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by

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COMPARATIVE TURBULENCE FOR A CANBERRA AND A VULCAN FLYING TOGETHER AT LOW ALTITUDE

by

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SUMMARY

Measurements have been made of the response to turbulence of two aircraft, a Vulcan and a Canberra, while flying together over land and over the sea. Gust velocities derived from the normal accelerations of the two aircraft are compared and reference is made to the spectral densities of the normal accelerations to account for differences in the results. Additional information on aircraft response is obtained from the spectra of wing strain measured near the wing root.

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* Replaces RAE Technical Report 71100 - ARC 33862

CONTENTS

1 INTRODUCTION

During flight trials by Hawker Siddeley Aviation Limited on a Vulcan aircraft (B Mk.2 XH 539) to obtain information on wing load distribution for fatigue life estimation one flight was made in which the Vulcan and an RAE Canberra (B Mk.6) aircraft were flown together at low altitude. The purpose of the flight was to use the Canberra, which had been used extensively for turbulence measurements[1,2], to assess the intensity of the turbulence through which the Vulcan was flying. As both aircraft were instrumented with counting and continuous trace accelerometers and with strain gauges built into the wings for measurement of flight loads, a comparison could be made of the derived gusts and wing strains in the light of the aircraft response.

The flight comprised four comparative runs, two over coastal waters followed by two over land. Values of the equivalent vertical gust velocities were obtained from the measured normal accelerations, using the discrete gust analysis[3], for all four runs. Power spectra of the normal accelerations at the aircraft centre of gravity and wing strains were obtained, using Fourier transform analysis, for part of one run over land.

2 INSTRUMENTATION

2.1 Accelerometers

Two accelerometers were installed in each aircraft near the centre of gravity to measure the normal accelerations; the output from one was recorded on an Observer Unit and indicated the number of crossings at particular g levels (Table 1); the other provided a continuous trace of acceleration on the flight record. In the case of the Vulcan the output of the counting accelerometer was obtained in stepped trace form and in the case of the Canberra the counters were photographed every two minutes during the runs. Information on the thresholds of the accelerometers and particular details of the two aircraft are given in Appendix A.

2.2 Strain gauges

Longitudinal strains in the spar booms of the port wing of each aircraft were measured by strain gauges which were attached, using araldite, to the wing booms at the required positions near the wing root. For the Canberra four British thermostat type strain gauges were connected in an electrical bridge to give the information required; for the Vulcan the gauges were Tinsley type of nominally 100 Ω resistance and the output from one of the bridges was used to supply the data for the spectrum of wing strain for comparison with that of the Canberra.

2.3 Other parameters

The height and speed of the aircraft were obtained by the usual method of measuring the static and total pressures.

3 ROUTE

The route was along the coast of N.E. England as shown in Fig.1. For the two runs over the sea the aircraft flew in a northerly direction about three to five miles out from the coast at a height of approximately 500 ft. Both runs were over a distance of about 20 miles, run 1 taking place between approximately Scarborough and Saltwick Bay and run 2 between Saltwick Bay and Hartlepool.

For the two runs over land the aircraft flew in a southerly direction; run 3, over 17 miles, took place between Hexham and a point about 30 miles west of Middlesborough and run 4 (48 miles) between a point about 20 miles west of Leeming and a point between Leeds and Lindholme.

4 DATA REDUCTION

4.1 The equivalent vertical gust velocities

The equivalent vertical gust velocities were obtained from the measured normal accelerations at a point near the aircraft centre of gravity, as given by the counting accelerometer, using the discrete gust analysis procedure[3].

4.2 Spectra of normal accelerations

The spectra of the aircraft normal accelerations were obtained from the Fourier transforms of the autocorrelation function of the time histories of the normal accelerations. The part of the flight record selected for the spectral analysis was that relevant to a distance of 20 miles covered during run 4; this run was used to provide the data because it was the most severe and because the turbulance encountered appeared more consistent than that of the other three runs. The flight record was read at 1/20 sec intervals and the readings were punched on cards to obtain the information in the required form on the ICT 1907 and ATLAS computers. The spectra relate to a frequency range of aircraft response from 0 to 10 c/s at an interval of 0.2 c/s.

4.3 Spectra of wing strains

The strain gauge outputs were read from the same part of the flight record of run 4 as for the normal accelerations and again relate to aircraft response frequencies from 0 to 10 c/s at intervals of 0.2 c/s. The data was processed on the ICT 1907 and ATLAS computers.

4.4 Values of the zero crossings per unit distance in each direction

The values quoted for the zero crossings per unit distance in each direction were obtained in four different ways:-

(a) By counting the actual number of zero crossings (without thresholds) given by the analysis of the flight record of normal accelerations referred to in paragraphs 4.2 and 4.3.

(b) By extrapolation of the derived gust curves (Fig.5) for run 4 over land.

(c) By calculation from the relationship:

$$N_0^2 = \frac{\int N^2 S_r(N)dN}{\int S_r(N)dN}$$, relating to the power spectrum

The integrals were evaluated using Simpson's rule.

(d) By calculation, using the method proposed by Kaynes[4] involving the evaluation of integrals for gust response and zero crossings factors obtained from a general gust spectrum and a particular transfer function.

5 DISCUSSION OF RESULTS

5.1 Aircraft normal accelerations and derived equivalent vertical gust velocities

The number of crossings at the different g levels, given by the counting accelerometers, are presented in Table 1 for the four runs and the number of derived equivalent vertical gust velocities per mile are given in Figs.2 to 5. Average results for the two sea runs and for the two land runs are plotted in Figs.6 and 7 and for all four runs in Fig.8. The conversion factors (accelerations to gusts) are given in Table 2.

The curves in Figs.6 and 7 show that the numbers of derived gusts over the sea are greater for the Canberra than the Vulcan but over land the numbers are about the same for both aircraft. Unpublished results for earlier flight trials over land have shown results similar to those obtained here over the sea. A possible explanation for the high values obtained for the Vulcan over land in the present tests is that the Vulcan, which was following the Canberra during the land runs was engaged in a greater amount of manoeuvring, in weather conditions which had become stormy, to maintain height relative to the Canberra.

Differences in the results for the two runs over the sea may be explained by coastal effects; a strong wind (18 knots) which was blowing from the West (280°) would generate turbulence at the coast which would decrease in intensity as it drifted out to sea. During run 1 (Fig.2) the Vulcan was nearer the coast and encountered a greater proportion of large gusts whereas in run 2 (Fig.3) when the positions were reversed, the Canberra encountered the greater proportion of large gusts.

Comparison of the average results for all four runs with those predicted by the theoretical curves in the R.Ae.S. fatigue data sheets[5] for flight at sea level and with those predicted by Bullen's curve[6] for low level flight indicates that the turbulence encountered was above average intensity. For example, at a vetical gust velocity of 10 ft/sec the curves predict approximate values of 1 gust per mile for flight at sea level and 0.5 gust per mile for low level flight, whereas the curves of average results described here give an approximate value of 3.5 gusts per mile for the Canberra.

5.2 Spectra of normal accelerations

The normalised spectrum of the normal accelerations of each aircraft, measured near the centre of gravity, is presented in Fig.9. The curves are reasonably parallel to each other with slopes of approximately -2.4.

