THE CHARACTERISTICS OF PERSISTENT SPORADIC METEOR ECHOES

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Summary

This paper examines the frequency distribution of the durations of nearly 8000 persistent radio echoes from sporadic meteors recorded at Adelaide during 1957. The maximum line densities in the trails formed by these meteors exceed 10^{13} electrons/cm, corresponding to visual magnitudes $<+3$. As the echo duration increases, the numbers of echoes are found to fall progressively further below the numbers expected from a power-law distribution. No significant seasonal or diurnal variation in the mass distribution of the meteors examined is apparent.

Echo trace irregularities, which have been classified into five distinct types, are present in 43% of the persistent echoes recorded. Four of these types of irregularity are attributed to distortion of the trail due to atmospheric turbulence, whilst the fifth (leader echo) type is associated with the process of trail formation. The characteristics and diurnal variation in incidence of each type are examined in detail.

I. Introduction

A comprehensive theoretical treatment of the scattering of radio waves by the ionized column formed when a meteor enters the Earth's atmosphere has been given by Kaiser and Closs (1952). They showed that two distinct types of scattering occur, depending on whether the electron line density α of the column is less than or greater than $2\cdot4\times10^{12}$/cm. If $\alpha<2\cdot4\times10^{12}$/cm, the incident wave penetrates throughout the ionized column and the electrons scatter coherently and independently; although in the case where the incident electric vector is normal to the trail there may be an enhancement of scattering due to resonance. As the column expands the echo exhibits an exponential decay, the time τ required for the amplitude to decay to 1/e of the maximum amplitude being

$$\tau=\lambda^2/16\pi^2D, \tag{1}$$

where λ is the wavelength and D the ambipolar diffusion coefficient. This is the so-called "decay" type echo.

If, however, $\alpha>2\cdot4\times10^{12}$/cm, the incident wave does not penetrate throughout the column and the reflection process is similar to that from an expanding metal cylinder. In this case the echo will persist, with little change in amplitude, until diffusion causes the axial electron density to fall below the critical value, after which the type of scattering changes and the echo decays rapidly and exponentially as before. Echoes such as these are classed as persistent. The

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time for which the echo persists before its eventual decay is given approximately by

$$\tau=1\cdot124\times10^{-12}(\lambda^2/16\pi^2D)\alpha. \qquad (2)$$

Theoretical curves showing the variation of the reflection coefficient with $D\tau/\lambda$ for different values of α, given by Kaiser and Closs (1952), show that, as is to be expected, there is not an abrupt change of echo type at $\alpha=2\cdot4\times10^{12}$/cm. The transition between the two types occurs smoothly in the range $10^{12}<\alpha<10^{13}$/cm.

Because of the exponential form of the decay, the duration measured for a decay type echo will depend on the echo amplitude. It is not until $\alpha>10^{13}$ electrons/cm that the echo duration becomes essentially independent of amplitude and hence of equipment sensitivity.

The problem of the frequency distribution of meteor echo durations measured by radio techniques has been treated theoretically by Kaiser (1953, 1955). He has shown that for persistent echoes received from meteor trails produced by evaporation of solid meteor particles in an isothermal atmosphere, the number of echoes N_τ whose duration exceeds τ is

$$N_\tau\propto\tau^{3(1-s)/4}. \qquad (3)$$

In this relation, which applies to both shower and sporadic meteors, s is the exponent in the assumed differential meteor mass distribution

$$\nu_m\mathrm{d}m=bm^{-s}\mathrm{d}m, \qquad (4)$$

where $\nu_m\mathrm{d}m$ is the number of meteors in the mass range m to $m+\mathrm{d}m$, crossing unit area normal to their direction of flight per unit time; b is a constant.

