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By J. TAYLOR
Structures Dept., RAE Farnborough

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SUMMARY

An examination is made of the relative frequency of occurrence of different normal accelerations, at points near the aircraft centre of gravity of 5 different aircraft, from about 200 hours of research flying sub-divided into about 12 000 time periods mainly of about 1 minute. It is shown that the commonly used assumption of a Rayleigh distribution for vertical gust velocity maxima for each period gives poor estimates of the cumulative totals of all the periods for each aircraft. If, however, it is assumed that

(i) the frequency of occurrence of different magnitudes of the maxima of the gust velocity vector is a Rayleigh distribution,
(ii) the vector changes direction sufficiently slowly for the maxima of the components to occur at the same time as the maxima of the vector,

hold for each period, the estimates of the cumulative totals of all the periods for each aircraft do not differ significantly from the measurements. Nor is there any significant difference between the measurements and the cumulative totals of gust velocity maxima in 36 traverses of severe turbulence encountered in 23 000 flying hours of civil aircraft operations.

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* Replaces RAE Technical Report 71169—A.R.C. 33 503.

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1. Introduction

The data on turbulence loads that are most extensive are in the form of normal accelerations at a point near the aircraft centre of gravity, together with height, speed and weight of the aircraft at the time of their occurrence. These accelerations are almost invariably tabulated as the frequency with which various increments from 1 g are exceeded. For any particular aircraft on which measurements are taken, these accelerations give a good indication of the overall load on that aircraft. For the purpose of design calculation, it is usually necessary to make some assumption of the functional relationship of the number of exceedances at the different acceleration levels. Much theoretical work has been done on the assumption that the vertical gust velocity (and also the centre of gravity acceleration) has a normal distribution on a time scale in any traverse of homogeneous turbulence and that any particular turbulence encounter is made up of a series of traverses of homogeneous turbulence of different intensities. On the usual assumption that the rate of change of gust velocity is independent of the magnitude of the velocity, the normal distribution of gust velocity is equivalent to a Rayleigh distribution of gust velocities exceeding specified values (this is usually referred to as a distribution of crossings).

Practically all workers in the field have noticed that on this assumption, no matter to what extent the areas are sub-divided, there is still a tendency for the higher gusts to occur more frequently than the Rayleigh distribution would predict. King[1] has found that for 36 severe turbulence areas the highest peak gust velocity was invariably greater than would have been expected from a Rayleigh distribution with the same root mean square of peak velocities and also that the average flying time in each was only half a minute. The purpose of the present investigation is to examine experimental data and sub-divide it into short periods of time which are mostly about 1 minute and check a distribution based on a Rayleigh distribution of the magnitude of the gust velocity vector rather than a Rayleigh distribution of the magnitude of its component.

The investigation also gives an opportunity of examining the total number of gusts in each interval (i.e. zero crossings), and compare these with theory. A recent report by Kaynes[2] gives an estimate of zero crossings that forms the basis of this comparison.

2. Theoretical Model of Turbulence

The relative frequency of occurrence of vertical gust components of different magnitude is calculated on the following assumptions:

(i) the frequency of occurrence of different magnitudes of the maxima of the gust velocity vector is a Rayleigh distribution,

(ii) the vector changes direction sufficiently slowly for the maxima of the components to occur at the same time as the maxima of the vector.

The proportion of maxima of gust velocity vectors greater than U are equal to $\exp(-U^2/2\sigma^2)$ where σ^2 = the mean square of the turbulence velocity. It is shown in the Appendix that on the above assumptions the corresponding proportions of maxima of vertical component of gust velocity greater than U will be equal to

$$\int_0^1 \exp(-U^2/2\sigma^2 x^2)\, dx. \tag{1}$$

These two distributions are shown in Fig. 1 and expression (1) is tabulated for a range of values of U/σ in Table 17.

3. Experimental Normal Acceleration Records

A large amount of records was available in unpublished documents for the following aircraft:

Anson
Canberra
Meteor
Viking
York

In the earlier documents the basic data have been added together for presentation. In the present analysis the records are sub-divided into short periods of time, usually about 1 minute with the exception of the Meteor which is in periods of a quarter of a minute. The records are all as stepped traces at prescribed levels of normal acceleration, the Anson, Viking and York being at multiples of 0·1 g increment the Meteor at multiples of 0·2 g and the Canberra at increments of 0·2 g, 0·3 g, 0·4 g, 0·6 g, and thereafter in multiples of 0·2 g. The analysis is done in two parts, firstly the records are reduced to a series of maxima and minima and secondly the maxima above 1 g and the minima below 1 g determined for various thresholds Tg (i.e. a maximum Pg above 1 g is only counted when a subsequent, but not necessarily the consecutive minimum of less than $(P - T)g$ occurs). It was found that the size of threshold did not matter much provided it was not greater than necessary to return to 1 g and for convenience of analysis only, the one largest increment between 1 g crossings was chosen. By being able to neglect differences due to the size of threshold, it is possible to calculate the number of crossings of any level as the number of maxima greater than that level. The number of crossings are determined for each short period of the records. These individual periods have been examined separately and the root mean square acceleration determined on two assumptions. Firstly that the distribution of maxima is a Rayleigh arising from a normal distribution of the vertical gust component; and secondly that the distribution of maxima is that given by expression (1) which arises from a Rayleigh distribution of the maxima of the gust vector. For any individual period the number of gusts is so small that the observed values can rarely be said to be significantly different from either of the assumptions. A typical period is shown in Fig. 2. When the periods are added together it is immediately apparent that the higher gust velocities occur more frequently than would have been expected from the summation of the Rayleigh distributions for the components. The totals for the Anson, Canberra, Meteor, Viking and York are given respectively in Tables 1 to 5 for a range of height bands; the calculated values are tabulated to the nearest 0·1 of a digit. In preparing the tables the root mean square of the measured peaks has been calculated and that value used to determine the appropriate Rayleigh distributions. Throughout the tables calculated values are given as follows:

Calculation A: A Rayleigh distribution of the maxima of the gust velocity vector.

Calculation B: A Rayleigh distribution of the maxima of the vertical component of the gust velocity.

The totals of the accelerations for all heights grouped together are plotted in Figs. 3 to 7 respectively for the Anson, Canberra, Meteor, Viking and York; the calculated values are not rounded off before plotting. It will be seen that the distribution based on a Rayleigh distribution of the maxima of the velocity vector, that is now proposed, gives a much better representation of the observed data than the distribution based on Rayleigh distribution of the vertical component. Also the Rayleigh distribution of the vertical component is invariably appreciably below the experimental data at the higher gust velocities. The Canberra and the Meteor were both recording data below 500 feet. It will be seen that at the higher increments the observed data on the Canberra is higher than the distribution that is now proposed, and that for the Meteor is lower. The amounts that the Meteor are lower, admittedly on a much shorter distance, are approximately equal to the amounts that the Canberra data are too high. The Viking, Anson and York are all recording data at higher altitudes, for the most part between 1500 and 9500 feet. York and Viking agree closely with the formula now being proposed, but the Anson does have rather higher experimental records than the theoretical which is discussed in Section 4.

4. Regions of Continuous Turbulence

4.1. Moderate Intensity Turbulence

By examining the records in large numbers of periods of time it is possible to make an assessment of when the turbulence is reasonably continuous. This has been done for all the aircraft examined. An assessment has been made of the intensity and total number of gusts (i.e. zero crossings) in each period. The intensity has been based on the mean square of the peak accelerations and converted to gust velocities by means of the gust response factor given by Kaynes.[2] The total number of gusts given in each case is the percentage of the total number that would be expected in continuous turbulence based on Kaynes' estimate. For the purpose of determining turbulence that is reasonably continuous and also of moderate intensity it was decided that traverses should be selected using as a basis a parameter that was equal to the product of intensity and percentage of zero crossings. Traverses of about 50 kilometres at each height band were selected where this parameter was high. In the case of the Anson, the total recorded time is 620 minutes mainly in the height band 1500–5500 feet and the two 50 kilometre traverses which give this parameter the highest value are given in Table 6, together with the numbers of gusts encountered.

Figure 8 gives a plot of the distributions of normal acceleration crossings for each of these two traverses of turbulence and compares the data with the theoretical predictions, of the two distributions being considered, on the assumption that the turbulence was homogeneous over the whole area. To give an indication of the intensity of the turbulence the scale used is in fact not normal acceleration but gust velocity. To make this conversion the turbulence is represented by a two-dimensional Von Karman spectrum with a scale of turbulence chosen empirically[3] to be equal to the altitude up to 1000 feet and thereafter equal to 1000 feet times the ratio of the air density at ground level to that at the altitude of the turbulence. Kaynes' gust response factors[2] for this spectrum are used and an additional dynamic factor[3] of 1·2 is made to allow empirically for the effect of structural flexibility on the acceleration records. It will be seen that the distribution based on gust vector gives a good representation in both cases, but the distribution based on velocity component gives appreciably too low values for the higher gusts in both cases.

The Meteor and the Canberra flights were all made below 500 feet. The Canberra data were sub-divided into flights at different intensities of solar radiation. The same sub-division is used in the present Report as was used by Bullen.[4] A 50 kilometre flight for each of the ranges of solar radiation is selected on the same basis as was used for the Anson. These are given in Table 7 and Fig. 9. The Meteor results are given in Table 8 and Fig. 10. The same procedure was repeated for the Viking and one traverse of turbulence for each of the height bands 1500–5500 feet, 5500–9500 feet was selected on the same basis. These are shown in Table 9 and Fig. 11.

The number of records taken for the York was small but it was possible to select one area of turbulence at 1000 feet, which is given in Table 10 and Fig. 12, but none at higher altitudes.

4.2. Moderately Severe Turbulence

An examination of the data from the Viking and Anson showed that there were a few individual minutes that had a fairly severe intensity of turbulence, being about double the intensity of the adjacent periods. In each of these cases a more detailed examination has been made. Each record from a period containing a high intensity turbulence was taken together with the period immediately preceding and immediately following it, and the total examined as a single period. This record was then sub-divided into three consecutive periods, the middle one being determined as that containing the high intensity turbulence. It was noticed that these high intensity traverses were about 2 to 5 kilometres. In the case of the Anson there was one such encounter in the height band 1500–5500 feet and for the Viking there were such encounters at each of the three height bands above 1500 feet. The most intense areas in each height band are shown in Table 11 and Fig. 13. Because of the short duration of these encounters of moderately severe turbulence the number of gusts is relatively small and appreciable scatter is to be expected. Nevertheless the agreement is again good for the Rayleigh distribution of the gust velocity vector and poor for the Rayleigh distribution of gust component at the higher gust velocities. In all these cases of moderately severe turbulence it is not possible to make an accurate estimate of the time duration as the time scale on the original records was only accurately made at discrete minute intervals.

The moderately severe turbulence traverse by the Anson occurred during the 50 kilometre traverse given in Fig. 8b and it is evident that it was significantly more intense than the rest of the area. On the particular day of the flying there were widespread thunderstorms and it is reasonable to suppose that there were a number of moderately severe areas of turbulence. As this day's flying accounted for much of the 620 minutes recorded, the total number of gusts encountered was nearly as many as those recorded on the Viking 4360 minutes. It would be expected therefore that any influence of the records of moderately severe turbulence would be greater for the Anson than for the Viking; in particular it is apparent from the above discussion that moderately severe turbulence will often have a duration of less than 1 minute and in such cases individual 1 minute periods will contain a combination of moderate and moderately severe turbulence. This could account for the higher number of large gusts than even the theory based on the gust vector would predict.

4.3. Severe Turbulence in Civil Operational Flying

An examination by King[1] of records from 23 000 flying hours by 3 four-engined pure jet civil transports gave 36 traverses of severe turbulence. The actual measured values of the peak centre of gravity normal accelerations in each of these traverses have been made available for analysis as used in Section 4.2. In order to make a cumulative comparison of a Rayleigh distribution of the magnitude of the gust vector and of the gust component, the individual traverses were converted from centre of gravity normal accelerations to gust velocity with Kaynes' response factors. The sum of the 36 traverses is given in Table 12 and Fig. 14. It can be seen that the agreement for the Rayleigh distribution based on gust vector is good and that based on gust component poor, especially at the high gust velocities.

4.4. Probabilities of High Gusts in Particular Traverses of Turbulence

The probability that the largest gust would have been greater than that measured has been calculated for each area of turbulence, where the number of gusts were sufficiently small for the calculation to be practicable; the method is the same as that used by King[2]. Tables 13, 14, 15 give the probabilities respectively for the 50 kilometre traverses, the 2 to 5 kilometre traverses, and the traverses of severe turbulence met in civil operations.

5. Total Number of Gusts in Continuous Turbulence

On general reasoning it is thought that the traverse of 50 kilometres given in Section 4.1 are in turbulence that is practically continuous and are therefore good samples to compare theoretical estimates of total numbers of gusts (i.e. zero crossings) with measured values. The estimates of the measured values are obtained by taking a Rayleigh distribution with the same root mean square velocity as that for the measured peaks and extrapolating it to zero velocity. This is done for each traverse and given in Table 16 on the assumption that the magnitude of the gust vector is a Rayleigh distribution; the corresponding values for the gust component having a Rayleigh distribution are much smaller but have approximately the same consistency. Whilst the theoretical values[2] of the zero crossings vary considerably between the different aircraft, the proportion of gusts is near 100 per cent for each of them.

6. Conclusions

An examination of the relative frequency of occurrence of different normal accelerations at points near the aircraft centre of gravity of about 200 hours of research flying, sub-divided into about 12 000 time periods mainly of about 1 minute, has shown that whilst for the individual time periods of about 1 minute there is not a significant difference between observed values of normal acceleration crossings and the commonly used Rayleigh distribution, the cumulative effect makes the difference definitely significant when a large number of periods are combined. Similarly there is no significant difference for individual time periods of about 1 minute if it is assumed that

(i) the frequency of occurrence of different magnitudes of the maxima of the gust velocity vector is a Rayleigh distribution,

(ii) the vector changes direction sufficiently slowly for the maxima of the components to occur at the same time as the maxima of the vector.

For this condition it was found that the cumulative effect did not produce significant differences when all the periods for each aircraft were grouped together. Nor was there any significant difference when the measurements from 36 traverses of severe turbulence encountered in 23 000 flying hours of civil operations were grouped together.

On the above assumptions the proportion of maxima of gust velocity vectors greater than U is equal to $\exp(-U^2/2\sigma^2)$ and the proportion of maxima of vertical component of gust velocity greater than U is equal to

$$\int_0^1 \exp\left(-U^2/2\sigma^2 x^2\right) dx.$$

It is also shown in this detailed analysis that Kaynes' aircraft responses based on the two-dimensional form of Von Karman's spectrum of turbulence give estimates of total numbers of gusts (zero crossings) that are close to the observed values for several aircraft with widely differing numbers of gusts per kilometre.

REFERENCES

No.	Author(s)	Title, etc.
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3	J. Taylor	Manual on aircraft loads. AGARDograph 83, Pergamon Press (1965).
4	N. I. Bullen	Gusts discrete and indiscrete. A.R.C. C.P. 1079 (1969).

APPENDIX

Proportion of Gust Components in One Direction for Gust Vectors having a Proportion $\exp(-U^2/2\sigma^2)$ **Greater than** U

It is assumed that the proportion of the maxima of gust velocity vectors that are greater than U is $\exp(-U^2/2\sigma^2)$.

The proportion that lies between U and $U + \delta U$ is

$$\frac{U}{\sigma^2}\exp(-U^2/2\sigma^2)\,\delta U.$$

The volume of the spherical shell bounded by U and $U + \delta U$ is $4\pi U^2 \delta U$. Hence the proportion per unit volume in the shell is

$$\frac{U}{\sigma^2}\exp(-U^2/2\sigma^2)\delta U/(4\pi U^2\,\delta U) = \exp(-U^2/2\sigma^2)/(4\pi U\sigma^2).$$

The volume of the ring bounded by U and $U + \delta U$ and by θ and $\theta + \delta\theta$ is

$$2\pi U^2 \cos\theta\,\delta U\,\delta\theta,$$

where θ is the angle between the direction of the gust vector and the plane perpendicular to the axis y.

Hence the proportion of gusts in this ring is

$$\frac{U}{2\sigma^2}\cos\theta\exp(-U^2/2\sigma^2)\,\delta U\,\delta\theta.$$

Let the magnitude of the gust vector component in the direction y be U_y so that $U = U_y \operatorname{cosec}\theta$. Then the proportion of gust vector components in the direction y that are greater than U_y is

$$\int_0^{\pi/2}\int_{U_y \operatorname{cosec}\theta}^{\infty}\frac{U}{2\sigma^2}\cos\theta\exp(-U^2/2\sigma^2)\,dU\,d\theta$$

$$= \frac{1}{2}\int_0^{\pi/2}\cos\theta\exp(-U_y^2\operatorname{cosec}^2\theta/2\sigma^2)\,d\theta$$

$$= \frac{1}{2}\int_0^{1}\exp(-U_y^2/2\sigma^2x^2)\,dx$$

where $x = \sin\theta$.

The corresponding proportion of components less than $-U_y$ is the same and hence the total proportion of gust components in the direction y of magnitude greater than U_y is

$$\int_0^1 \exp(-U_y^2/2\sigma^2x^2)\,dx$$

TABLE 1

Comparison on an Anson of Measured Numbers of Exceedances of Different Normal Acceleration Increments and Calculated Numbers with the Same Number at the Lowest Measured Increment

A measured increment is the highest value between crossing of the 1 g datum. The calculations are made for each of 620 time intervals of 1 minute.

Height ft	Distance km	Accel. g-incr.	Number of times exceeded		
			Calc. A	Calc. B	Measured
1500–5500	1992·1	0·00	46 207·6	22 064·9	
		0·10	11 220·0	11 220·0	11 220
		0·20	2 050·5	2 121·5	2 072
		0·30	338·3	251·4	388
		0·40	55·8	27·9	87
		0·50	10·9	4·4	17
		0·60	2·8	0·9	5
		0·70	0·9	0·2	1
5500–9500	319·7	0·00	1 069·6	441·2	
		0·10	162·0	162·0	162
		0·20	15·7	15·2	18
		0·30	1·6	1·1	1
All	2311·8	0·00	47 277·2	22 506·0	
		0·10	11 382·0	11 382·0	11 382
		0·20	2 066·2	2 136·7	2 090
		0·30	339·9	252·5	389
		0·40	56·0	28·0	87
		0·50	10·9	4·5	17
		0·60	2·8	0·9	5
		0·70	0·9	0·2	1

TABLE 2

Comparison on a Canberra of Measured Numbers of Exceedances of Different Normal Acceleration Increments and Calculated Numbers with the Same Number at the Lowest Measured Increment

A measured increment is the highest value* between crossing of the 1 g datum. The calculations are made for each of 6133 time intervals of an average of 0·86 minute.

Height ft	Distance km	Accel. g-incr.	Number of times exceeded		
			Calc. A	Calc. B	Measured
200	46 685·5	0·00	877 238·8	443 664·7	
		0·20	252 549·0	252 549·0	252 549
		0·30	122 333·5	133 533·8	129 860
		0·40	55 814·2	58 698·8	59 871
		0·60	9 940·0	7 304·3	8 980
		0·80	1 498·3	592·5	1 153
		1·00	202·8	40·7	184
		1·20	27·6	4·9	28
		1·40	5·0	1·6	12
		1·60	1·6	0·7	4

* The actual measurements were not precisely the highest value between crossings but the numerical values should not be significantly different.

TABLE 3

Comparison on a Meteor of Measured Numbers of Exceedances of Different Normal Acceleration Increments and Calculated Numbers with the Same Number at the Lowest Measured Increment

A measured increment is the highest value between crossing of the 1 g datum. The calculations are made for each of 240 time intervals of a quarter of a minute.

