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Atmospheric Turbulence Encountered by Comet 2 Aircraft Carrying Cloud Collision Warning Radar

by

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ATMOSPHERIC TURBULENCE ENCOUNTERED BY COMET 2 AIRCRAFT CARRYING CLOUD COLLISION WARNING RADAR

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Judy E. Aplin

SUMMARY

Counting accelerometer records have been obtained of the turbulence encountered by R.A.F. Comet 2 aircraft, equipped with cloud collision warning radar, in 335,000 miles of operational flying largely on routes connecting the U.K. with Singapore.

It is shown that the Comet 2 met significantly less turbulence at all altitudes than the Comet 1 which was not carrying this radar, and that the reduction in the frequency of occurrence of gusts increased with gust magnitude. No gusts as great as 20 ft/sec were recorded by Comet 2 aircraft during the cruise.

Comparable data from U.S. aircraft have also been considered, and show a similar reduction in the occurrence of large gusts.

Replaces R.A.E. Tech. Note No. Structures 335 - A.R.C. 25141.

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1 INTRODUCTION

Counting Accelerometers have been installed in a number of aircraft to investigate the atmospheric turbulence encountered during flight, and results already published include those from B.O.A.C. Comet 1 aircraft[1]. The present paper discusses results from two Comet 2 aircraft of the Royal Air Force Transport Command which were fitted with cloud collision warning radar. As the Comet 1 aircraft were not fitted with this equipment, comparison of the two sets of results will show any reduction in the turbulence encountered which is due to its use since, although slight differences may exist between the operation of B.O.A.C. and R.A.F. aircraft, past experience suggests that such differences should have little effect on the data.

A similar comparison has been made with some N.A.C.A. information from twin-engine short-haul transport aircraft[2], some of which were fitted with cloud collision warning radar and some of which were not.

2 INSTRUMENTATION AND TYPE OF FLYING

2.1 *The Compound Counting Accelerometer*

The type 4 Counting Accelerometer installed in the Comet 2 is a later version of the type 2 installed in the Comet 1, and a full description of these instruments can be found in an Instruction Leaflet[3].

Briefly, the type 4 Counting Accelerometer consists of two units: the accelerometer unit, which is installed as near as possible to the centre of gravity of the aircraft and which responds to the aircraft normal acceleration, and the observer unit, which automatically counts the number of times given acceleration levels are exceeded and then photographically records the counter readings, airspeed, altitude and time at regular intervals.

2.2 Airspeed switch

To ensure that the accelerations recorded were true gust accelerations and not bumps in take-off, landing or taxying, the type 4 Counting Accelerometer was fitted with an airspeed switch, which switched on the instruments automatically when the airspeed exceeded 125 knots I.A.S. after take-off, and switched them off when the airspeed fell below 110 knots I.A.S. before landing.

2.3 Barometric switch

In the type 4 Counting Accelerometer the camera can be operated at two speeds. These are adjusted so that pictures are taken more frequently during climb and descent than during cruise. The change is controlled by a barometric switch and for these tests it was arranged that the camera should record at intervals of 4 minutes below 28,000 ft and at intervals of 11.6 mins above 28,000 ft. Because of the action of the barometric and airspeed switches the last interval before the camera changed speed or the recorder was switched off, may not be complete.

2.4 Type of flying and area covered

The two Comet 2 aircraft of Transport Command on which the Counting Accelerometers were installed, were flown mainly on routes from the U.K. to Singapore with very occasional flights to Africa, Australia or Christmas Island, as shown by the map in Fig. 1. These flights covered some 335,000 miles overall and were mainly training flights.

3 BASIC AND PROCESSED DATA

3.1 Basic data

The basic data are taken from two sources: the film record of the counter and instrument readings previously mentioned, and supplementary flight data sheets which are completed by the operators to give the date, time of take-off, duration and route of each flight, together with the weight of the aircraft at the time of take-off.

3.2 The data processing and results

The data are coded and transferred to punched cards for processing and details of the method of handling these have been given by Heath-Smith[4].

During processing each interval is classified as belonging to one of the following flight conditions:

(a) Initial climb. The first interval of each flight.

(b) Final descent. The last interval of each flight.

(c) Climb. Any interval during which the aircraft increased altitude by 2000 ft or more.

(d) Descent. Any interval during which the aircraft decreased altitude by 2000 ft or more.

(e) Cruise. The remaining intervals.

The mean speed and altitude of each interval are taken to be representative of conditions throughout the interval, except for the initial climb and final descent records. For these the final airspeed and mean altitude were assumed for the initial climb intervals, and the initial speed and mean altitude for the final descent intervals.

The tables of Comet 1 results given in this note are the outcome of a recent re-analysis standardising the altitude bands of Counting Accelerometer data, thus rendering them more directly comparable with the Comet 2 results.

The time spent at different speeds and altitudes is given for the initial climb and final descent in Table 1, the climb in Table 2, the descent in Table 3 and the cruise in Table 4, for the Comet 1 and similarly in Tables 5, 6, 7 and 8 for the Comet 2.

The acceleration data are arranged as the number of counts at the different acceleration levels in successive altitude bands, with the total recorded time appropriate to each band and the corresponding estimate of statute miles flown; they are presented in Table 9 for the Comet 1 under the two headings of climb and descent together, and cruise; and in Table 10 for the Comet 2 under the headings initial climb, final descent, climb and descent, and cruise. The initial climb and final descent acceleration records for the Comet 1 were not used since they included ground loads.

Tables 4 and 8 show that the cruise took place largely between 30,000 and 40,000 feet, particularly in the 33,500 to 36,500 ft band for the Comet 1 aircraft, and between 35,000 and 42,500 ft, particularly in the 37,500 to 41,500 ft band for the Comet 2 aircraft.

The method of processing the acceleration counts to convert them into gust counts is the same as that used by Heath-Smith[1] involving the use of the discrete gust concept, with gust alleviation factors from work by Zbrozek[5]. The aircraft characteristics necessary for these calculations are listed in Table 11, and representative acceleration to gust velocity conversion factors are given in Tables 12 and 13 for the Comets 1 and 2 respectively. The resulting gust velocities are presented in Tables 14 and 15 in the same way as the acceleration counts in Tables 9 and 10.

The monthly distribution of the 744 hours of flying time recorded between June 1957 and August 1960 with Comet 2 aircraft, is shown in Fig. 2; but it was found that insufficient gusts had been recorded at the cruising altitudes to merit investigation of the seasonal, or geographical, variations of the turbulence intensity.

Table 16 is a list of the altitude bands into which the data were grouped, together with the code numbers used for them in the figures.

4 DISCUSSION OF RESULTS

4.1 Overall variation of gust frequency with gust speed

The variation of gust frequency with gust speed is illustrated in Figs. 3, 4, 5 and 6 by plotting the miles/gust against feet/second for each altitude band in the combined climb and descent data and in the cruise data from Comet 1 and Comet 2 aircraft. For this purpose, the initial climb and final descent records of the Comet 2 were amalgamated with the rest of the climb and descent.

In these four figures the general tendency is seen to be for the gust frequency to decrease with both altitude and gust magnitude, although it should be remembered that the small numbers of counts at the higher gust speeds make this end of the curves less reliable than the low speed end. If the upgust and downgust curves are compared on each figure, it is found that the ratio of upgusts to downgusts remains fairly constant in each altitude band.

4.2 Comparison of intensity of turbulence for Comet 1 and Comet 2

The complexity of the four figures mentioned in the preceding paragraph makes comparison of the slopes of the Comet 1 and Comet 2 curves difficult, so the data from all altitudes were combined to give one upgust and one downgust curve for climb and descent, and a similar pair of curves for cruise, for each aircraft. Since they were not used in the Comet 1 analysis, the initial climb and final descent records were omitted for the Comet 2 for this comparison.

The resultant curves are shown on Fig. 7 and the slope of the Comet 2 curve is seen to be steeper than that of the Comet 1 curve in each case.

The slopes of each pair of curves being similar, it was felt justifiable to simplify these results further by adding the upgusts and the downgusts to give one curve for the climb and descent of each aircraft, Fig. 8, and one for the cruise, Fig. 9. On these figures the slopes of the Comet 2 curves are considerably steeper than those of the Comet 1, indicating that the ratio of large gusts to small gusts is lower in the Comet 2 data.

The previous Comet 1 analysis[1] showed that all gusts greater than approximately 23 ft/sec were associated with cumuliform cloud. Since the maximum gusts encountered by the Comet 2 were between 15 and 20 ft/sec during cruise, and between 25 and 30 ft/sec during climb and descent, it would seem that the aircraft avoided nearly all the cumuliform cloud and its associated turbulence, due no doubt to the cloud collision warning radar with which they were equipped. Gusts of all magnitude were met far more frequently by Comet 1 aircraft than Comet 2 and a general conclusion could be drawn that the slopes of the Comet 1 curves in Figs. 8 and 9 are typical of atmospheric turbulence which includes that associated with cumulo nimbus, whilst the steeper slopes of the Comet 2 curves are representative of turbulence occurring in clear air, cirrus or stratus.

4.3 Variation of gust frequency with altitude for Comet 1 and Comet 2 aircraft

The frequency of occurrence of gusts greater than, or equal to, $7\frac{1}{2}$ ft/sec was plotted against altitude in Fig. 10 for both Comet 1 and Comet 2 aircraft. Both curves were drawn with due regard to 95% confidence limits calculated by a method given by Bullen[6], but for greater clarity these have been omitted from the graph.

The choice of a particular gust velocity for this type of investigation is governed by two considerations, one of which is that the velocity should be low to give a relatively large number of counts. The other fact of importance is that a given acceleration counter of the counting accelerometer is actuated by gusts of different velocity according to the speed, altitude and weight of the aircraft at the time when the gust is encountered so, in order to ensure that for all but exceptional conditions of flight the estimated number of gusts is an interpolation of the recorded acceleration counts rather than an extrapolation, the gust velocity chosen should correspond to an acceleration greater than 0.2g, the lowest threshold of the instrument. The $7\frac{1}{2}$ ft/sec velocity satisfies these requirements for almost all conditions of flight for both Comet 1 and Comet 2 aircraft.

The climb, cruise and descent data from all routes were combined for Fig. 10 since results from low level cruise, probably recorded during stand-off and landing approach, were felt to be really more typical of climb and descent rather than cruise, in that the pilot would be unable to exercise so much discretion in the avoidance of turbulence. Also, some cruise is probably included in the high altitude climb and descent records since, as described in section 3.2, the criterion is a change of altitude of 2000 ft or more during one interval of time, and this is rather a small change for 11.6 mins flying.

As both Comet 1 and Comet 2 aircraft flew predominantly the U.K. to Singapore routes, these data represent a mixture of overland and oversea information.

The Comet 2 initial climb and final descent records have been shown as single points on the graph, which indicate more and less severe gust frequency, respectively, than the rest of the low altitude data. A possible explanation of this difference lies in the fact that immediately after take-off many flight operations are performed in a very short space of time, whereas the corresponding operations prior to landing are spread over a much longer period, and so the associated accelerations will be condensed into the first few minutes of climb but distributed more widely throughout the descent.

Inspection of the curves indicates a steady decrease in turbulence with altitude up to about 35,000 ft for Comet 1 and 30,000 ft for Comet 2, although it should be noted that very few gusts were recorded between 17,500 and 33,500 ft with Comet 2 aircraft so that the curve through these four points is rather arbitrary. However, the general trend is for the gust frequency to decrease with altitude up to the region of the tropopause, and at all altitudes the curve for the Comet 2 lies above that for the Comet 1, the difference being roughly constant at the lower altitudes. The increase in turbulence at the higher altitudes shown on these curves is illustrated and discussed in greater detail in Fig. 12 and section 4.4.

