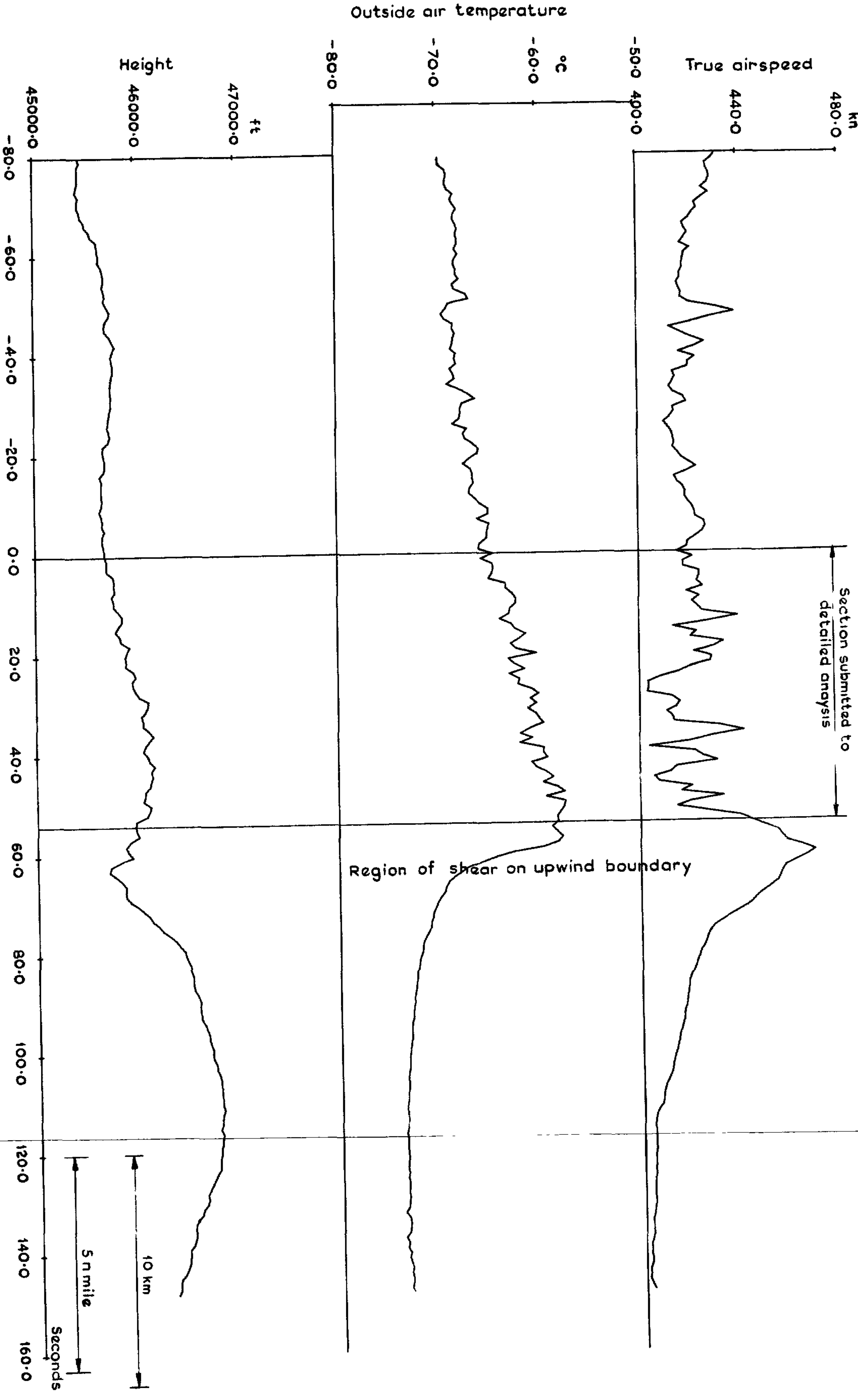

Fig.1 Corrected recordings of airspeed height and temperature patch of turbulence May 27, 1965

