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Results of a Flight Investigation on clear air Turbulence at low altitude using a Meteor Mk: 7 Aircraft

By

Flt. Lt. R.M.Allan, R.N.Z.A.F.

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Results of a flight investigation on clear air turbulence at low altitude using a Meteor Mk.7 aircraft

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Flt. Lt. R. M. Allan, R.N.Z.A.F.

SUMMARY

Low level runs were made over a given route at heights below 1000 feet above ground and at an airspeed of 400 knots. A distance of 6080 nautical miles was covered and the accelerations due to gusts were recorded by a continuous trace accelerometer. The results of all the runs showed that, on the average a 1g gust or greater occurred every 7.06 minutes. Comparison with other information on this subject showed that the results from this investigation fitted in with existing data.

There were considerably more positive than negative gusts, the factor being 10 at 1.2g or greater. It would appear that for the area in which the flights were made, turbulence near the ground is not isotropic.

A consideration of meteorological factors showed that on this route wind is far more powerful in producing turbulence at low altitude than the effect of sun.

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1 Introduction

Although most high speed flying takes place at altitudes in excess of 5000 feet, certain types of military aircraft may be forced by the nature of their operational requirements to fly at speeds in excess of 400 knots and at altitudes of less than 1000 feet. Two examples of such aircraft are the ground attack type, and the fighter which may be required to fly fast at low altitude as a means of evasion.

It has long been recognized by pilots that flying below 1000 feet may involve considerable discomfort due to turbulence. At high indicated airspeeds the accelerations due to gusts may be much more than merely uncomfortable and may lead to serious fatigue loads on the aircraft structure. Another aspect of prolonged flight in bumpy conditions is the effect of accelerations applied at several cycles per second on the human body.

To provide some information on gust distribution at altitudes of less than 1000 feet, flights were made with a Meteor Mk.7 aircraft at 400 knots over a fixed route during which a continuous trace of acceleration against time was recorded. It was hoped to show from the data obtained, the variation of occurrence of gusts with severity and also from the accelerometer trace to find the order of the gradient distances of the gusts encountered.

2 Flight Procedure

The aircraft used was a Meteor Mk.7 equipped with wing and ventral auxiliary fuel tanks to give improved endurance at sea level. All flights were made over the same route, namely Lasham to Lyme Regis and return. This route was not decided with any particular regard to the land contour but was more or less dictated from the point of view of available low flying areas. The speed for the runs was 400 knots and this was chosen as being the highest speed consistent with the limitation of 435 knots imposed on the aircraft by the external wing tanks.

At the start of the outward run Lasham airfield was crossed at some height between 200 and 500 feet and at a stabilized airspeed of 400 knots. During the course of the programme flights were made at various altitudes from 50 to 1000 feet above ground level and for any particular flight the pilot was briefed to maintain approximately a selected height. Figure 1 shows the land contour cross-section between Lasham and Lyme Regis. To minimize the effect of pilot applied acceleration, pilots were asked to employ gentle elevator movement to avoid obstacles such as hills, and once over not to attempt to descend rapidly to regain correct height.

The coast was crossed at Lyme Regis and the return run was made over the same course after a 180° turn. Each flight of 2 runs lasted about 40 minutes although only 24 minutes was spent on the low level runs. A total of 50 flights were made resulting in 15 hours 11.75 minutes of recording.

Measurement of acceleration was accomplished using a modified Barnes type accelerometer which was mounted between the rudder pedals in the rear cockpit, at a distance of 5.35 feet forward of the C.G. The accelerometer gave a continuous trace on 35 mm film with timing marks every 0.5 second. This accelerometer has a natural frequency of 10 cycles per second at 0.65 critical damping. Some typical records are shown in Fig.2.

For each flight a note was made of local weather conditions including wind strength, amount of cloud cover, and visibility.

3 Results

The film from the accelerometer (examples of which are shown in Fig.2) was read by counting the number of acceleration peaks greater than ±0.3g excess, in steps of 0.1g. When peaks occurred in rapid succession, they were only counted if the trace crossed a 0.1g threshold between the peaks. The result of these counts made of all films is shown in Table I where the first line is the total of all acceleration peaks, positive and negative, experienced in the 15 hrs 11.75 mins of recording. The next line of figures in the table gives the number of peaks, hereafter called gusts, equal to or greater than a given value of excess acceleration and follows from the previous line. The last line gives the average time in minutes between the occurrence of a gust of given magnitude or greater and is derived from line 2 combined with a knowledge of the total recording time of the accelerometer (911.75 minutes).

Table II shows the number of positive and negative loads in the total shown in line 1 of Table I.

The variation of severity of gust (in terms of aircraft acceleration) with the average time of occurrence (minutes per gust) is shown graphically in Fig.3. One gust of +2.6g was encountered and has been plotted but is obviously not statistically representative.

In this treatment the gust severity is given in terms of the vertical acceleration imposed on the Meteor aircraft because this is how it was measured but a more general method of presentation would have been to deduce gust strengths in ft/sec. The conversion can be made by using the following well known equation but there is some doubt concerning the value of K which should be used and this is particularly so at the high speeds at which the Meteor flights were made.

$$\Delta n = \frac{K\, s_o\, U_e\, V_i\, a}{2w_s} \qquad (1)$$

where Δn = acceleration in units of 'g'

s_o = air density at sea level

V_i = indicated airspeed

U_e = equivalent gust velocity, E.A.S.

a = wing lift curve slope, $\frac{\partial C_L}{\partial \alpha}$

w_s = wing loading

K = alleviation factor.