If the distribution described by the relation (3) applies in practice, it should be possible to obtain the value of s, both for the major showers and the sporadic background, by measuring the distribution of radio echo durations. Results for three of the major showers, the Perseids, Arietids, and Geminids, have been given by Kaiser (1953) and Browne *et al.* (1956). In the case of the sporadic background, however, no previous extended survey seems to have been made. The value of s for sporadic meteors has been derived from visual and photographic measurements, as well as by an alternative radio technique which involves the comparison of echo rates obtained from two equipments, identical in every respect other than sensitivity. Kaiser (1953), using results obtained by McKinley (1951), has given the value of $s=2\cdot00\pm0\cdot02$ over the zenithal magnitude range $+5$ to $+10$. The visual and photographic determinations of s, which apply to bright meteors, involve large corrections for subjective factors and it is not surprising that the values obtained show considerable variation. Watson (1939) gives the same value as that obtained by Kaiser for fainter meteors ($s=2\cdot0$); Millman (1935), however, suggests that for very bright meteors ($-7<M_v<-2$) $s=2\cdot4$. The most recent photographic determination, made by Hawkins and Upton (1958), gives $s=2\cdot3$ over the range $0<M_v<+4\cdot5$.

Besides measuring the value of the mass distribution parameter s, it is important to establish whether that parameter shows any real temporal variations. For instance, a knowledge of such variations is necessary before it can be decided whether the very small diurnal and seasonal changes, found in meteor height distributions by Evans (1955), reflect properties of the upper atmosphere, or are due to real variations in s, on which the measured radio echo height distribution also depends. The data used in the determinations of s mentioned above were either too fragmentary or too sparse to give any information on this point.

This paper deals with the measurement and analysis of durations of meteor echoes recorded at Adelaide during 1957, as part of an extended survey of meteor activity in the southern hemisphere. The records provide an adequate diurnal and seasonal cover, and include also the periods of activity of most of the known showers. The diurnal and seasonal variations in the mass distribution of brighter sporadic meteors are investigated in detail. An analysis of the data for showers will be presented separately (Weiss 1961*b*).

II. The Equipment

The equipment used in the Adelaide survey was essentially the 67 Mc/s narrow-beam radiant equipment described by Weiss (1955), with the transmitter power increased to 50 kW. The minimum detectable line density during the survey was close to 1×10^{11} electrons/cm. The transmitter was double pulsed with 12 μs pulses 110 μs apart, at a repetition frequency of 93/s. The film speed of the existing camera system, 12 cm/hr, was far too slow for the accurate measurement of echo durations. To obtain adequate writing speed, the receiver output was fed to a second intensity-modulated display and photographed by a camera incorporating a rocking mirror optical system, which sweeps the trace to and fro across the continuously moving 70 mm recording paper. The effective film speed so obtained was slightly greater than 4 in/min.

The shortest echo trace length which could be reliably measured was 0·025 in., corresponding to a duration of 0·36 s. This time interval was adopted as the basic unit of measurement. Using curves given by Kaiser and Closs (1952, Fig. 12) and taking the value of the ambipolar diffusion coefficient D to be 3×10^4 cm^2/s, the electron line density corresponding to an echo duration of 0·36 s, for an equipment for which $\lambda = 448$ cm, is approximately 1×10^{13}/cm. This means that echo durations were measured only above the limit for which the effect of equipment sensitivity may be neglected and were therefore insensitive to the position of the echoing point within the aerial beam.

III. Analysis of Echo Durations

The radiant equipment was operated continuously throughout 1957, and durations recordings were made from the middle of February until the end of August, and again during November and December. Because they provided a good seasonal cover with freedom from interruptions due to excessive external interference and minor equipment failures, the months of March, May, July-August, and December were chosen for analysis. Every persistent echo recorded during these months was individually examined and classified according to its duration and time of occurrence, and at the same time any indication of irregularity in the form of the echo which could be attributed to distortion of the trail was noted. After periods of known shower activity and excessive interference were removed, 7825 persistent echoes (i.e. those with durations $\geqslant 0 \cdot 36$ s) remained. Of these, 3360 or 43% showed obvious sign of disturbance, as evidenced by the fact that their traces were not formed of unbroken straight lines at constant slant range. It seems highly probable that there were many more echoes in which the disturbance was not obvious, because an investigation of records from the Adelaide 27 Mc/s wind equipment (where the echoes, exhibited on an A-scope rather than an intensity-modulated display, can be examined in much finer detail) suggests that at least 60% of all echoes are disturbed to some extent.