Fig.1

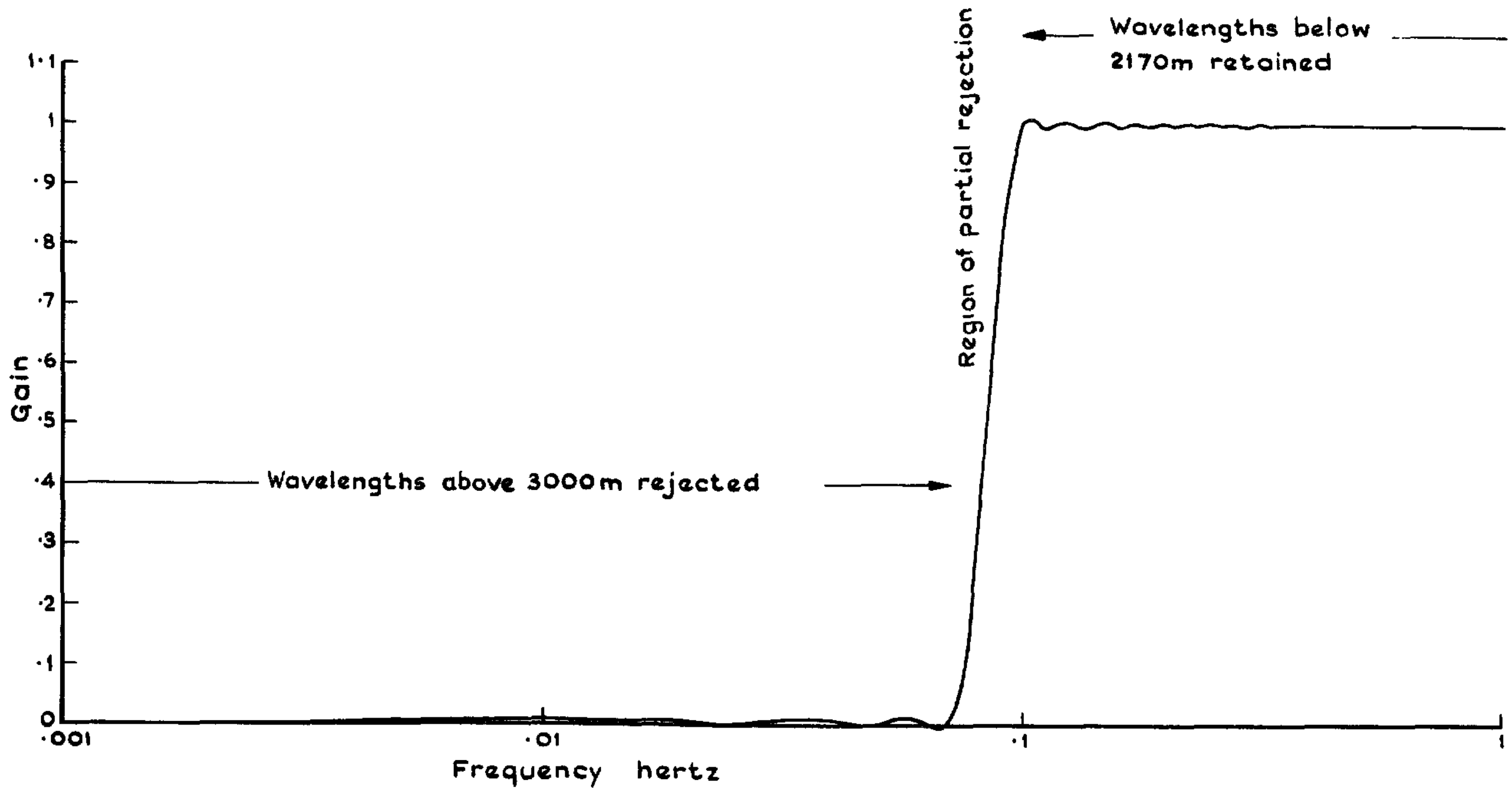

Fig.2 Characteristics of high pass filter used in deriving gust velocities

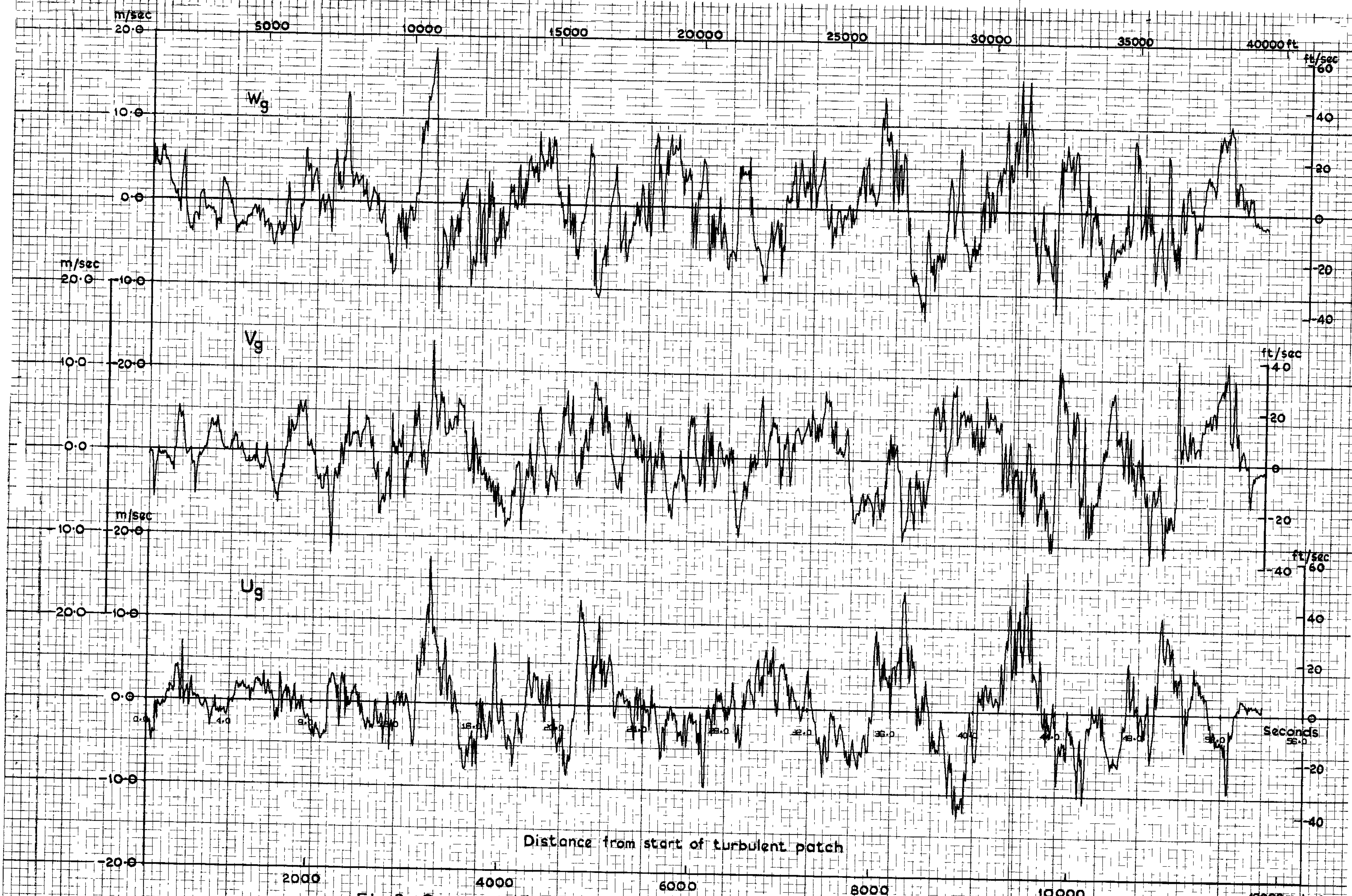

Fig. 3 Gust velocities measured in patch of turbulence May 27, 1965

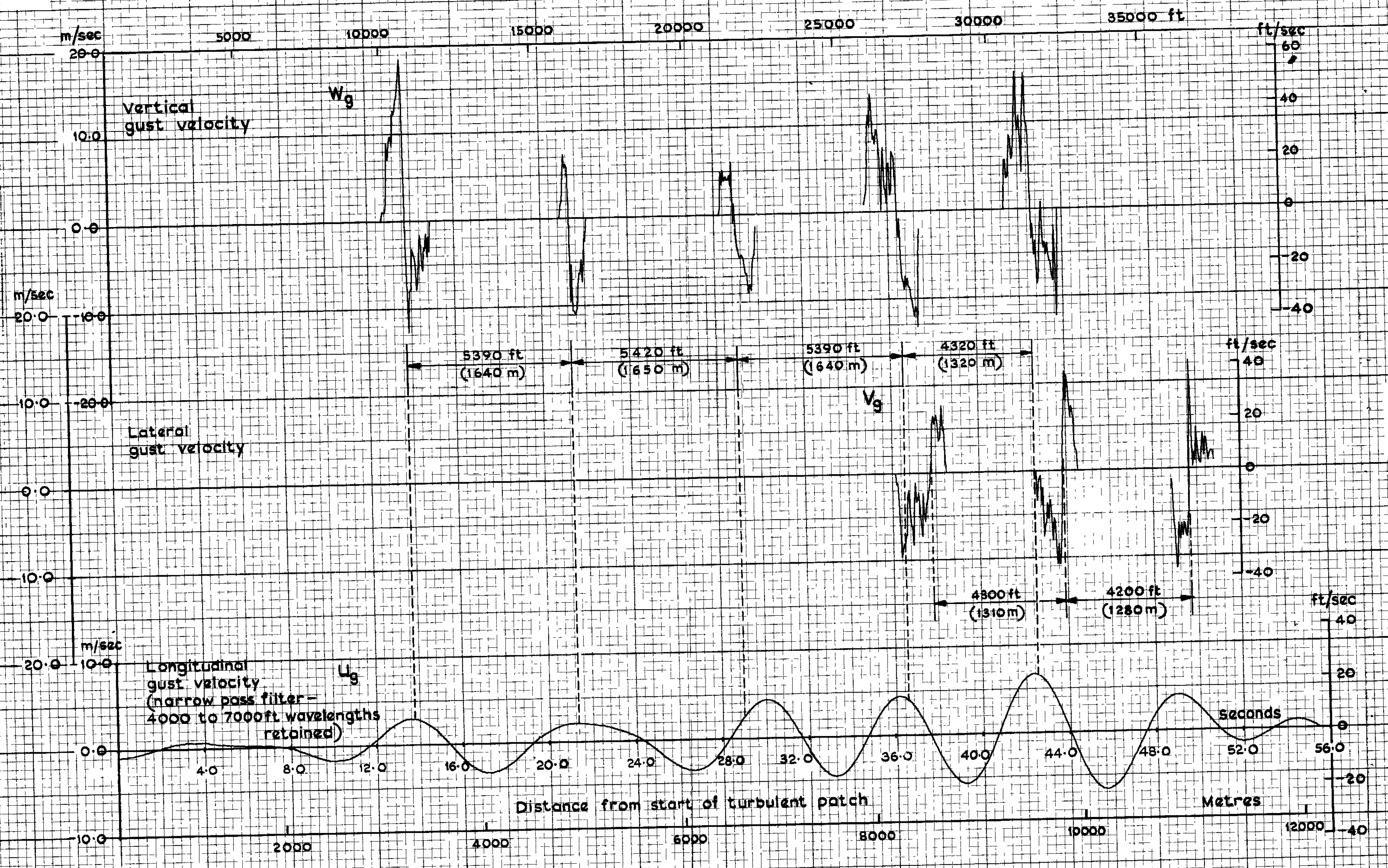