Height ft	Distance km	Accel. g-incr.	Number of times exceeded		
			Calc. A	Calc. B	Measured
300	494·2	0·00	10 331·2	6213·8	
		0·20	4 576·0	4576·0	4576
		0·40	1 877·6	2135·3	1941
		0·60	733·1	751·5	831
		0·80	272·1	213·7	334
		1·00	96·2	51·7	94
		1·20	32·7	11·1	19
		1·40	10·8	2·2	4
		1·60	3·5	0·4	1

TABLE 4

Comparison on a Viking of Measured Numbers of Exceedances of Different Normal Acceleration Increments and Calculated Numbers with the Same Number at the Lowest Measured Increment

A measured increment is the highest value between crossing of the 1 g datum. The calculations are made for each 4360 time intervals of 1 minute.

Height ft	Distance km	Accel. g-incr.	Number of times exceeded		
			Calc. A	Calc. B	Measured
0–1 500	40·7	0·00	389·3	158·8	
		0·10	56·0	56·0	56
		0·20	4·7	4·4	3
		0·30	0·3	0·2	1
1 500–5 500	6 318·6	0·00	43 112·4	19 802·4	
		0·10	9 450·0	9 450·0	9 450
		0·20	1 794·6	1 892·4	1 849
		0·30	371·6	308·6	414
		0·40	82·6	49·1	86
		0·50	20·4	9·0	30
		0·60	5·8	2·1	8
		0·70	1·9	0·6	3
5 500–9 500	10 086·9	0·00	18 375·1	7 466·3	
		0·10	2 675·0	2 675·0	2 675
		0·20	328·0	337·8	319
		0·30	59·0	46·5	62
		0·40	10·8	4·9	13
		0·50	1·8	0·4	3
		0·60	0·3	0·0	1
9 500–13 500	6 163·2	0·00	12 807·8	5 164·4	
		0·10	1 794·0	1 794·0	1 794
		0·20	204·7	211·3	213
		0·30	50·2	50·2	48
		0·40	18·8	16·4	17
		0·50	7·7	4·9	7
		0·60	3·1	1·3	3
		0·70	1·2	0·3	1
All	22 609·4	0·00	74 684·6	32 591·9	
		0·10	13 975·0	13 975·0	13 975
		0·20	2 331·9	2 445·9	2 384
		0·30	481·1	405·3	525
		0·40	112·3	70·4	116
		0·50	29·9	14·3	40
		0·60	9·1	3·3	12
		0·70	3·1	0·8	4

TABLE 5

Comparison on a York of Measured Numbers of Exceedances of Different Normal Acceleration Increments and Calculated Numbers with the Same Number at the Lowest Measured Increment

A measured increment is the highest value between crossing of the 1 g datum. The calculations are made for each of 360 time intervals of 1 minute.

Height ft	Distance km	Accel. g-incr.	Number of times exceeded		
			Calc. A	Calc. B	Measured
0–1500	108·1	0·00	1313·2	633·2	
		0·10	330·0	330·0	330
		0·20	65·9	69·0	72
		0·30	11·9	9·0	12
		0·40	2·0	0·8	2
5500–9500	1902·5	0·00	4578·5	1880·2	
		0·10	681·0	681·0	681
		0·20	70·9	70·8	67
		0·30	10·1	7·5	10
		0·40	1·6	0·6	2
All	2010·6	0·00	5891·7	2513·4	
		0·10	1011·0	1011·0	1011
		0·20	136·8	139·8	139
		0·30	22·1	16·6	22
		0·40	3·6	1·5	4

TABLE 6

Comparison on an Anson of Measured Numbers of Exceedances of Different Normal Acceleration Increments and Calculated Numbers with the Same Number at the Lowest Measured Increment for Approximately 50 km Traverses of Turbulence of Moderate Intensity

A measured increment is the highest value between crossing of the 1 g datum. The calculations are made for each traverse taken as one entity.

Height ft	Distance km	Accel. g-incr.	Number of times exceeded				
					Measured		
			Calc. A	Calc. B	Total	−ve	+ve
3000	50·4	0·00	1386·04	820·35			
		0·100	589·00	589·00	589	289	300
		0·200	197·43	218·00	174	92	82
		0·300	50·78	41·60	53	30	23
		0·400	9·81	4·09	19	10	9
		0·500	1·40	0·21	4	2	2
		0·600	0·15	0·01	1	0	1
3000	50·4	0·00	1357·30	852·22			
		0·100	660·00	660·00	660	310	350
		0·200	270·30	306·56	234	116	118
		0·300	91·54	85·41	85	43	42
		0·400	25·26	14·27	32	17	15
		0·500	5·62	1·43	14	9	5
		0·600	1·00	0·09	4	3	1
		0·700	0·14	0·00	2	1	1
		0·800	0·02	0·00	1	1	0

TABLE 7

Comparison on a Canberra of Measured Numbers of Exceedances of Different Normal Acceleration Increments and Calculated Number with the Same Numbers at the Lowest Measured Increment for Approximately 50 km Traverses of Turbulence at Midday over Flat Desert with a Range of Solar Radiations

A measured increment is the highest value* between crossing of the 1 g datum. The calculations are made for each traverse taken as an entity.

Height ft	Solar radiation mW/cm²	Distance km	Accel. g-incr.	Number of times exceeded				
						Measured		
				Calc. A	Calc. B	Total	− ve	+ ve
200	30–34	50·0	0·00	866·09	531·36			
			0·200	400·00	400·00	400	176	224
			0·300	252·98	280·48	248	100	148
			0·400	151·91	170·64	149	54	95
			0·600	46·42	41·25	47	15	32
			0·800	11·22	5·65	14	3	11
			1·000	2·12	0·44	3	0	3
200	35–39	61·3	0·00	1416·48	734·33			
			0·200	427·00	427·00	427	152	275
			0·300	199·35	216·82	210	53	157
			0·400	82·62	83·95	85	13	72
			0·600	9·68	5·58	9	0	9
200	40–44	61·1	0·00	1240·11	649·05			
			0·200	384·00	384·00	384	166	218
			0·300	182·89	199·25	202	83	119
			0·400	77·71	79·52	83	35	48
			0·600	9·72	5·76	7	4	3
200	45–49	49·8	0·00	991·24	582·43			
			0·200	414·00	414·00	414	206	208
			0·300	244·43	270·21	245	111	134
			0·400	135·15	148·69	151	69	82
			0·600	33·51	26·98	32	12	20
			0·800	6·17	2·47	6	4	2
200	50–54	49·5	0·00	1094·72	622·55			
			0·200	422·00	422·00	422	176	246
			0·300	235·56	259·56	237	89	148
			0·400	121·69	131·44	129	48	81
			0·600	25·34	18·81	25	7	18
			0·800	3·71	1·24	3	1	2
			1·000	0·38	0·04	1	0	1

* The actual measurements were not precisely the highest value between crossings but the numerical values given should not be significantly different.

TABLE 7 (Contd)

Height ft	Solar radiation mW/cm²	Distance km	Accel. g-incr.	Number of times exceeded: Calc. A	Calc. B	Measured: Total	−ve	+ve
200	55–59	50·3	0·00	897·57	516·33			
			0·200	356·00	356·00	356	161	191
			0·300	202·74	223·67	206	90	116
			0·400	107·32	116·68	105	46	59
			0·600	23·80	18·18	26	11	15
			0·800	3·79	1·35	3	0	3
			1·000	0·42	0·05	1	0	1
200	60–64	43·5	0·00	885·01	506·72			
			0·200	347·00	347·00	347	149	198
			0·300	196·03	216·16	202	82	120
			0·400	102·75	111·43	109	41	68
			0·600	22·21	16·78	19	8	11
			0·800	3·42	1·18	5	2	3
200	65–69	57·5	0·00	1320·91	783·97			
			0·200	565·00	565·00	565	269	296
			0·300	339·12	375·17	348	157	191
			0·400	191·27	211·49	226	100	126
			0·600	49·88	41·12	42	14	28
			0·800	9·81	4·15	8	4	4
			1·000	1·43	0·22	1	1	0
200	70–74	54·8	0·00	1166·72	685·95			
			0·200	488·00	488·00	488	223	265
			0·300	288·41	318·85	290	115	175
			0·400	159·67	175·71	151	58	93
			0·600	39·71	32·02	37	15	22
			0·800	7·34	2·95	10	4	6
			1·000	0·99	0·14	3	1	2
			1·200	0·10	0·00	1	0	1
200	75–79	54·9	0·00	1100·19	654·98			
			0·200	474·00	474·00	474	212	262
			0·300	285·91	316·39	291	111	180
			0·400	162·23	179·65	165	45	120
			0·600	42·95	35·66	41	10	31
			0·800	8·62	3·71	10	2	8
			1·000	1·29	0·20	2	0	2
200	80–84	61·8	0·00	1395·48	821·81			
			0·200	586·00	586·00	586	275	311
			0·300	347·27	383·98	362	150	212
			0·400	192·89	212·46	206	72	134
			0·600	48·38	39·17	51	14	37
			0·800	9·05	3·67	5	1	4
			1·000	1·24	0·17	1	0	1

TABLE 8

Comparison on a Meteor of Measured Numbers of Exceedances of Different Normal Acceleration Increments and Calculated Numbers with the Same Number at the Lowest Measured Increment for Approximately 50 km Traverses of Turbulence of Moderate Intensity

A measured increment is the highest value between crossing of the 1 g datum. The calculations are made for the traverse taken as one entity.

Height ft	Distance km	Accel. g-incr.	Number of times exceeded				
					Measured		
			Calc. A	Calc. B	Total	−ve	+ve
300	49·4	0·00	1127·82	742·31			
		0·200	606·00	606·00	606	304	302
		0·400	286·14	329·71	283	131	152
		0·600	117·22	119·55	128	52	76
		0·800	41·23	28·89	48	15	33
		1·000	12·34	4·65	11	1	10
		1·200	3·12	0·50	1	0	1

TABLE 9

Comparison on a Viking of Measured Numbers of Exceedances of Different Normal Acceleration Increments and Calculated Numbers with the Same Number at the Lowest Measured Increment for Approximately 50 km Traverses of Turbulence of Moderate Intensity

A measured increment is the highest value between crossing of the 1 g datum. The calculations are made for each traverse taken as one entity.

Height ft	Distance km	Accel. g-incr.	Number of times exceeded				
			Calc. A	Calc. B	Measured		
					Total	−ve	+ve
3000	48·4	0·00	916·13	526·80			
		0·100	363·00	363·00	363	183	180
		0·200	109·26	118·77	108	61	47
		0·300	24·17	18·45	28	18	10
		0·400	3·84	1·36	5	3	2
8000	48·8	0·00	807·65	444·29			
		0·100	286·00	286·00	286	145	141
		0·200	72·08	76·29	76	47	29
		0·300	12·39	8·43	13	10	3
		0·400	1·41	0·39	2	1	1

TABLE 10

Comparison on a York of Measured Numbers of Exceedances of Different Normal Acceleration Increments and Calculated Numbers with the Same Number at the Lowest Measured Increment for Approximately 50 km Traverses of Turbulence of Moderate Intensity

A measured increment is the highest value between crossing of the 1 g datum. The calculations are made for each traverse taken as one entity.

Height ft	Distance km	Accel. g-incr.	Number of times exceeded				
					Measured		
			Calc. A	Calc. B	Total	−ve	+ve
1000	44·4	0·00	540·24	286·21			
		0·100	173·00	173·00	173	74	99
		0·200	37·01	38·21	37	14	23
		0·300	5·02	3·08	6	2	4
		0·400	0·42	0·09	1	0	1

TABLE 11

Comparison on an Anson and Viking of Measured Numbers of Exceedances of Different Normal Acceleration Increments and Calculated Numbers with the Same Number at the Lowest Measured Increment for Traverses of Moderately Severe Turbulence

A measured increment is the highest value between crossing of the 1 g datum. The calculations are made for each traverse taken as an entity.

Aircraft	Height ft	Distance km	Accel. g-incr.	Number of times exceeded				
				Calc. A	Calc. B	Measured		
						Total	− ve	+ ve
Anson	3 000	4·1	0·00	159·49	112·48			
			0·100	98·00	98·00	98	50	48
			0·200	55·53	64·82	58	29	29
			0·300	28·82	32·55	26	13	13
			0·400	13·62	12·41	15	7	8
			0·500	5·83	3·59	6	4	2
			0·600	2·25	0·79	3	2	1
			0·700	0·78	0·13	1	0	1
Viking	2 000	1·5	0·00	37·99	26·58			
			0·100	23·00	23·00	23	10	13
			0·200	12·78	14·90	15	6	9
			0·300	6·47	7·23	6	2	4
			0·400	2·96	2·63	3	1	2
			0·500	1·22	0·72	2	1	1
	8 000	1·7	0·00	35·47	23·91			
			0·100	20·00	20·00	20	13	7
			0·200	10·10	11·70	8	5	3
			0·300	4·51	4·79	5	3	2
			0·400	1·77	1·37	3	1	2
			0·500	0·61	0·27	1	1	0
	11 000	5·8	0·00	89·39	64·97			
			0·100	58·00	58·00	58	30	28
			0·200	35·29	41·26	39	22	17
			0·300	20·03	23·39	21	12	9
			0·400	10·56	10·57	11	5	6
			0·500	5·15	3·80	5	3	2
			0·600	2·32	1·09	2	1	1
			0·700	0·96	0·25	1	1	0

TABLE 12

Comparison on Three 4-Engined Pure Jet Transports of Measured Numbers of Exceedances of Different Gust Increments and Calculated Numbers with the Same Number at the Lowest Measured Increment During 36 Traverses of Severe Turbulence Encountered in 23 000 Hours of Civil Flying

A measured increment is the highest value between crossing of the 1 g datum. The calculations are made for each traverse taken as one entity.

Height ft	Distance km	Gust incr. m/s eas	Number of times exceeded		
			Calc. A	Calc. B	Measured
0–1500	0·0				
1500–5500	4·1	0·00	11·5	6·9	
		1·00	9·1	6·7	
		2·00	7·1	6·1	
		3·00	5·4	5·2	
		4·00	4·0	4·3	4
		5·00	2·9	3·2	1
		6·00	2·1	2·3	1
		7·00	1·5	1·6	1
		8·00	1·0	1·0	1
		9·00	0·7	0·6	1
		10·00	0·4	0·3	1
		11·00	0·3	0·2	1
5500–9500	71·3	0·00	301·5	170·0	
		1·00	221·3	161·8	
		2·00	159·9	140·6	
		3·00	114·6	113·6	
		4·00	81·7	87·1	79
		5·00	58·0	64·1	50
		6·00	40·9	45·4	38
		7·00	28·6	30·9	26
		8·00	19·7	20·2	19
		9·00	13·4	12·8	17
		10·00	9·0	7·9	12
		11·00	6·0	4·7	7
		12·00	4·0	2·8	5
		13·00	2·6	1·6	4
		14·00	1·7	0·9	4
		15·00	1·1	0·5	2
9 500–13 500	20·1	0·00	169·1	94·9	
		1·00	124·2	90·2	
		2·00	88·7	77·7	
		3·00	61·7	61·1	
		4·00	41·9	44·4	43
		5·00	27·9	30·3	30
		6·00	18·3	19·7	23
		7·00	11·8	12·3	11
		8·00	7·6	7·5	8

TABLE 12 (Contd.)

Height ft	Distance km	Gust incr. m/s eas	Number of times exceeded		
			Calc. A	Calc. B	Measured
9 500–13 500		9·00	4·9	4·6	5
		10·00	3·2	2·8	2
		11·00	2·1	1·7	2
		12·00	1·4	1·1	1
		13·00	1·0	0·8	1
		14·00	0·7	0·5	1
		15·00	0·5	0·4	1
13 500–17 500	22·4	0·00	128·7	68·6	
		1·00	93·7	65·3	
		2·00	65·9	56·3	
		3·00	44·7	44·0	
		4·00	29·2	31·2	29
		5·00	18·3	20·1	17
		6·00	11·1	11·8	8
		7·00	6·5	6·4	7
		8·00	3·6	3·2	4
		9·00	2·0	1·5	3
		10·00	1·1	0·7	1
		11·00	0·6	0·3	1
17 500–21 500	4·8	0·00	24·5	15·4	
		1·00	20·1	15·1	
		2·00	16·2	14·1	
		3·00	12·9	12·5	
		4·00	10·1	10·7	8
		5·00	7·8	8·7	4
		6·00	5·9	6·7	4
		7·00	4·4	5·0	4
		8·00	3·3	3·6	4
		9·00	2·4	2·4	4
		10·00	1·7	1·6	3
		11·00	1·2	1·0	3
		12·00	0·8	0·6	2
21 500–29 500	47·1	0·00	310·7	166·5	
		1·00	206·1	153·7	
		2·00	129·8	121·1	
		3·00	77·9	82·3	
		4·00	44·7	49·1	40
		5·00	24·9	26·5	21
		6·00	13·6	13·5	13
		7·00	7·4	6·7	9
		8·00	4·1	3·2	6
		9·00	2·3	1·5	2
		10·00	1·3	0·7	1
		11·00	0·7	0·3	1

TABLE 12 (Contd.)