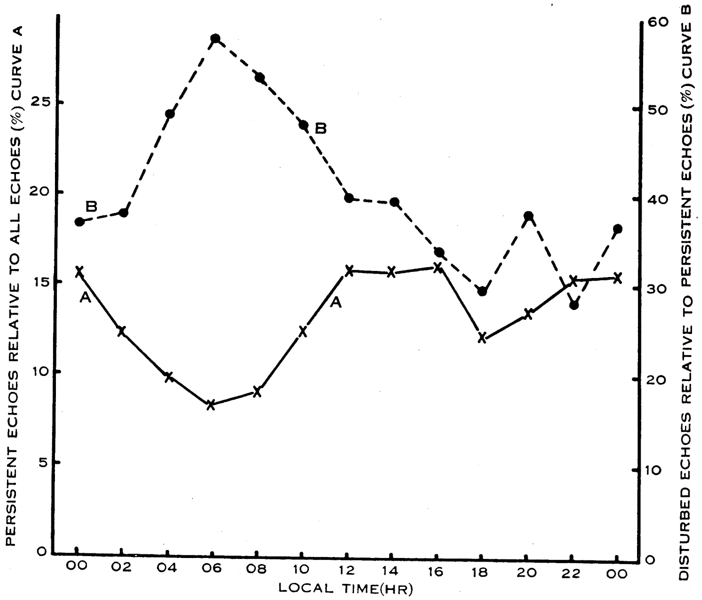


Fig. 1.—Diurnal variations in the number of persistent echoes relative to the total number of echoes received (curve A), and in the number of disturbed persistent echoes relative to the total number of persistent echoes (curve B) in each 2-hourly group.

(a) *Diurnal Variation in the Incidence of Persistent Echoes*

The diurnal variation in the incidence of persistent echoes relative to the total number of echoes is given in Figure 1 (curve A). Curves for individual months were almost identical, so only the average for all months is given. Also shown in Figure 1 is a plot of the diurnal variation of the ratio of the number of disturbed echoes relative to the total number of persistent echoes (curve B). Both plots show a strong diurnal variation, although of different character. The small, sharp dip in curve A near 18 hr is present in the results for every month.

There seems to be no simple explanation for the form of these diurnal variations. However, both the echo rate and the geocentric velocities of meteors tend to be highest around 06 hr and this may contribute to the low percentage of persistent echoes at this time. It is possible, too, that the higher velocities, leading to the formation of trails at greater heights, may also be responsible for the increased proportion of disturbed echoes. These are no more than suggestions, however, and more extensive information relating echo duration with trail height and trail disturbance is required before a firm explanation for the form of these diurnal variations can be sought.