Table 7 of the Comet 1 report[1] gives the counts occurring in cumuliform cloud and clear air as a percentage of those occurring under known conditions for average gust speeds and, interpolating, it is found that about 70% of the $7\frac{1}{2}$ ft/sec gusts encountered under known conditions between 17,500 and 42,500 ft, occurred in cumuliform cloud. In this analysis the gust frequency of the Comet 2 between 29,500 and 41,500 ft was 30-38% of that of the Comet 1, indicating once more that the decrease in gust frequency was due to the avoidance of cumuliform cloud and its associated turbulence by use of the cloud collision warning radar on the Comet 2 aircraft.

4.4 The pilot's influence on accelerations recorded

When analysing the turbulence encountered by an aircraft, it is, of course, necessary to take into consideration the pilot's influence on the accelerations recorded. Perhaps the most obvious and direct effect of the pilot's handling of the aircraft is the increase in positive acceleration counts resulting from manoeuvre loads. To illustrate this, and to investigate further the atmospheric turbulence encountered by Comet 2 aircraft, the ratio of upgusts to downgusts for gusts of magnitude greater than, or equal to, $7\frac{1}{2}$ ft/sec was plotted against altitude on Fig. 11. For this purpose the climb and descent records were combined, and kept separate from the cruise records, also where the recorded gusts or miles flown were too few to be considered significant, certain altitude bands were combined. During climb and descent at the lower altitudes, the ratio of upgusts to downgusts is seen to be relatively high, which is probably due to manoeuvring in the vicinity of airfields, with possibly some overland convective turbulence effect also[7]. At the higher altitudes, the climb and descent ratio tends towards the cruise ratio which shows slightly more positive counts than negative.

Another important consequence of the pilot's handling is that the aircraft is to some extent able to avoid certain types of turbulence. With aircraft not equipped with cloud collision warning radar, this avoidance is usually limited, particularly for continuous cloud, to climbing above it. On the other hand, pilots of aircraft which do carry this radar have a greater degree of freedom in their choice of avoiding action, as the extent of the cloud is known and a single cloud, or sparse cloud, will simply cause the aircraft to make a detour, changing altitude only when the cloud is known to be very dense.

It is to be expected then that this operating difference will have a direct effect on the turbulence encountered by the Comets 1 and 2 at their cruising altitudes. The Comet 2 data should show mainly the effect of the clear air turbulence which is known to occur at these high altitudes[8,9,10] over both sea as well as land routes, and which cannot be avoided since the cloud collision warning radar can give no warning of its presence. The Comet 1 results, in addition to this, should show the effects of increasing altitude in rough weather to climb above the storm clouds.

Accordingly, the increase in the frequency of occurrence of gusts in the region of the tropopause, noted on Fig. 10 for both Comet 1 and Comet 2 aircraft, was investigated in greater detail by plotting, in Fig. 12, the magnitude of gust against its frequency of occurrence, separate curves having been drawn for each altitude band of the high level cruise.

It will be seen that the Comet 2 curves have the steep slope and total absence of big gusts previously associated in section 4.2 with clear air turbulence and it seems that the observed increase in gust frequency at these altitudes is an actual feature of clear air turbulence, which on the Comet 1 has become somewhat masked by the effect of convective turbulence.

Some U.S. results from high altitude turbulence measurements showed the same trend as these British data, and in their report[10] Coleman and Steiner suggested that 'The increase in the amount of rough air at altitudes between 30,000 and 40,000 ft is probably due to the high winds and wind shears associated with jet streams which are normally prevalent at these altitudes for the mid-latitude area .....'

When an aircraft does encounter turbulence the pilot tries to alleviate its effects by reducing speed; this is illustrated in Fig. 13 which shows the variation of gust frequency with airspeed at each of the main cruising altitudes of the Comet 2, for gusts exceeding $7\frac{1}{2}$ ft/sec. This figure shows quite clearly that as the gust frequency increased, the airspeed decreased.

4.5 Comparison of British and American results with special reference to the effect of airborne radar

A comparison of the turbulence encountered by twin-engine short-haul transport aircraft with and without cloud collision warning radar, has been made by Copp and Walker[2] with Vgh and Vg records. The result of this comparison must be treated with some reserve since the recording periods for the aircraft with and without radar are not strictly comparable, being April, 1956 - May, 1957 with radar and October, 1955 - April, 1956 without radar, and other investigations have shown that the overall level of turbulence is likely to be much less for the winter than for the complete year[11,12].

If the mile/gust value was plotted against each gust magnitude for the U.S. data, as it has been for the Comet data in Figs. 8 and 9 of this report, the 'without-radar' curve would cross the 'with-radar' curve, since the aircraft with radar encountered more gusts of all magnitudes up to about 30 ft/sec, but fewer gusts of magnitude greater than this.

Assuming that the relative frequency of gusts of different magnitude does not change appreciably with the season, and the evidence supports this, then the effect of seasonal variation on either curve will be to move the curve up or down leaving its slope unchanged. Therefore, in the case of this U.S. data, the result of correcting for the seasonal variation on the 'without-radar' curve would be to decrease the mile/gust value at each gust speed and thus to lower the curve. The two curves would then be relatively similar to those given in this report.

5 CONCLUSIONS

The analysis of atmospheric turbulence data from Counting Accelerometers installed on Comet 2 aircraft carrying cloud collision warning radar, showed the gust frequency to be less at all altitudes than that encountered by the Comet 1 which was not so equipped.

The numbers of all gusts exceeding $7\frac{1}{2}$ ft/sec at the cruising altitudes for the Comet 2 were found to be about 30-38% of those for the Comet 1, i.e. the proportion found previously in the Comet 1 data to be associated with clear air, cirrus or stratus.

This avoidance of cumuliform cloud by use of the cloud collision warning radar also resulted in the frequency of occurrence becoming progressively less with increasing gust magnitude, and no gusts greater than 15 ft/sec were met during cruise by Comet 2 aircraft.

Comparable data from U.S. aircraft have been considered also, and these show a similar reduction on the occurrence of large gusts.

ACKNOWLEDGEMENTS

Thanks are due to the Royal Air Force for their help in the collection of these data.

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TABLE 1

Estimated time in minutes spent at each speed and altitude during initial climb and final descent by Comet 1 aircraft

Indicated airspeed in knots	Altitude above sea level (I.C.A.N.) in 1000s of feet																					
	INITIAL CLIMB																	FINAL DESCENT				
	00	C1	C2	03	C4	05	06	07	08	09	10	11	12	13	14	15	16	00	01	02	03	
100	19											9						47	28			100
110	9				9													150	122	75	9	110
120	9	9		9		9												56	254	66	47	120
130	28	9	9		19	9												28	235	169	47	130
140	56	66	28	9															103	188	38	140
150	56	103	9		19		9	19											38	141	47	150
160		103	28	9	38	19													19	66	56	160
170	19	103	38	28	56				9										9	56	28	170
180	9	122	103	56	28	38	19	19	19	9										19	9	180
190		56	38	47	66	28	9	47	19	9	28	28	19	9	9		19			28	9	190
200	9	66	122	47	75	66	66	38	38	38	19	19	38	19		19			9	9	28	200
210		19	38	56	85	75	47	28	9	9	47	38	19	19	19	9				19	19	210
220	9	38	66	66	75	75	38	9	19	28	47	38	38	75	9	9	19				19	220
230		9	38	28	66	47	56	94	150	141	132	94	113	113	47	38	19					230
240			28	38	47	56	113	169	160	141	141	66	47	19			19					240
250			9	19	28	66	75	47	66	9	9											250
260			9	9	19	19																260
TOTAL	223	703	563	421	630	507	432	470	489	384	423	292	274	254	84	75	76	281	817	836	356	

Total initial climb: 6300 mins.

Total final descent: 2290 mins.

TABLE 2

Estimated time in minutes spent at each speed and altitude during climb by Comet 1 aircraft

Altitude above sea level (I.C.A.N.) x 1000 ft

Indicated airspeed in knots	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19
110								9		9										
120			9					19												
130				9		9														
140									9											
150			9	9		19														
160					9	28		9	19		9		9							
170				9	19	28	19		47	9		9								
180		9		9	9	85	103	28	9	9		19								9
190				9		75	113	75	75	19	28	9	19	19	19		9		9	66
200				9		85	141	132	169	141	56	66	28	28	19	66	75	66	103	66
210			9		9		47	94	103	47	160	66	56	66	85	141	113	301	235	376
220					9	19	94	75	132	235	169	132	235	244	282	207	320	357	254	244
230			19		9	9	19	56	85	85	207	188	132	160	141	103	47	75	28	19
240						9		19	38	28	66	28	19	19				9		
250								9					9							
250								9												
TOTAL		9	46	54	64	366	536	534	686	582	695	517	507	536	546	517	564	808	629	780

Indicated airspeed in knots	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
110																			
120																			
130																			
140																			
150	9																		
160																			
170											9				19	9	9		
180				9	19		9		38	9	94	75	160	160	85	103	47		9
190	9	28	9	56	66	66	169	254	517	761	865	667	733	423	235	47	9		
200	103	141	244	367	667	677	733	959	790	479	555	273	141	150	94	9	19		
210	451	498	592	442	320	357	179	66	113	85	56	19	19	28	38				
220	235	132	28	38	19	9	9			9	28								
230		9																	
240						9			9										
250										9									
250																			
TOTAL	807	808	873	912	1091	1118	1099	1279	1467	1352	1607	1034	1053	761	471	168	84	-	9

Total climb: 24,969 minutes

TABLE 3

Estimated time in minutes spent at each speed and altitude during descent by Comet 1 aircraft

Altitude above sea level (I.C.A.N.) in 1000s of feet

Indicated airspeed in knots	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20
110						9	19													
120	19			28																
130	19	19	9	28	19															
140	9	28	28	28	19	28	9	19	9					9						
150	9	38	19	47	66	38	9	47	19	9	9									
160	9	47	38	94	38	132	113	113	75	47	19	9			9					
170	9	28	66	47	85	169	141	150	122	85	28	[illegible]			9	9				9
180			19	47	113	103	132	75	188	66	103	75		9	9		38		9	9
190				38	19	56	66	75	122	132	94	28	38	19	28	9	85	19	19	28
200			19	9		56	19	94	56	94	122	75	75	66	85	113	75	47	47	75
210						19	28	65	94	141	113	94	113	85	113	122	188	160	179	132
220							19	38	85	38	75	132	122	103	94	94	197	150	132	273
230					9				38	9	66	38	19	47	47	47	113	47	38	38
240								9					9	19	19	38		19	28	
TOTAL	74	160	198	366	368	610	555	705	808	621	629	470	376	357	413	432	696	442	452	564

Indicated airspeed in knots	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
110																			
120																			
130																			
140																			
150																			
160																			
170		9				9													
180	19			9															
190		38	9	28		28	9	19	28	19	19	9	19		9	9			
200	56	75	66	66	38	75	85	19	56	56	85	56	94	56	28	47	28	19	9
210	207	197	207	169	188	141	160	273	273	404	282	536	310	451	320	169	66	66	47
220	273	179	226	301	254	310	207	320	301	235	367	301	338	451	282	141	66	28	19
230	75	28	47	85	75	28	47	66	94	75	56	28	9	28	28				
240	9	9	19	28	19		9												
TOTAL	639	535	574	686	574	591	517	697	752	789	809	930	770	986	667	366	160	113	75

Total descent: 20,526 minutes

TABLE 4

Estimated time in minutes spent at each speed and altitude during cruise by Comet 1 aircraft

Altitude above sea level (I.C.A.N.) in 1000s of feet

Indicated airspeed in knots	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14
110	9	9				9									
120	19	47													
130	19	122	19												
140	19	141	28			9									
150		19	19	9											
160															19
170		19	9	9											
180		9	19			9									
190			38				9								
200						9	9								
210			9			19									
220															19
230															
240															
250															
260															
270															
TOTAL	66	366	141	18	-	55	18	-	-	-	-	-	-	-	38