For the Meteor 7 with loadings as detailed in section 2

s_o = 0.00238 slugs/cu ft

V_i = 675 ft/sec (400 knots)

a = 4.15

w_s = 47 lb/sq ft for a mean A.U.W. of 16,500 lb

K = 0.83 (from Ref.3).

This gives 1g ≑ 20.3 ft/sec.

3.1 Comparison with other results

The majority of available statistical information on the occurrence of gusts is in the form of gust velocity in relation to miles or minutes per gust. An example of this presentation is shown in Fig.4 and is the result of recent work by J. Taylor[1] in which statistical records were taken on a Viking flying over S. England. The low altitude curve of Fig.4 has been recast by the use of equation 1 to apply to the Meteor and is shown in Fig.3 by a dotted line. The third curve on this figure is the results of directly comparable flight tests on an F80A aircraft at altitudes of less than 1500 feet and a speed of 400 knots[3].

4 Comments on Results

The route over which all measurements were made was from Lasham airfield to Lyme Regis, as mentioned in section 2. Several records of altimeter readings were taken during the flight programme, using an auto-observer with a camera photographing at 10 second intervals. It was hoped to give several such flight paths in Fig.1 to show to within what limits a constant height above ground could be maintained. However, it was found that, for runs made below 300 feet the altimeter records could not be fitted on to the contour cross-section. This was thought to be due to the aircraft being slightly off track at times. It was noticed that pilots tended to go round, rather than over isolated obstructions such as hill peaks. There is accordingly only one flight path shown in Fig.1 which was taken during a run made nominally at 500 feet above ground.

4.1 Gust distribution

The results for all flights made are included in Tables I and II, and are shown graphically in Fig.3. Flights were made whenever the aircraft was available and the visibility was adequate for low level high speed flying. No attempt was made to either encounter or avoid turbulent conditions. The aim was to obtain an average set of figures for accelerations due to gusts covering a period of 12 months.

The results, shown in Fig.3 are compared with some flight tests by J. Taylor[1] using a Viking aircraft. The altitude band covered during this programme was 0 - 2,500 feet and the accelerations were measured by a counting accelerometer. These accelerations were then converted to gust velocities using the appropriate alleviation factor from AP 970 (see section 3.1). The results of this work as shown in Fig.4 are suitably factored in Fig.3 to represent the Meteor at 400 knots, using a value for alleviation factor given in ref.2. It is seen that the curve for the Viking results which is based on 6,000 statute miles of flight in the altitude band, lies to the left of the Meteor curve, that is to say that the Meteor results show a greater frequency of occurrence for a given gust. This seems reasonable, since if the transformation of the results obtained on one aircraft to the other is reliable, the altitude band for the Meteor is much smaller and closer to the ground where larger gusts might be expected.

Also shown in Fig.3 are the results from flight tests on an F80A aircraft[3] which were conducted under similar conditions to the Meteor tests. The speed was 400 knots and the similarity between the two aircraft $\left(\text{e.g. } \mu_{g_{(Meteor)}} = \mu_{g_{(F80A)}}\right)$ makes the results directly comparable. However, the distance flown was only 420 statute miles so that statistically, the sample is not very significant. In the early stages of the Meteor programme, the results lined up exactly with the F80A curve but as more flights were made, and the sample became larger and more representative the Meteor curve moved to the left of the F80A curve. A significant point is that the slope of each of the three curves is approximately the same. This would seem to provide some confirmation of the method used to transform the Viking results.

The height of each run was of course noted but as conditions were never the same it was not possible to show if there was any variation in severity of gusts with altitude, irrespective of wind speed and amount of sun. However, it did seem to both the pilot and observer that the most severe turbulence was always encountered between 300 and 500 feet above ground.

4.2 Distribution of positive and negative gusts

The total number of positive and negative gusts counted during the analysis of the accelerometer film is given in Table II. The totals of positive and negative gusts of 0.3g or greater were averaged and the frequency of occurrence, relative to that of an average gust of 0.3g or greater was then found for gusts of given magnitudes or greater, positive and negative. These figures are given in Table II and shown graphically in Fig.5.

The results show that in turbulence near the ground there were appreciably more positive loads applied to the aircraft than negative loads. The ratios of positive to negative loads were 2.3 at 0.4g or greater, 4.5 at 0.8g or greater and 17.9 at 1.2g or greater. It is possible that some of the additional positive loads were applied by the pilot but every effort was made to reduce the pilot applied loads to the minimum and it therefore appears probable that there were rather more positive gusts than negative gusts.

It might be as well to point out at this stage the unlikelihood of horizontal gusts playing any part in this discussion. It can be shown[3] that to realize the same vertical acceleration for the Meteor at ground level and 400 knots a horizontal gust would have to have a magnitude 16.5 times that of a vertical gust. That is to say a vertical gust of 6.1 ft/sec gives 0.3g acceleration and a horizontal gust would have to be 100 ft/sec to give a similar acceleration. Admittedly, the method of estimating these figures is only approximate but it does indicate the order of the effect of horizontal gusts.