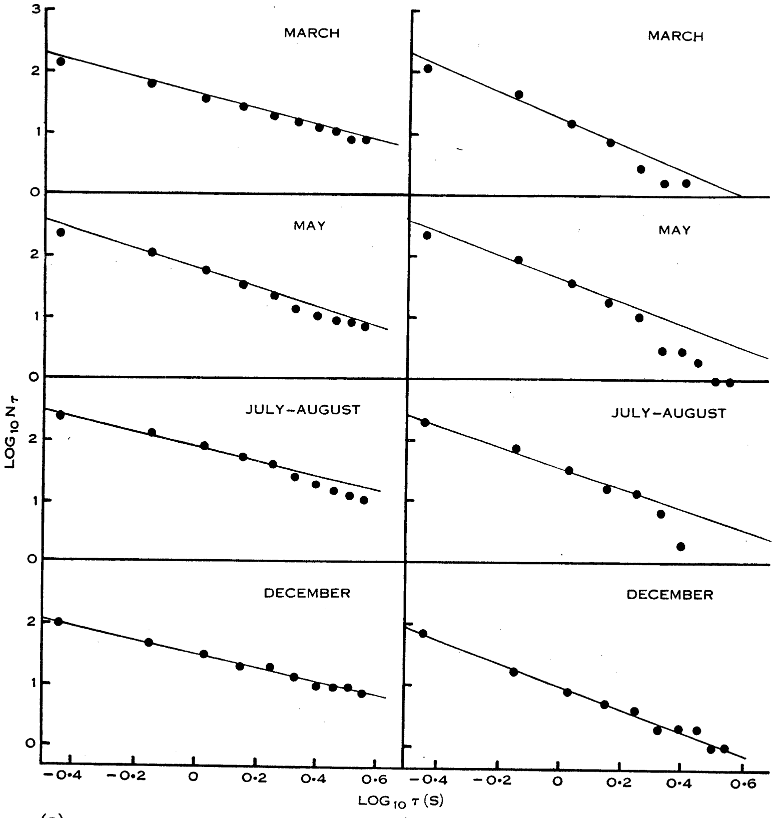


Fig. 2.—The distributions of sporadic echo durations obtained for typical 2-hr periods during 1957. N_τ is the number of echoes of duration greater than, or equal to, τ s. (*a*) All persistent echoes, 23–01 hr; (*b*) undisturbed persistent echoes, 00–02 hr.

(*b*) *The Distribution of Echo Durations*

If the theoretical distribution given by the relation (3) can be applied, a double logarithmic plot of the distribution of durations of persistent meteor echoes should result in a straight line whose gradient, $\mathrm{d}N/\mathrm{d}\tau$, is $3(1-s)/4$. Such plots were made from the results for each month, using firstly all persistent echoes collected into 2-hourly groups, and then repeating the process using only those persistent echoes showing no disturbance. Straight lines could be fitted fairly satisfactorily to a few of these plots, but more often the fit was poor and sometimes quite meaningless. Almost without exception the poor fit was caused by the number of echoes falling increasingly further below the expected number as τ increased. In Figure 2 the results for the group 23–01 hr for all persistent echoes are shown, together with those for the equivalent group (00–02 hr) of undisturbed echoes. These are quite typical examples showing perhaps rather better than average fit to straight lines. The scatter of points is much more pronounced for the early evening hours, when the echo rate is lowest. In almost every case the fall away in N_τ with increasing τ is apparent

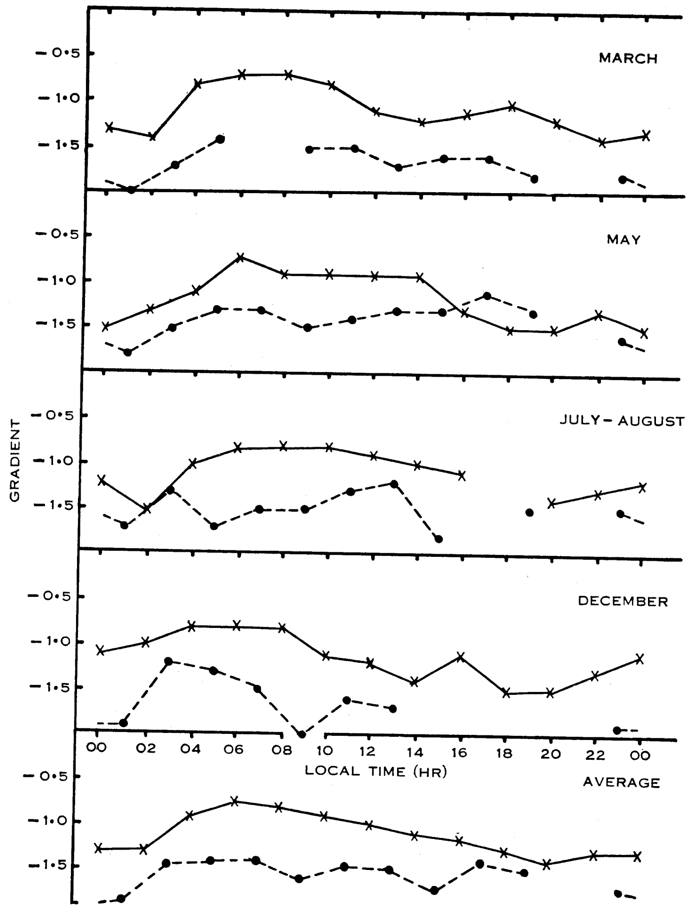


Fig. 3.—Diurnal variations in the gradients ($\delta N_\tau/\delta\tau$) of the lines fitted to the 2-hourly plots of distributions of echo durations. ×—×, All persistent echoes; ●---●, undisturbed persistent echoes only.

and would be even more pronounced if the end four or five points had been disregarded when fitting the lines. It is also apparent that the gradients are steeper and the fall-off more pronounced for the undisturbed echo plots than for the plots made from all persistent echoes.