Indicated airspeed in knots	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
110															
120							9								
130															
140															
150											9				
160								9							
170					9		9								
180															
190	19										9				19
200	19							9				9		19	19
210				9								9		9	
220			38	9							9			28	160
230	19		19	9										85	94
240	19														
250															
260															
270															
TOTAL	76	-	57	27	9	-	18	18	-	-	27	18	-	141	292

Indicated airspeed in knots	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44
110															
120															
130															
140															
150															
160															
170							18	19	19		9				
180			28	19	47	47	84	65	85	28	47	38	9	9	19
190	9	47	47	179	179	235	150	216	207	132	85	9			
200	19	47	113	207	527	809	827	1015	968	630	263	28	19		
210	94	423	1419	3196	4060	4182	4784	3976	2340	1053	376	38			
220	733	1870	2763	3872	3703	3853	2960	1823	761	320	47				
230	216	567	630	536	676	508	272	85	19						
240	9	9	47	9	28		9								
250															
260															
270	9														
TOTAL	1039	2960	5047	8018	9220	9634	9104	7199	4399	2163	827	113	28	9	19

Total cruise: 61,214 minutes

TABLE 5

Estimated time in minutes spent at each speed and altitude during initial climb and final descent by Comet 2 aircraft

		Altitude above sea level (I.C.A.N.) in 1000s of feet													
		INITIAL CLIMB					FINAL DESCENT								
		01	02	03	04	05	00	01	02	03	04	05	06	07	
Indicated airspeed in knots	100						8								100
	110						16								110
	120						33	7							120
	130						42	21	5	2					130
	140						33	24	1	4					140
	150	4					38	65	3	2					150
	160			2			11	11	4						160
	170		2				2								170
	180														180
	190		21	4											190
	200	3	25	6		4		3							200
	210	3	43	8				5	8					12	210
	220	20	85	22	8			9	3				13	9	220
	230	10	125	54	19										230
	240	3	21	12	11										240
	250	4													250
	TOTAL	47	322	108	38	4	183	145	24	8	–	–	13	21	

Total initial climb: 519 minutes

final descent: 394 minutes

TABLE 6

Estimated time in minutes spent at each speed and altitude during climb by Comet 2 aircraft

	ALTITUDE ABOVE SEA LEVEL (I.C.A.N.) IN 1000s OF FEET																																							
Indicated airspeed in knots	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
140	1																																								
150																																									
160																																					9				
170																																									
180				4					4																																27
190	3	4	4			4																																10	12		14
200				4	11	9	4		4				8				4			4					10								15		10	21	53	37	34	23	15
210			7	21	19	36	8			7	10			4	4	8		4	44	11	9		4	4	8	8	5	16	43	131	86	33	82	93	163	158	177	59	88		
220			21	80	61	59	33	29	53	85	67	43	75	81	82	112	69	105	92	122	107	129	146	125	124	208	170	273	248	272	226	72	176	128	106	80	78				
230				26	43	53	39	72	50	55	63	33	50	66	62	44	64	64	52	64	71	78	83	89	38	64	23	24		45	21	97	141	58	36	24					
240			4		5																																				
TOTAL	4	4	36	135	139	161	84	101	111	147	140	76	133	151	148	164	137	173	188	201	187	207	233	218	180	280	198	313	291	448	333	302	414	279	315	283	317	106	134	23	56

Total climb: 7550 minutes

TABLE 7

Estimated time in minutes spent at each speed and altitude during descent by Comet 2 aircraft

	ALTITUDE ABOVE SEA LEVEL (I.C.A.N.) IN 1000s OF FEET																																									
Indicated airspeed in knots	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
120	12																																										
130	14	11	4	4																																							
140	12	20	4	4	5																																						
150	4	18	4	4																																							
160		29	15	4									4																														13
170		14	61	12	12	18	9		5	26		13			4																												
180		20	17	64	38	20	11	20	4	4				10																													
190		11	18	44	12	27	4	13		5	16																												12				
200				15	14	15	22	26	4	4	15		8	3	4			18	8					4			10					12	14	26	52	18	26	70	122	51	101	60	
210				17	9	25	11	49	50	28	24	20	68	39	28	27	46	52	18	33	29	38	48	8	28	24	81	51	65	45	90	134	68	103	77	165	200	147	214	177	141		
220						25	28	31	14	46	62	59	26	55	64	61	73	77	59	76	72	97	42	19	63	78	49	78	85	72	111	53	11	66	42	22	45	38		12		4	
230							4	5		5		4					4				4		4		4				14														
240																					4									11													
250										4																																	
260														5																													
TOTAL	42	123	123	168	90	130	89	144	77	122	117	96	106	112	100	88	123	147	85	109	109	135	94	31	95	102	140	129	164	128	201	199	93	195	171	205	271	255	348	240	242	64	13

Total descent: 5815 minutes

TABLE 8

Estimated time in minutes spent at each speed and altitude during cruise by Comet 2 aircraft

ALTITUDES ABOVE SEA LEVEL (I.C.A.N.) × 1000 FT

Indicated airspeed in knots	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15
120	4														
130	25	3													
140	40	12													
150	38	48	8		9										
160	9	28	12	3	4										
170		13	8												
180	4	4	4				3								
190			9		4										
200			3			3			4	3				3	
210				8											
220				4	4										
230															
240															
250															
TOTAL	120	108	44	15	21	3	3	-	4	3	-	-	-	3	-

Indicated airspeed in knots	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
120															
130															
140															
150															
160															
170															
180															
190															
200				4	4										
210			5	8	10	4	8		5	7					
220	5		12		12		17	4	5			3			
230								8		4					
240															
250															
TOTAL	5	-	17	12	26	4	25	12	10	11	-	3	-	-	-

Indicated airspeed in knots	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
120															
130															
140															
150													13		
160															
170													13		
180						23					13	60	38	72	
190										16	68	294	70	33	12
200								28	219	308	1708	2234	432	43	11
210						23	143	271	1036	4233	3887	643			
220				50	107	216	863	3149	2772	1340	81	12			
230		13	12	166	354	930	1720	1436	35						
240				177	101	282	51								
250			50	48											
TOTAL	-	13	62	441	562	1474	2777	4884	4062	5897	5757	3243	566	148	23

Total cruise: 30,358 minutes

TABLE 9

Summary of acceleration data from Counting Accelerometers Mk. 1 in Comet 1 aircraft

Flight condition	Altitude band feet	Mean altitude feet	Recorded time min	Statute miles	Number of times each acceleration increment was exceeded: Down 1.32 g	1.22 g	1.12 g	1.02 g	0.92 g	0.82 g	0.72 g	0.62 g	0.52 g	0.43 g	0.33 g	0.23 g	Up 0.23 g	0.33 g	0.43 g	0.52 g	0.62 g	0.72 g	0.82 g	0.92 g	1.02 g	1.12 g
Climb and Descent (excluding initial climb and final descent)	0- 1,500	1,000	83	838												1	11	7								
	1,500- 3,500	2,600	458	1,497						2	6	5	7	11	32	78	216	78	15	10	2	2				
	3,500- 5,500	4,600	1,164	4,130								1	4	14	79	243	514	162	46	17	5	3	1			
	5,500- 9,500	7,600	5,016	20,723	1	1	1	1	2	3	9	13	82	96	420	1,143	2,124	779	231	75	22	12	3	1		
	9,500-13,500	11,300	4,351	20,863					1	1	3	5	13	36	160	447	739	254	67	17	8	3	2			
	13,500-17,500	15,700	4,333	22,737					1	3	5	6	14	26	93	215	337	134	45	11	8	3				
	17,500-21,500	19,600	5,121	28,401			1	1	1	2	6	10	22	43	120	230	360	156	69	36	19	11	4	1	1	1
	21,500-25,500	23,600	6,363	37,063					1	2	2	2	5	11	42	122	214	60	17	7	1	1	1	1	1	
	25,500-29,500	27,600	7,754	47,329								2	2	8	48	167	303	52	12	6	2					
	29,500-33,500	31,300	7,753	50,199								1	5	8	31	113	185	62	20	6	3	3	1	1		
	33,500-37,500	34,800	2,902	20,699					1	1	1	2	4	8	29	86	114	39	9	3	1					
	37,500-41,500	38,400	197	1,538												1	1									
TOTAL			45,495	255,417	1	1	2	2	7	14	31	47	108	261	1,054	2,846	5,118	1,783	531	188	71	38	12	4	2	1
Cruise	0- 1,500	900	432	1,134									2	21	157	413	675	219	41	15	5	3				
	1,500- 3,500	2,100	159	521										3	27	95	122	38	6	1						
	3,500- 5,500	5,000	55	204									1	2	8	42	74	27	4	2						
	5,500- 9,500	6,000	18	77												–	1									
	9,500-13,500															–	–									
	13,500-17,500	15,100	171	876												6	28	6	4	4	2	2				
	17,500-21,500	19,200	54	272											1	6	13	5	1							
	21,500-25,500	22,600	45	243												1	3	1								
	25,500-29,500	28,600	451	3,036										4	7	15	29	14	10	5	2	1				
	29,500-33,500	32,200	17,114	121,442					1	1	3	6	10	20	78	274	343	89	20	9	7	6	2	1		
	33,500-37,500	35,400	35,157	260,273				1	5	8	15	23	51	125	403	916	1,234	432	171	77	43	31	18	8	3	2
	37,500-41,500	38,600	7,502	57,985								3	10	13	57	168	310	106	29	11	4	3	1	1		
	41,500-45,500	42,800	56	436												3	8	2								
TOTAL			61,214	446,499				1	6	9	18	32	74	188	738	1,939	1,840	939	286	124	63	46	21	10	3	2

TABLE 10

Summary of acceleration data from Counting Accelerometers Mk. 4, in Comet 2 aircraft

Flight condition	Altitude range feet	Mean altitude feet	Recording time mins	Statute miles	Number of times each acceleration increment was exceeded (+ Up, - Down)														
					-1.4 g	-1.2 g	-1.0 g	-0.8 g	-0.6 g	-0.4 g	-0.3 g	-0.2 g	+0.2 g	+0.3 g	+0.4 g	+0.6 g	+0.8 g	+1.0 g	+1.2 g
Initial climb	0- 1,500	1,000	47	200						3	12	36	49	21	5	1			
	1,500- 3,500	2,250	430	1,882				1	2	23	84	312	499	158	39	4	2		
	3,500- 5,500	4,100	42	195						1	7	33	42	11	2				
Final descent	0- 1,500	580	328	897			1	1	1	2	6	57	132	22	3	2	1	1	
	1,500- 3,500	2,250	32	106							1	4	19	3	1				
	5,500- 9,500	6,620	34	156									2	1					
Climb and descent	0- 1,500	1,000	42	108							1	8	33	5	2				
	1,500- 3,500	2,510	250	822						1	23	80	180	55	10	1			
	3,500- 5,500	4,420	298	1,146						1	7	62	113	26	5				
	5,500- 9,500	7,380	959	4,358						6	22	138	212	51	16				
	9,500-13,500	11,540	940	4,669							9	44	82	15	3				
	13,500-17,500	15,640	931	5,005						1	7	39	63	9	2				
	17,500-21,500	19,510	1,112	6,375							3	30	32	4	1				
	21,500-25,500	23,470	1,183	7,302						2	10	24	17	1					
	25,500-29,500	27,580	1,411	9,301							4	19	20	2					
	29,500-33,500	31,530	2,006	14,066							3	26	40	3					
	33,500-37,500	35,540	2,152	16,205						9	35	107	121	41	13				
	37,500-41,500	39,290	1,925	15,241		1	1	3	4	20	80	222	254	80	33	7	3	1	
	41,500-45,500	42,420	156	1,233						1	3	6	12	2	1				
TOTAL			13,365	85,831		1	1	3	4	41	207	805	1179	294	86	8	3	1	
Cruise	0- 1,500	1,000	120	335							1	12	40	3					
	1,500- 3,500	2,290	152	480							1	8	42	4					
	3,500- 5,500	4,580	36	137							1	6	15	4					
	5,500- 9,500	7,500	10	42									1						
	9,500-13,500	10,000	3	13															
	13,500-17,500	15,250	8	41															
	17,500-21,500	19,290	59	326									4						
	21,500-25,500	23,120	58	352								1	1						
	25,500-29,500	27,000	3	20															
	29,500-33,500	32,800	75	603															
	33,500-37,500	36,250	5,254	42,428							2	48	56	10	4				
	37,500-41,500	39,610	20,600	168,688						15	70	450	469	81	17	1			
	41,500-45,000	42,230	3,980	32,405					1	7	29	149	259	69	15	1			
TOTAL			30,358	245,870					1	22	104	674	887	171	36	2			