Height ft	Distance km	Gust incr. m/s eas	Number of times exceeded		
			Calc. A	Calc. B	Measured
29 500–37 500	161·8	0·00	585·7	322·1	
		1·00	421·1	305·1	
		2·00	292·8	260·0	
		3·00	197·2	200·2	
		4·00	129·0	140·6	130
		5·00	82·3	91·1	87
		6·00	51·5	55·3	51
		7·00	31·8	32·0	30
		8·00	19·5	17·8	20
		9·00	11·8	9·6	14
		10·00	7·1	5·0	7
		11·00	4·3	2·5	4
		12·00	2·5	1·2	3
All	331·6	0·00	1531·7	844·5	
		1·00	1095·5	797·9	
		2·00	760·3	675·7	
		3·00	514·2	518·9	
		4·00	340·6	367·4	333
		5·00	222·2	244·1	210
		6·00	143·4	154·8	138
		7·00	92·0	94·8	88
		8·00	58·8	56·5	62
		9·00	37·4	32·9	46
		10·00	23·8	18·9	27
		11·00	15·1	10·7	19
		12·00	9·6	6·0	11
		13·00	6·1	3·4	5
		14·00	3·9	1·9	5
		15·00	2·5	1·1	3

TABLE 13

Probabilities of Larger Gusts Being Encountered than those Recorded in Traverses of Approximately 50 km of Turbulence of Moderate Intensity

Aircraft	Height ft	Solar radiation mW/cm^2	Probability based on a Rayleigh distribution of	
			A—the gust vector	B—the vertical component
Anson	3000		0·069	0·002
	3000		0·008	0·000
Canberra	200	30–34	0·504	0·071
	200	35–39	0·730	0·287
	200	40–44	0·855	0·454
	200	45–49	0·827	0·307
	200	50–54	0·164	0·012
	200	55–59	0·189	0·015
	200	60–64	0·616	0·159
	200	65–69	0·538	0·078
	200	70–74	0·045	0·001
	200	75–79	0·360	0·036
	200	80–84	0·480	0·061
Meteor	300		0·868	0·214
Viking	3000		0·666	0·185
	8000		0·497	0·124
York	1000		0·167	0·026

TABLE 14

Probabilities of Larger Gusts Being Encountered than Those Recorded in Traverses of Turbulence of Moderately Severe Intensity

Aircraft	Height ft	Length of traverse km	Probability based on a Rayleigh distribution of	
			A—the gust vector	B—the vertical component
Anson	3 000	4·1	0·430	0·071
Viking	2 000	1·5	0·610	0·373
	8 000	1·7	0·354	0·149
	11 000	5·8	0·520	0·144

TABLE 15

Probabilities of Larger Gusts Being Encountered than Those Recorded in Traverses of Turbulence of Severe Intensity During 23 000 Hours of Civil Flying

Aircraft	Height ft	Length of traverse km	Probability based on a Rayleigh distribution of	
			A—the gust vector	B—the vertical component
Type I	33 800	3·2	0·323	0·288
	33 000	3·3	0·214	0·118
	6 000	2·1	0·362	0·249
	18 800	2·2	0·302	0·189
	19 100	2·6	0·245	0·193
	9 500	4·6	0·128	0·050
	15 500	19·7	0·233	0·089
	8 300	6·7	0·392	0·269
	11 000	2·3	0·282	0·231
	31 000	3·2	0·430	0·369
	32 300	29·3	0·020	0·004
	6 000	3·7	0·182	0·086
	29 000	3·1	0·396	0·284
Type III (later version of Type I)	22 200	8·5	0·377	0·182
	12 000	5·5	0·060	0·012
	13 500	9·8	0·561	0·347
	9 000	2·4	0·068	0·014
	27 200	35·5	0·109	0·023
	9 000	9·1	0·612	0·434
	10 300	2·5	0·317	0·368
	8 600	2·5	0·116	0·058
	32 000	12·7	0·404	0·158
Type II	7 500	7·1	0·301	0·221
	1 800	4·1	0·161	0·095
	34 900	7·4	0·308	0·163
	32 600	10·3	0·223	0·127
	8 000	14·1	0·649	0·553
	30 800	3·5	0·236	0·163
	36 000	3·7	0·536	0·455
	9 100	5·2	0·275	0·185
	35 000	3·9	0·341	0·268
	35 700	11·2	0·153	0·104
	16 100	2·7	0·348	0·302
	33 800	3·5	0·259	0·142
	34 000	66·5	0·425	0·186
	5 600	13·8	0·015	0·005

TABLE 16

Comparison of Calculated Number of Gusts in Continuous Turbulence with Estimates from Approximately 50 km Traverses of Turbulence of Moderate Intensity, Based on the Assumption that there is a Rayleigh Distribution of the Magnitudes of the Maxima of the Gust Velocity Vector

Aircraft	Height ft	Solar radiation mW/cm^2	Number of sub-divisions	Calculated number of gusts per km in cont. turb.	Estimates from the measurements of the number of gusts encountered in continuous turbulence									
					Individual sub-divisions percentage of calculated number								Mean of values in sub-divisions percentage of calculated number	Whole traverse taken together percentage of calculated number
Anson	3000		12	31·07	56·1	83·0	109·7	96·5	154·4	119·3	97·0	117·4	93·5	88·6
					63·1	91·1	95·6	45·1						
	3000		12	31·07	44·1	107·1	73·3	86·6	133·5	86·1	78·4	115·5	94·2	86·7
					93·6	128·8	93·4	90·5						
Canberra	200	30–34	7	24·67	73·3	59·8	75·0	92·5	53·2	85·0	70·6		72·8	70·3
		35–39	7	24·17	97·3	104·9	111·4	99·1	107·3	79·6	80·5		97·3	95·6
		40–44	7	24·15	92·3	74·7	89·2	74·8	113·4	78·2	66·3		84·1	84·1
		45–49	7	24·62	102·2	70·0	92·4	69·5	76·0	77·1	90·7		82·6	80·9
		50–54	7	24·13	91·4	119·0	111·5	81·1	97·8	62·7	84·2		92·5	89·8
		55–59	7	24·13	72·2	81·1	59·8	70·0	74·7	74·0	109·5		77·3	74·0
		60–64	7	24·41	81·9	92·7	93·8	85·0	78·1	60·6	108·7		85·8	83·4
		65–69	7	24·02	168·2	68·1	101·0	62·1	103·7	69·3	124·8		99·6	95·6
		70–74	7	25·03	78·4	74·4	96·9	90·6	90·6	110·9	101·6		91·9	85·1
		75–79	7	22·69	86·8	116·6	96·3	84·0	92·2	74·9	83·7		90·7	88·3
		80–84	7	24·72	123·8	97·3	96·8	77·1	96·3	84·8	75·1		93·0	91·0
Meteor	300		24	26·66	74·0	84·2	48·1	117·0	111·2	65·2	81·7	100·8	88·7	85·6
					62·3	88·5	136·2	70·9	31·7	75·4	57·4	47·9		
					78·5	123·7	115·8	95·8	86·7	77·3	151·3	147·1		
Viking	3000		10	20·80	90·1	100·5	98·5	86·7	98·8	96·6	98·6	86·9	96·7	92·2
					119·6	91·6								
	8000		10	19·21	83·3	59·2	115·5	60·8	93·7	88·5	79·4	81·8	90·8	86·2
					110·9	135·4								
York	1000		9	17·43	98·7	54·5	77·0	83·0	92·8	126·6	81·2	63·5	83·8	69·7
					77·0									

TABLE 17

Calculated Values of $\int_0^1 \exp(-U^2/2\sigma^2x^2)\,dx$

U/σ	$\int_0^1 \exp(-U^2/2\sigma^2x^2)\,dx$	U/σ	$\int_0^1 \exp(-U^2/2\sigma^2x^2)\,dx$
0·1	8·79664, −1	2·6	3·66940, −3
0·2	7·69271, −1	2·7	2·65729, −3
0·3	6·68671, −1	2·8	1·90776, −3
0·4	5·77625, −1	2·9	1·35777, −3
0·5	4·95802, −1	3·0	9·57919, −4
0·6	4·22800, −1	3·1	6·69894, −4
0·7	3·58145, −1	3·2	4·64345, −4
0·8	3·01315, −1	3·3	3·19017, −4
0·9	2·51744, −1	3·4	2·17224, −4
1·0	2·08841, −1	3·5	1·46590, −4
1·1	1·72004, −1	3·6	9·80367, −5
1·2	1·40628, −1	3·7	6·49749, −5
1·3	1·14122, −1	3·8	4·26737, −5
1·4	9·19134, −2	3·9	2·77728, −5
1·5	7·34612, −2	4·0	1·79105, −5
1·6	5·82590, −2	4·1	1·14450, −5
1·7	4·58407, −2	4·2	7·24647, −6
1·8	3·57836, −2	4·3	4·54603, −6
1·9	2·77091, −2	4·4	2·82567, −6
2·0	2·12830, −2	4·5	1·74013, −6
2·1	1·62137, −2	4·6	1·06171, −6
2·2	1·22499, −2	4·7	6·41772, −7
2·3	9·17823, −3	4·8	3·84326, −7
2·4	6·81914, −3	4·9	2·28010, −7
2·5	5·02363, −3	5·0	1·34008, −7

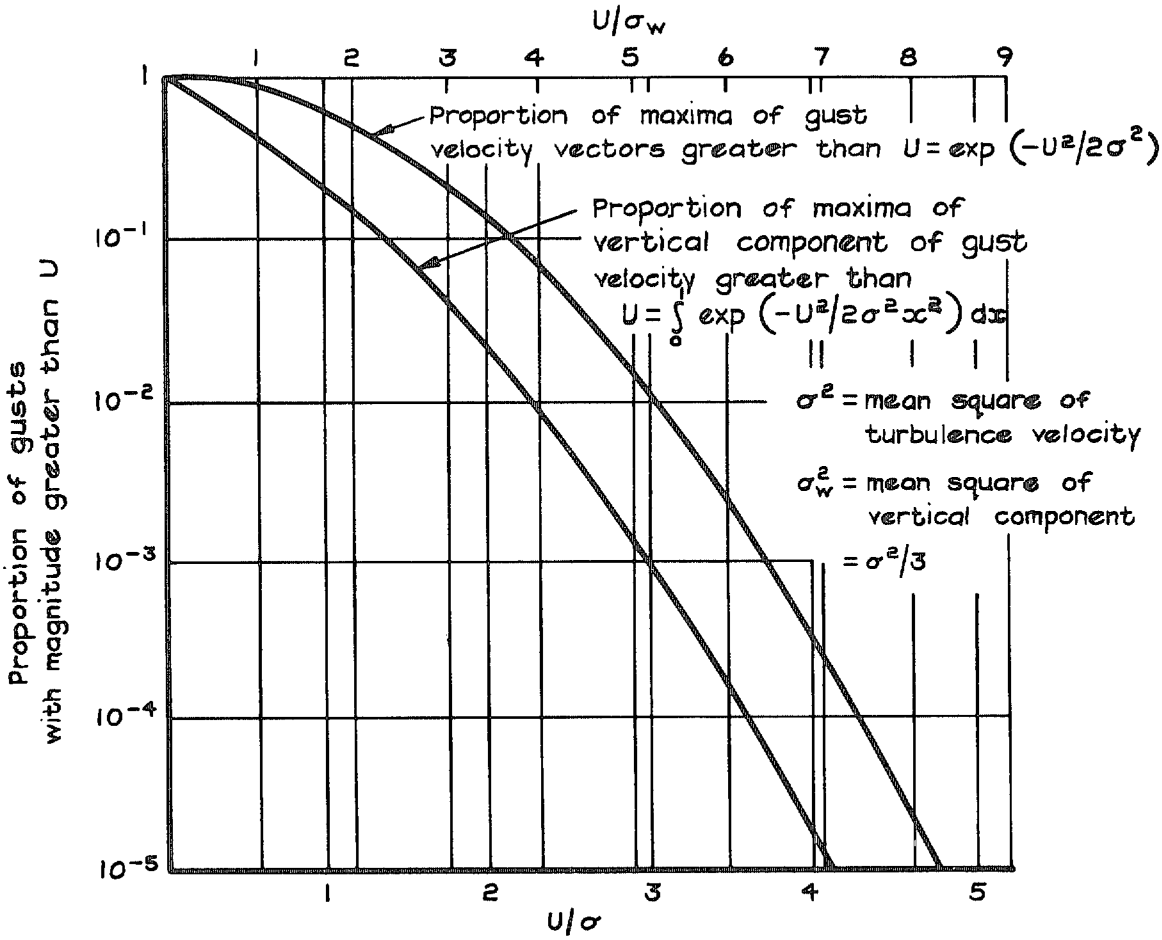

FIG 1. Relative frequency of occurrence of gusts with Rayleigh distribution of maxima of gust velocity vector.

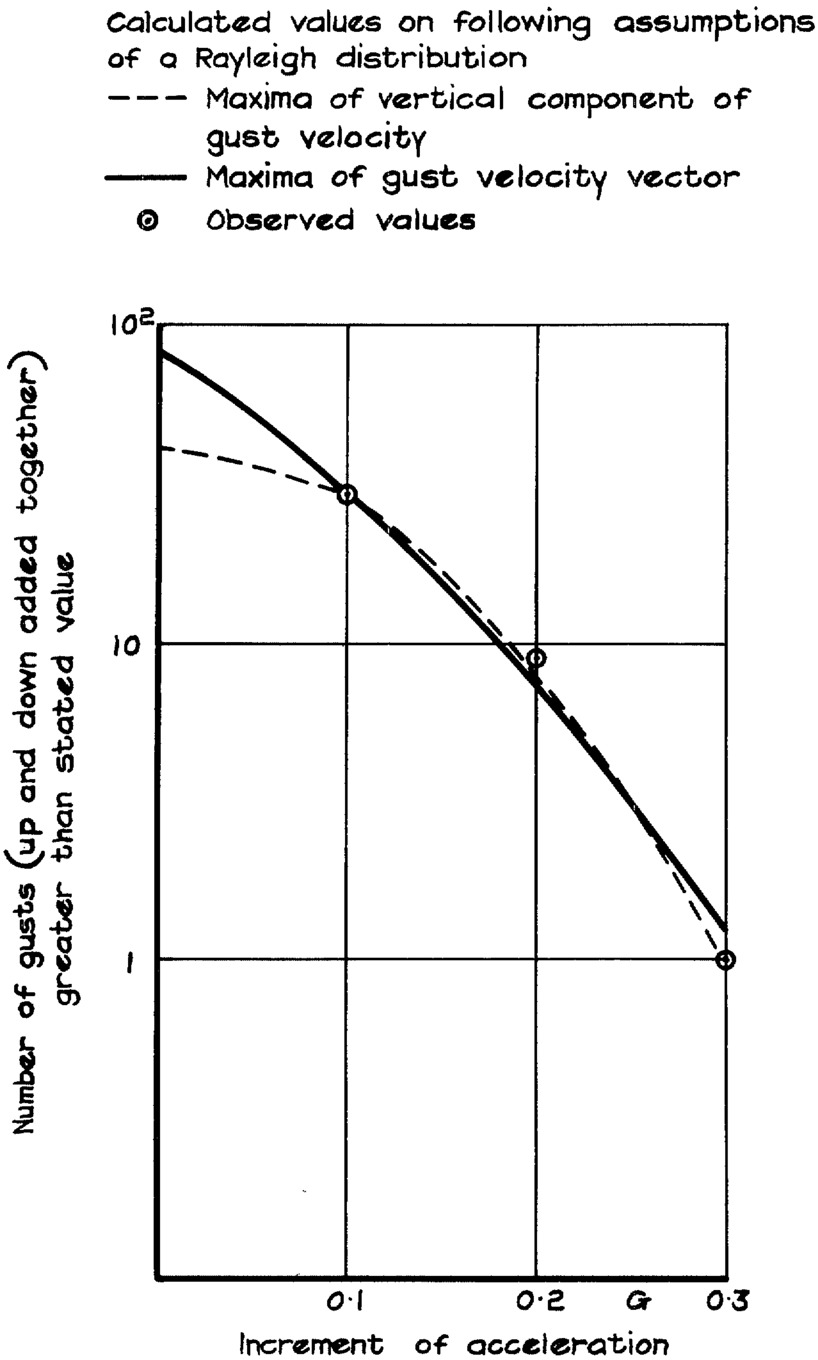

FIG 2. Number of gusts encountered in one minute of typical flying turbulence.

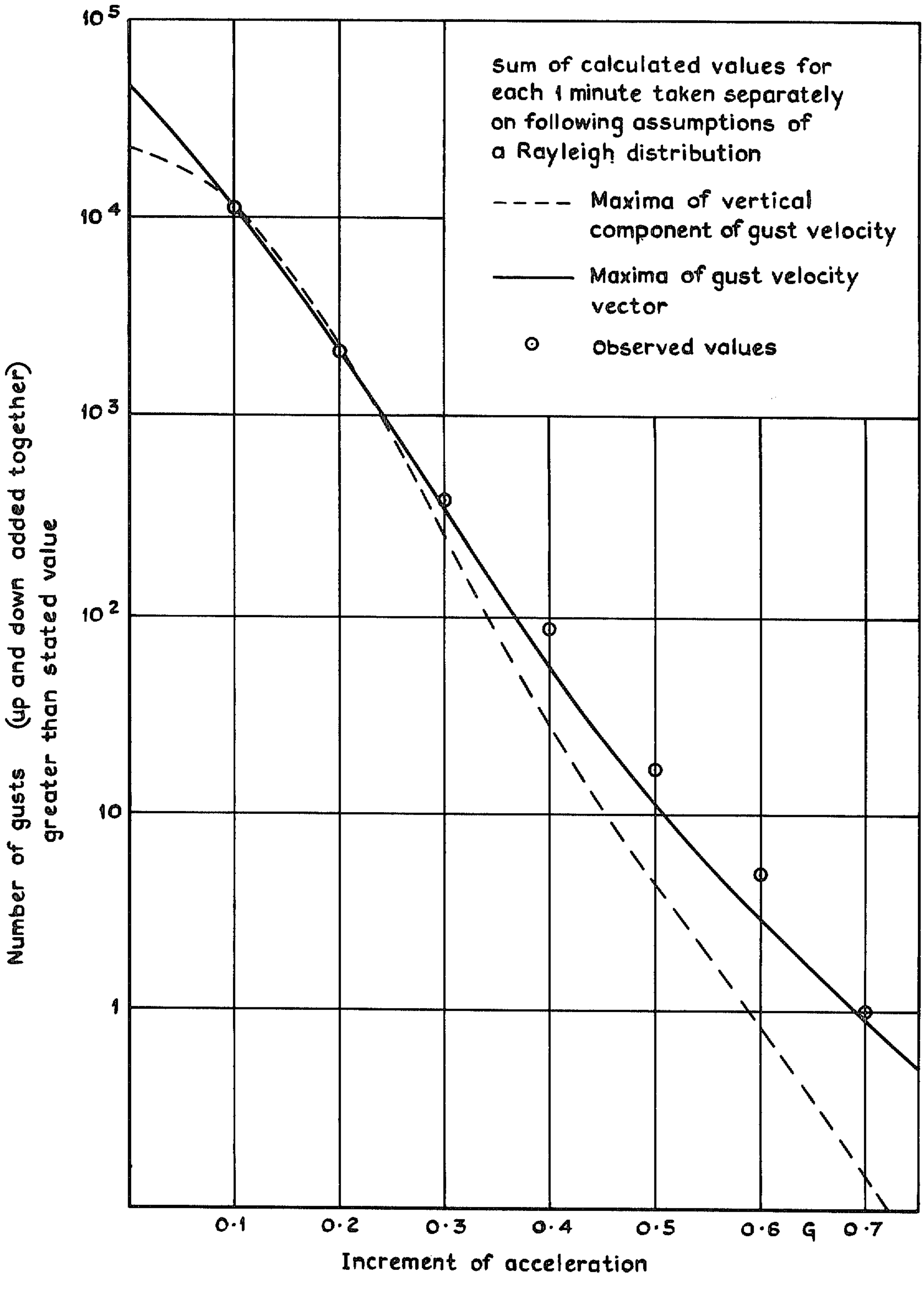

FIG. 3. Anson, number of gusts encountered in 620 minutes flying.

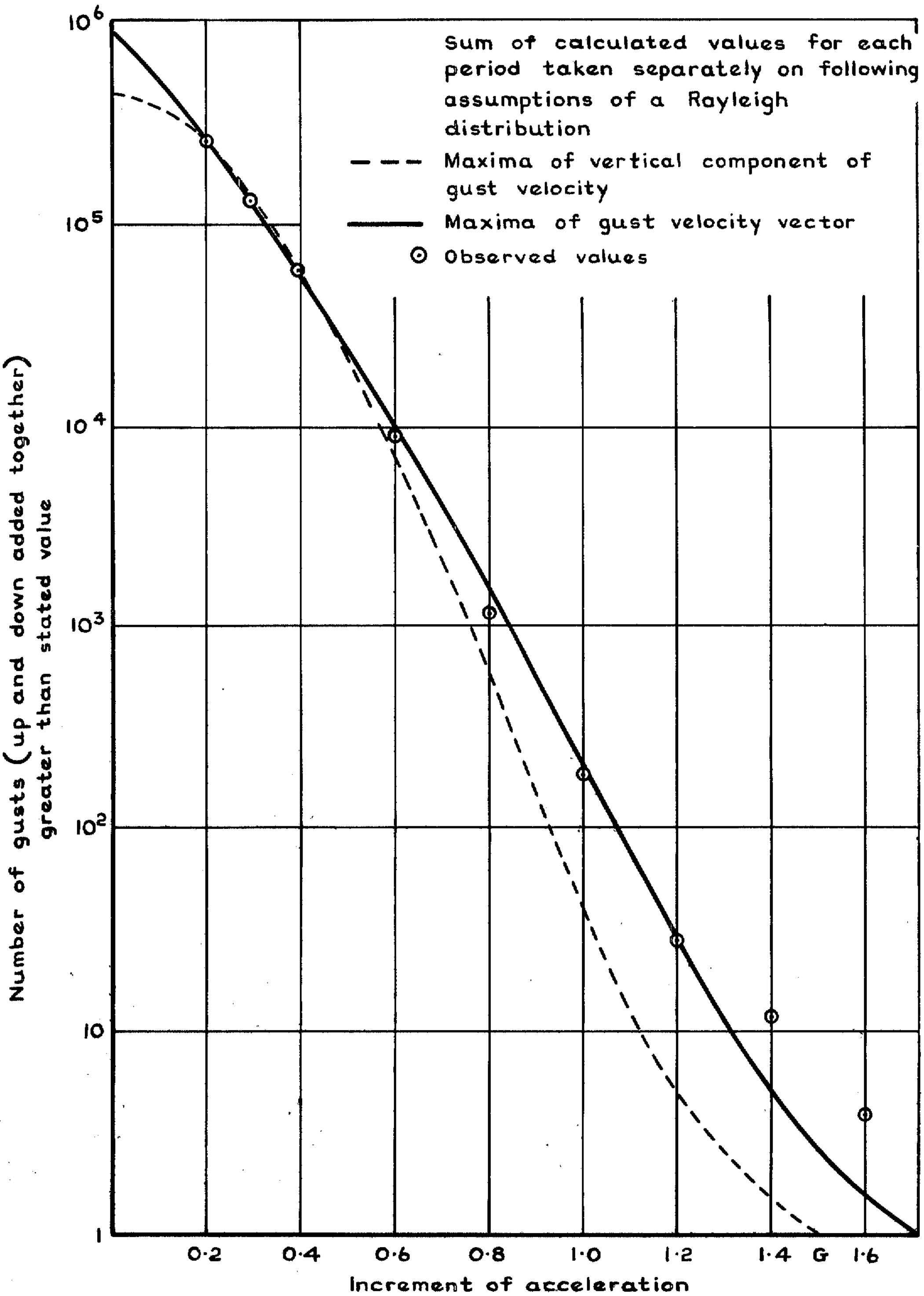

FIG. 4. Canberra, number of gusts encountered in 6133 periods of flying, each period being about 0·86 minutes.