(c) *Diurnal Variation in Durations Distribution*

The diurnal variations in the gradients of the straight lines fitted to the plots of the distributions of echo durations similar to those in Figure 2 are shown for each month in Figure 3. Since there is no significant seasonal variation in either case, scatter can be reduced by averaging for all months ; these plots are also included. The plots show that there is quite a strong diurnal variation when disturbed echoes are included, but almost none when they are excluded. As already mentioned, the results obtained using the Adelaide wind equipment suggest that at least 60% of echoes are disturbed, rather than only the 40% obvious in the durations records. This, together with the fact that the diurnal variation in the gradients of the lines fitted to the durations distribution plots parallels the diurnal variation in the relative incidence of disturbed echoes (Fig. 1), suggests that, if all the disturbed echoes could be removed, the diurnal variation in gradient (and hence in the mass distribution parameter s) would vanish altogether.

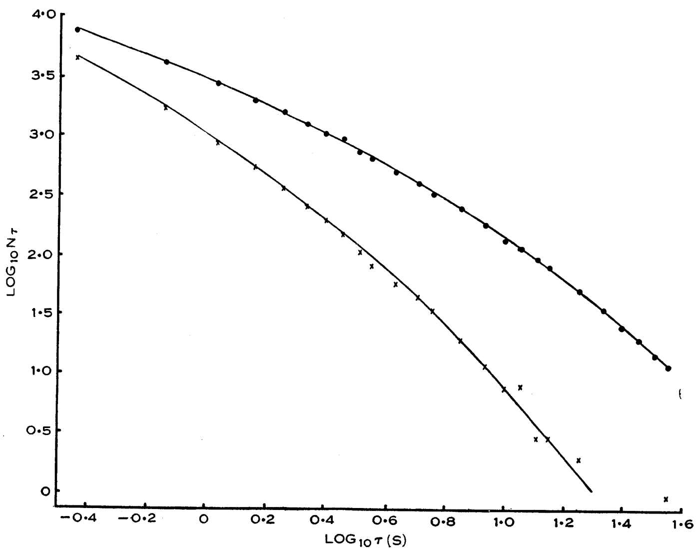


Fig. 4.—The integral distributions of echo durations obtained by adding together the echoes for all hours and all months. ●—●, All persistent echoes ; ×—×, undisturbed persistent echoes only.

(*d*) *Average Distribution of Durations*

In Figure 4 double logarithmic plots of the distribution of all echo durations measured are shown, again one set comprising all persistent echoes and the other undisturbed persistent echoes only. It is evident that straight lines cannot be fitted to the points, but that they lie on smooth curves whose gradients are becoming more negative with increasing duration. As expected, it is the undisturbed echoes curve which throughout has the steeper and more negative gradient. In Table 1 the gradients and corresponding s values (from (3)) are given for several intervals along the curves. Even the lowest is considerably higher than the accepted s-value for fainter meteors ($s=2\cdot0$).