TABLE 11

Aircraft characteristics assumed

	Comet 1	Comet 2
Wing area:	2,015 sq ft	2,027 sq ft
Mean chord:	17.52 ft	17.63 ft
Aspect ratio:	6.60	6.51
Low speed value of slope of the lift curve for incompressible flow	4.80/radian	4.85/radian

TABLE 12

Representative values of acceleration/gust speed conversion factors

COMET 1

Indicated air speed (knots)	Gust speed/acceleration in ft/sec/g								
	Sea level			25,000 ft			45,000 ft		
	(Aircraft weight (x 1,000 lb)								
	60	80	100	60	80	100	60	80	100
100	47.46	59.62	70.46	39.45	51.27	61.08	36.18	47.17	58.94
150	31.97	40.14	47.43	26.46	34.44	41.02	23.79	31.02	38.77
200	24.22	30.42	35.94	20.26	25.68	31.35	16.70	21.78	27.22
250	19.32	24.26	28.67	15.68	19.88	24.26	11.68	15.21	18.59

TABLE 13

Representative values of acceleration/gust speed conversion factors

COMET 2

Indicated Air speed (knots)	Gust/speed/acceleration in ft/sec/g											
	Sea level				25,000 ft				45,000 ft			
	Aircraft weight (x 1,000 lb)											
	60	80	100	120	60	80	100	120	60	80	100	120
100	47.41	57.81	68.36	79.88	39.31	49.85	60.84	71.29	35.20	45.90	57.37	67.33
150	31.93	38.93	46.03	53.78	26.40	33.46	40.85	47.88	23.66	30.17	37.73	44.27
200	24.19	29.49	34.89	40.75	19.68	24.95	30.47	35.72	16.62	21.65	26.49	31.08
250	19.30	23.53	27.81	32.50	15.23	19.80	23.57	27.64	11.62	15.14	18.50	21.70

TABLE 14

Gusts encountered on all routes by Comet 1 aircraft

Flight condition	Altitude band feet	Mean altitude feet	Recorded time mins	Statute miles	Number of times each gust speed was exceeded — Vertical gust speed in ft/sec E.A.S. (+Up, -Down)															
					-40	-35	-30	-25	-20	-15	-10	-7½	+7½	+10	+15	+20	+25	+30	+35	+40
	0- 1,500	1,000	83	238								2	13	9	1					
Climb	1,500- 3,500	2,600	458	1,497				4	6	14	54	108	291	135	24	4	1			
and	3,500- 5,500	4,600	1,164	4,130					1	14	140	337	636	292	59	16	6	3		
Descent	5,500- 9,500	7,600	5,016	20,723	1	2	2	7	20	95	556	1228	2091	980	193	39	5	1		
(exclud-	9,500-13,500	11,300	4,351	20,863			1	1	3	14	115	343	528	197	19	3				
ing	13,500-17,500	15,700	4,333	22,737				1	4	12	61	148	238	95	13	2				
Initial	17,500-21,500	19,600	5,121	28,401				1	5	14	76	156	240	109	29	7	2			
Climb	21,500-25,500	23,600	6,363	37,063				1	2	4	22	67	104	33	4	1				
and	25,500-29,500	27,600	7,754	47,329						2	27	82	126	27	4	1				
Final	29,500-33,500	31,300	7,753	50,199						2	18	53	90	28	4	1				
Descent)	33,500-37,500	34,800	2,902	20,699					1	1	8	28	34	11						
	37,500-41,500	38,400	197	1,538								-	-							
TOTAL			45,495	255,417	1	2	3	15	42	172	1077	2552	4441	1916	350	74	14	4		
Cruise	0- 1,500	900	432	1,134					9	83	353	653	1100	549	125	25	6	1		
	1,500- 3,500	2,100	159	521						1	32	82	109	37						
	3,500- 5,500	5,000	55	204						2	23	84	139	59	11	3	1			
	5,500- 9,500	6,000	18	77								-	-							
	9,500-13,500											-	-							
	13,500-17,500	15,100	171	876								-	6	5	1					
	17,500-21,500	19,200	54	272								1	7	2						
	21,500-25,500	22,600	45	243								1	1							
	25,500-29,500	28,600	451	3,036							5	9	18	11	3					
	29,500-33,500	32,200	17,114	121,442			1	1	1	8	49	151	174	57	9	3	2	1		
	33,500-37,500	35,400	35,157	260,273				2	8	29	169	474	564	208	52	18	2	1		
	37,500-41,500	38,600	7,502	57,985						2	16	56	114	29	3	1				
	41,500-45,500	42,800	56	436								-	2							
TOTAL			61,214	446,499			1	3	18	125	647	1511	2134	957	204	50	11	3		

TABLE 15

Gusts encountered on all routes by Comet 2 aircraft

Flight condition	Altitude band feet	Mean altitude feet	Recording time mins	Statute miles	Number of times each gust speed was exceeded Vertical gust speed in ft/sec E.A.S. (+Up, -Down)															
					-40	-35	-30	-25	-20	-15	-10	-7½	+7½	+10	+15	+20	+25	+30	+35	+40
Initial climb	0- 1,500	1,000	47	200					1	5	23	42	49	29	8	3	2	1		
	1,500- 3,500	2,250	430	1,882				1	3	15	89	235	396	160	24	6	2	1		
	3,500- 5,500	4,100	42	195							4	17	24	7						
Final descent	0- 1,500	580	328	837	1	1	1	1	1	2	18	60	142	42	4	2	1	1	1	1
	1,500- 3,500	2,250	32	106							1	4	16	6						
	5,500- 9,500	6,620	34	156									1							
Climb and descent	0- 1,500	1,000	42	108							3	9	44	14	2	1				
	1,500- 3,500	2,510	250	822						1	23	59	150	61	5	1				
	3,500- 5,500	4,420	298	1,146							6	32	75	24	1					
	5,500- 9,500	7,380	959	4,358					1	5	23	70	134	44	5					
	9,500-13,500	11,540	940	4,669							3	13	38	9	1					
	13,500-17,500	15,640	931	5,005						1	3	15	24	6	2					
	17,500-21,500	19,510	1,112	6,375							1	6	7	1						
	21,500-25,500	23,470	1,183	7,302							6	11	2							
	25,500-29,500	27,580	1,411	9,301								3	2							
	29,500-33,500	31,530	2,006	14,066								4	8							
	33,500-37,500	35,540	2,152	16,205							9	35	39	12						
	37,500-41,500	39,290	1,925	15,241				1	2	4	17	69	74	29	6	2				
	41,500-45,500	42,420	156	1,233							1	2	2	1						
TOTAL			13,365	85,831				1	3	11	95	328	599	201	22	4				
Cruise	0- 1,500	1,000	120	335							3	14	56	13						
	1,500- 3,500	2,290	152	480							2	7	42	12						
	3,500- 5,500	4,580	36	137							2	7	15	6						
	5,500- 9,500	7,500	10	42																
	9,500-13,500	10,000	3	13																
	13,500-17,500	15,250	8	41																
	17,500-21,500	19,290	59	326																
	21,500-25,500	23,120	58	352																
	25,500-29,500	27,000	3	20																
	29,500-33,500	32,800	75	603																
	33,500-37,500	36,250	5,254	42,428								2	11	4						
	37,500-41,500	39,610	20,600	168,688						1	16	66	84	19	1					
	41,500-45,500	42,230	3,980	32,405						1	7	30	62	15	1					
TOTAL			30,358	245,870						2	30	126	270	69	2					

TABLE 16

Altitude bands used in analysis

	Feet
00	0 - 1,500
02	1,500 - 3,500
04	3,500 - 5,500
06	5,500 - 9,500
10	9,500 - 13,500
14	13,500 - 17,500
18	17,500 - 21,500
22	21,500 - 25,500
26	25,500 - 29,500
30	29,500 - 33,500
34	33,500 - 37,500
38	37,500 - 41,500
42	41,500 - 45,500

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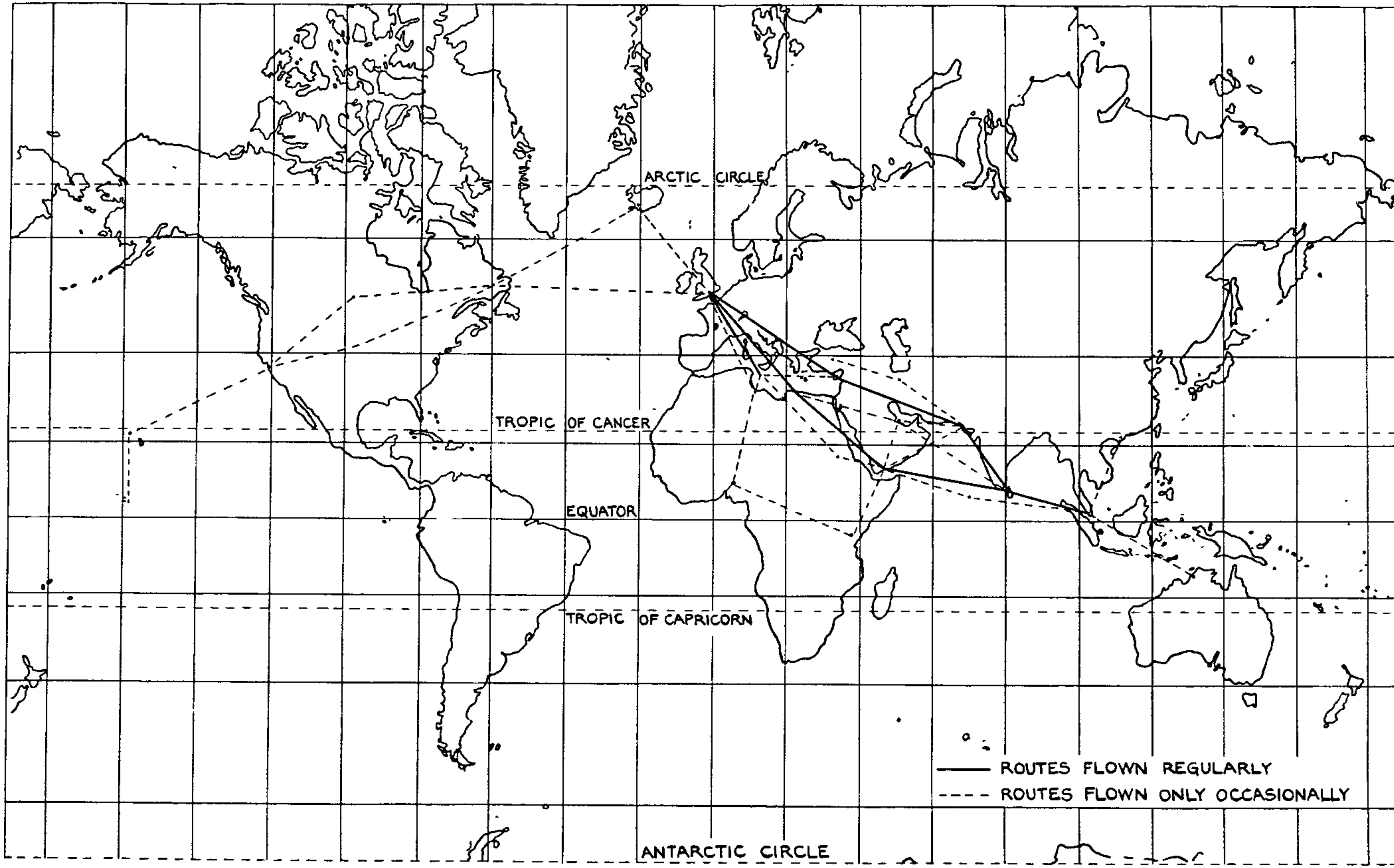

FIG.1. MAP OF THE ROUTES FLOWN BY COMET 2 AIRCRAFT.