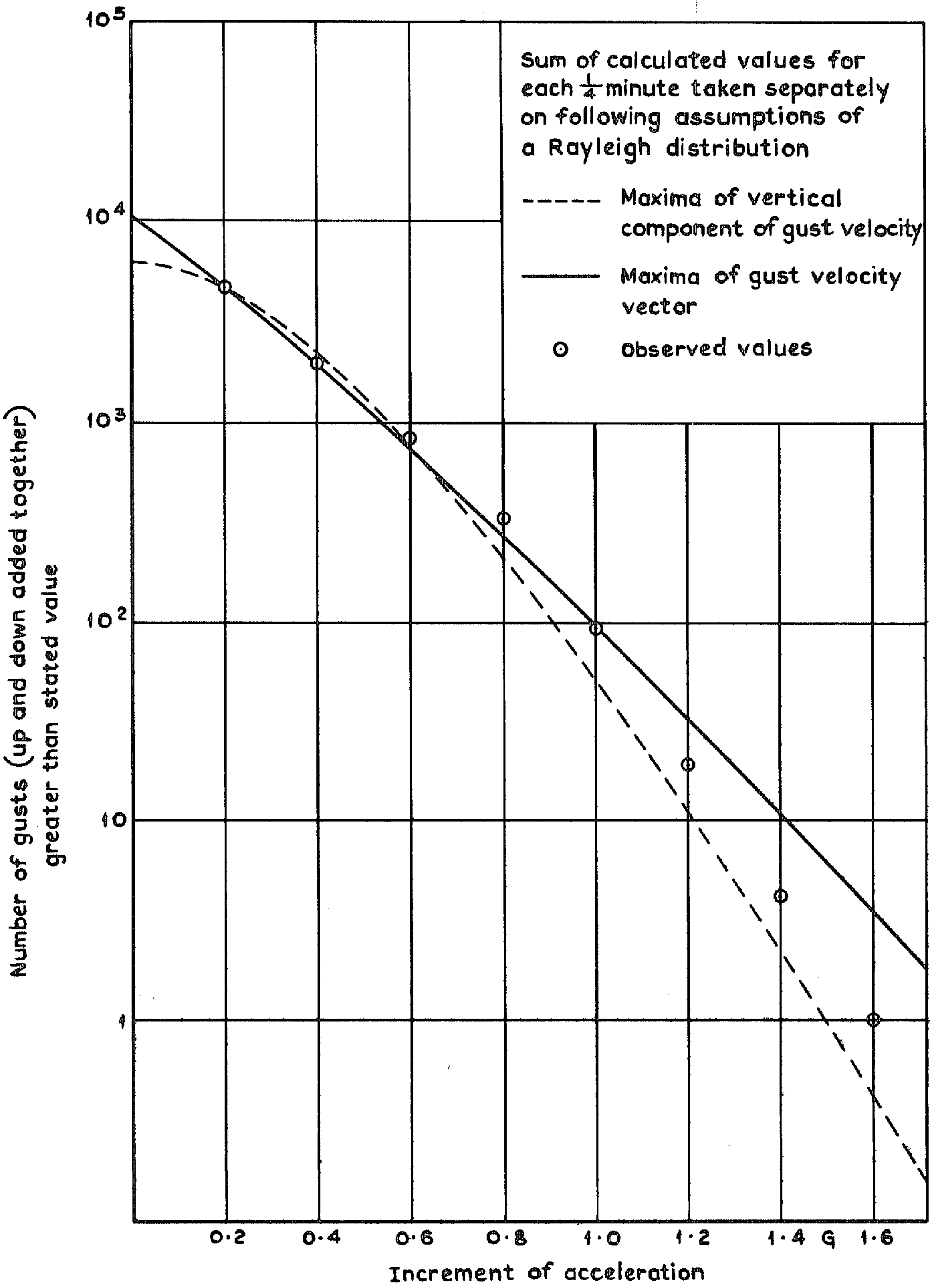

FIG. 5. Meteor, number of gusts encountered in 240 periods of flying, each period being $\frac{1}{4}$ minute.

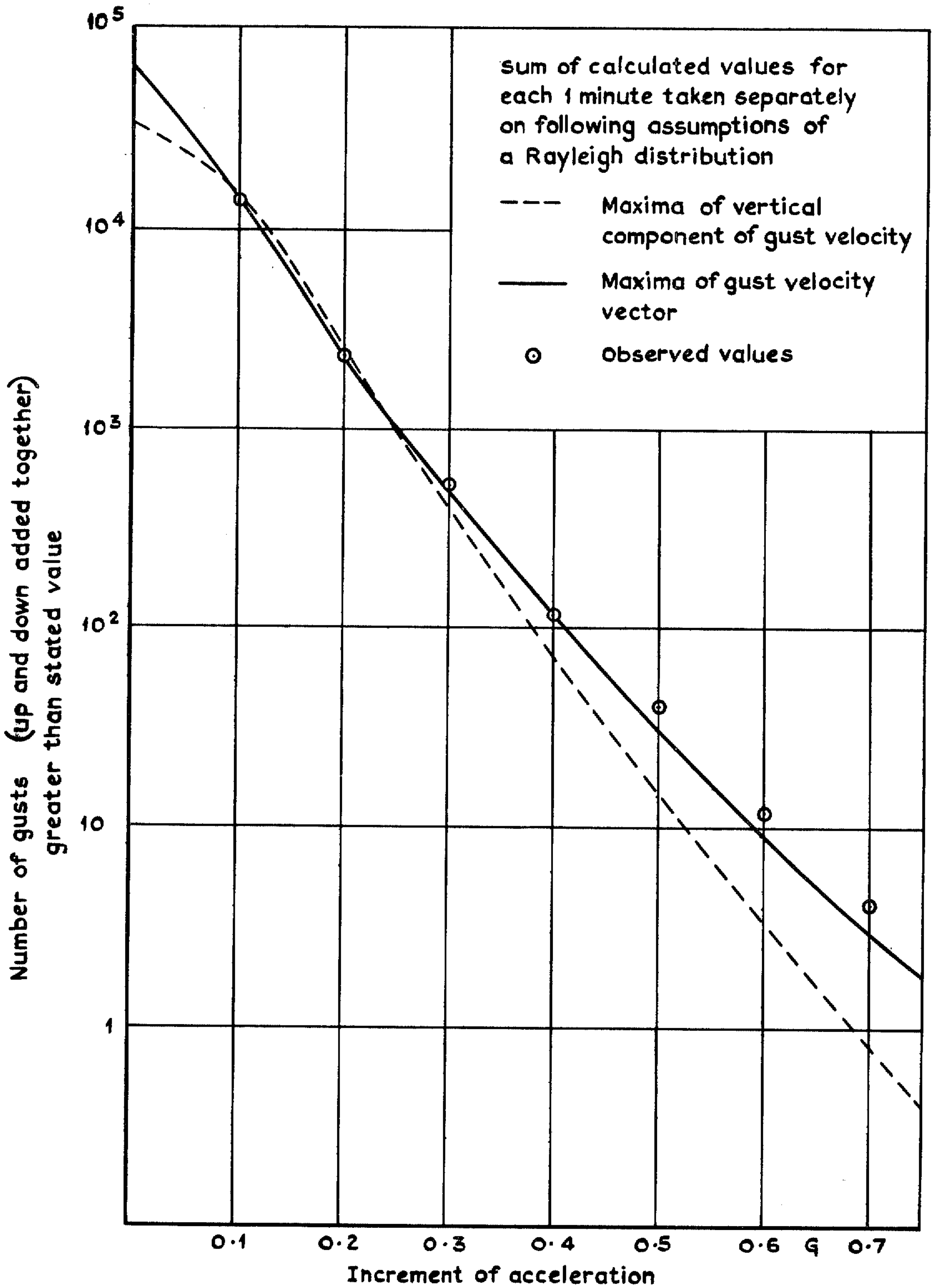

FIG. 6. Viking, number of gusts encountered in 4360 minutes flying.

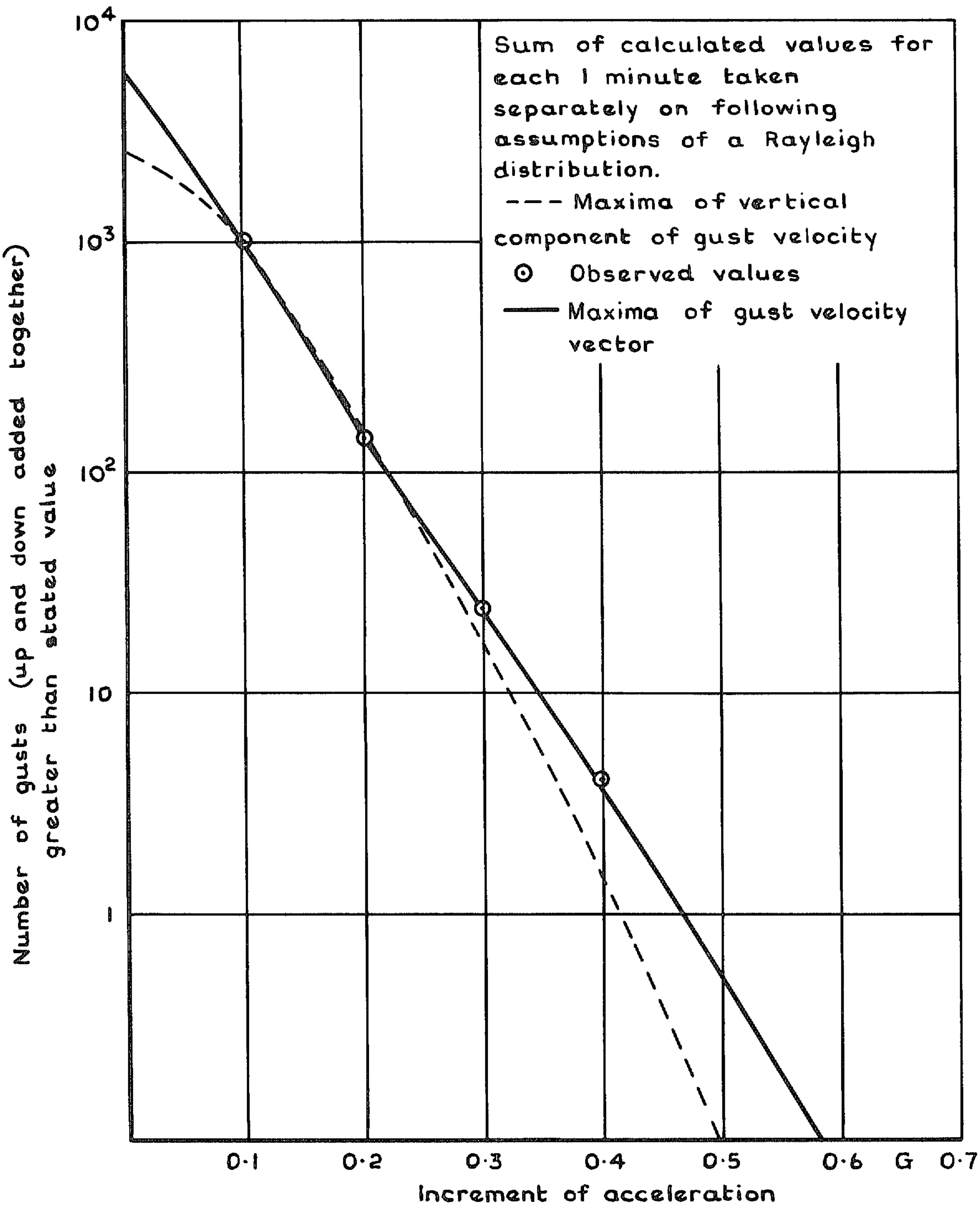

FIG. 7. York, number of gusts encountered in 360 minutes flying.

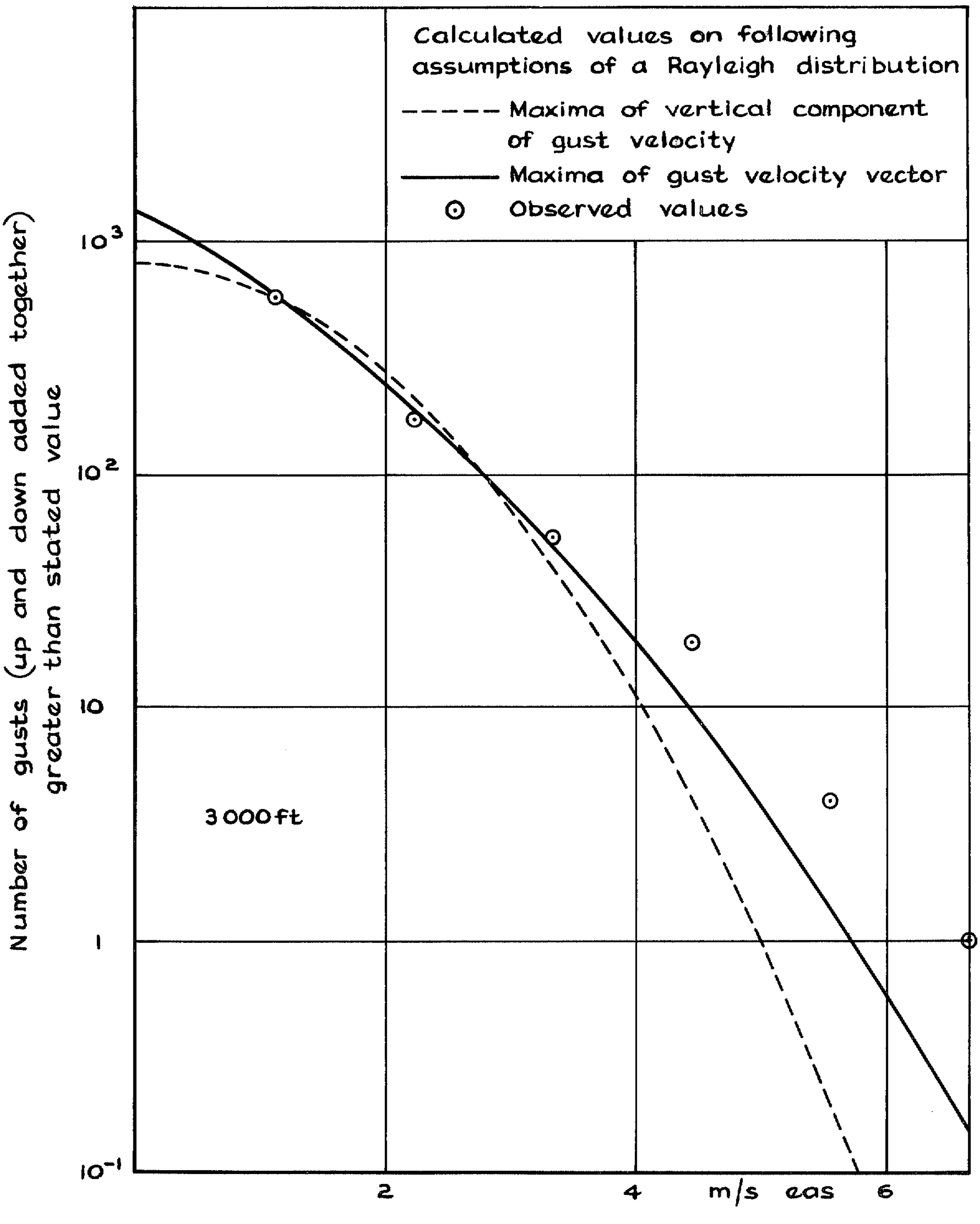

FIG. 8a. Anson, number of gusts encountered in approximately 50 km flying through individual areas of turbulence.

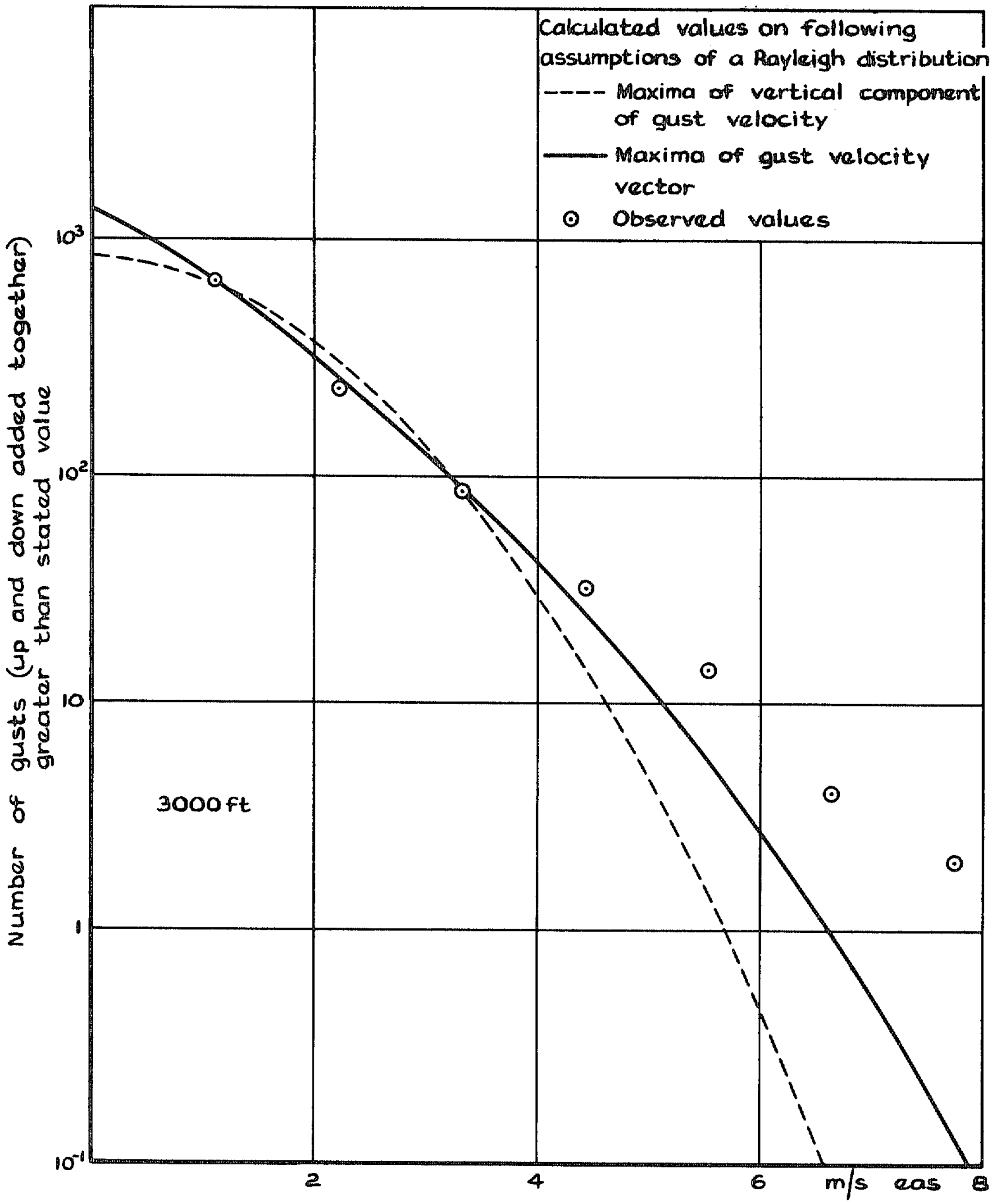

FIG. 8b. Anson, number of gusts encountered in approximately 50 km flying through individual areas of turbulence.