Fig.4 Organised motions in patch of turbulence May 27, 1965

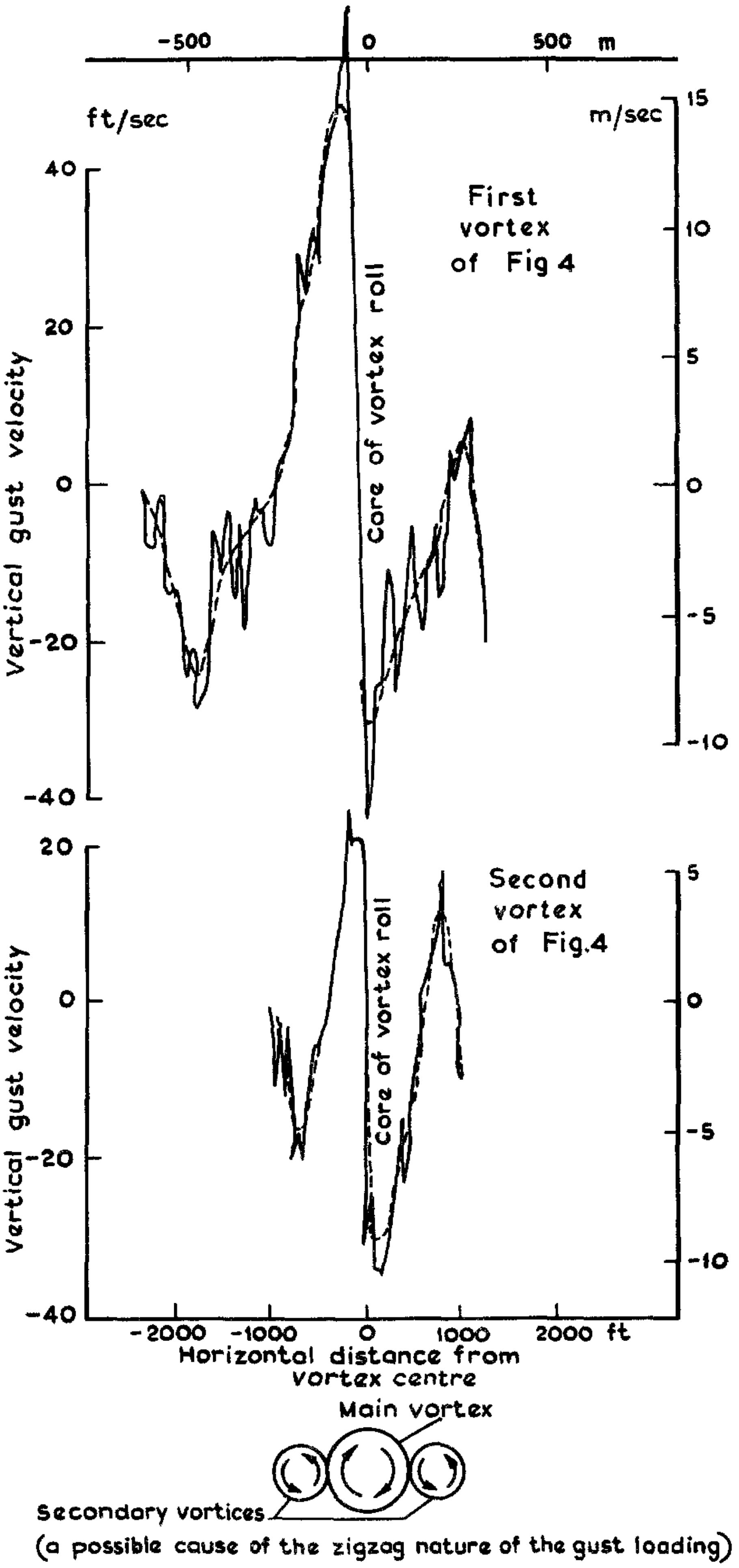

Fig.5 Gusts of alternating sign in the region of the vortex rolls

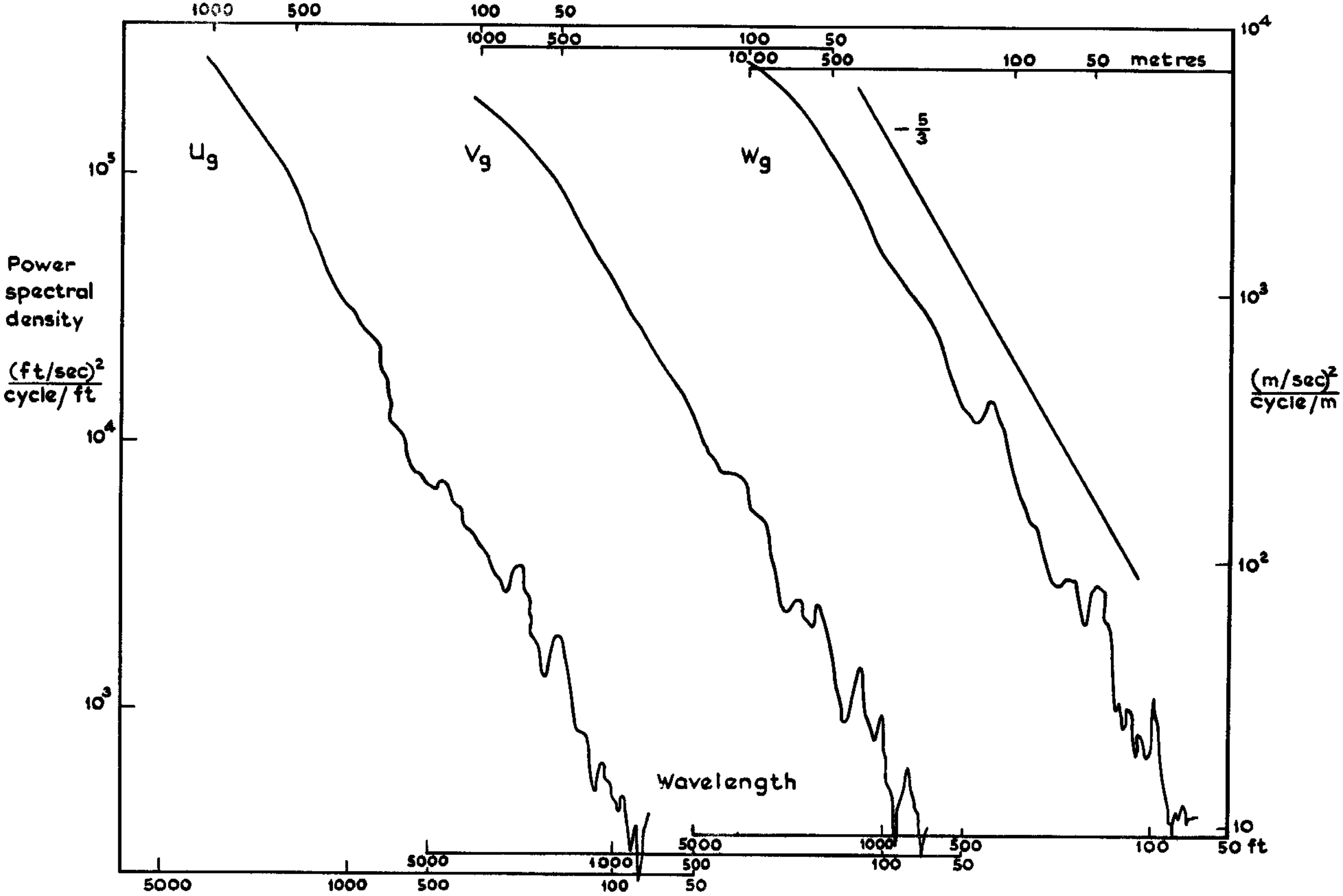

Fig.6 Power spectra of the three components