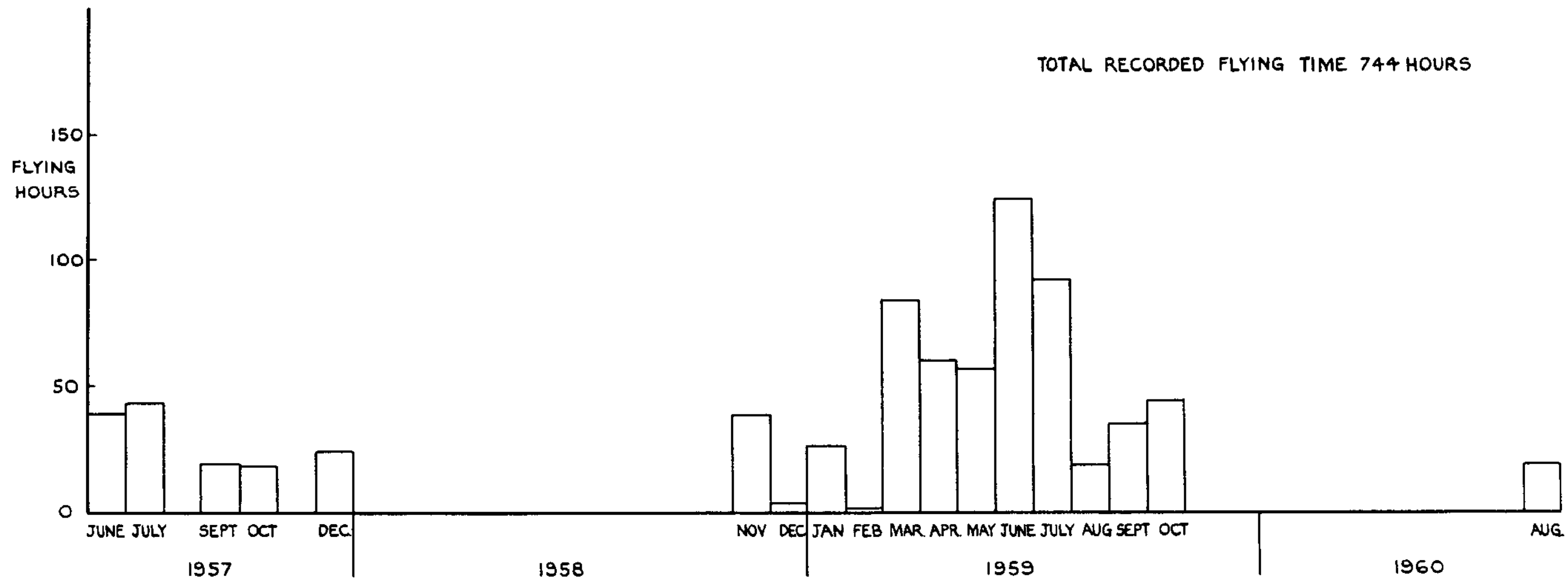

FIG. 2. MONTHLY DISTRIBUTION OF RECORDED FLYING TIME FOR COMET 2 AIRCRAFT.

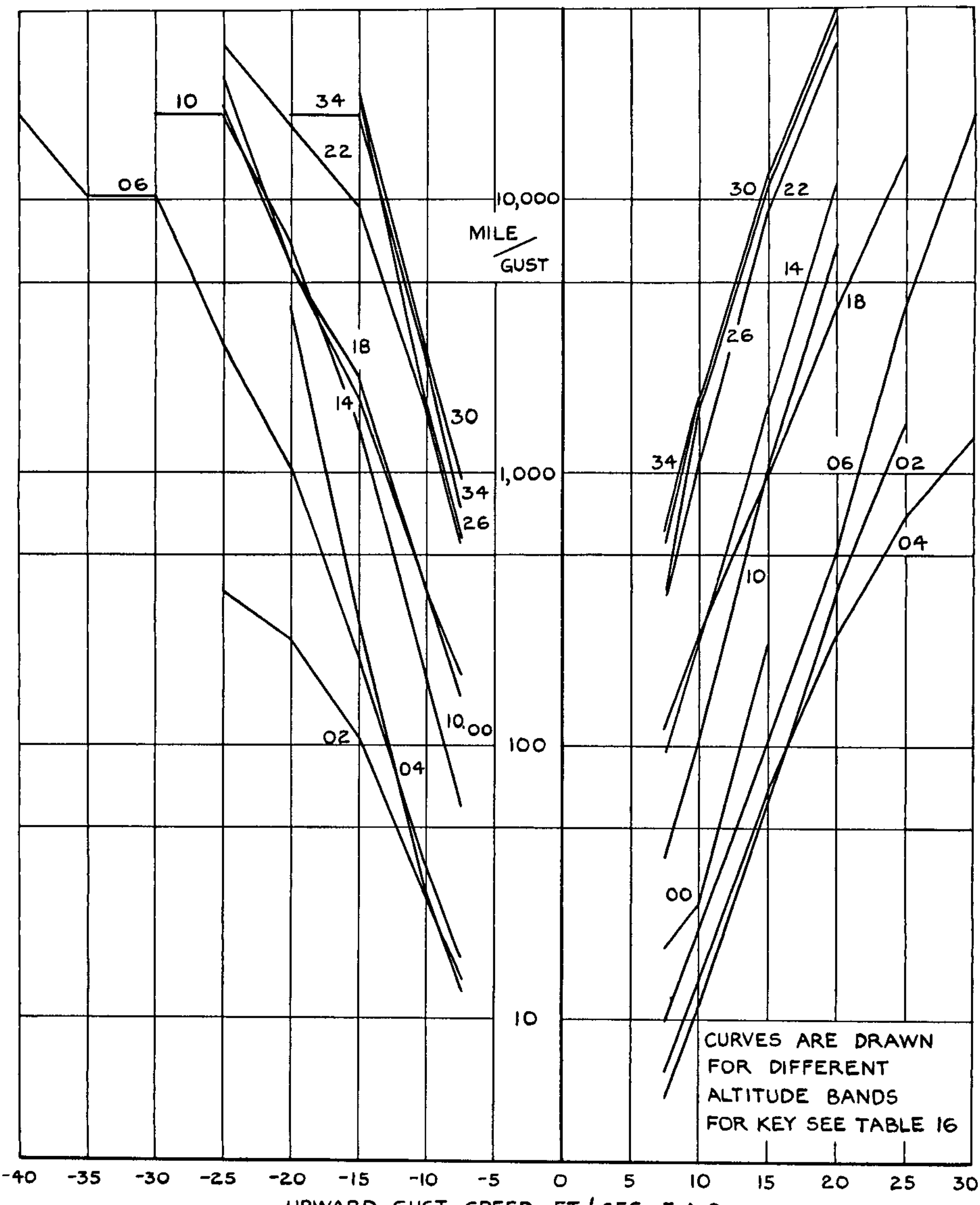

FIG.3. VARIATION OF GUST FREQUENCY WITH GUST SPEED DURING CLIMB AND DESCENT FOR COMET I AIRCRAFT.

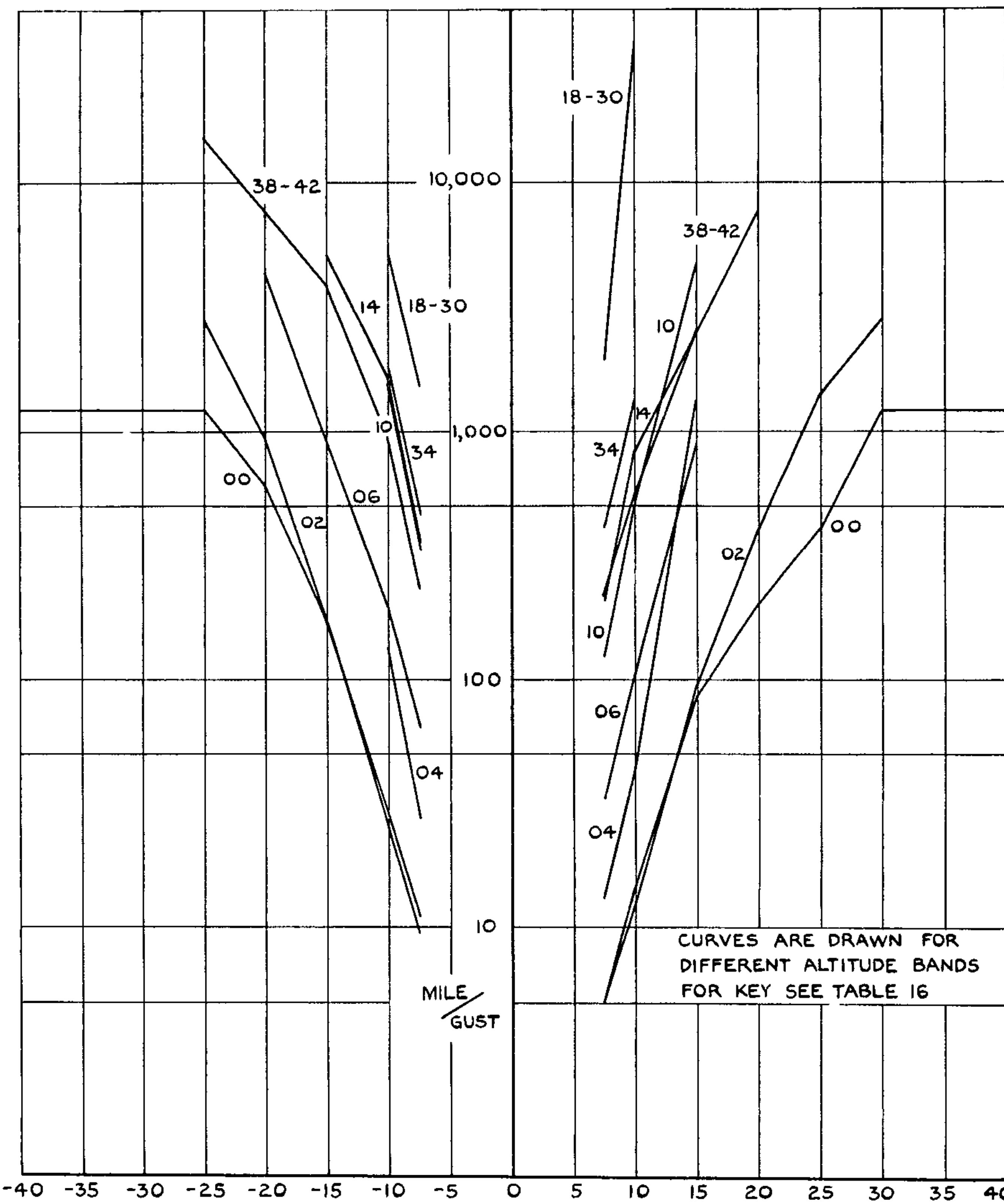

FIG.4. VARIATION OF GUST FREQUENCY WITH GUST SPEED DURING CLIMB AND DESCENT FOR COMET 2 AIRCRAFT.