On the curve for the Vulcan the peaks occur at frequencies which are in close agreement with those of the first four symmetric natural modes established in a ground resonance test; these were 3.42 c/s (fundamental bending), 5.79 c/s (fuselage torsion-wing bending), 7.59 c/s (second wing bending), and 9.58 c/s wing torsion. On the curve for the Canberra the first small peak at approximately 2.8 c/s is not readily explained but the two larger peaks are probably associated with the first two symmetric modes of the structure whose frequencies, established in the ground resonance test, were 6.02 c/s (wing fundamental bending) and 8.2 c/s (fuselage bending). The flight peak frequencies are lower than those of the resonance tests but the fact that the aircraft was about 10000 lb heavier in the flight case may have some bearing on this.

The percentage contribution of the flexibility of the structure to the mean square aircraft normal acceleration has been calculated for the Canberra up to 6 c/s and for the Vulcan up to 4 c/s assuming the rigid body motions to be represented by the broken lines of Fig.9. For the Canberra the modes at 2.8 c/s and 4.5 c/s make a contribution of 6.4% and for the Vulcan the mode at 2.8 c/s makes a contribution of only 0.89%. Modes at higher frequencies have not been considered because their overall contribution is small and difficult to determine.

The percentage contribution to N_0 of the first fundamental modes only has been calculated using the relationship in section 4.4(c) and assuming the curves to continue as shown by the broken line up to 4 c/s for the Vulcan and up to 6 c/s for the Canberra. The calculations give a percentage increase in N_0 due to these modes of 29.5% in the case of the Canberra and 8.0% in the case of the Vulcan.

The higher values of N_0 (see section 5.4) for the Canberra compared with those for the Vulcan and indicated by the curves in Figs.2 to 8 are consistent with the rigid body responses being such that the ratio of high frequency energy to low frequency energy is greater for the Canberra than the Vulcan.

5.3 Spectra of wing strain

The normalised spectra of wing strains obtained from one strain gauge bridge near the wing root of each aircraft are presented in Fig.10. The curves are rather different and show that the Canberra response has a comparatively greater high frequency content than the Vulcan.

The significant peak frequencies on the Vulcan curve are those relating to fundamental bending and wing torsion as for the acceleration spectrum, but those at the higher frequencies of 6.5 c/s and 8 c/s could be associated with the second wing bending mode at 7.59 c/s or with the measured asymmetric wing mode frequencies of 6.48 c/s and 8.6 c/s. The peak at 9 c/s is probably associated with the wing torsion mode frequency of 9.58 c/s. It is noted, however, that at frequencies higher than 3 c/s the contribution to the overall strain energy falls off rapidly to a very low value.

On the curve for the Canberra, the first small peak at approximately 2.8 c/s and the large peak at 4.5 c/s confirms those on the normal acceleration spectrum curve, but there is little additional contribution to the strain energy at the peak frequencies above the latter value. Assuming the aircraft rigid body motions to be represented by the broken lines drawn up to 6 c/s for the Canberra and 4 c/s for the Vulcan, the calculated contributions of the flexibility of the structure to the wing strains is 20% for the Canberra and 4.5% for the Vulcan; the calculated contribution to the number of zero crossings is 83% for the Canberra and 33% for the Vulcan.

5.4 Values of zero crossings per unit distance in each direction

The observed values of the zero crossings, obtained, as described in section 4.4(a), by counting the crossings on the accelerometer trace for the part of run 4 selected for spectral analysis, were 18.36 gusts per mile for the Canberra and 11.0 gusts per mile for the Vulcan. Extrapolation of the derived gust curves (run 4, Fig.5) give comparative values of approximately 17.5 gusts per mile for the Canberra and 9.0 gusts per mile for the Vulcan.

The corresponding values estimated from the spectral density curves using the relationship of section 4.4(c) were 20.24 gusts per mile for the Canberra and 14.8 gusts per mile for the Vulcan, while those derived using Kaynes' method, assuming a general gust spectrum were 15.0 per mile and 10.81 per mile respectively. It is noted that the values of 20.24 and 14.8 were estimated from the spectral density data for a range of aircraft response frequencies up to 10 c/s; if the range is limited to 7.2 c/s the estimated values of N_o then become 18.23 per mile and 11.84 per mile for the two aircraft and are in closer agreement with the observed values.

6 CONCLUSIONS

A Canberra and a Vulcan have been flown together both over land and sea in N.E. England.

Flying northwards over the sea more derived gusts were obtained for the Canberra than the Vulcan but the aircraft nearer the coast (the Vulcan during run 1 and the Canberra during run 2) gave a greater proportion of large to small derived gusts and this was probably due to coastal effects.

Flying southwards over land more derived gusts per mile were obtained for the Vulcan than for the Canberra at the higher gust velocities when the weather become stormy, due possibly to more manoeuvring of the Vulcan, which was following the Canberra, in an effort to maintain height.

The intensity of the turbulence was, on average, greater than that predicted by the standard curve in the R.Ae.S. fatigue data sheets for flight at sea level and by Bullen's curve for flight at low altitude.

The curves of power spectral density of aircraft normal accelerations indicate a greater ratio of high to low frequency energy for the Canberra than for the Vulcan, consistent with the rigid body transfer functions. This leads to a higher value of N_0 for the Canberra and confirms the practical result.

The contribution of the first wing mode of the Vulcan to the mean square aircraft normal acceleration and to N_0, calculated up to 4 c/s is 0.89% and 8.0% respectively. Similar calculations for the Canberra up to 6 c/s, to include the first wing mode, give values of 6.4% and 29.5% respectively. The contribution of the same modes to the wing strain and associated zero crossings are 4.5% and 33% respectively for the Vulcan and 20% and 83% respectively for the Canberra. These results indicate that the Canberra has more structural response to turbulence at the fundamental wing modes than the Vulcan.

Calculations of N_0 from the acceleration power spectra curves up to 7.2 c/s in aircraft response gives values for each aircraft which are in good agreement with the observed zero crossings and with those obtained by extrapolation of the curves of gust levels exceeded. Calculations using Kaynes' method give reasonable agreement with the observed values for the Vulcan but the calculated value is a little low in the case of the Canberra.

Appendix A

Details of the Canberra and Vulcan and of the counting accelerometers:-

Canberra B6

Wing span	64 ft	(19.51 m)
Mean chord	15 ft	(4.57 m)
Wing area	960 ft^2	(89.19 m^2)
Aspect ratio	4.25	(4.25)
Slope of lift curve	3.6 per rad	(3.6 per rad)

Vulcan B Mk.2

Wing span	110 ft	(25.78 m)
Mean chord	35.7 ft	(8.37 m)
Wing area	3964 ft^2	368.28 m
Aspect ratio	3	3
Slope of lift curve	2.6 per rad	(2.6 per rad)
Sweep back at L.E.	49° 54'	(49° 54')

The increments of acceleration relative to 1 g at which crossings were recorded and the thresholds (return increments) of the counting accelerometers were as follows:-

In the Canberra (Type Structure 4)

Acceleration increment (g)	±0.1	±0.15	±0.2	±0.3	±0.4	±0.5	±0.6	±0.7	±0.8
Threshold (g)	0.1	0.15	0.15	0.2	0.25	0.3	0.3	0.3	0.3