of turbulent velocity in the patch of turbulence May 27, 1965

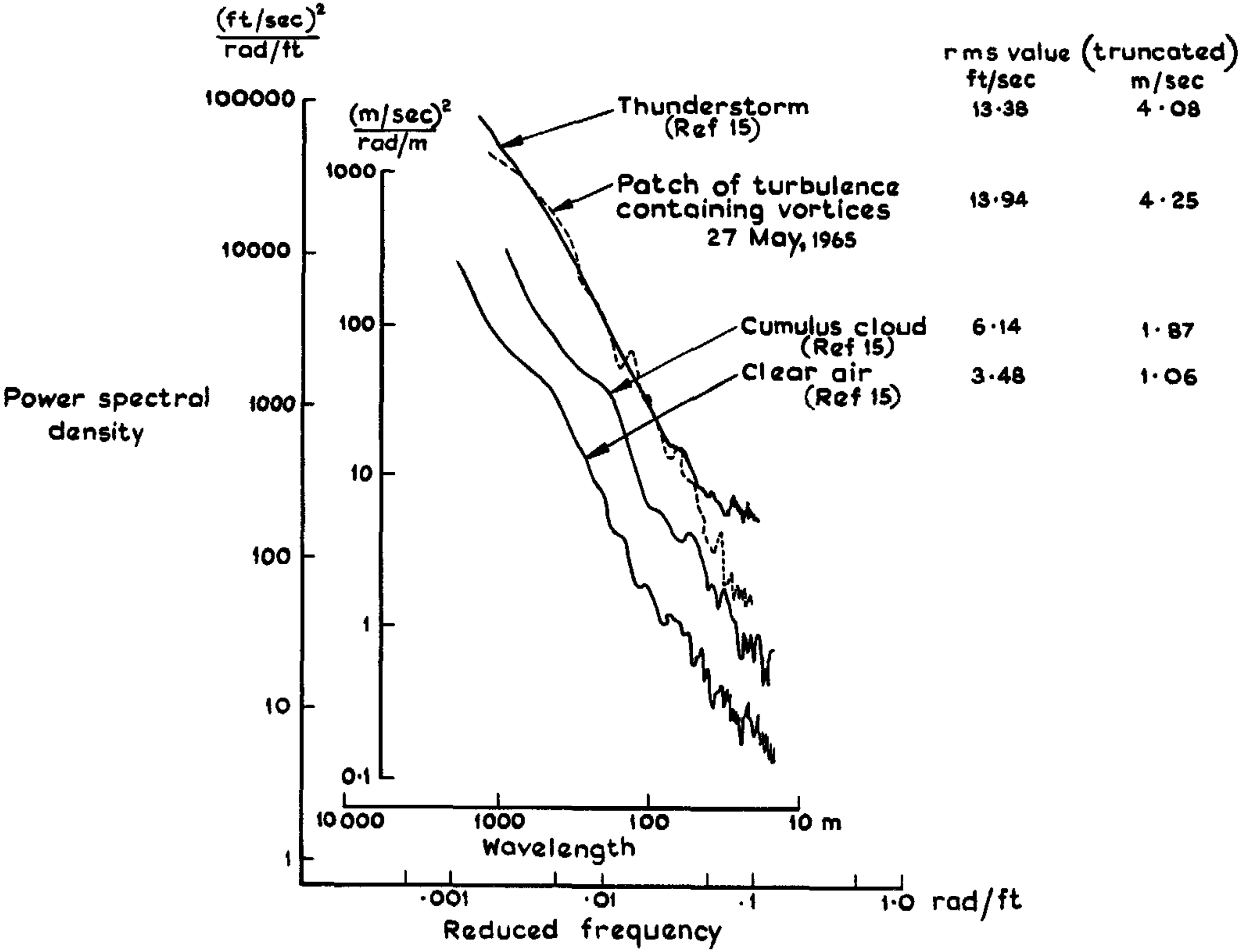

Fig.7 Power spectra of vertical component of turbulent velocity in the patch of turbulence, May, 27 1965, compared with spectra typical of other conditions