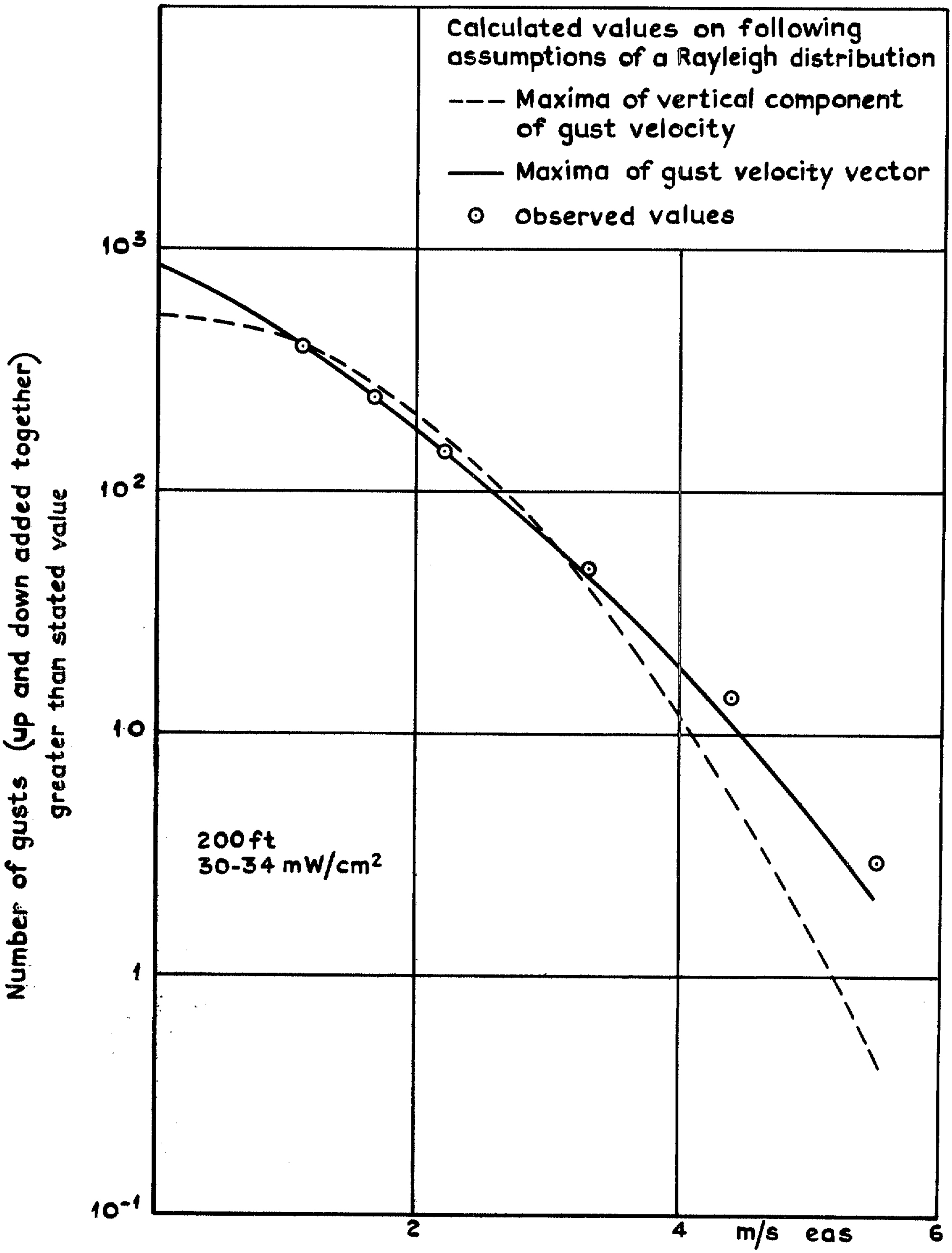

FIG. 9a. Canberra, number of gusts encountered in approximately 50 km flying through individual areas of turbulence.

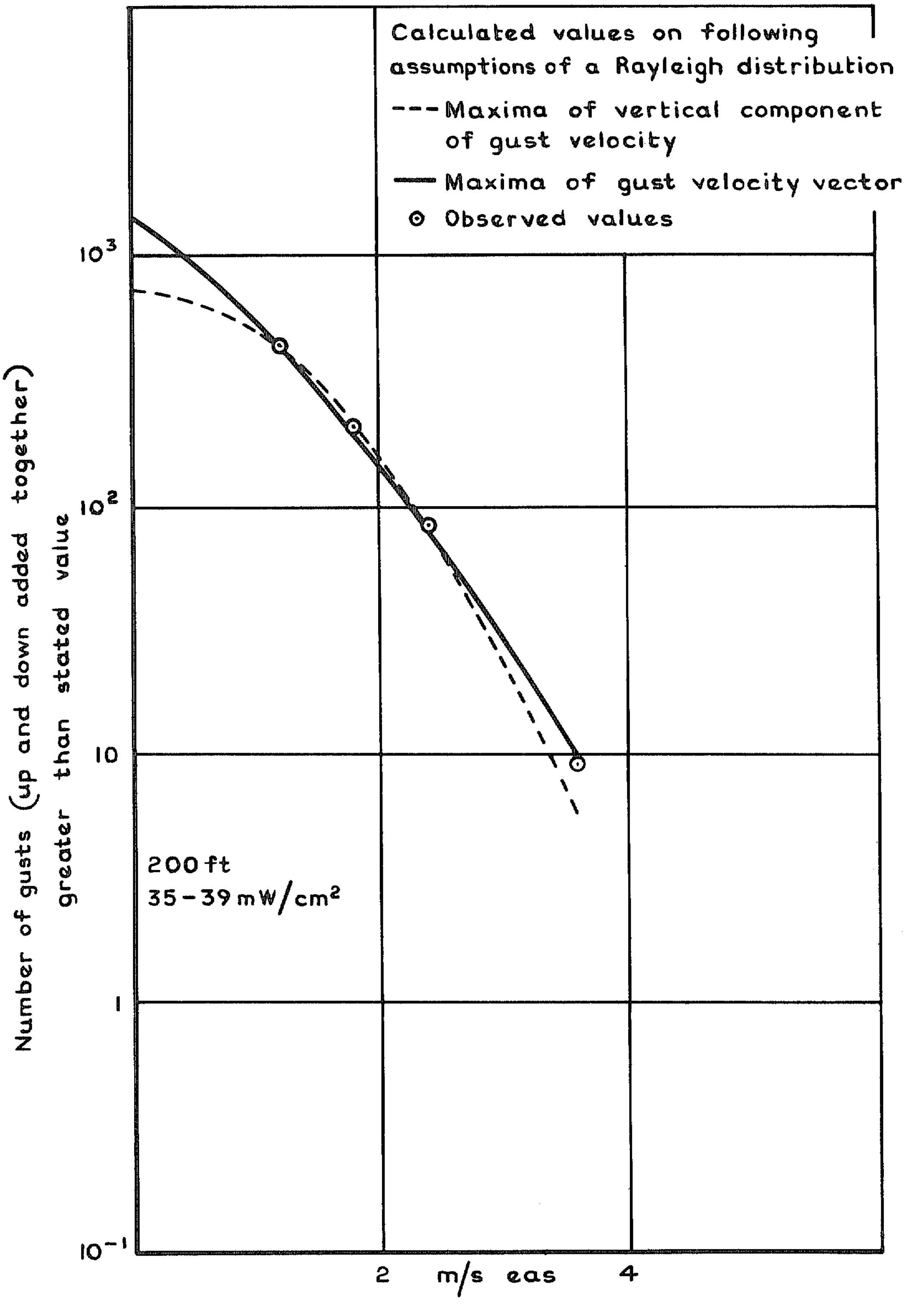

FIG. 9b. Canberra, number of gusts encountered in approximately 50 km flying through individual areas of turbulence.

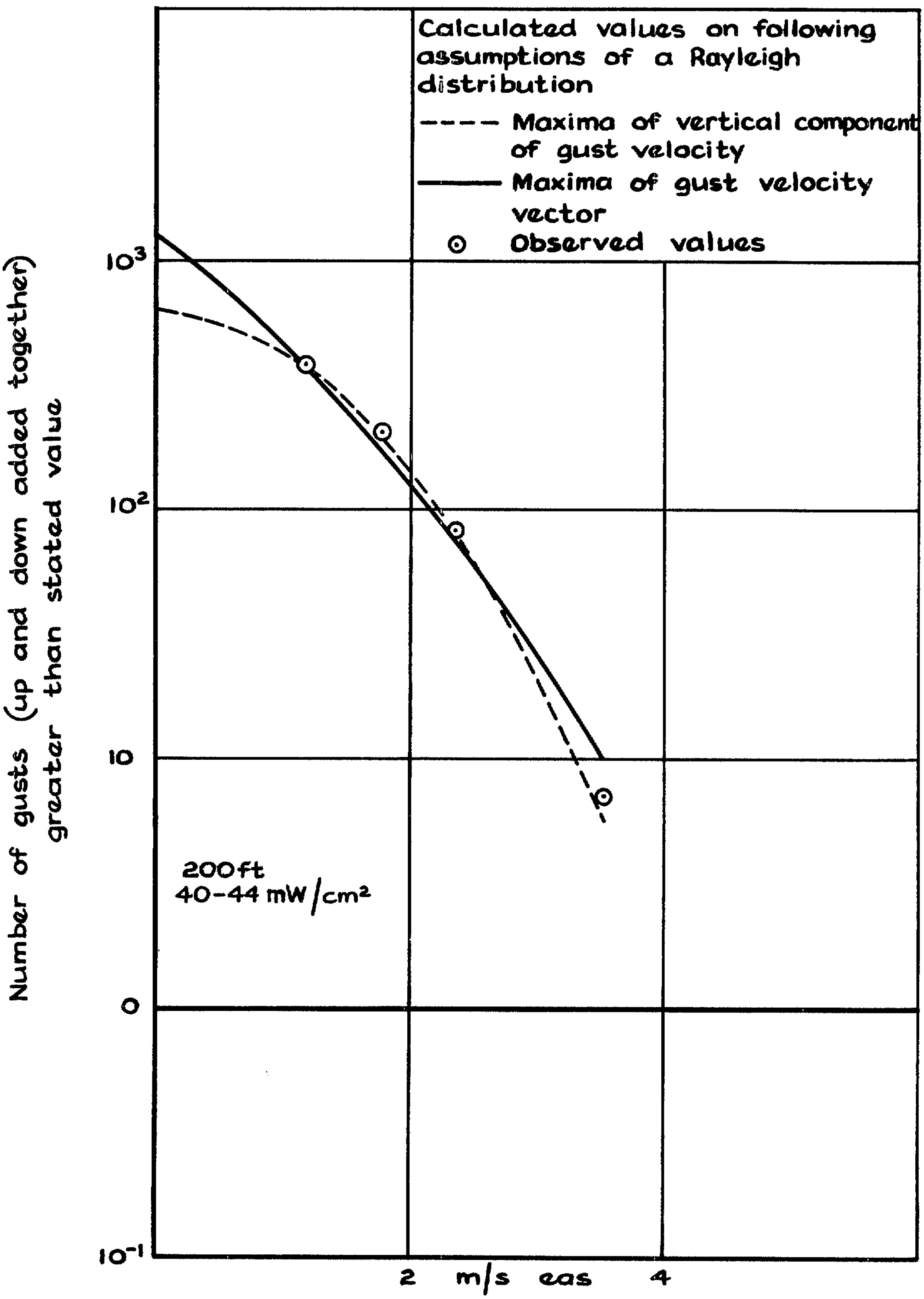

FIG. 9c. Canberra, number of gusts encountered in approximately 50 km flying through individual areas of turbulence.

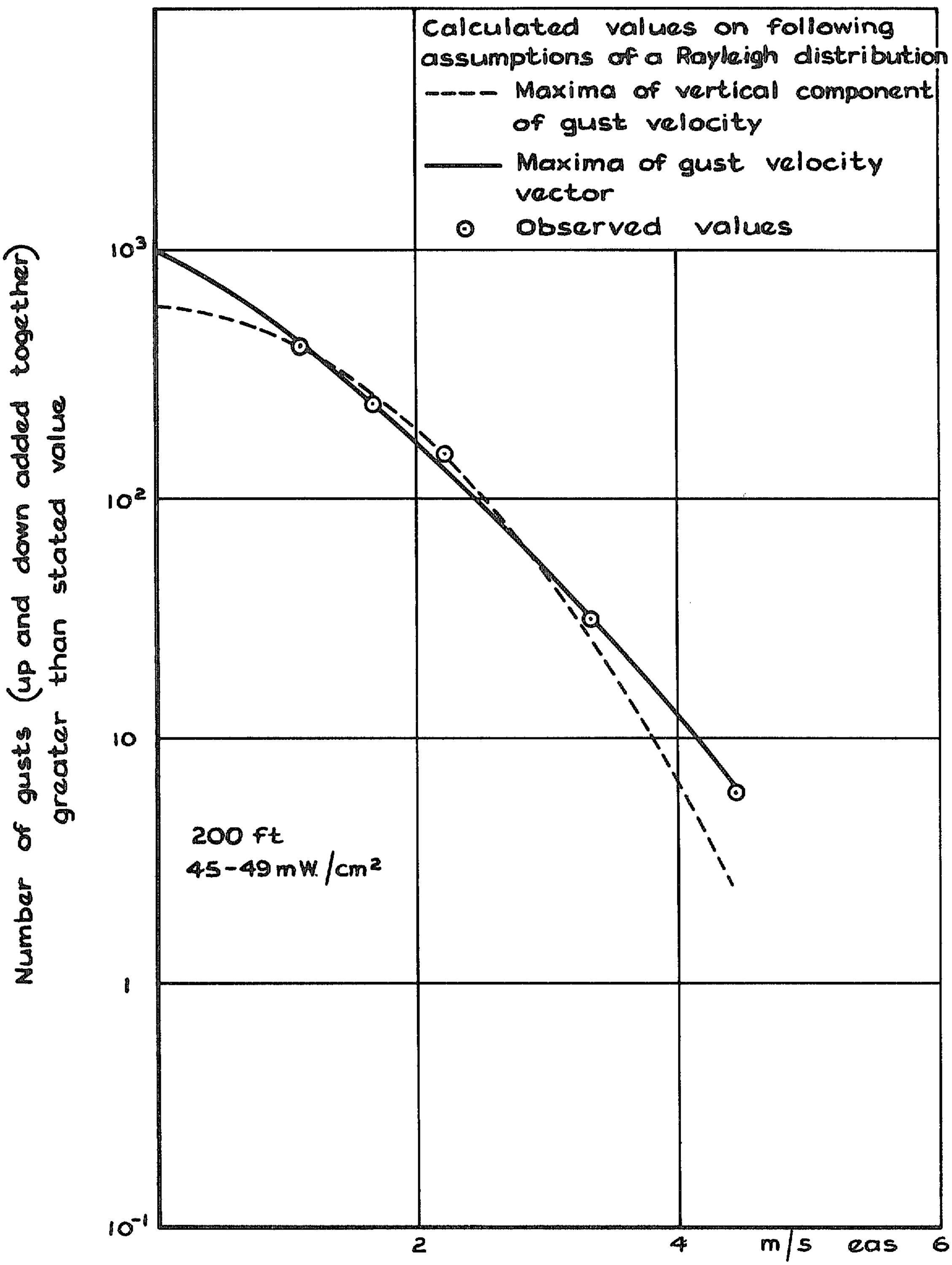

FIG 9d. Canberra, number of gusts encountered in approximately 50 km flying through individual areas of turbulence.

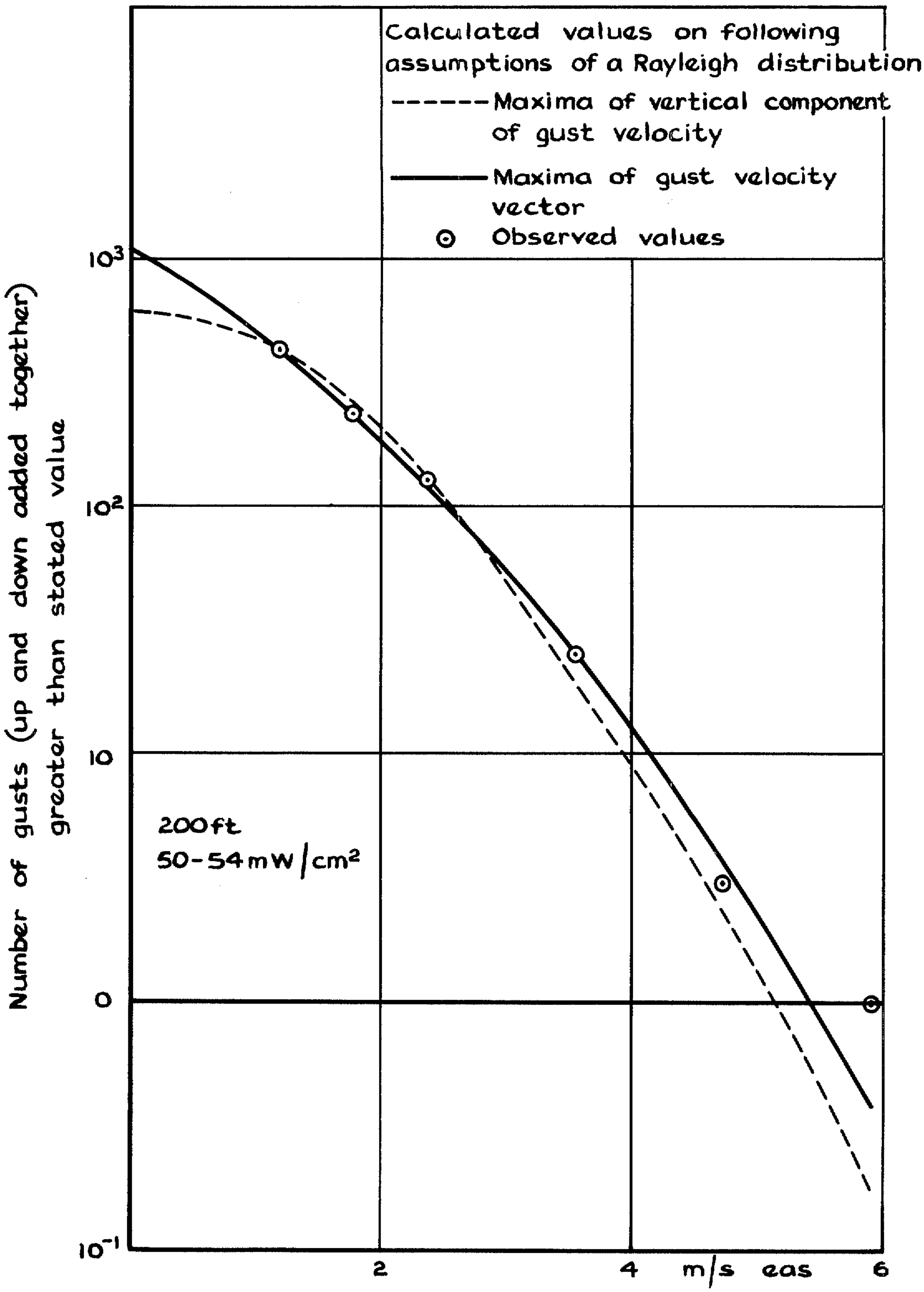

FIG. 9e. Canberra, number of gusts encountered in approximately 50 km flying through individual areas of turbulence.