In Vulcan (Type RAE 2)

Acceleration increment (g)	-0.1	±0.2	±0.3	±0.4	±0.6	±0.8
Threshold (g)	0.1	0.2	0.3	0.4	0.5	0.6

Table 1

NUMBERS OF CROSSINGS AT DIFFERENT G LEVELS

A/C	Run	Height (ft)	Distance (miles)	Time		Crossings at g levels relative to 1 g																	
				min	sec	-0.8	-0.7	-0.6	-0.5	-0.4	-0.3	-0.2	-0.15	-0.1	+0.1	+0.15	+0.2	+0.3	+0.4	+0.5	+0.6	+0.7	+0.8
CANBERRA	1	421	24.5	5	3½			1	1	9	36	93	130	183	173	122	80	30	12	4	2	2	1
	2	574	26.2	5	25	2	4	5	16	36	83	161	180	234	219	176	154	79	53	28	7	1	
	3	2681	16.6	3	20				3	4	17	58	80	120	110	67	47	14	5	3			
	4	537	48.0	9	55	3	17	29	50	100	153	329	391	504	496	387	309	185	99	55	31	18	8
	C4					5	21	35	270	149	289	641	781	1041	998	752	590	308	169	90	40	21	9
VULCAN	1	400	24.4	5	4½						3	20					34	6	5				
	2	550	26.4	5	26					3	19	50					74	21	5				
	3	2650	16.7	3	21						4	24					25	7	1				
	4	500	48.4	9	55½	3		14		55	89	147					160	98	58		16		
	C4			23	47	3		14		58	115	241					293	132	69		16		

Table 2

FACTORS USED TO DERIVE THE EQUIVALENT GUST VELOCITIES FROM THE MEASURED NORMAL ACCELERATIONS

CANBERRA	ft/sec per g	VULCAN	ft/sec per g
RUN 1	29.13	RUN 1	37.7
RUN 2	28.8	RUN 2	37.3
RUN 3	28.0	RUN 3	36.1
RUN 4	27.2	RUN 4	35.9

SYMBOLS

N_0 = number of zero crossings per unit distance in each direction.

N = aircraft response frequency

$S_r(N)$ = normal acceleration spectrum

REFERENCES

No.	Author(s)	Title, etc.
1	E. W. Wells	Low altitude turbulence measurements over land and sea during flights in a Canberra aircraft. ARC CP No.1081 (1969)
2	E. W. Wells	Low altitude gusts measurements over three routes in the UK. ARC CP No.676 (1962)
3	J. K. Zbrozek	Gust alleviation factors ARC R & M 2970 (1953)
4	I. W. Kaynes	Aircraft centre of gravity response to two-dimensional spectra of turbulence. ARC R & M 3665 (1969)
5	Royal Aeronautical Society	Fatigue data sheets L.01.01 (1958)
6	N. I. Bullen	A review of information on the frequency of gusts at low altitude. ARC CP No.873 (1965)

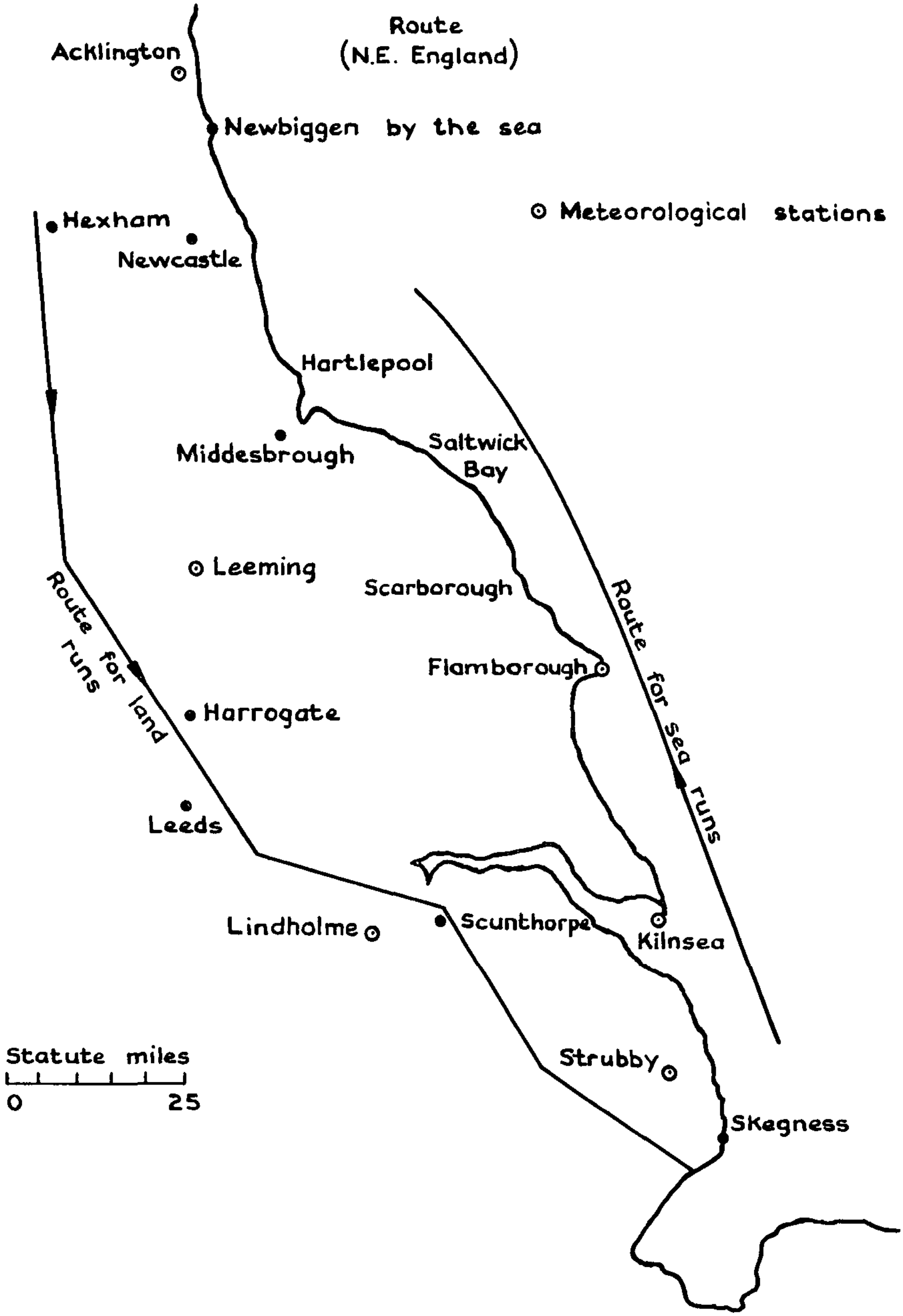


Fig. 1 Route and positions of meteorological stations along the coast of N.E. England