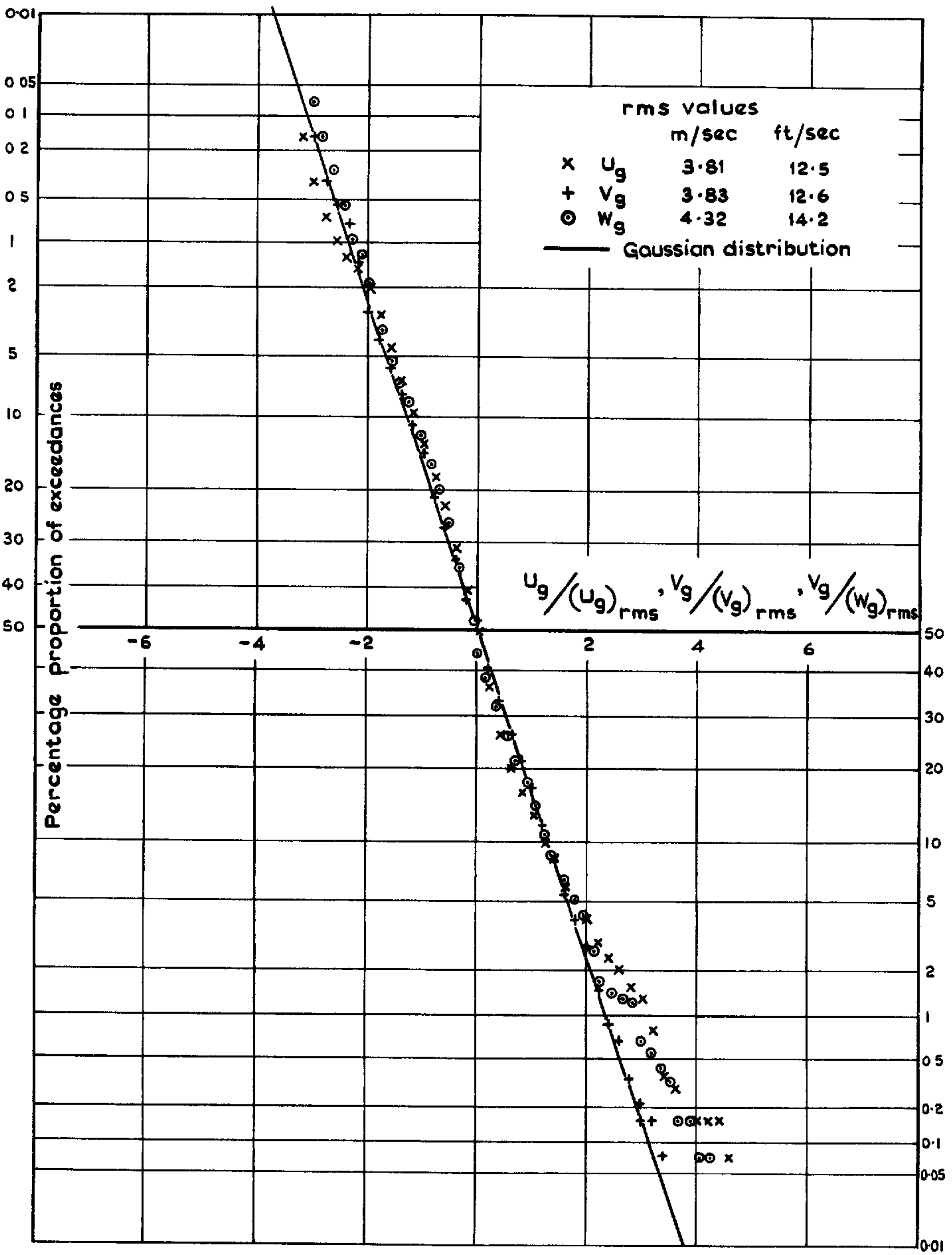

Fig. 8 Probability distributions of U_g, V_g and W_g

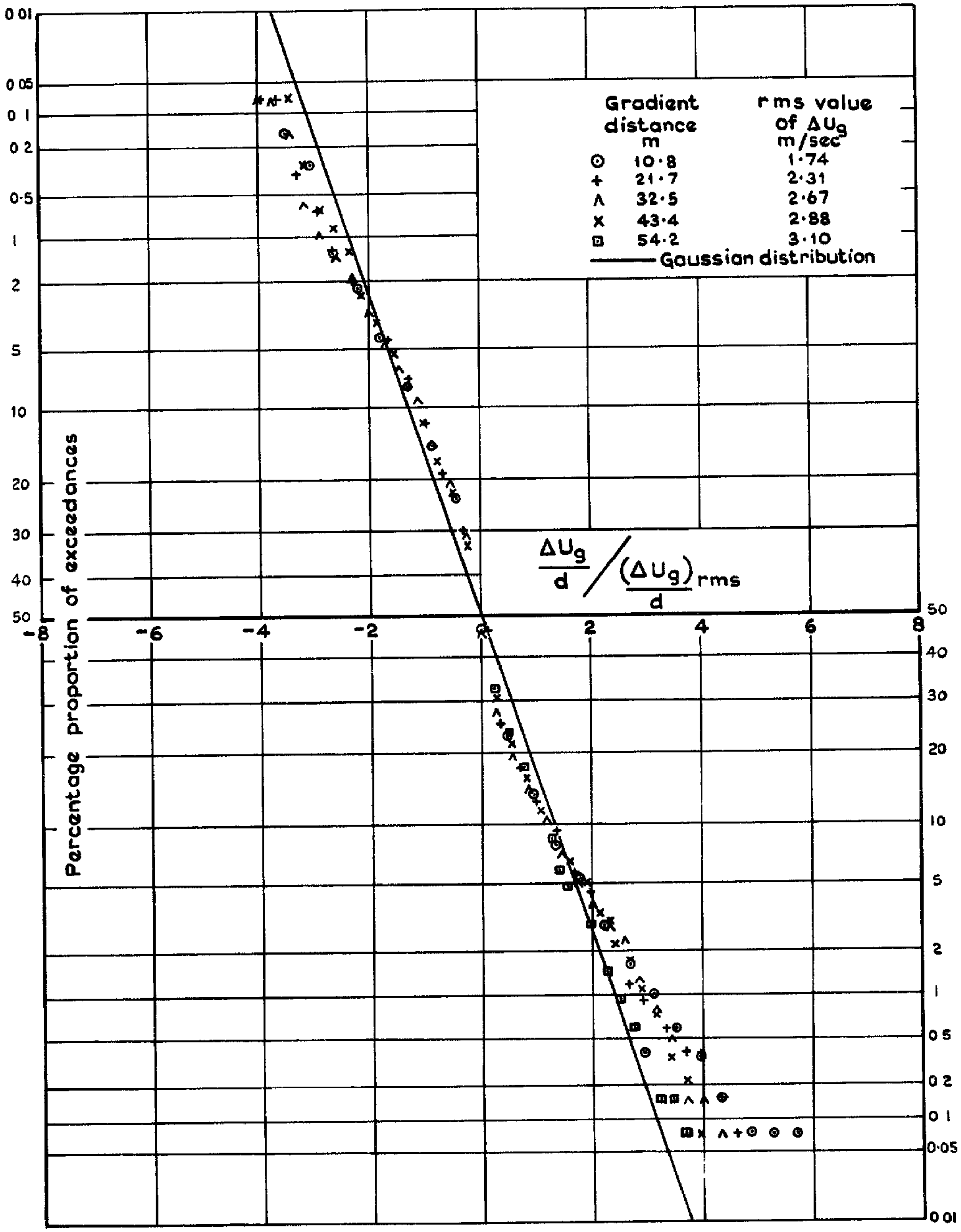

Fig.9a Probability distributions of U_g gradients