The meteors examined in the Adelaide durations survey all have an electron line density $\alpha \geqslant 10^{13}$/cm (corresponding to a meteor of visual magnitude +3) and it is known (e.g. Hawkins and Southworth 1958) that these larger meteors do not obey the evaporation theory on which the relation (3) is based. Instead the trails show evidence of fragmentation and are shorter than expected. The consequences of such a fragmentation process have been investigated by Weiss (1961*a*), who finds that starting with the assumptions $\tau \propto \alpha^q$ and $D \propto p^r$ (where p is the atmospheric pressure) the distribution of the durations of persistent echoes becomes

$$N_\tau = k\tau^{3(1-s)/(3q+r)}, \tag{5}$$

where k is an extremely slowly varying function of τ, provided $\alpha > 10^{13}$ electrons/cm. This result is independent of trail length and is expected to be insensitive to the shape of the ionization curve. Inserting the values $q=1\cdot0$ and $r=0\cdot35$ (Murray 1959), (5) reduces to

$$N_\tau = k\tau^{3(1-s)/3\cdot25}, \tag{6}$$

which, although it gives lower values of s, is of the same form as Kaiser's original relation (3).

TABLE 1

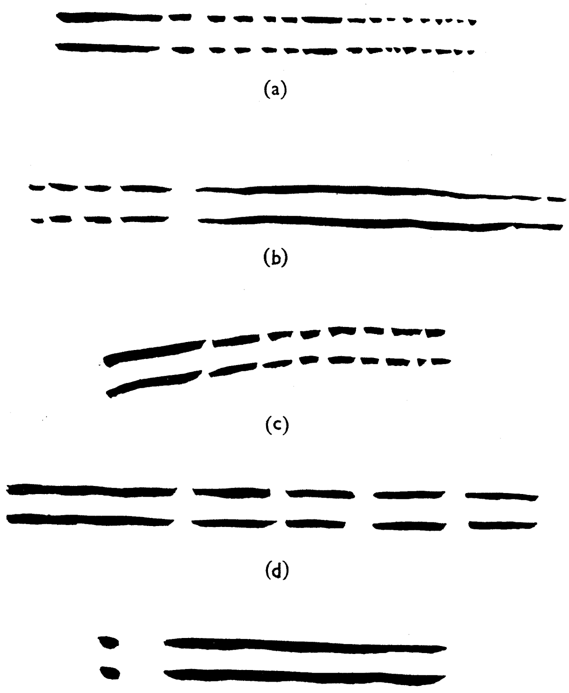
THE GRADIENTS $dN/d\tau$ AND ASSOCIATED s-VALUES, DETERMINED USING EQUATION (3), FOR DIFFERENT DURATIONS INTERVALS

Duration Interval (in units of 0·36 s)	All Persistent Echoes		Undisturbed Persistent Echoes	
	Gradient	s	Gradient	s
1– 2	—0·88	2·17	—1·37	2·83
4– 5	—1·05	2·40	—1·72	3·29
8–10	—1·34	2·79	—2·72	4·63
16–20	—1·30	2·73	—2·51	4·35
32–40	—1·56	3·08	—4·40	6·87
64–80	—2·24	3·99	—	—

Davis, Greenhow, and Hall (1959) have recently drawn attention to the importance of the removal of electrons from a meteor trail, by attachment to neutral air molecules, in shortening the durations of longer persistent echoes. However, until a satisfactory analysis of the effect of trail distortion on echo duration has been made, it is not possible to determine whether the progressive departures of the observations from a linear relationship (Fig. 4) can be attributed entirely to the effects of electron attachment, or reflect a real decrease in the numbers of more massive meteors below those expected from the assumed meteor mass distribution law (4).

IV. An Analysis of Disturbances

The irregularities shown by the traces of persistent echoes are of five distinct types, although in many echoes two, or even three, of these are present together. An enlarged drawing of a typical example of each type of irregularity is shown in Figure 5. From Figure 6 it can be seen that the relative incidences of echoes showing three of these types, namely, the irregularly dotted trace echoes, those with weak beginnings and those showing range drift, have similar pronounced and regular diurnal variations, while that of the fourth type, in which the trace appears as a regular series of dashes, has a marked semi-diurnal variation. The fifth irregularity, in which the main echo is preceded by a short, strong preliminary echo, appears to have no significant diurnal variation in incidence. Since it is known that the motions in the atmosphere at meteor heights have strong diurnal and semidiurnal components (e.g. Elford 1959) it is probable that the first four



(a) (b) (c) (d) (e)

Fig. 5.—The five types of trace irregularity. (*a*) Irregularly dotted trace; (*b*) weak beginning; (*c*) range drift; (*d*) regularly dashed trace; (*e*) leader echoes.

types of trace irregularity are the result of distortion of originally straight trails by atmospheric disturbances. In contrast, the preliminary leader echoes presumably reflect a property of the meteors themselves; and it is suggested that they can be identified with the head echoes noted by earlier observers (e.g. McKinley 1955).