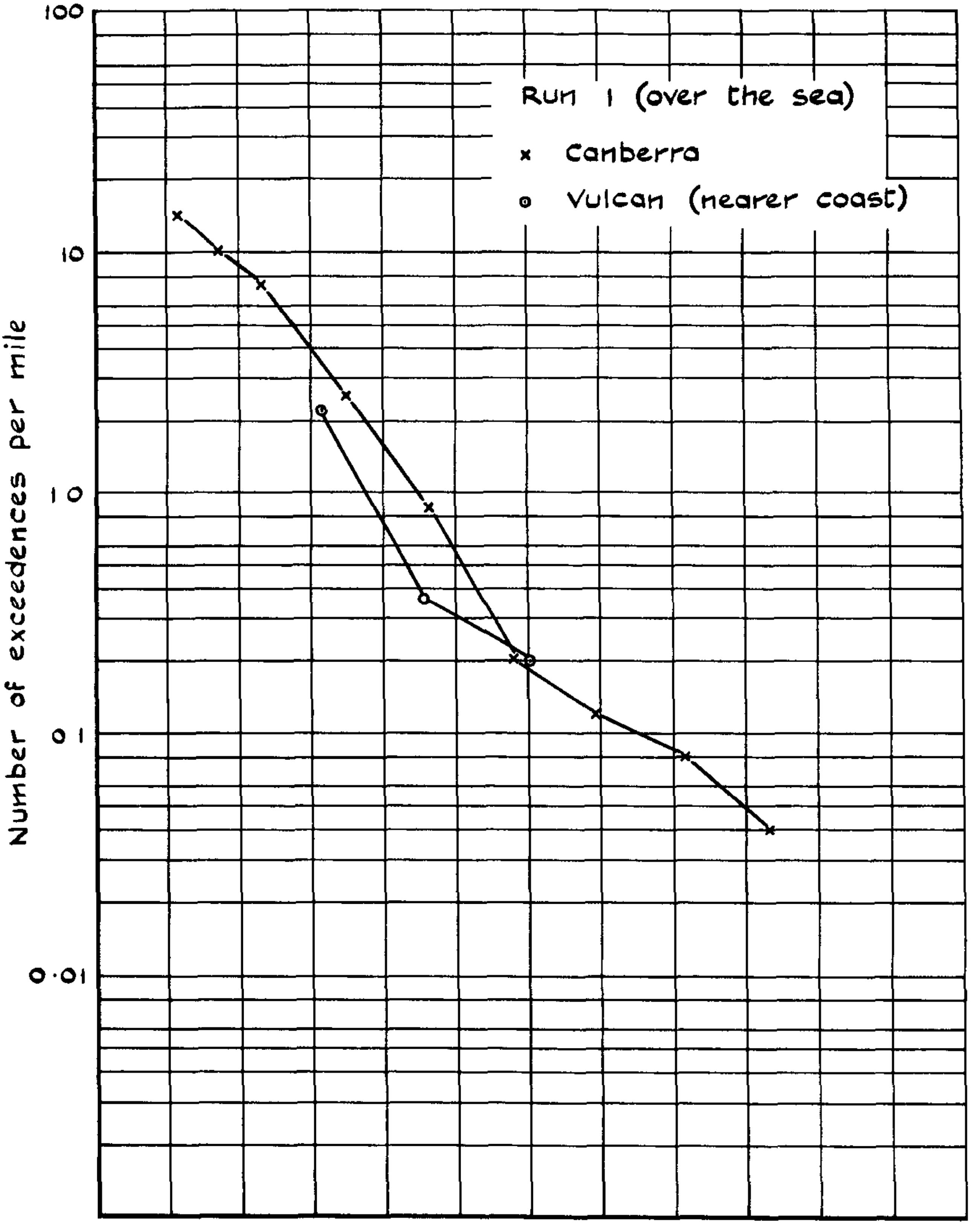

100
10
1 0
0 1
0·01
Number of exceedences per mile
0
5
10
15
20
25
30
Equivalent gust velocity (ft/sec)
Run 1 (over the sea)
× Canberra
⊙ Vulcan (nearer coast)

Fig. 2

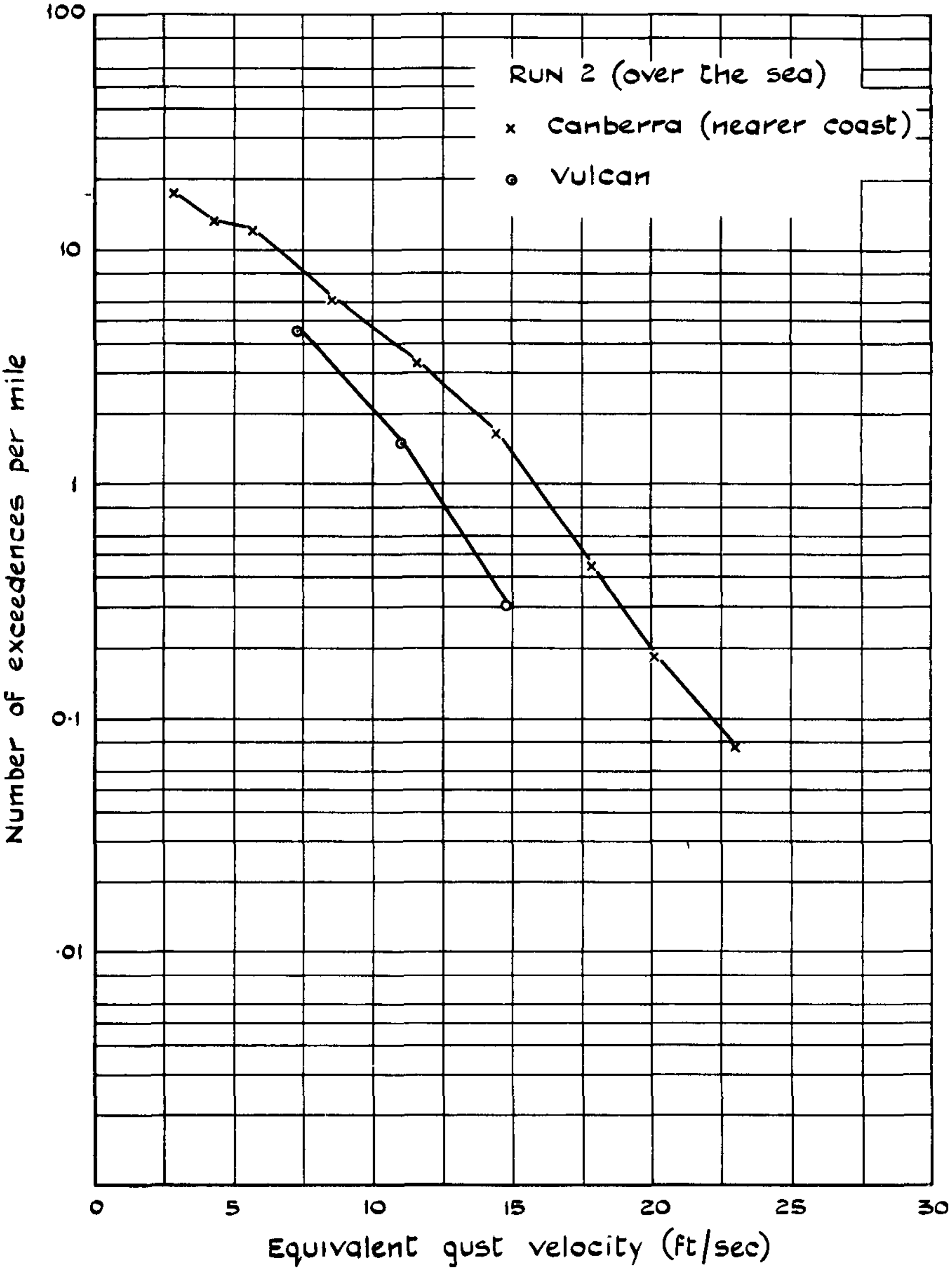
RUN 2 (over the sea)
× Canberra (nearer coast)
⊙ Vulcan
Number of exceedences per mile
100
10
1
0·1
·01
Equivalent gust velocity (ft/sec)
0
5
10
15
20
25
30