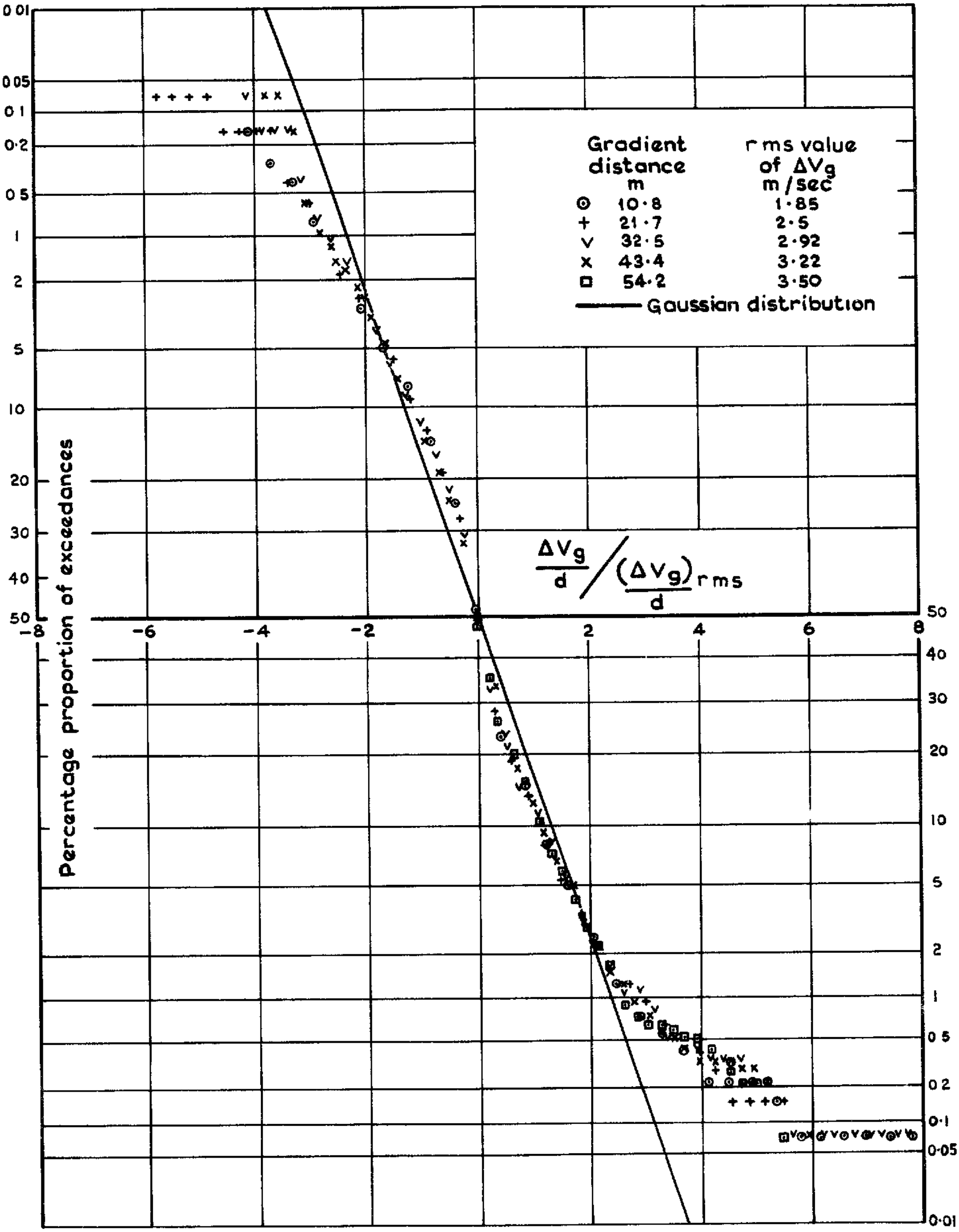

Fig.9b Probability distributions of V_g gradients

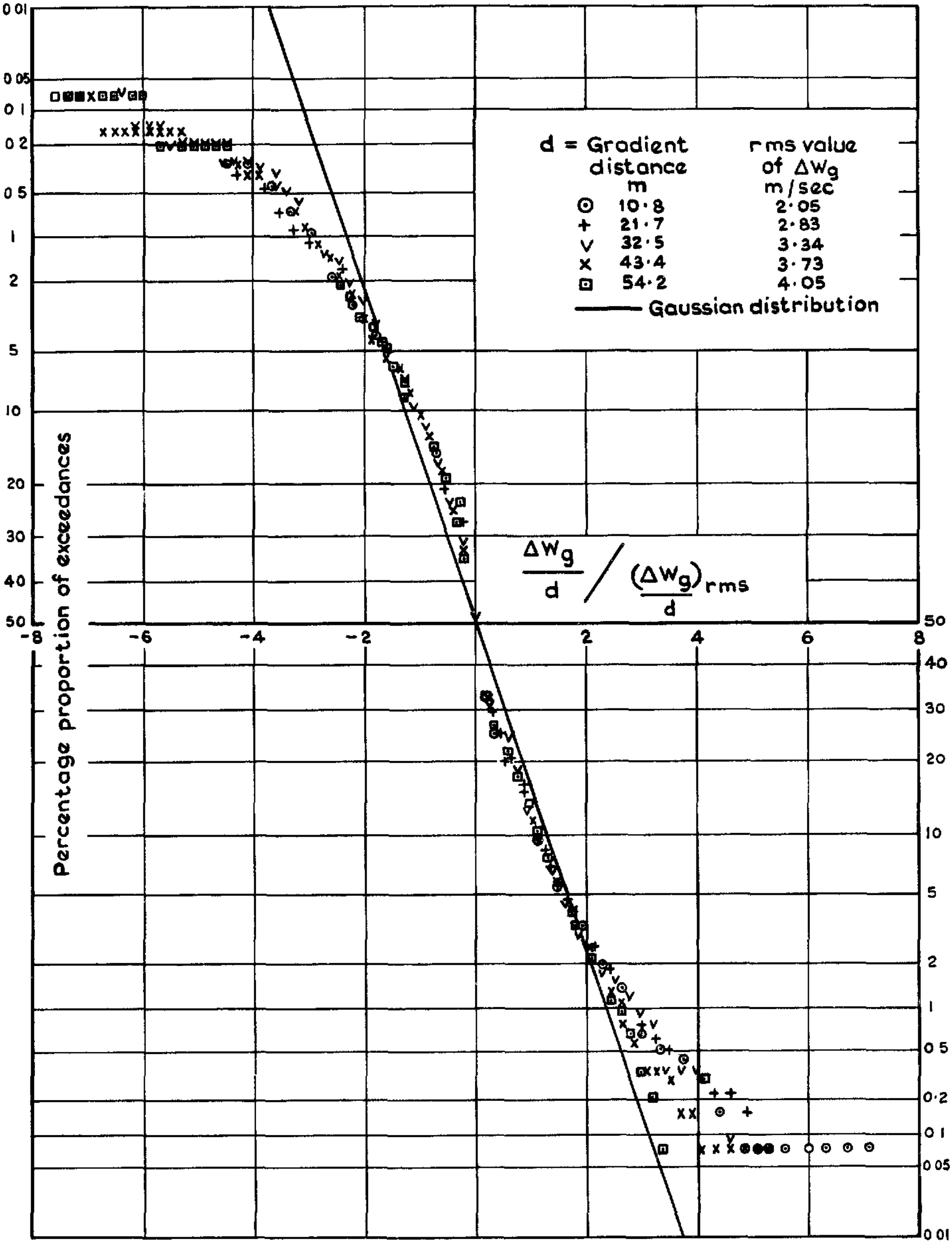

Fig.9c Probability distributions of W_g gradients