4.3 Effect of meteorological conditions on the severity of turbulence

A note was made of weather conditions prevailing at the time of each flight, and an attempt has been made to show the relative importance of the main factors, namely wind and sun on the severity of turbulence encountered. Four combinations of sun and wind were chosen:-

light wind,	sun
" "	weak sun
strong "	sun
" "	weak sun.

After a survey of the notes made on the weather for all the flights, four typical flights in each of the above categories were selected. The average figures in each category for the occurrence of gusts of magnitudes 0.3g and greater were then plotted in terms of gusts of a given magnitude or greater, relative to the occurrence of a 0.3g gust or greater.

This is shown in Fig.6 and it will be seen that the points appropriate to the four conditions lie, to a fair degree of accuracy on two curves. Bearing in mind that four flights or approximately 580 nautical miles is not a large sample statistically, there is still a strong indication that wind speed has a much greater effect on the severity of gusts encountered than does the amount of sun on this particular route.

4.4 Gust gradient distance

Analysis of samples of films selected at random was done to find typical gust gradient distances for gusts of varying severity. There was a tendency for larger gusts to have larger gradient distances but the scatter at a given magnitude was considerable.

Gusts of ±0.5g gave acceleration gradient distances of between $3\frac{1}{2}$ chords (35 feet) and 18 chords (170 feet) and gusts of ±1.0g gave gradient distances between 12 chords (110 feet) and 30 chords (280 feet). In a few cases acceleration peaks of low 'g' values (say less than 0.5g) were repeated for several cycles with a frequency of the order of 7 cycles per second. These were more likely to be due to wing vibration than to gusts (gradient distance for 7 cps is $2\frac{1}{2}$ chords or 24 feet) as the natural frequency of the wing in bending is 7 cycles per second.

It should be noted that the instrument for measuring gust gradient distance is the aircraft itself which has response characteristics, the effect of which is included in the acceleration/time history shown on the trace. The effect of this response is that for the shorter gust gradient distances the measurements made with the accelerometer will show values of the acceleration gradient distance which would correspond to gusts of larger gradient distances than those actually encountered.

5 Pilots' Comments

High speed flying at low altitude is a normal manoeuvre in fighter type aircraft but it was thought useful to quote the impressions of pilots who flew the Meteor on this work as all the flying was done under controlled conditions of speed and height and over the same route.

All agreed that no extreme concentration was required, apart from keeping a good look-out for other low flying aircraft, down to 300 feet above ground. It was also possible to map read down to this height. Below this the concentration on flying required mounted steeply and at 100 feet there was little time available for map reading, which demanded the full-time attention of the observer. The aircraft did not require excessive control movements to maintain course, but to hold a constant height above ground required considerable judgement, particularly when pulling up over hills. Unless due care was exercised the aircraft did not regain correct height until some considerable distance past the obstacle. It was not possible to make changes in heading rapidly, and any substantial change required large angles of bank thereby restricting the pilot's view.

Flying at 50 feet demanded full attention on flying the aircraft and was only undertaken when the visibility was very good. All pilots were conscious of the lack of height and time available to take action following failure of some aircraft component.

Visibility was an important consideration and the most exacting case was that of flying into late afternoon sun, particularly if a slight haze was present. In this case the visibility set a height limit of 300 feet above ground.

After flights made in the summer there were complaints of excessive heating in the cockpit. The disturbing effect of combination of heat and accelerations of ±1g and above at frequent intervals was commented on.

A further hazard was found to be the possibility of collision with birds. On one flight a large bird (thought to be a seagull) was hit by the port wing leading edge and the damage caused was considerable. The impact resulted in a hole 9 inches along the leading edge and about 4 inches wide necessitating the replacement of a nose rib and introduction of a large reinforced patch. On many occasions flocks of birds were passed through as there was practically no time available to avoid them. The possibility of meeting such flocks seemed to extend up to 500 feet above ground. It would seem that at high airspeeds at low altitudes there is a significant danger of a bird hitting the front of the canopy and, at least momentarily, completely obstructing the pilot's view. If an impact occurred near a removable wing or fuselage panel the resulting distortion might cause the panel to fly off leading to further structural failure.

6 Conclusions

(1) From the results of the flight tests during which 6080 nautical miles were covered at 400 knots it was found that, on the average an acceleration of 0.5g or greater occurs every 12 seconds, 1.0g or greater every 7.06 minutes, and 1.5g or greater every 304 minutes.

(2) There was a marked preponderance of positive over negative loads and the factor was 18 at 1.2g or greater.

(3) Wind caused more severe turbulence than sunshine on the route flown over.

(4) Gust gradient distances appeared to be less for gusts of lower values of 'g' but there was a considerable range of gradient distances found at any given value of acceleration. The smallest gust gradient distance measured was $3\frac{1}{2}$ chords. The average gradient distance seemed to be of order of 6 chords or greater.

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No.	Author	Title, etc
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2	J.K. Zbrozek	Gust Alleviation Factor. R & M.2970, August 1953.
3	E.T. Binckley J.L. Armstrong	A Flight Investigation of the Effect of Wing Surface Roughness on Accelerations experienced in Low Level Clear Air Turbulence. USAF Technical Report No. 6587, P34689, May 1951.
4	G.S. Hislop	Clear Air Turbulence over Europe. Journal of the Royal Aeronautical Society, pp.185-225, April 1951.
5	R.S. Scorer	Theory of Waves in the Lee of Mountains. Quarterly Journal of the Royal Meteorological Society, pp. 41-56, January 1949.