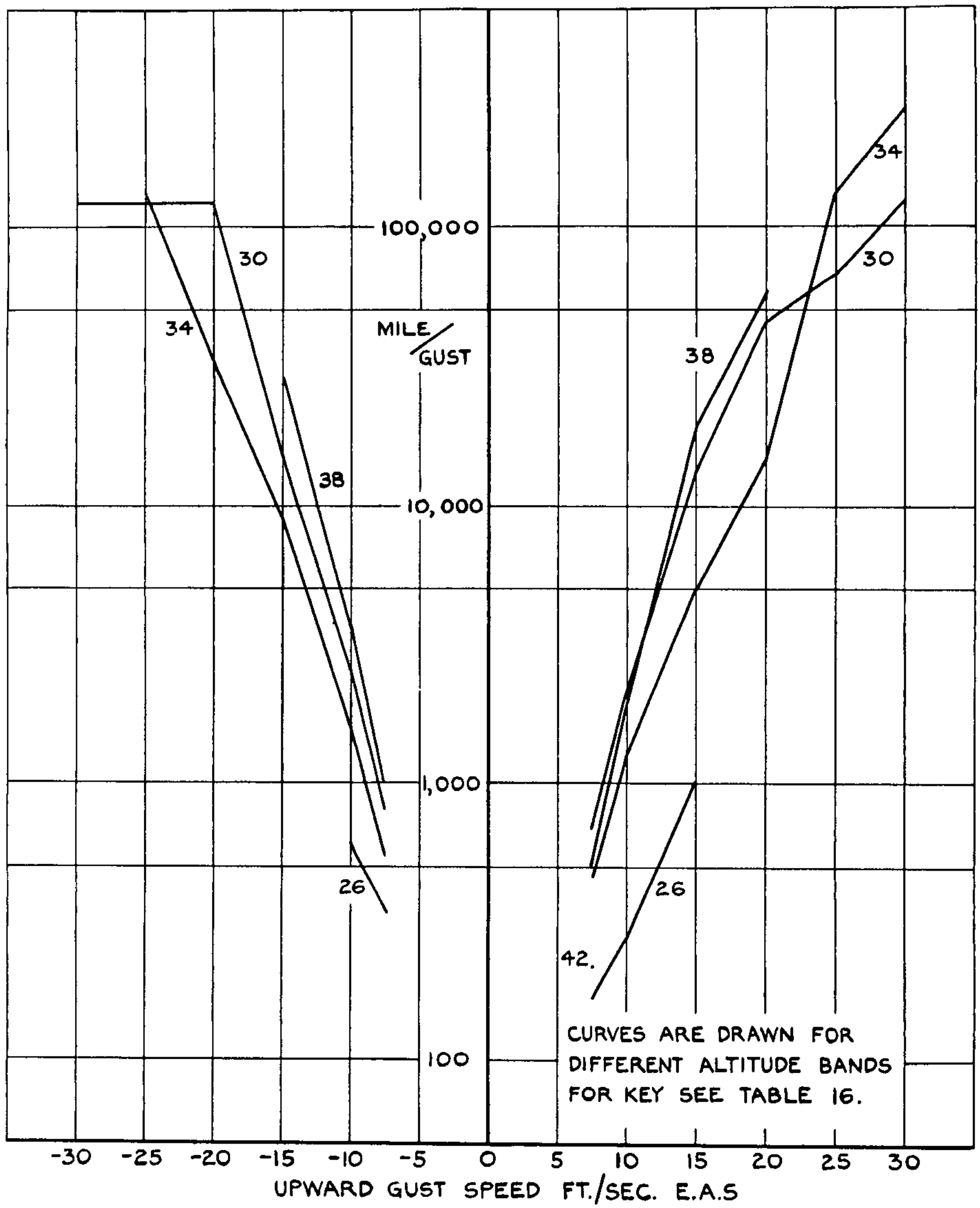

FIG.5. VARIATION OF GUST FREQUENCY WITH GUST SPEED DURING CRUISE FOR COMET I AIRCRAFT.

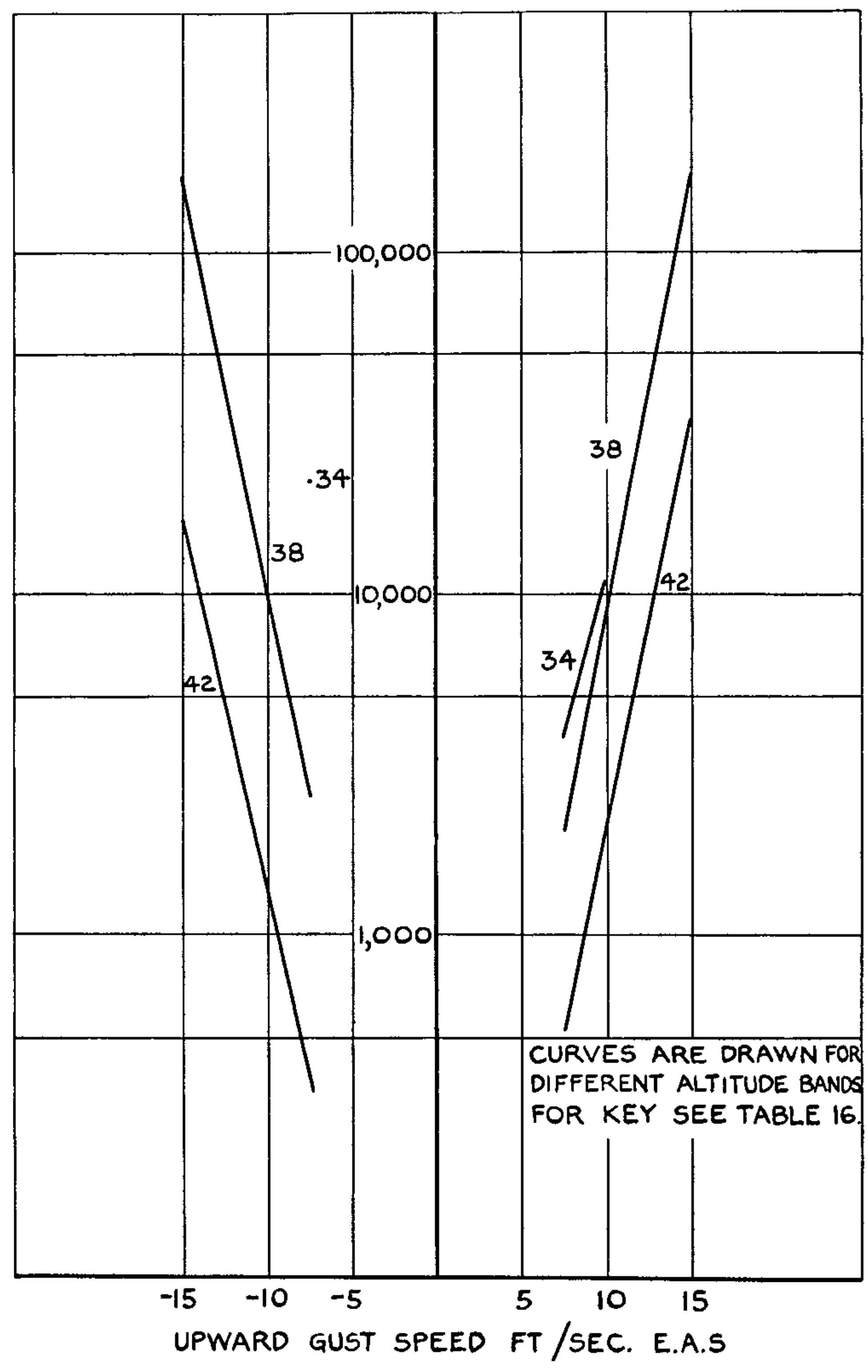

FIG.6. VARIATION OF GUST FREQUENCY WITH GUST SPEED DURING CRUISE FOR COMET 2 AIRCRAFT.

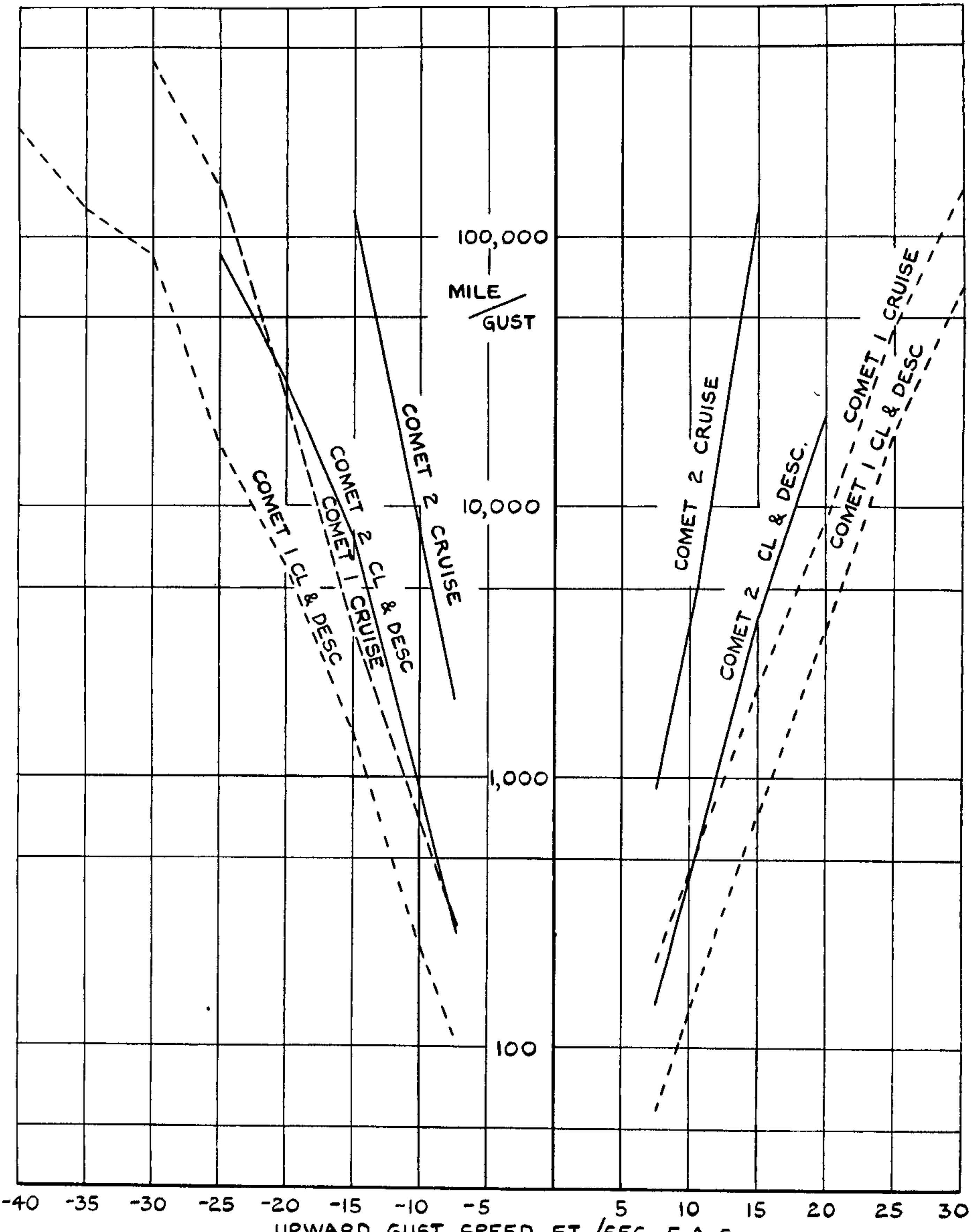

FIG.7. OVERALL VARIATION OF GUST FREQUENCY WITH GUST SPEED FOR COMET 1 AND COMET 2 AIRCRAFT.