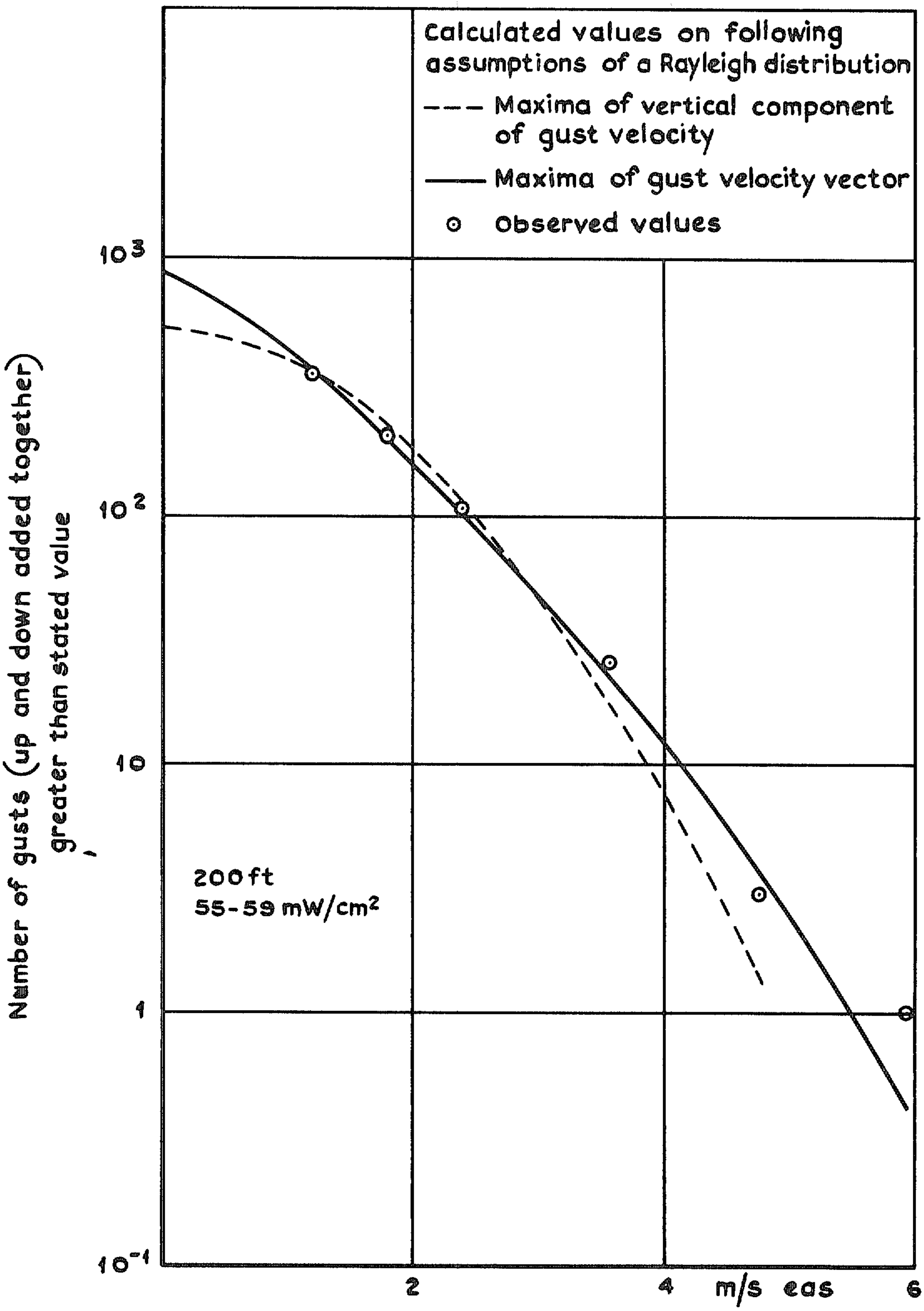

FIG. 9f. Canberra, number of gusts encountered in approximately 50 km flying through individual areas of turbulence.

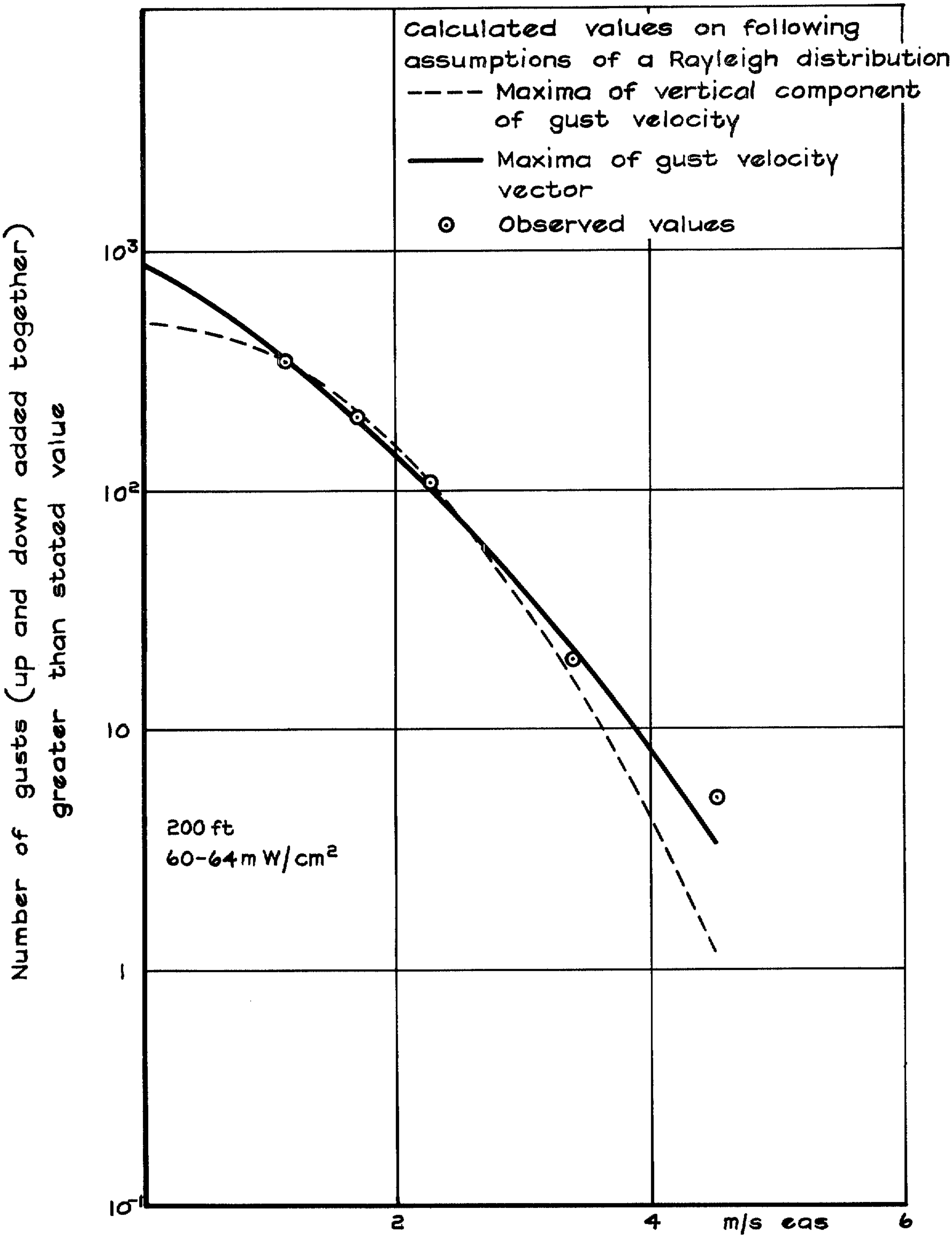

FIG. 9g. Canberra, number of gusts encountered in approximately 50 km flying through individual areas of turbulence.

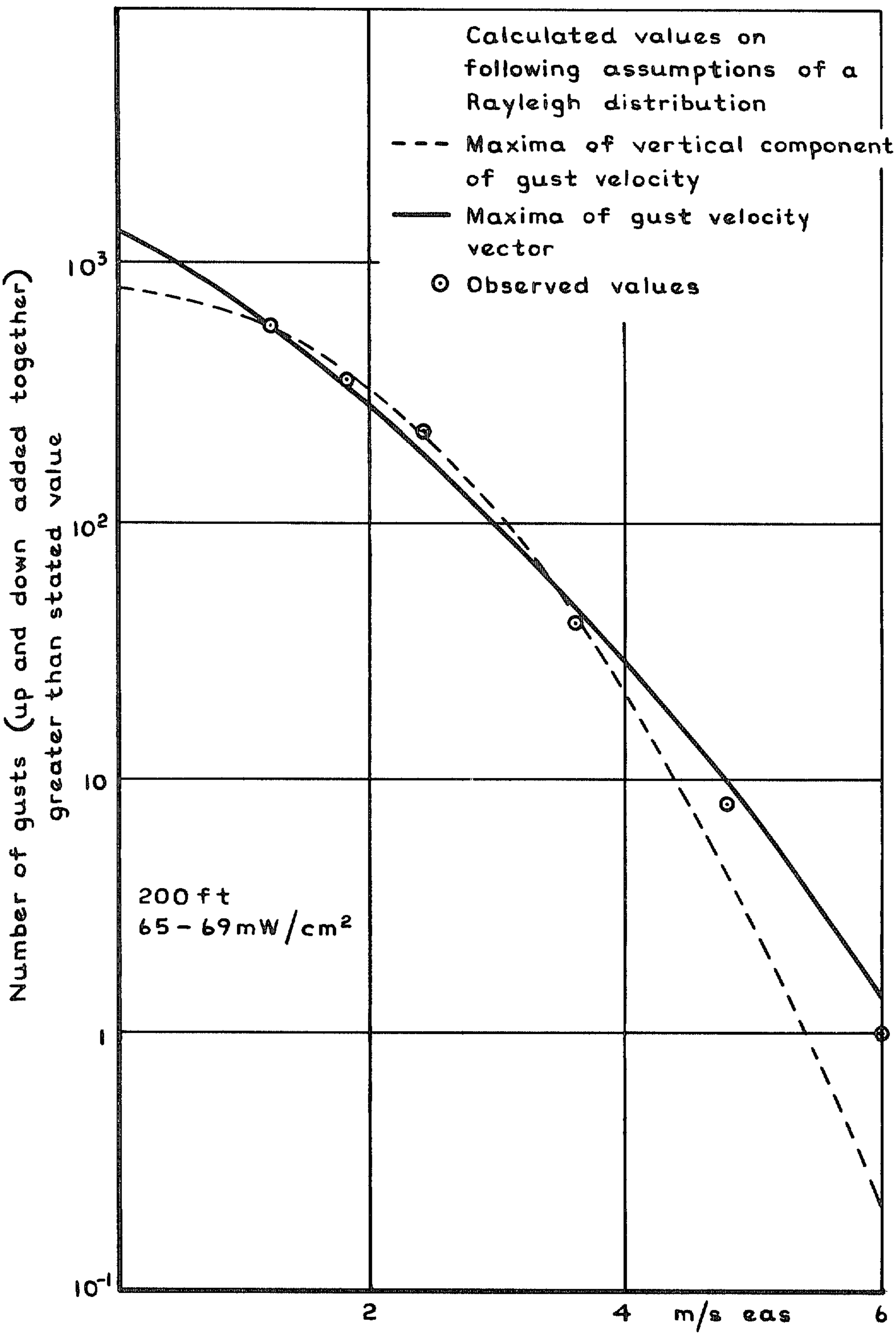

FIG. 9h. Canberra, number of gusts encountered in approximately 50 km flying through individual areas of turbulence.

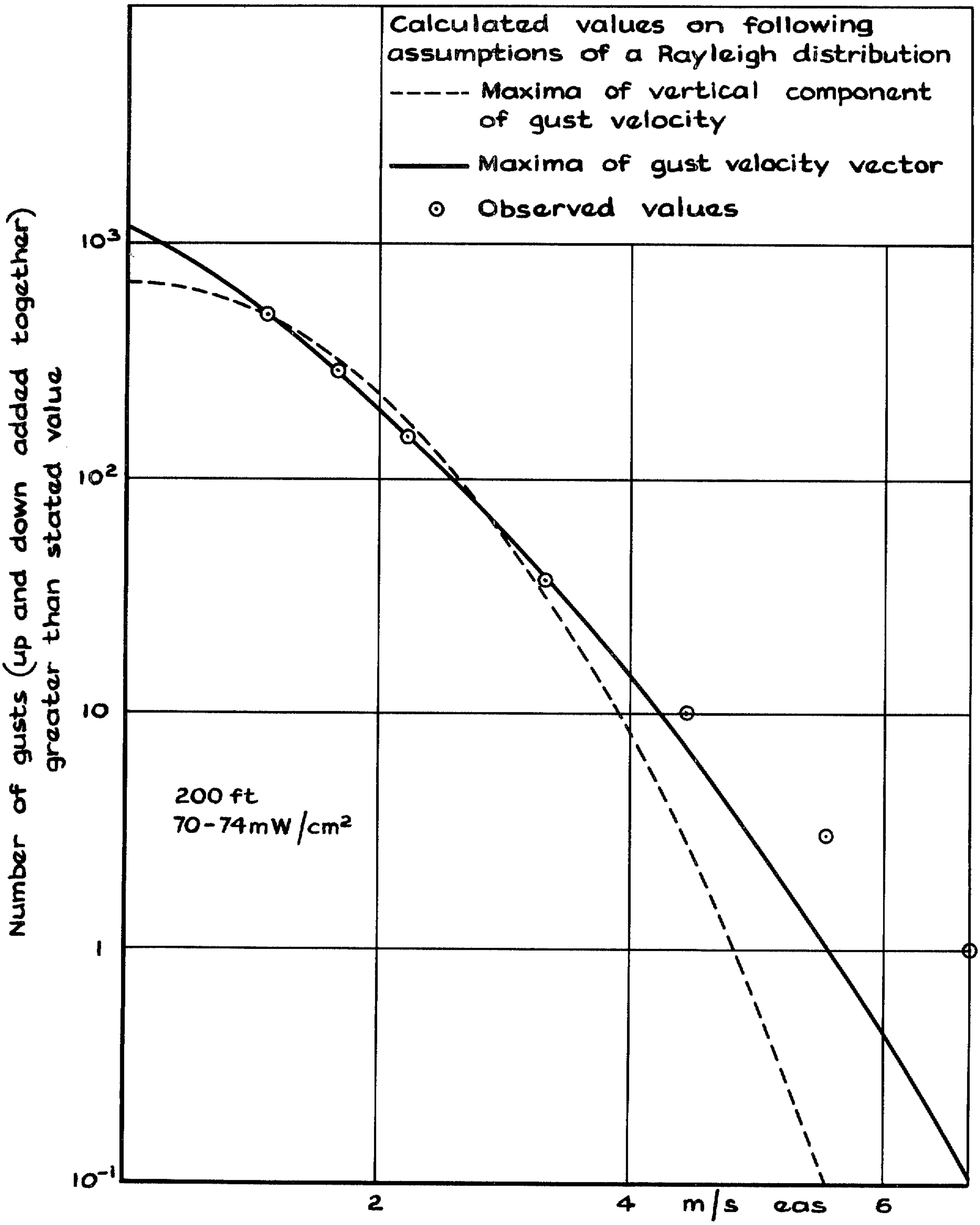

FIG. 9i. Canberra, number of gusts encountered in approximately 50 km flying through individual areas of turbulence.

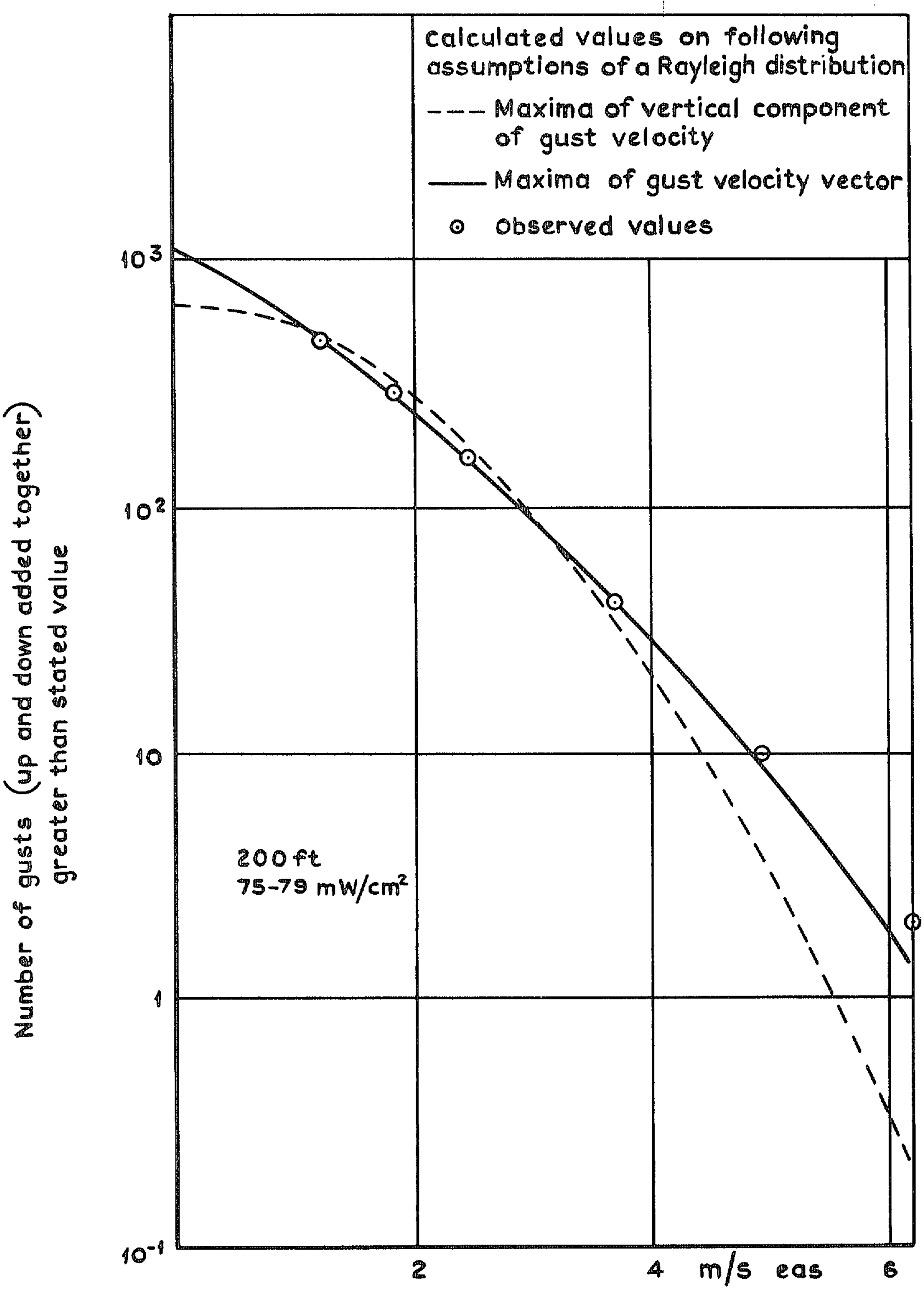

FIG. 9j. Canberra, number of gusts encountered in approximately 50 km flying through individual areas of turbulence.