Fig. 3

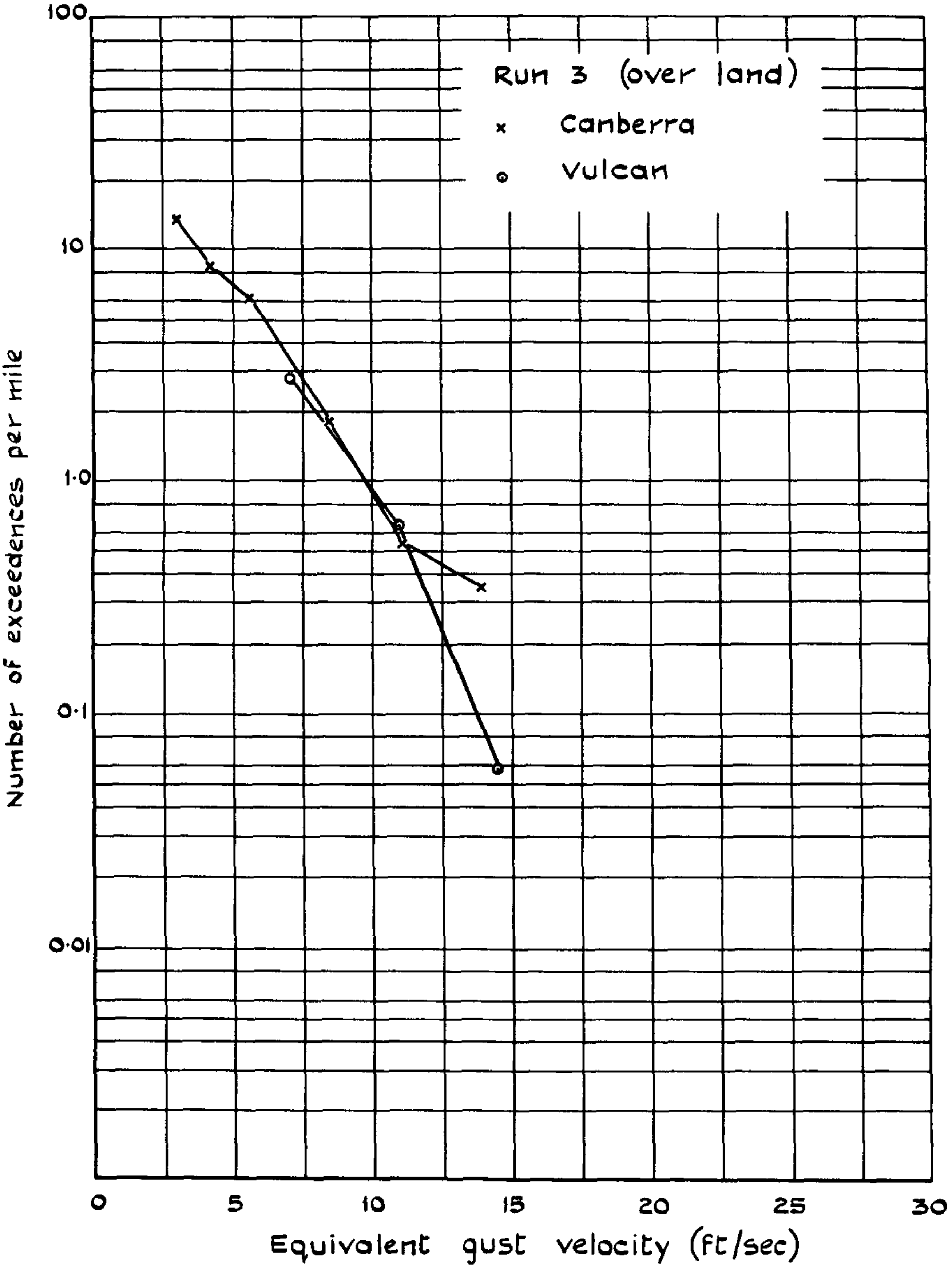
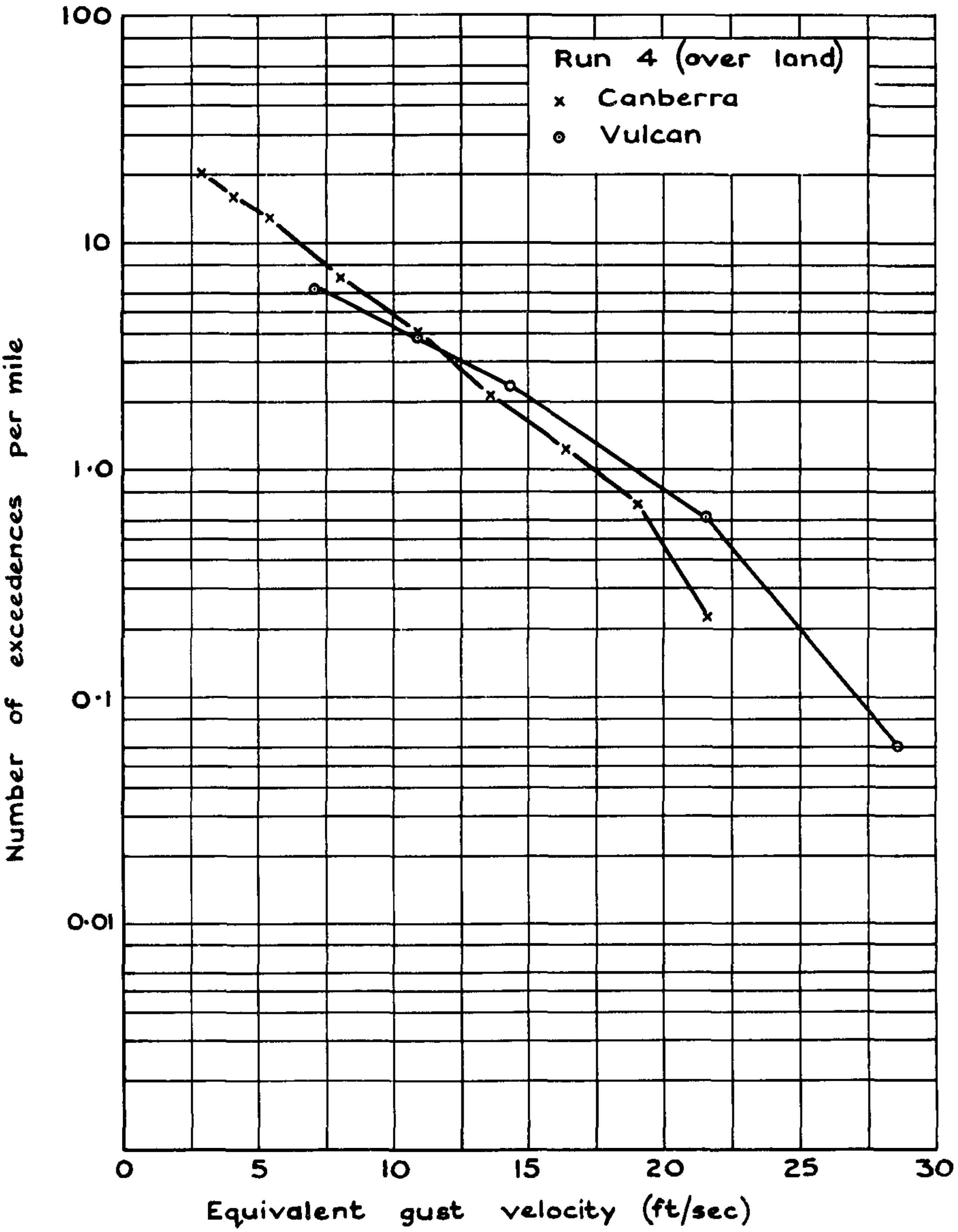