TABLE I

Results of Meteor Flights. Recording Time: 911.75 mins.

Excess 'g'	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	2.6
Number of gusts at 400 knots. Positive and negative	10,981	5,726	2,340	1,205	547	290	145	64	27	17	11	8	2	1
Number of gusts of given magnitude or greater	21,364	10,383	4,657	2,317	1,112	565	275	130	66	39	22	11	3	1
Minutes per gust of given magnitude or greater	0.0426	0.0878	0.196	0.394	0.82	1.615	3.32	7.06	14.0	24.0	43.4	91.18	303.9	911.75

TABLE II

Numbers of Positive and Negative Gusts Counted and Frequency of Occurrence Relative to an Average Gust of ±0.3g or Greater

Excess 'g'	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	2.6
Number of positive gusts at 400 knots	6,830	3,744	1,547	903	418	237	112	52	25	16	10	8	2	1
Number of negative gusts at 400 knots	4,151	1,982	793	302	129	53	33	12	2	1	1	0	0	0
Number of positive gusts of a given magnitude or greater	13,905	7,075	3,331	1,784	881	463	226	114	62	37	21	11	3	1
Number of negative gusts of a given magnitude or greater	7,459	3,308	1,326	533	231	102	49	16	4	2	1	0	0	0
Frequency of occurrence of gusts of given magnitude or greater relative to an average 0.3g gust or greater - positive gusts	1.305	0.663	0.312	0.167	0.0825	0.0434	0.0211	0.0104	0.0057	0.0034	0.0019	0.0009	-	-
Frequency of occurrence of gusts of given magnitude or greater relative to an average 0.3 g gust or greater - negative gusts	0.698	0.284	0.124	0.0499	0.0216	0.0096	0.0046	0.0015	0.0004	0.0002	-	-	-	-

NOTE: Average Number of 0.3g gusts or greater = 21,363/2 = 10,681.

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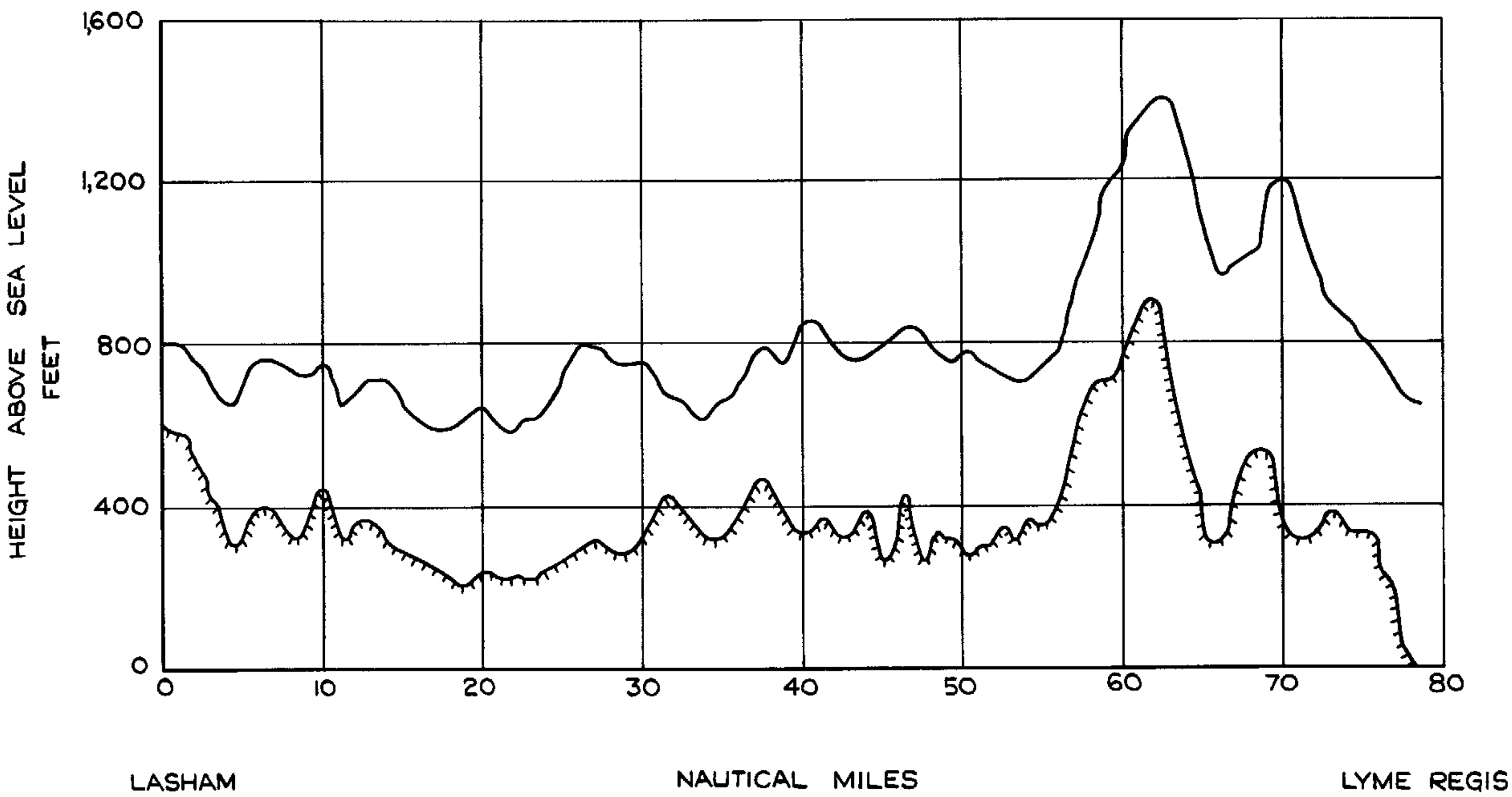