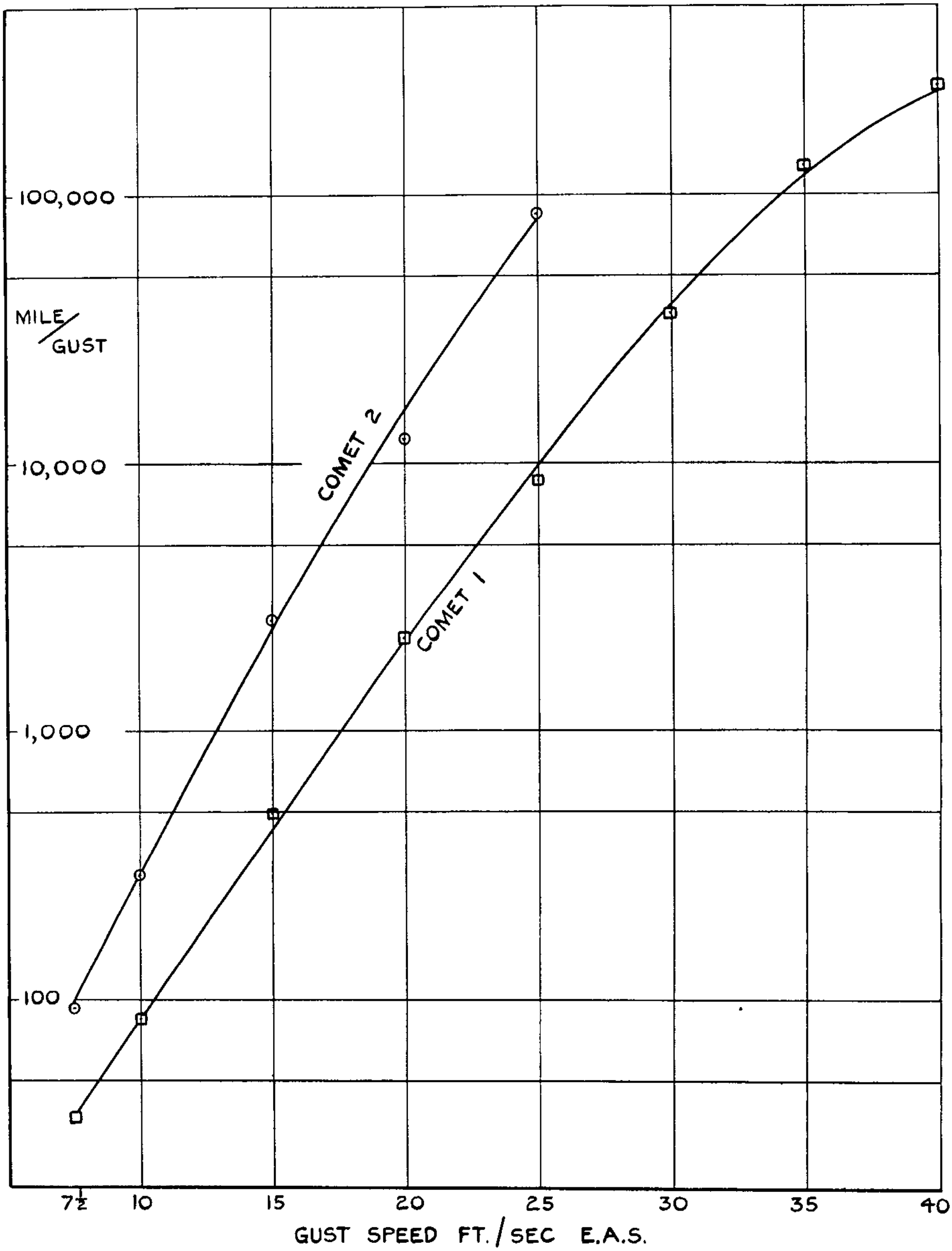

FIG.8. VARIATION OF GUST FREQUENCY WITH GUST SPEED DURING CLIMB AND DESCENT BY COMET 1 AND COMET 2 AIRCRAFT.

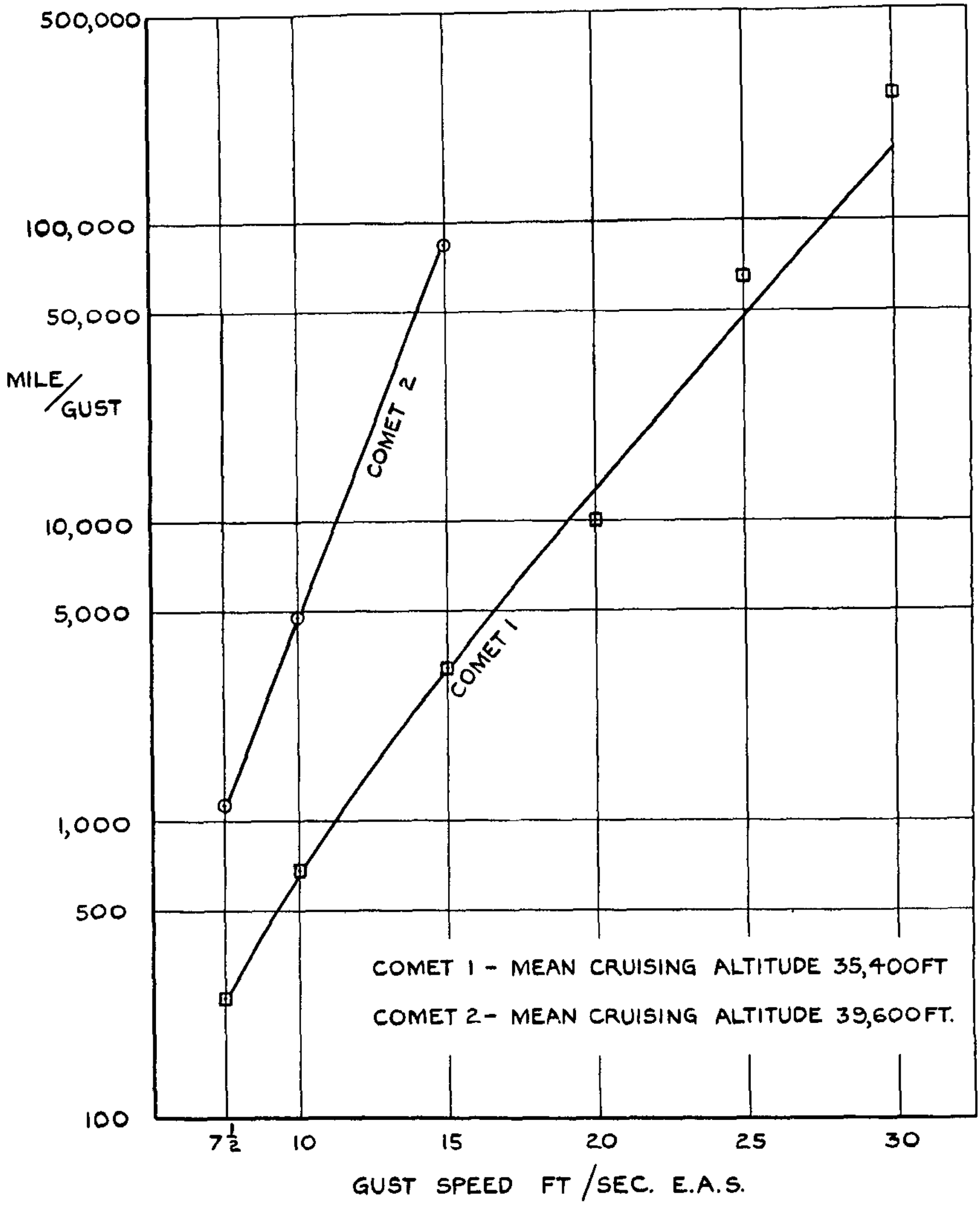

FIG.9. VARIATION OF GUST FREQUENCY WITH GUST SPEED DURING CRUISE OF COMET 1 AND COMET 2 AIRCRAFT.

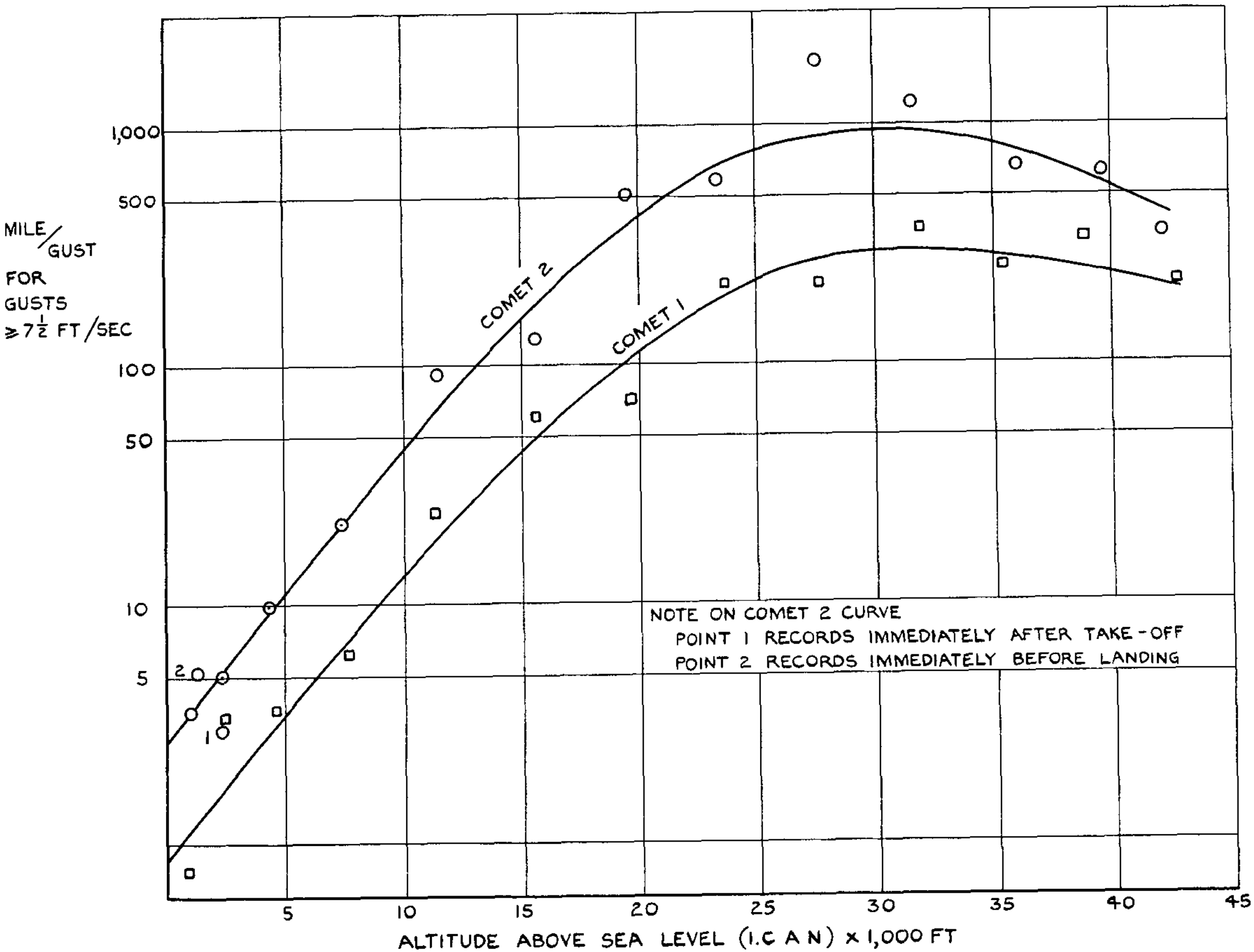

FIG.10. VARIATION OF GUST FREQUENCY WITH ALTITUDE.