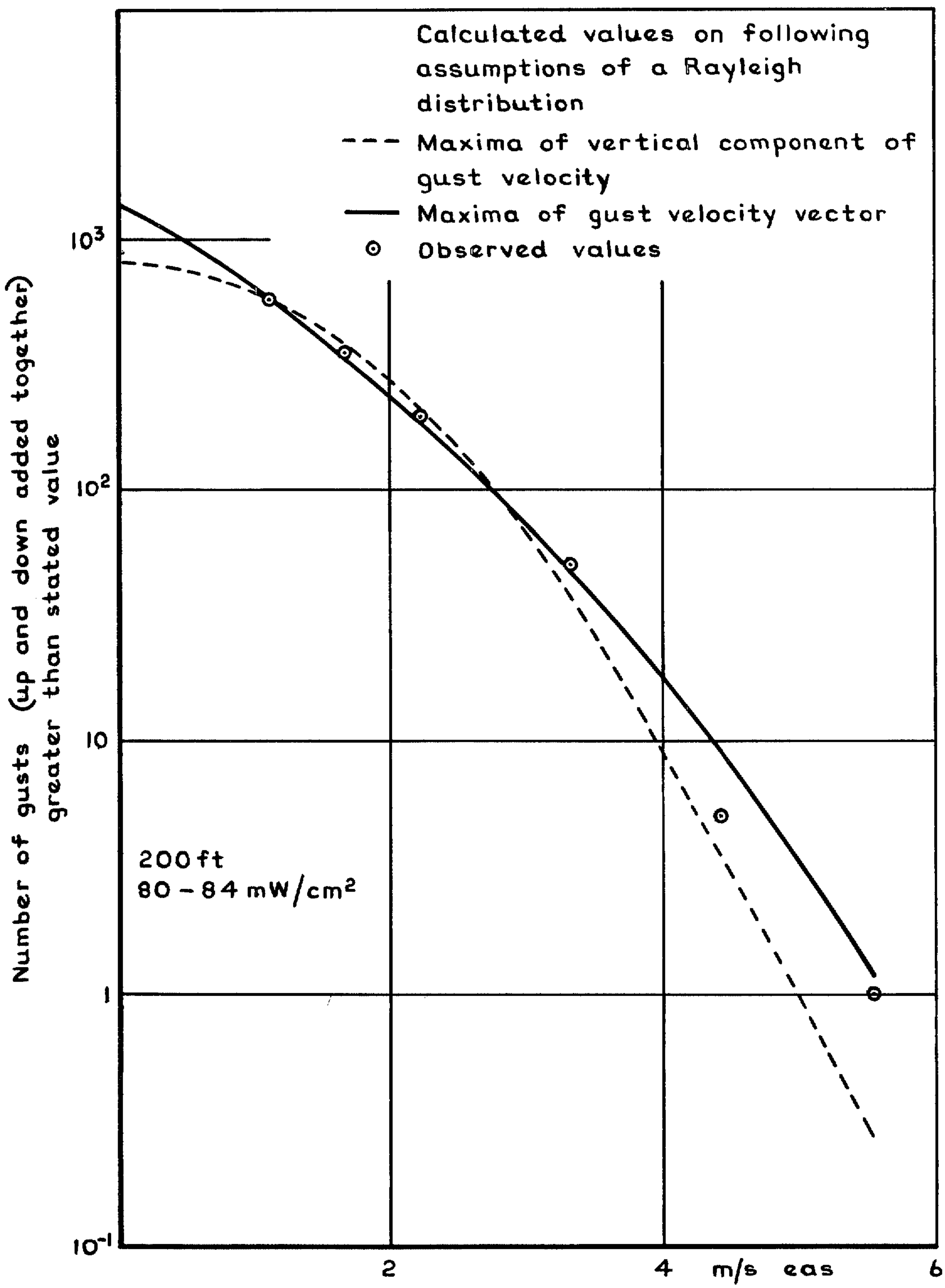

FIG. 9k. Canberra, number of gusts encountered in approximately 50 km flying through individual areas of turbulence.

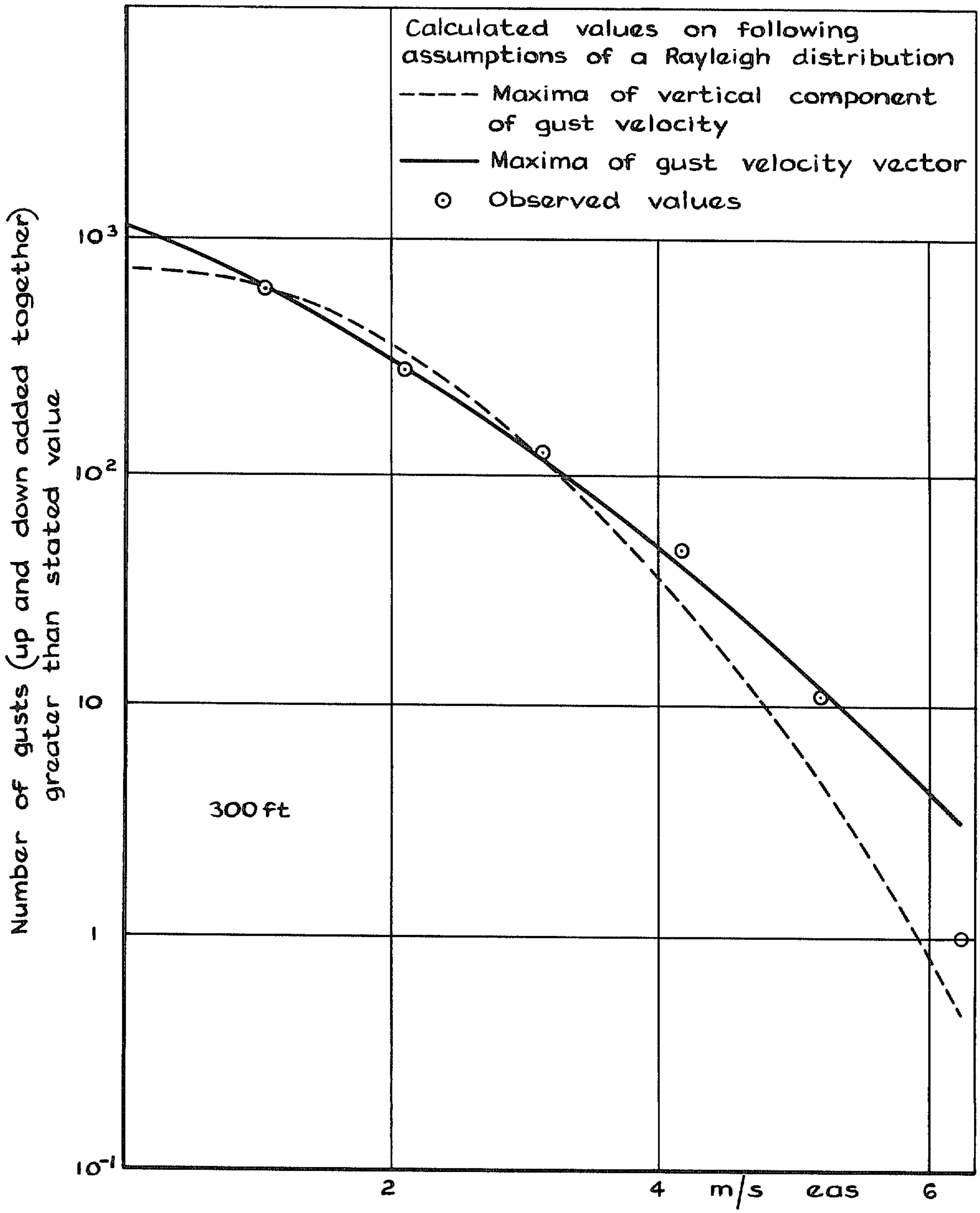

FIG. 10. Meteor, number of gusts encountered in approximately 50 km flying through individual areas of turbulence.

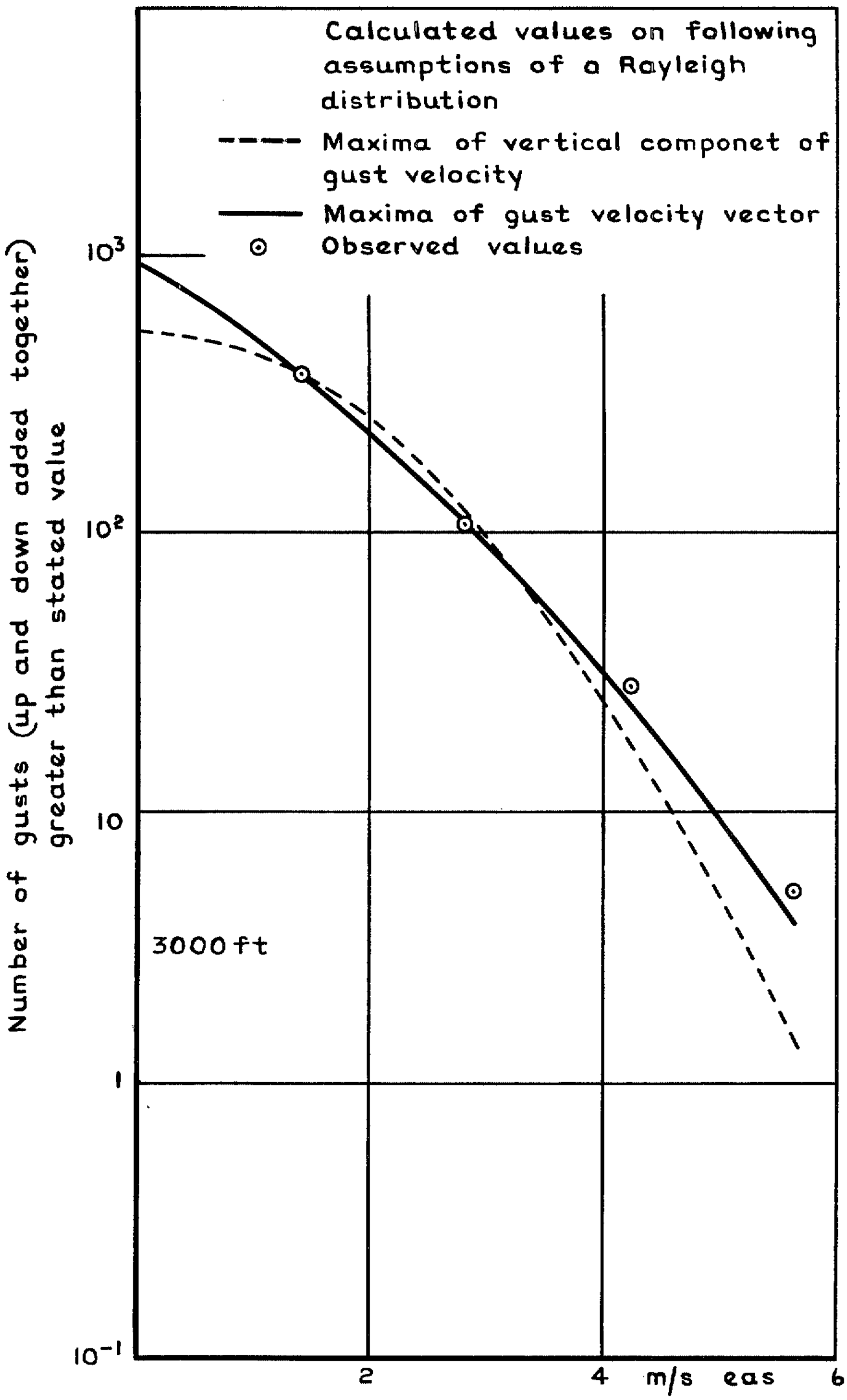

FIG. 11a. Viking, number of gusts encountered in approximately 50 km flying through individual areas of turbulence.

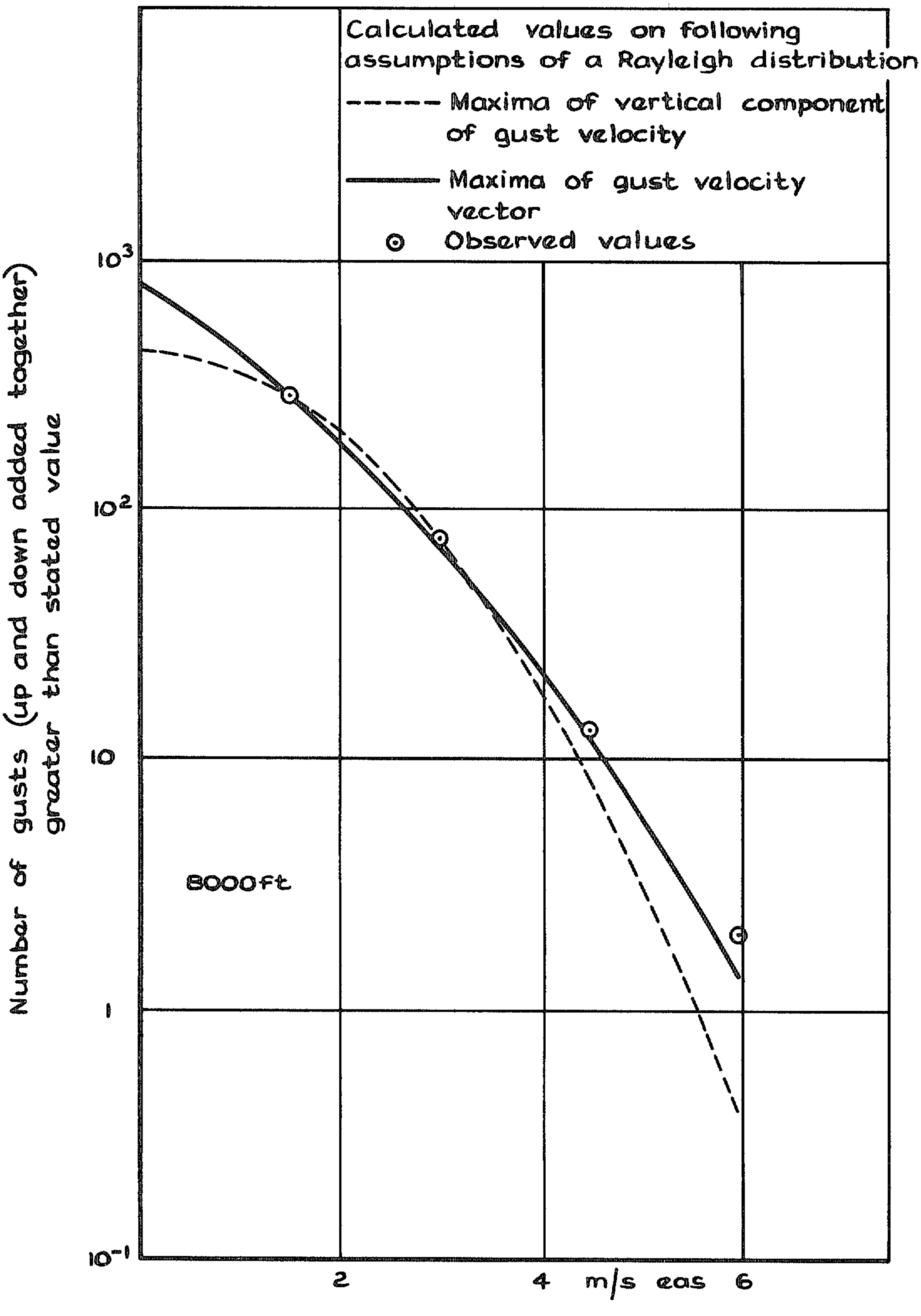

FIG. 11b. Viking, number of gusts encountered in approximately 50 km flying through individual areas of turbulence.

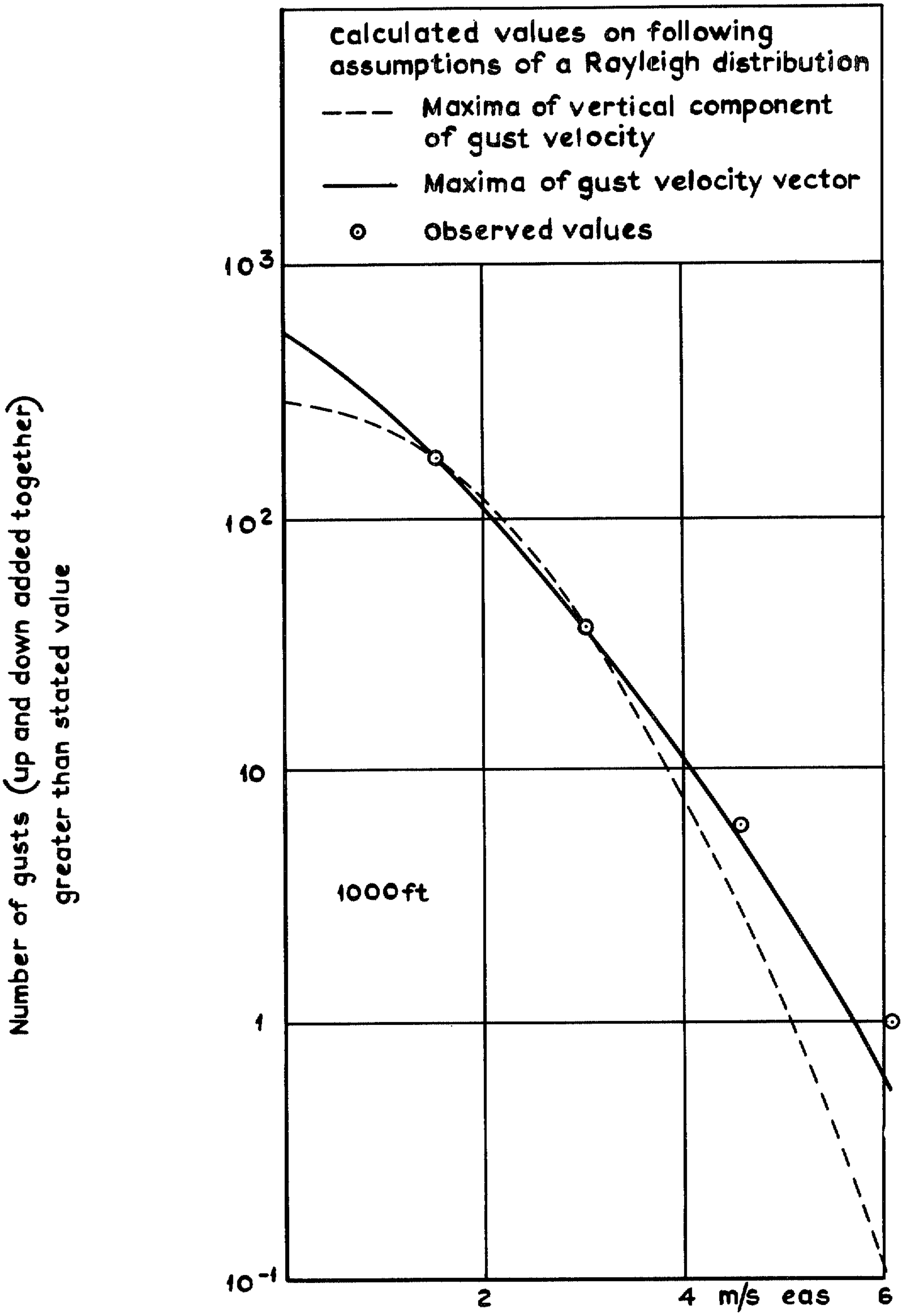

FIG. 12. York, number of gusts encountered in approximately 50 km flying through individual areas of turbulence.