Run 3 (over land)
× Canberra
⊙ Vulcan
100
10
1·0
0·1
0·01
0
5
10
15
20
25
30
Number of exceedences per mile
Equivalent gust velocity (ft/sec)

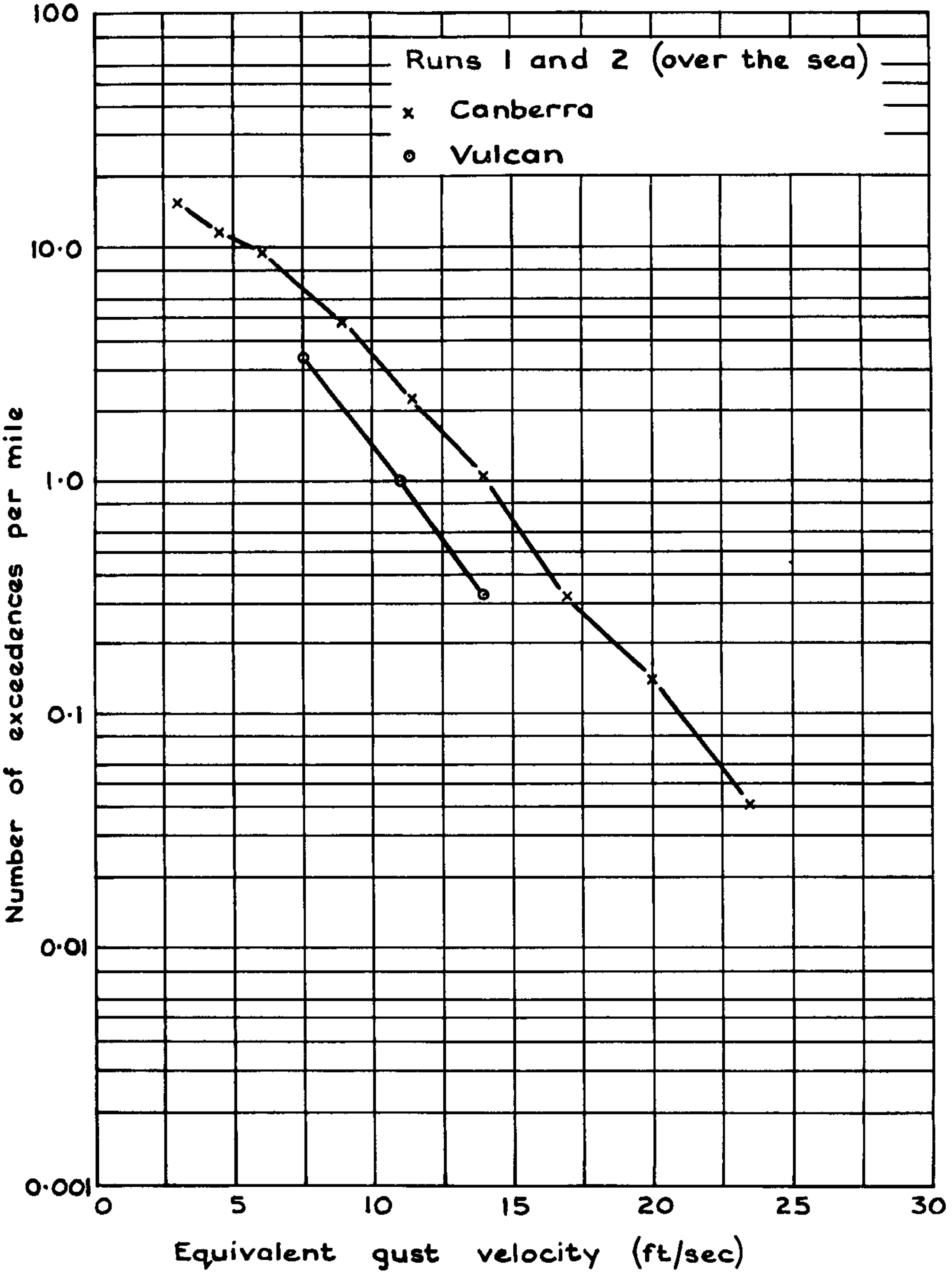
Fig.4



Run 4 (over land)
x Canberra
⊙ Vulcan
100
10
1·0
0·1
0·01
Number of exceedences per mile
0
5
10
15
20
25
30
Equivalent gust velocity (ft/sec)

Fig. 5

Fig. 6


Runs 1 and 2 (over the sea)
x Canberra
⊙ Vulcan
100
10·0
1·0
0·1
0·01
0·001
0
5
10
15
20
25
30
Number of exceedances per mile
Equivalent gust velocity (ft/sec)