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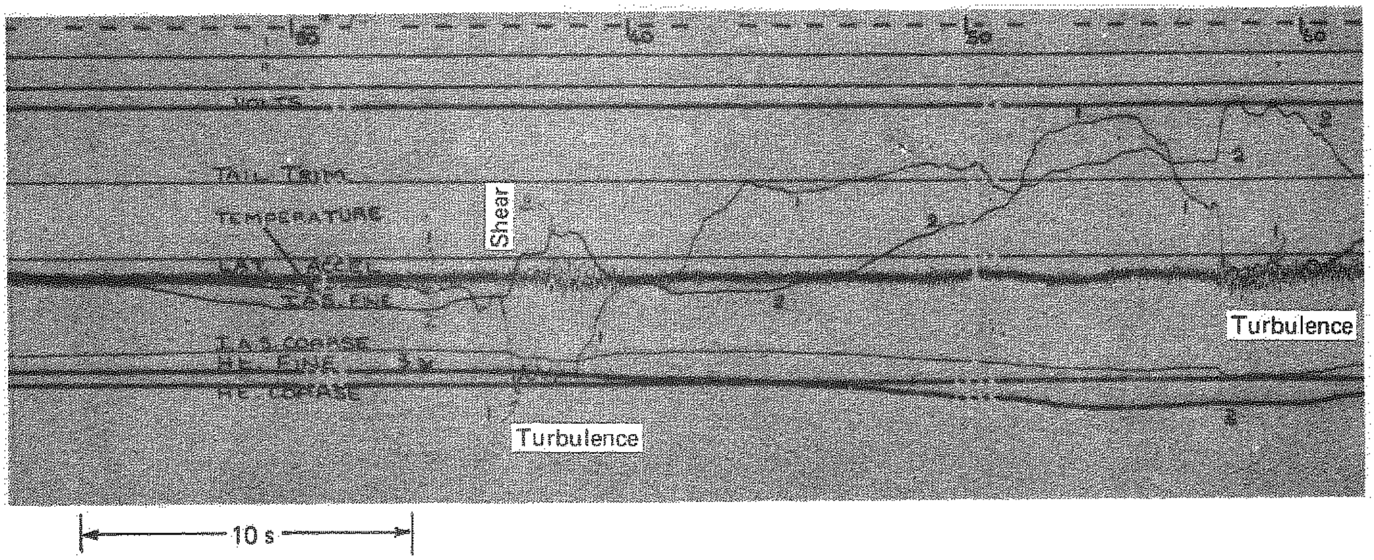

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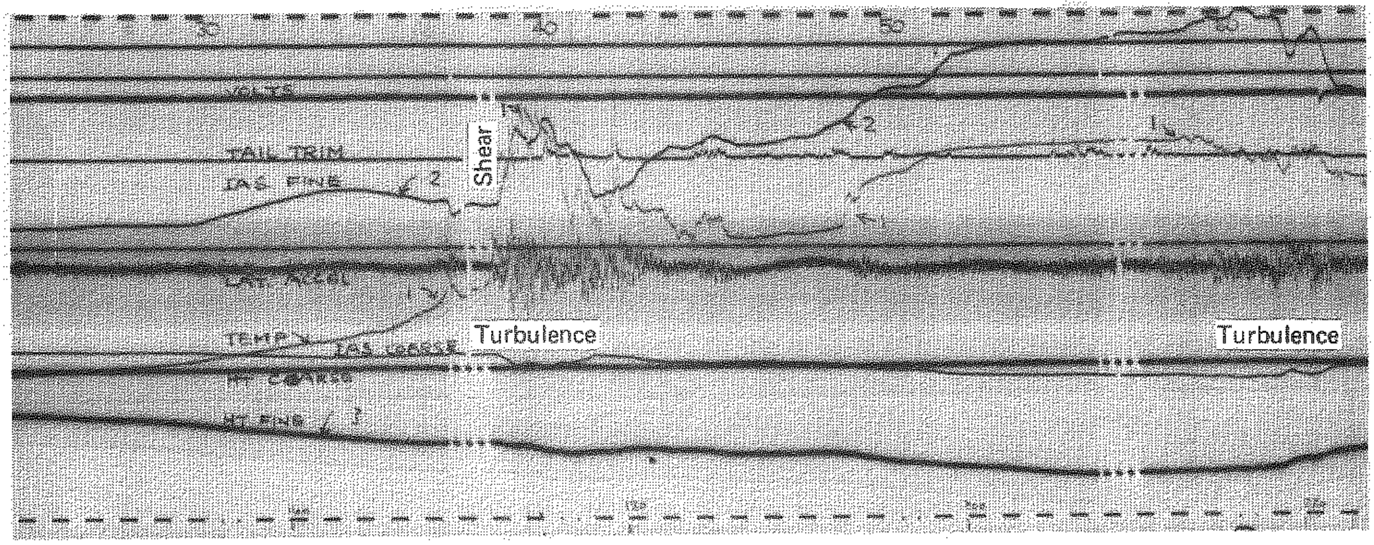