FIG. 1. CROSS - SECTION OF ROUTE LASHAM - LYME REGIS SHOWING TYPICAL FLIGHT PATH (FROM ALTIMETER RECORDS)

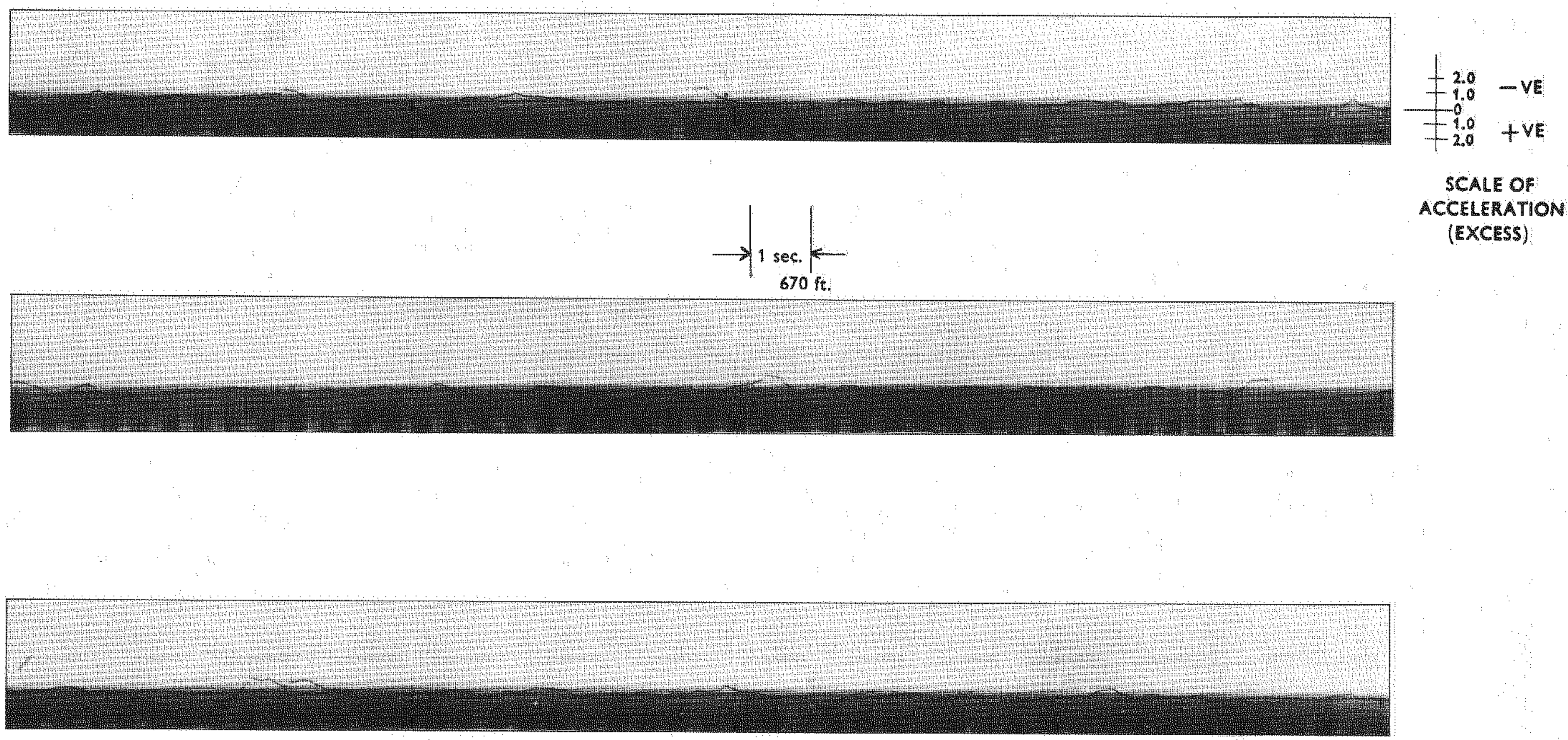

FIG.2. SAMPLE PRINTS OF ACCELEROMETER FILM TAKEN IN FLIGHT THROUGH ROUGH AIR AT LOW ALTITUDE AND AT HIGH SPEED