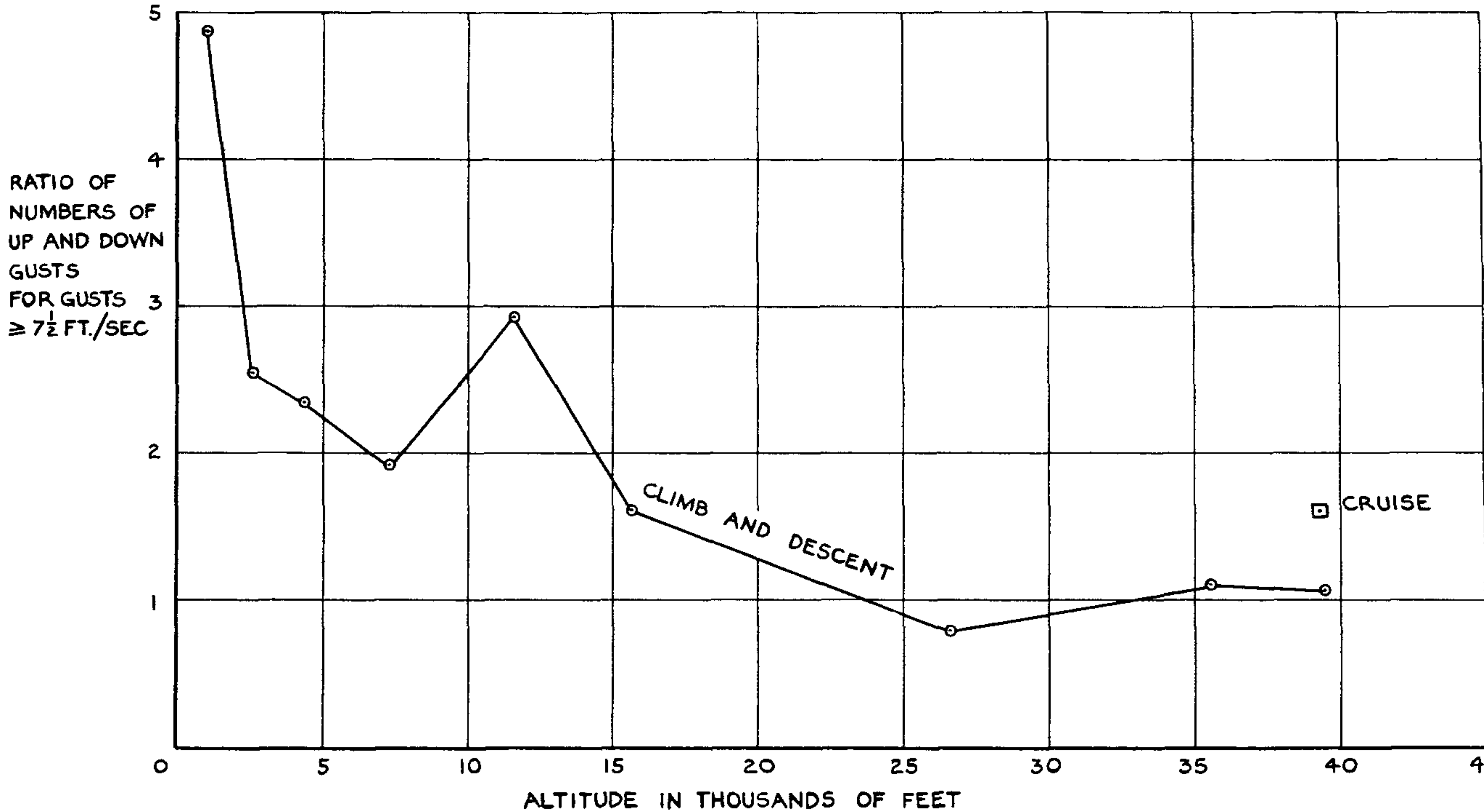

FIG.11. RATIO OF UP AND DOWN GUSTS ENCOUNTERED BY COMET 2 AIRCRAFT AT DIFFERENT ALTITUDES.

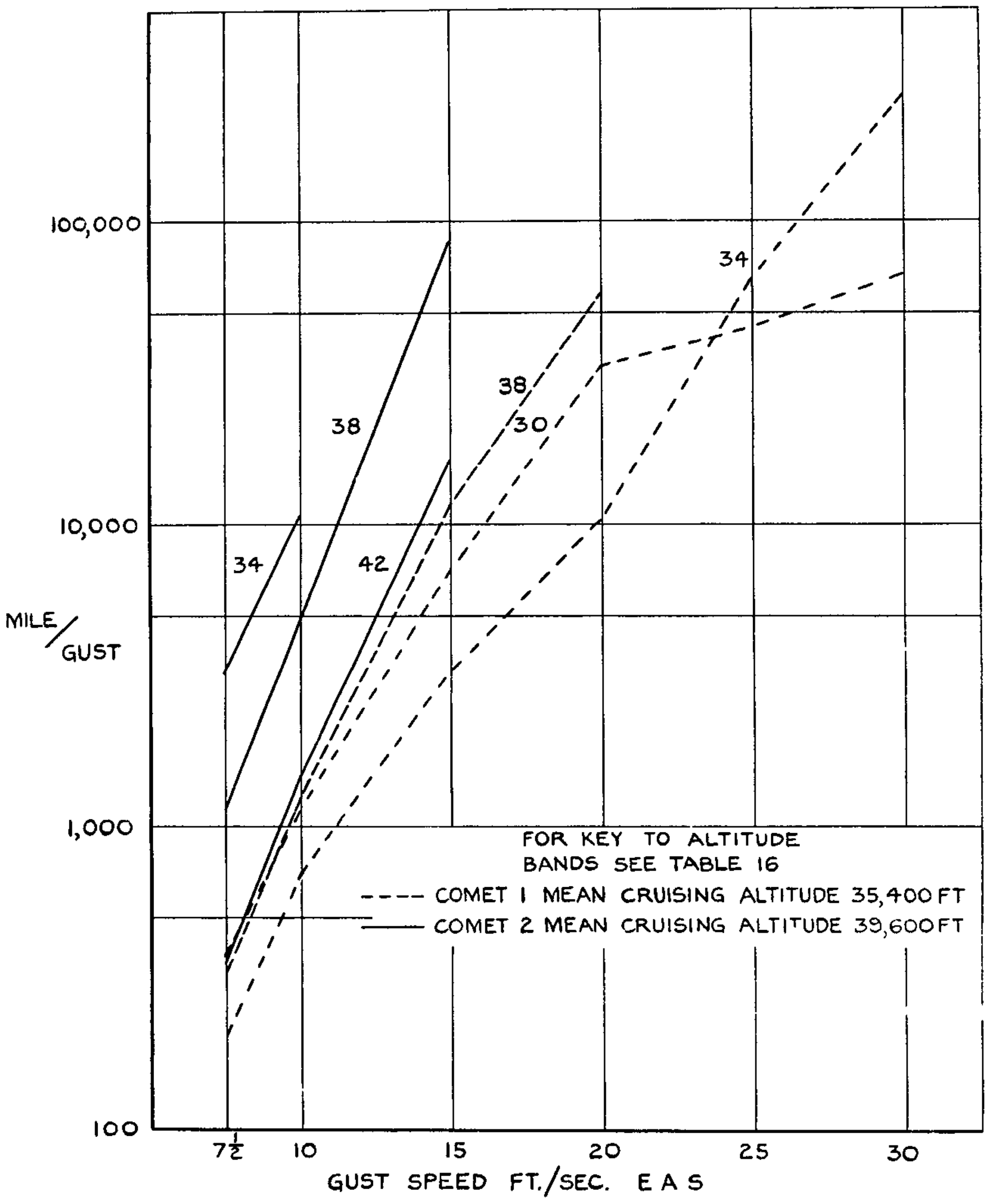

FIG.12. VARIATION OF GUST FREQUENCY WITH GUST SPEED AT DIFFERENT ALTITUDE BANDS DURING CRUISE BY COMET 1 AND COMET 2 AIRCRAFT.

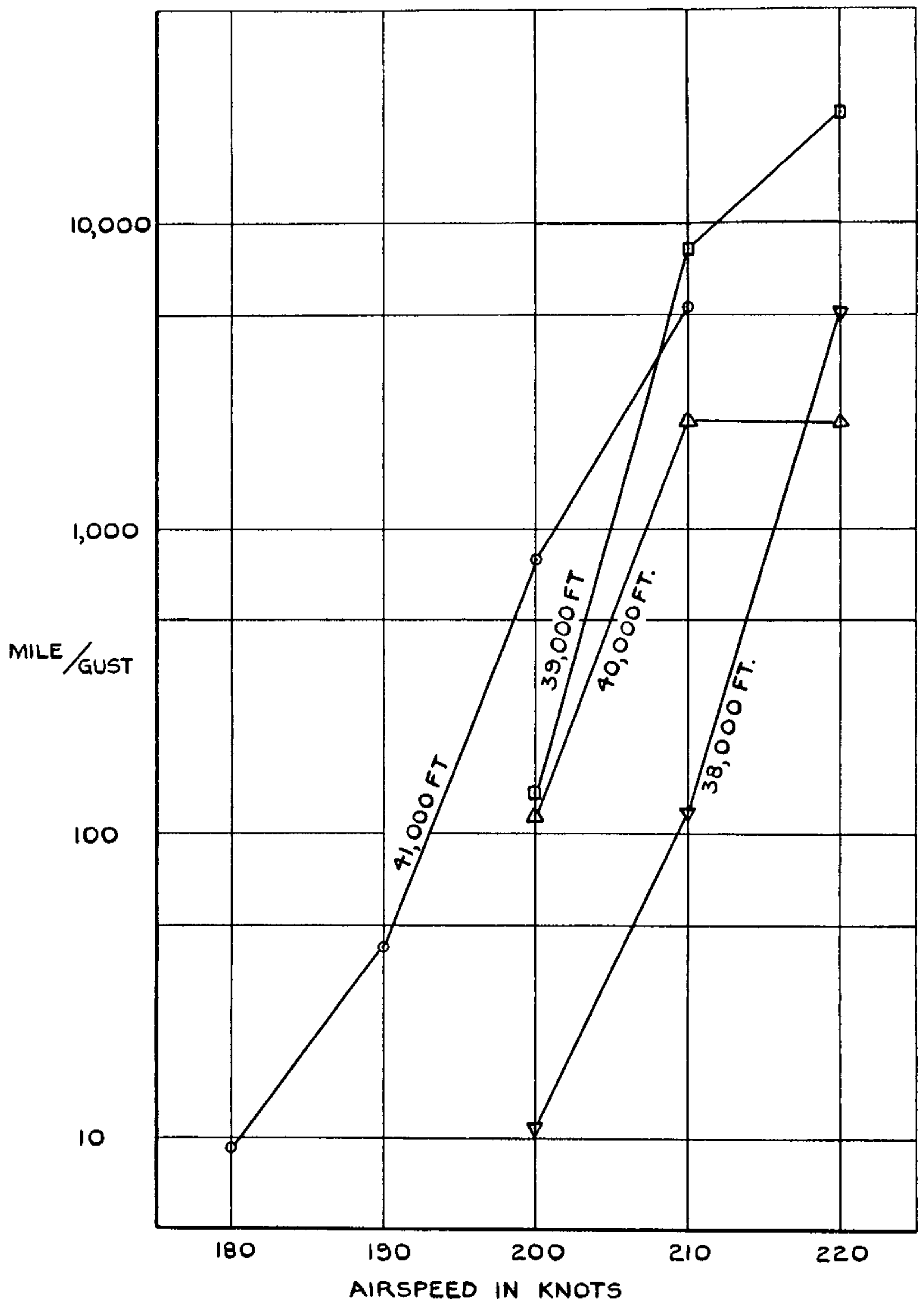

FIG. 13. VARIATION OF GUST FREQUENCY WITH AIRSPEED AT DIFFERENT ALTITUDES DURING CRUISE OF COMET 2.

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Aplin, Judy E. June 1963.

Counting accelerometer records have been obtained of the turbulence encountered by R.A.F. Comet 2 aircraft, equipped with cloud collision warning radar, in 335,000 miles of operational flying largely on routes connecting the U.K. with Singapore.

It is shown that the Comet 2 met significantly less turbulence at all altitudes than the Comet 1 which was not carrying this radar, and that the reduction in the frequency of occurrence of gusts increased

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