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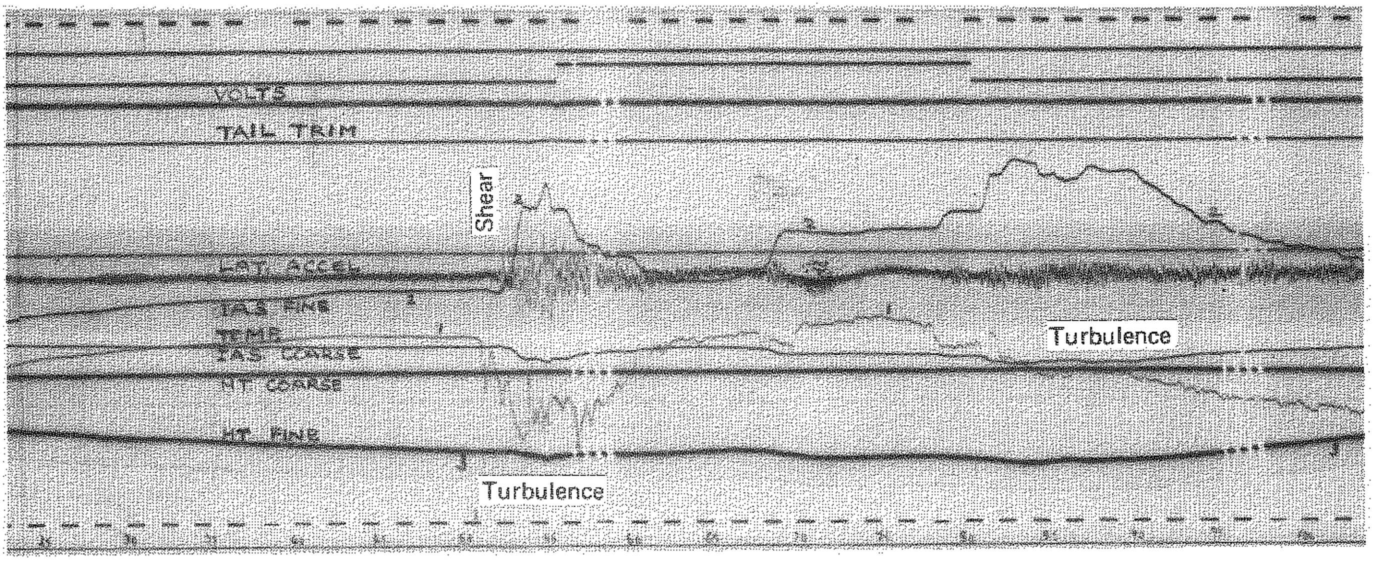

Fig.10 Three instances of small patches of clear air turbulence bounded by wind shear (Oklahoma 1965)

Note: Shear denoted by rapid change in airspeed (Trace 2) and temperature (Trace 1)

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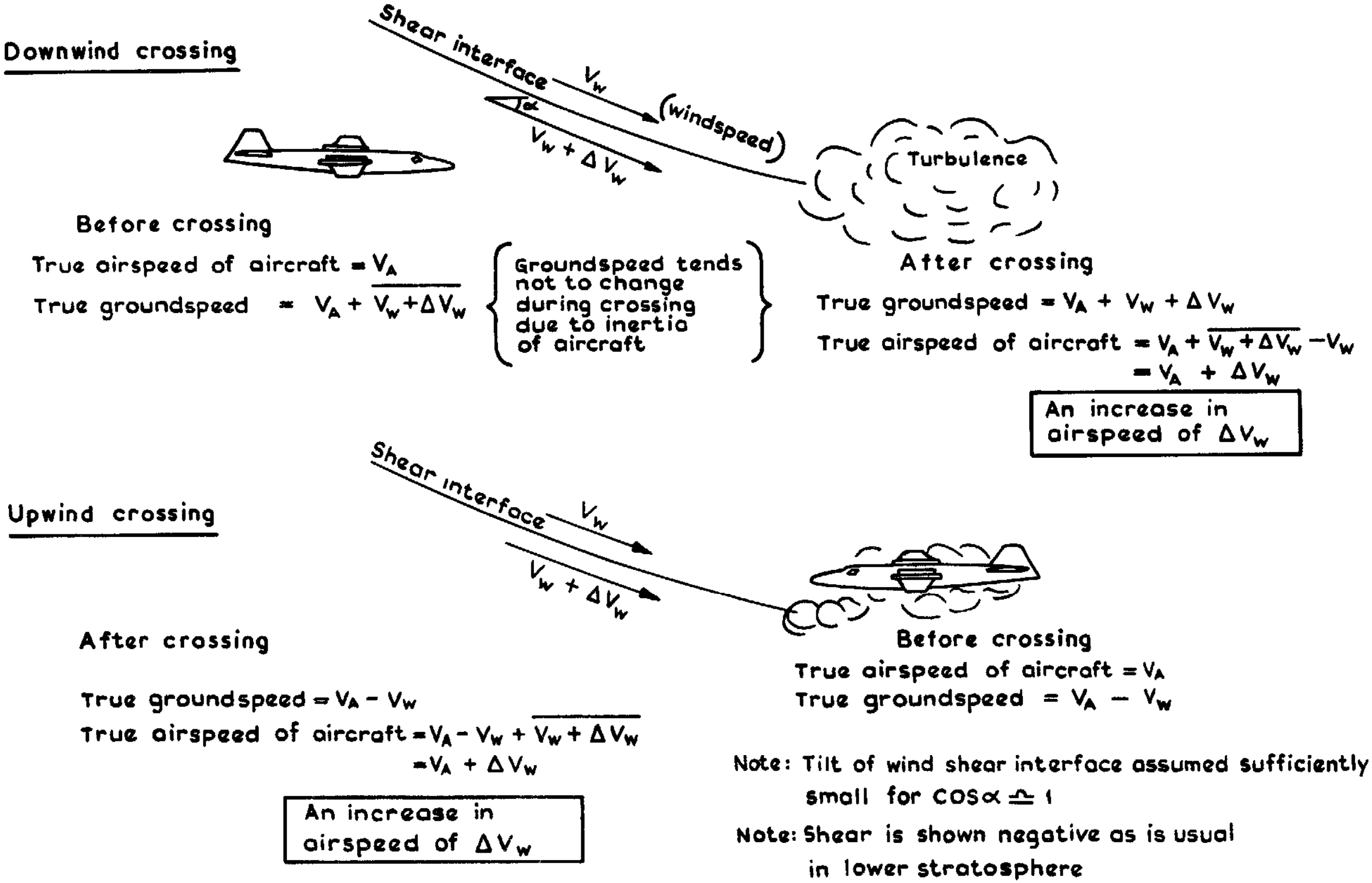

Fig.11 Diagram illustrating that the change of airspeed experienced by an aircraft crossing a tilted shear interface is independent of the direction of crossing

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