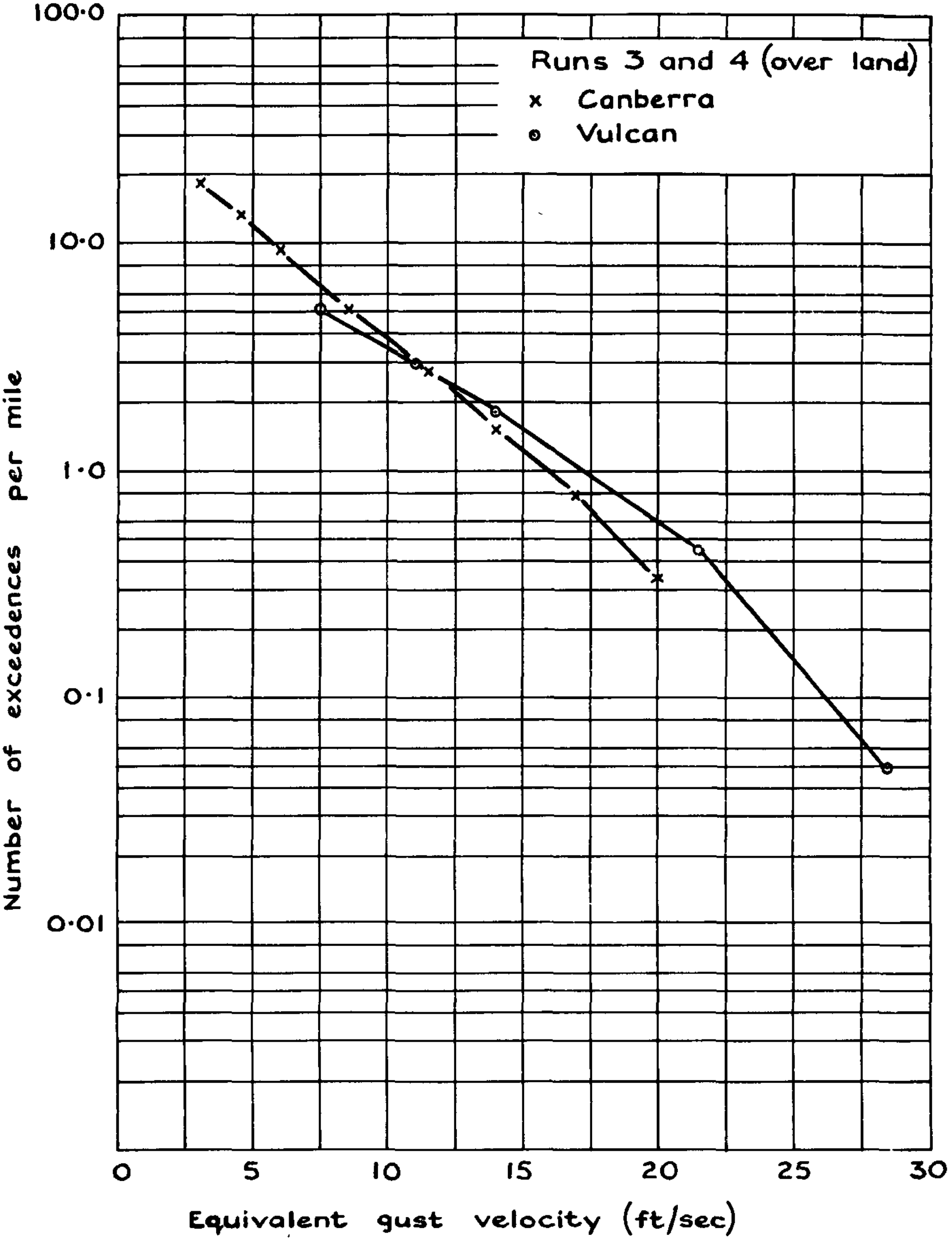

Runs 3 and 4 (over land)
x Canberra
⊙ Vulcan
100·0
10·0
1·0
0·1
0·01
Number of exceedences per mile
0
5
10
15
20
25
30
Equivalent gust velocity (ft/sec)

Fig.7

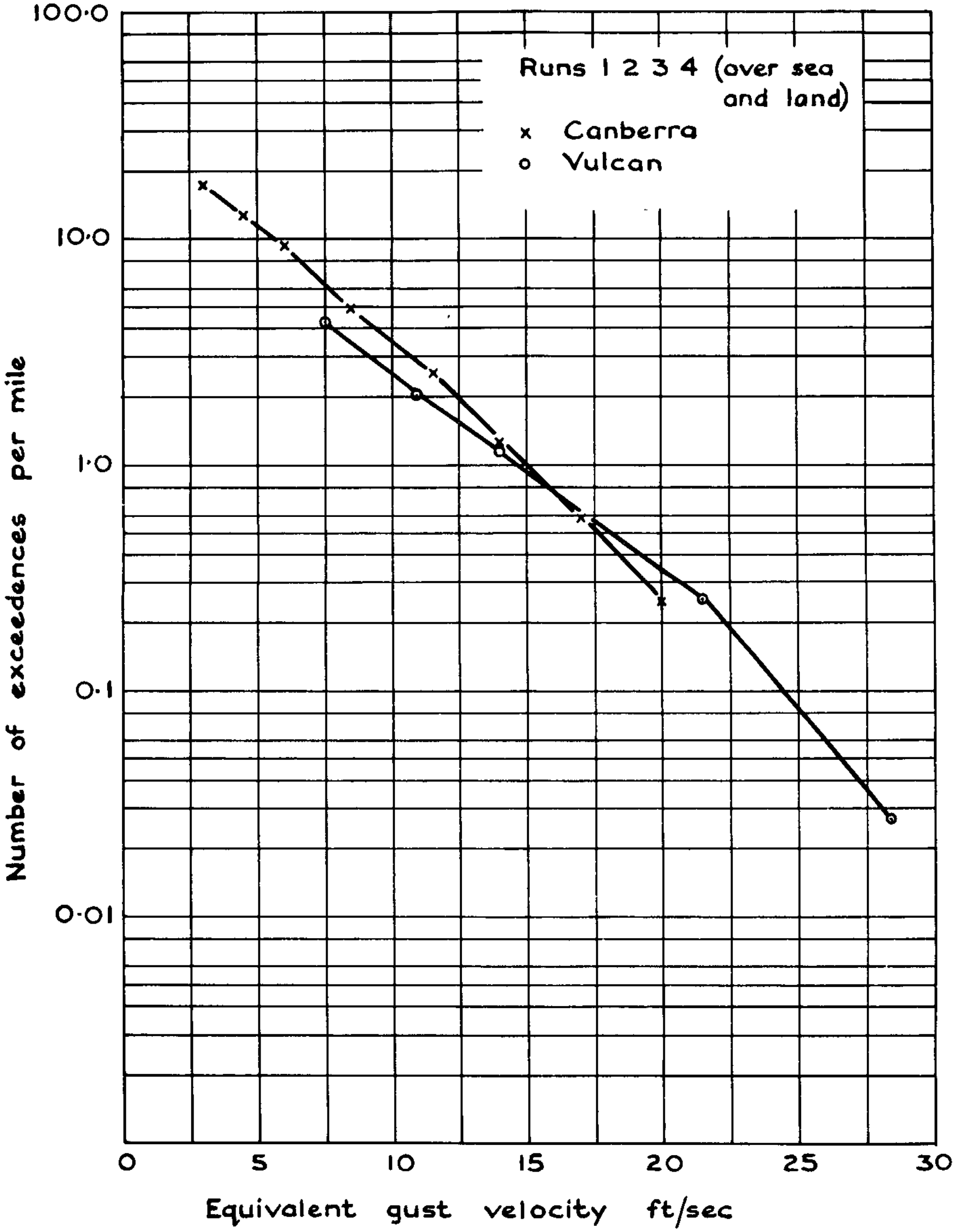

Runs 1 2 3 4 (over sea and land)
x Canberra
o Vulcan
100·0
10·0
1·0
0·1
0·01
Number of exceedences per mile
0
5
10
15
20
25
30
Equivalent gust velocity ft/sec