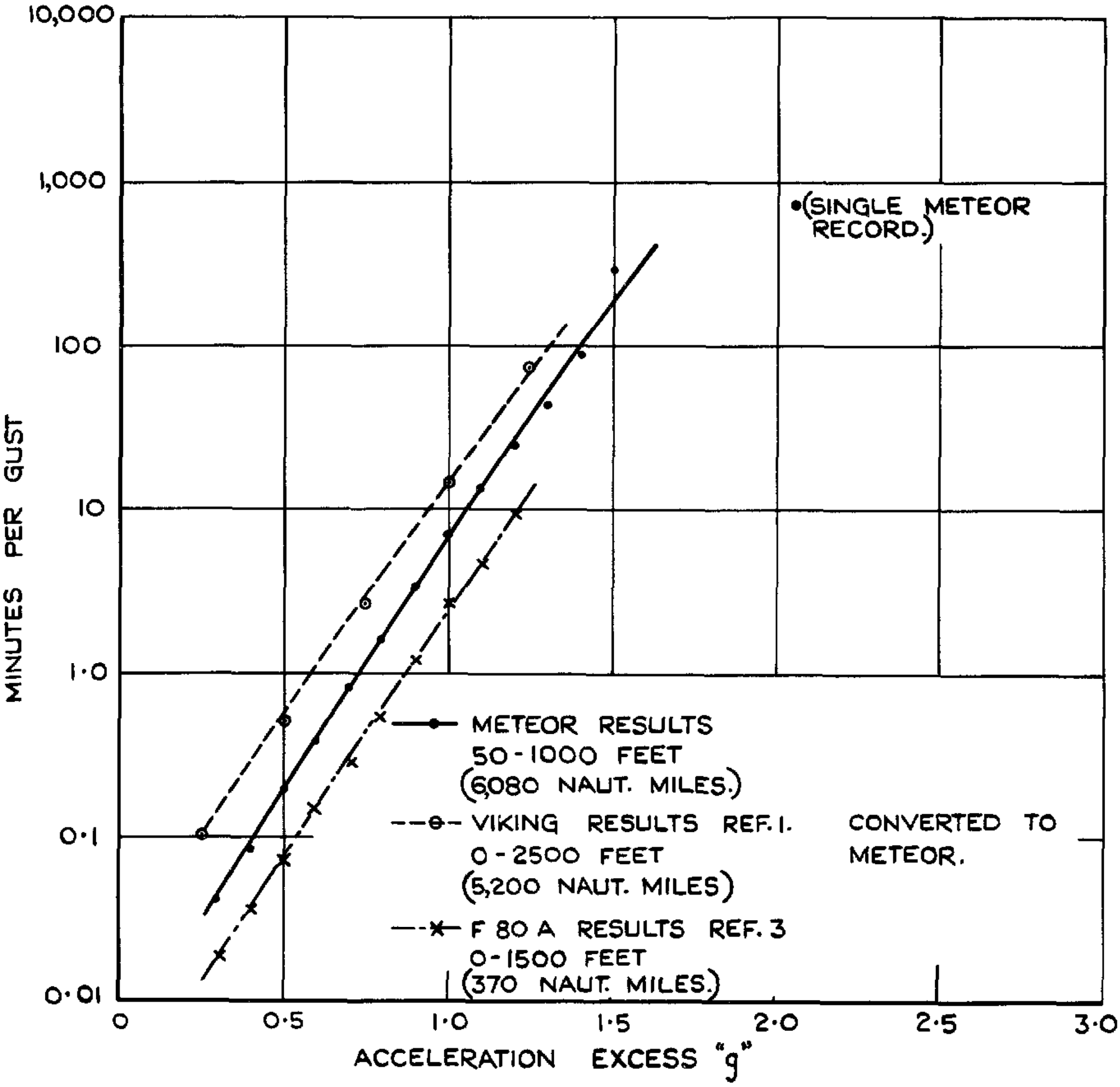

FIG. 3. GUST DISTRIBUTION AT LOW ALTITUDE. IN TERMS OF MINUTES PER GUST OF GIVEN MAGNITUDE OR GREATER FOR METEOR 7 WITH WING & VENTRAL TANKS. AIRSPEED 400 KNOTS.