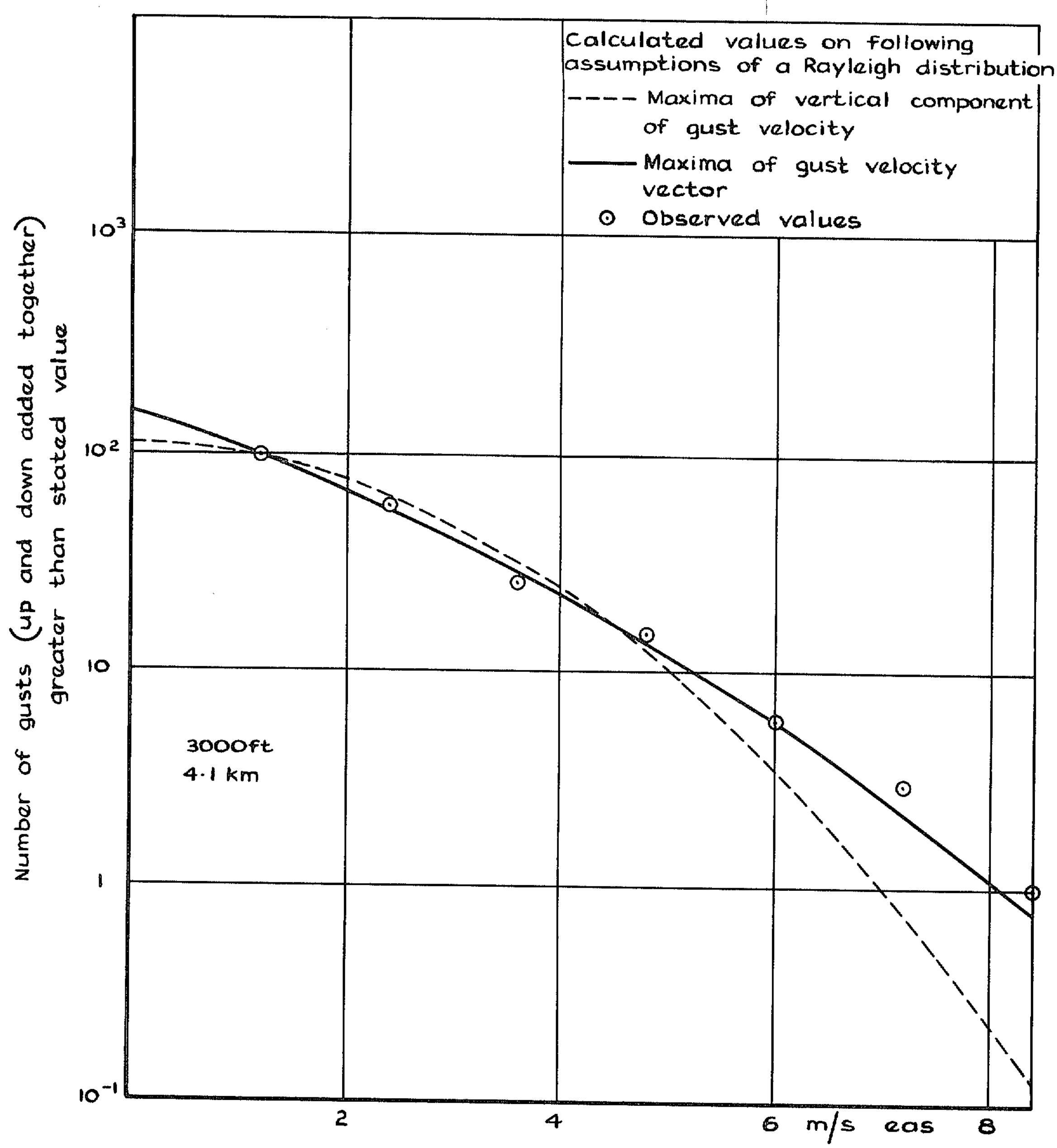

FIG. 13a. Anson, number of gusts encountered in individual areas of moderately severe turbulence.

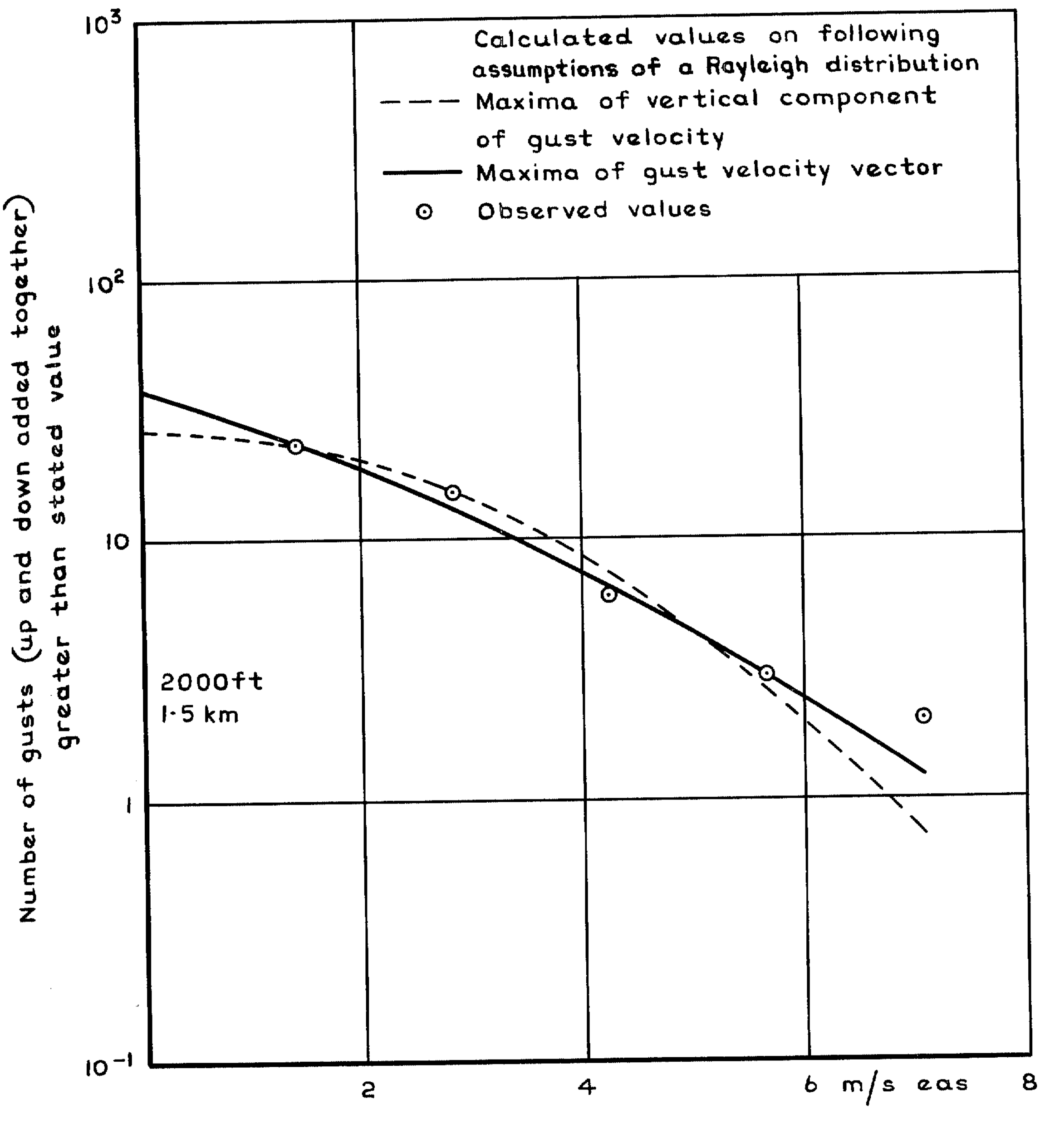

FIG. 13b. Viking, number of gusts encountered in individual areas of moderately severe turbulence.

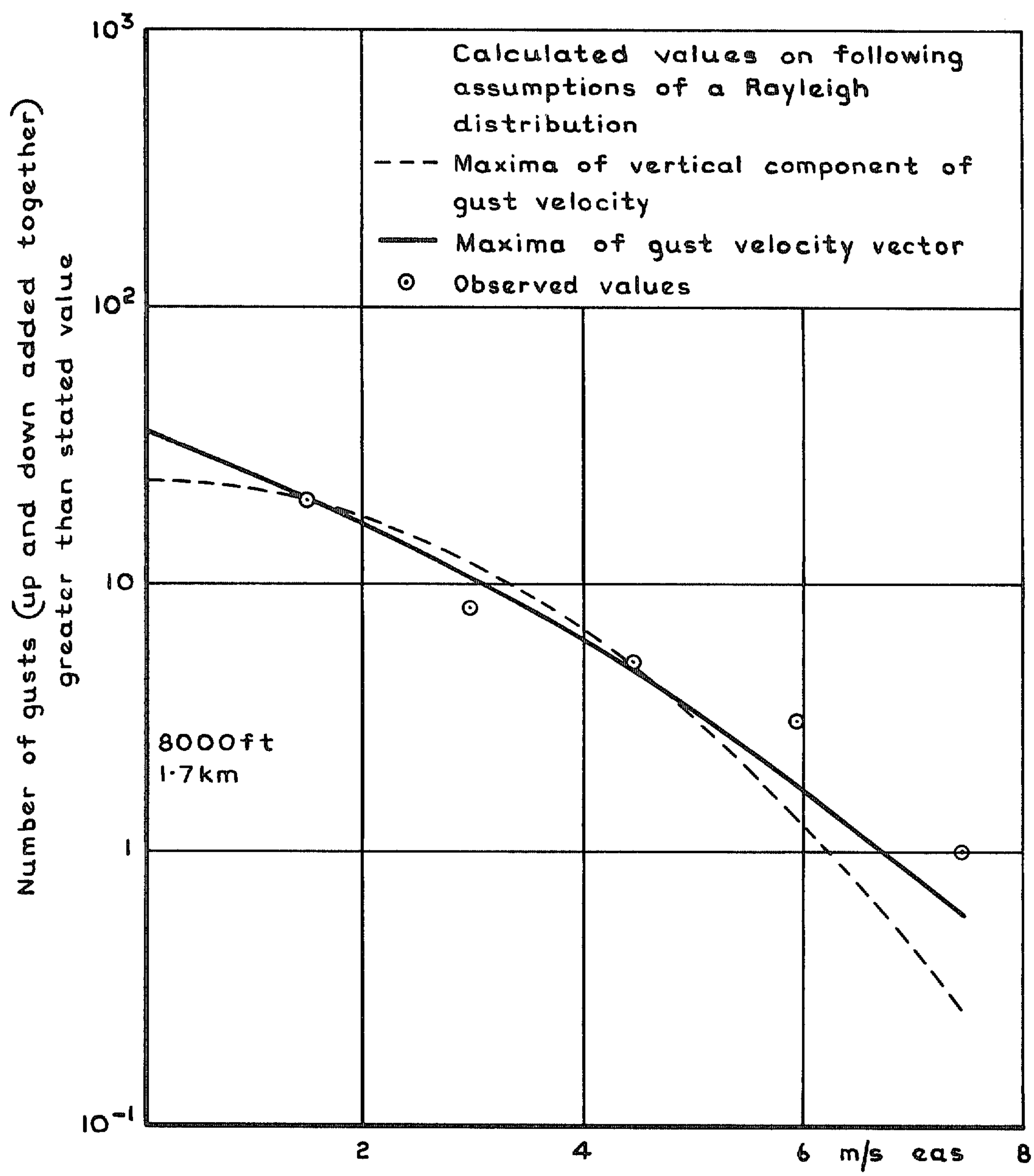

FIG. 13c. Viking, number of gusts encountered in individual areas of moderately severe turbulence.

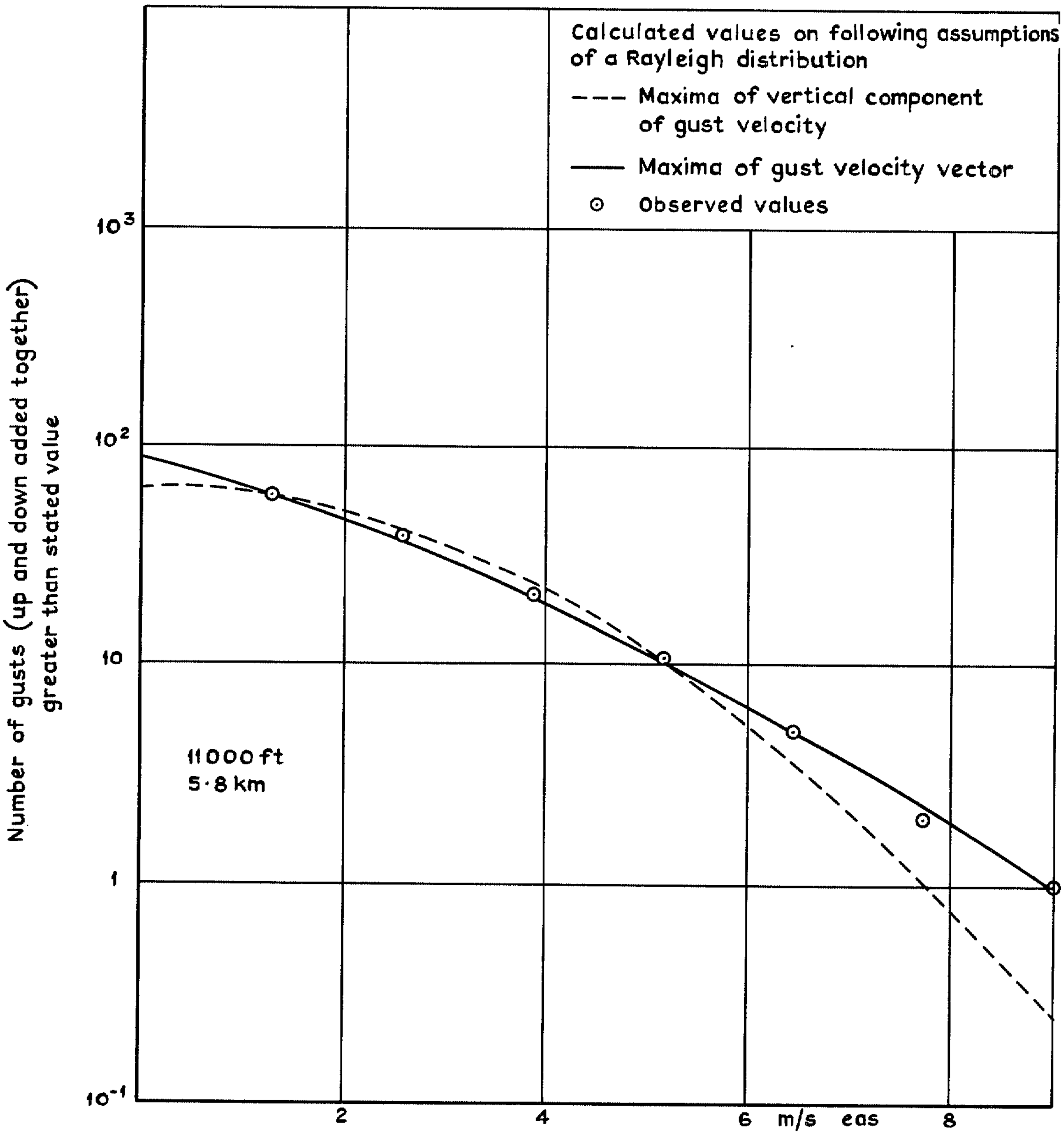

FIG. 13d. Viking, number of gusts encountered in individual areas of moderately severe turbulence.

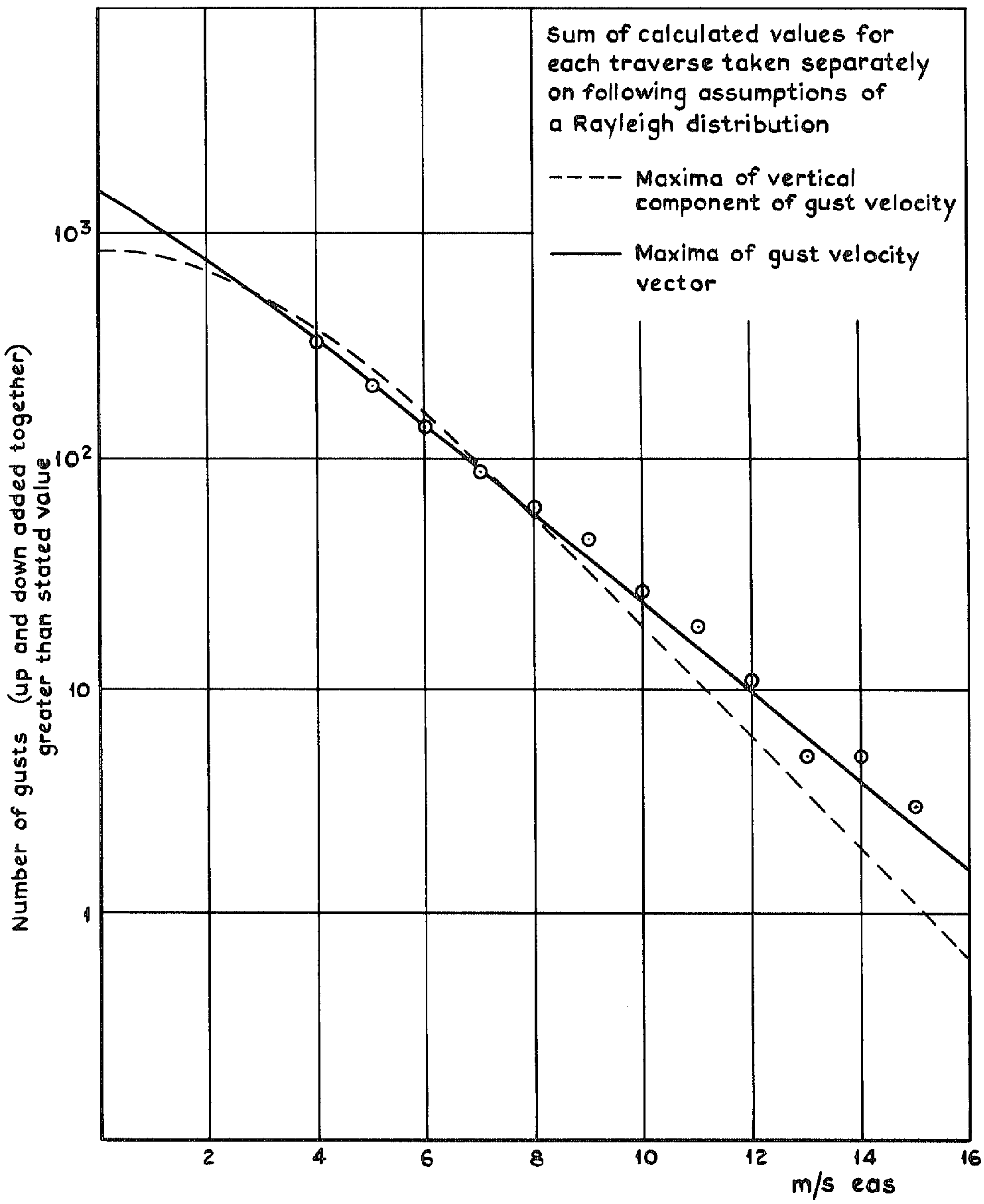

FIG. 14. 36 traverses of the most severe turbulence in 23 000 hours of civil flying by 3 4-engined pure jet transports.

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