Fig. 8

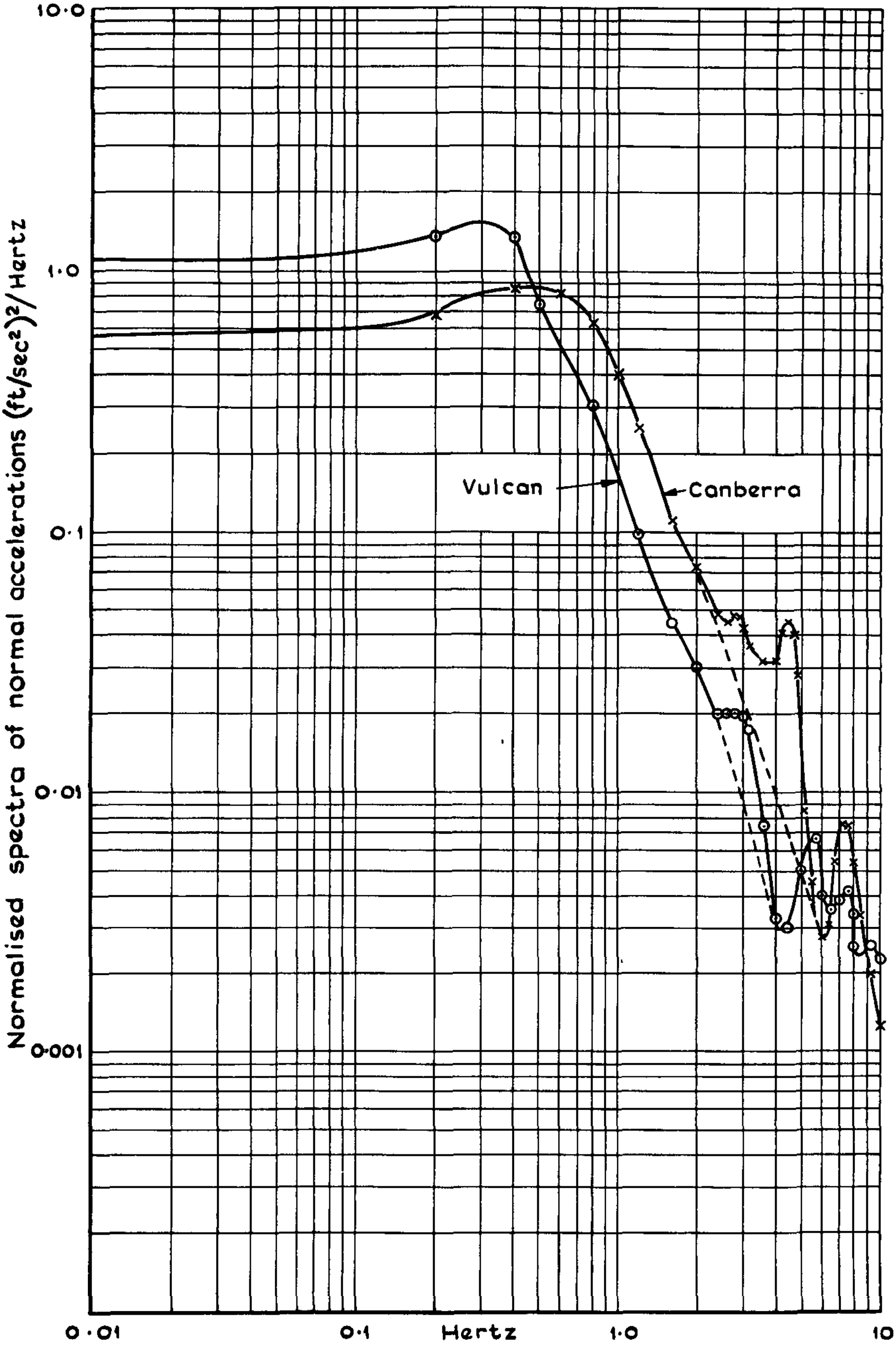


Fig. 9 Spectra of normal accelerations

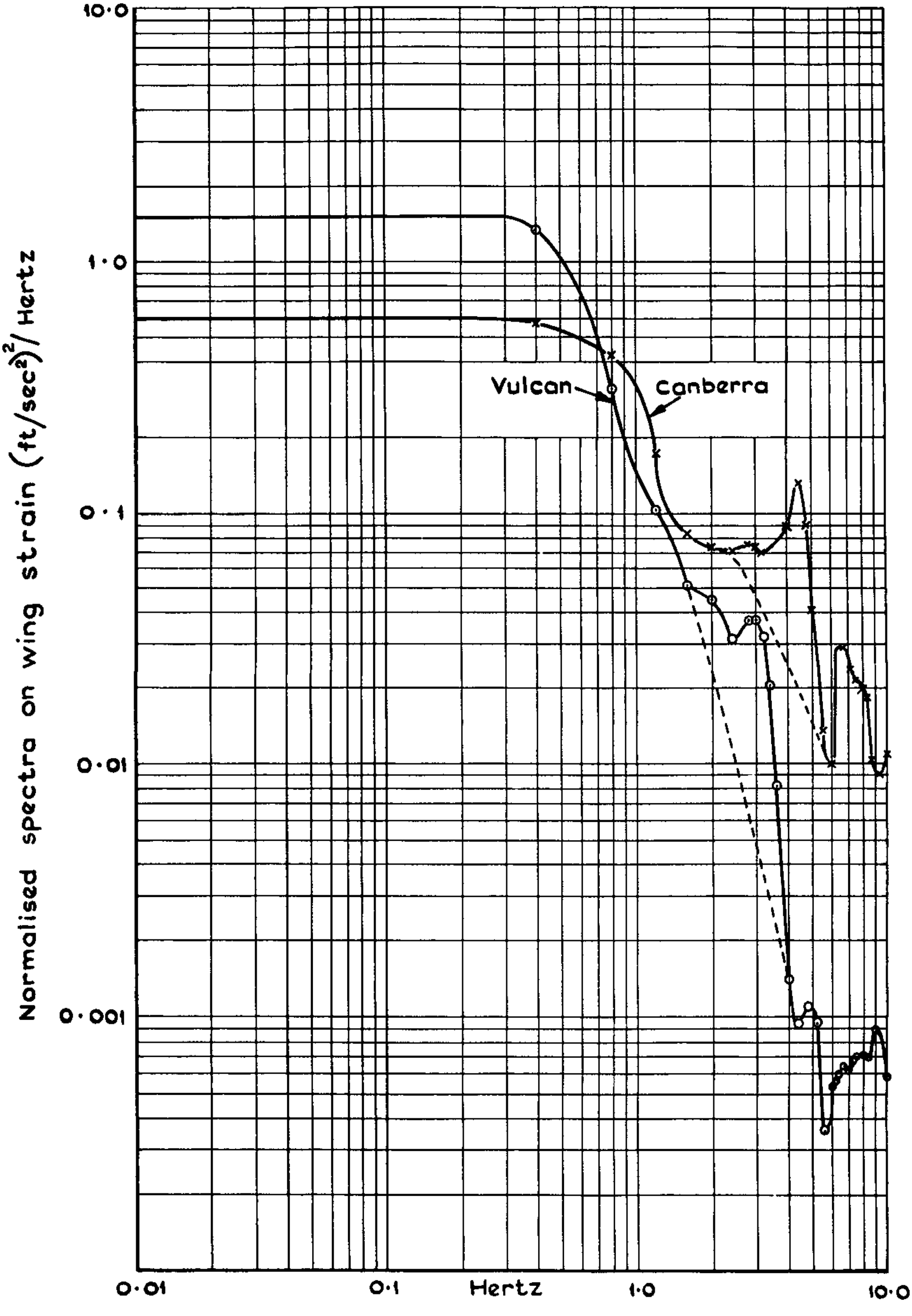


Fig 10 Spectra of wing strains

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