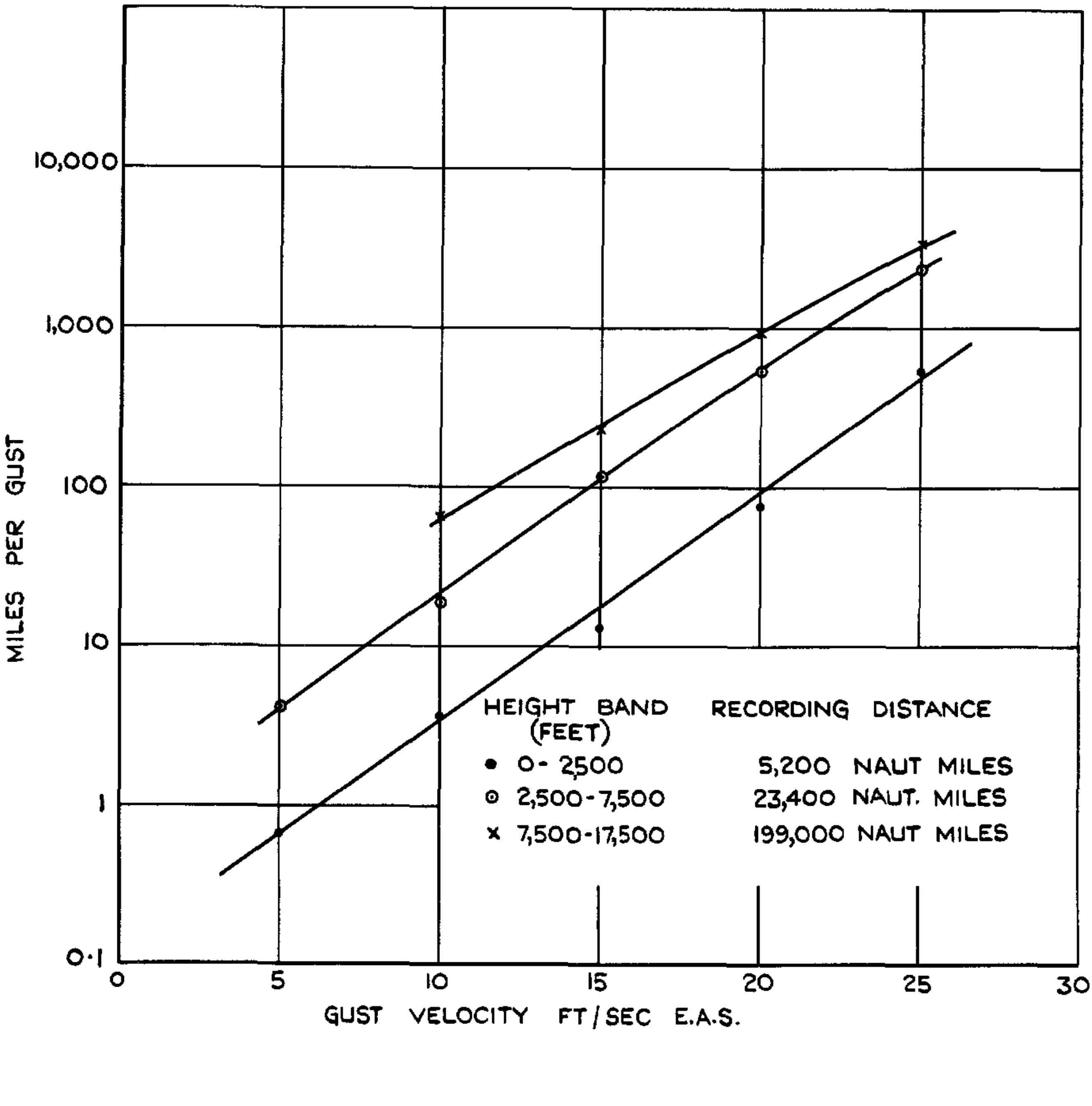

FIG. 4. GUST SPECTRUM AT DIFFERENT HEIGHT BANDS (REF. 1.)
IN TERMS OF MILES PER GUST OF GIVEN MAGNITUDE OR GREATER & GUST VELOCITY
VIKING FLIGHTS OVER S. ENGLAND.

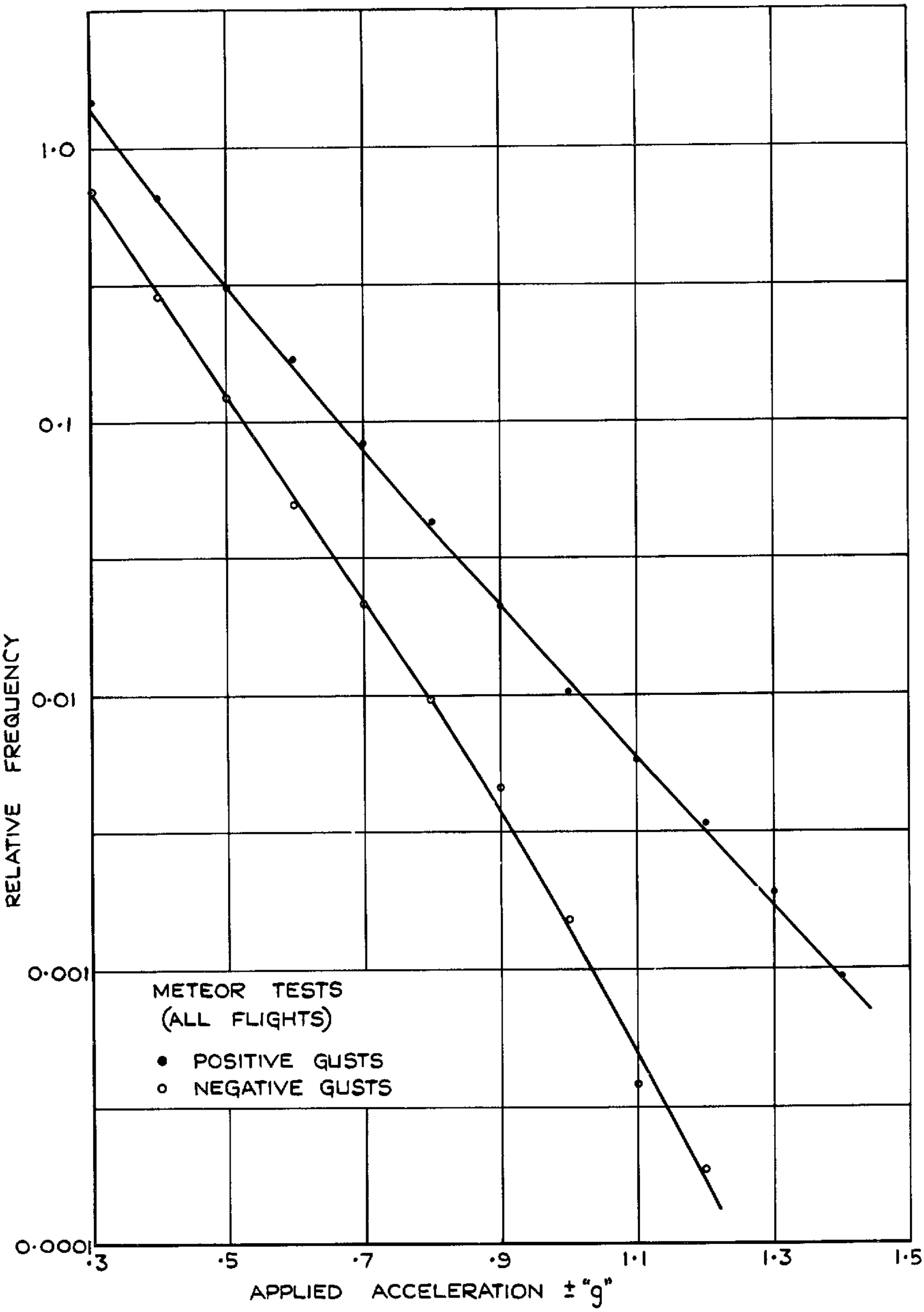

FIG. 5. RELATIVE FREQUENCY OF OCCURRENCE OF POSITIVE AND NEGATIVE GUSTS OF A GIVEN MAGNITUDE OR GREATER - RELATIVE TO THE AVERAGE OCCURRENCE OF A 0·3 g GUST.

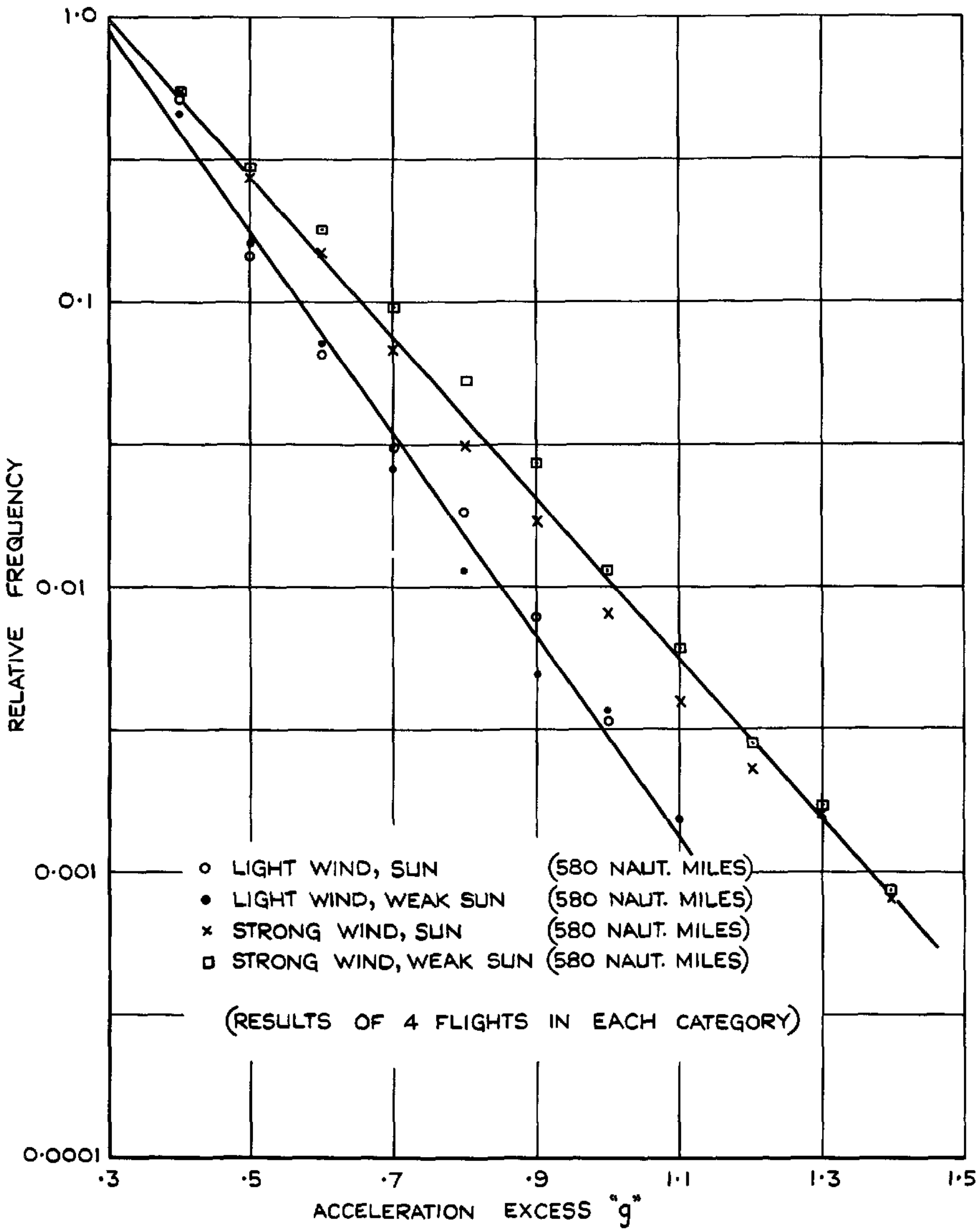

FIG. 6. EFFECT OF WEATHER CONDITIONS. RELATIVE FREQUENCY OF OCCURRENCE OF GUSTS OF A GIVEN MAGNITUDE OR GREATER-RELATIVE TO THE OCCURRENCE OF A 0·3 g GUST.

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