By far the largest group of disturbed echoes are those having an irregularly dotted trace (2974 cases, 38·0%). The form of the trace, representing fairly rapid and often irregular variations in echo amplitude, is presumably due to the changing phase relationships between signals returned from separate reflecting centres along a distorted trail. The 46 echoes (0·6%) whose traces start weakly are probably special cases of dotted trace echoes, and represent trails which, although they did not satisfy the conditions of specular reflection when first formed, were subsequently distorted until some part of them did so.

The present records do not allow accurate measurements of the rate of range drift; in fact, only range drifts faster than about 2 km/s can be detected at all. It is estimated, however, that among the 310 echoes (4·0%) showing recognizable range drifts, drift rates in the vicinity of 10–20 km/s are quite common. It has been suggested (Browne 1958) that these high drift rates can

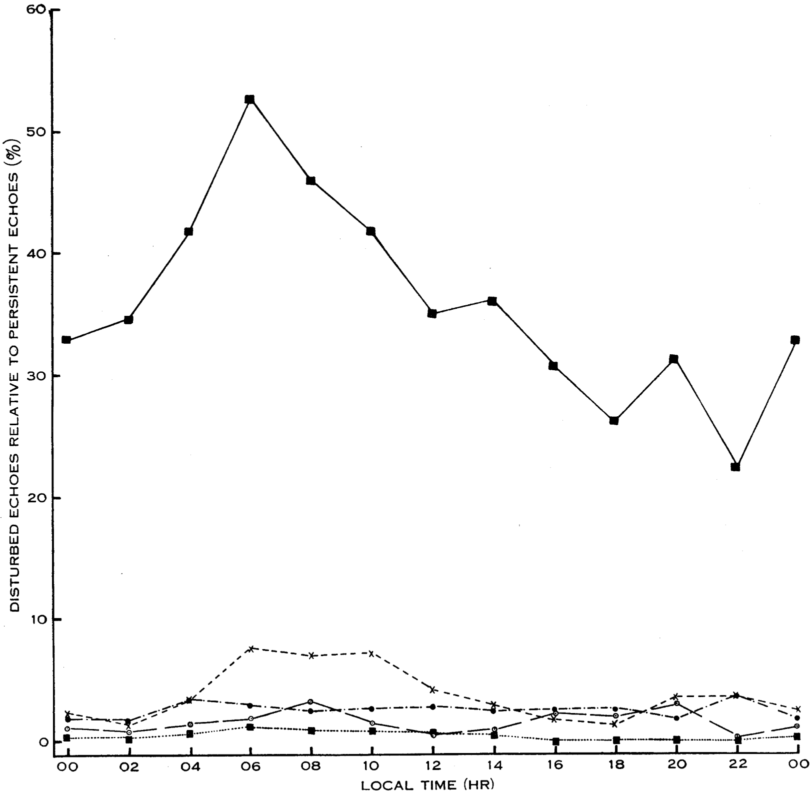


Fig. 6.—Diurnal variations in the incidence of echoes showing the various types of trace irregularities, relative to the total number of persistent echoes in each 2-hourly group. ■——■, Dotted trace echoes; ■····■, echoes with weak beginnings; ×– – –×, echoes showing range drift; ⊙— —⊙, dashed trace echoes; ●–·–·●, echoes preceded by leaders.

be explained much more satisfactorily by assuming that the trail is being bent, so that the position of the specular reflection point moves rapidly along it, rather than by assuming that the whole trail is being bodily moved at such high speeds. It is probable, therefore, that range drifts are caused by the effects of uniform wind shear, whereas the first two types of trace irregularity discussed are more likely to represent trail distortions caused by atmospheric turbulence on a smaller scale.

The 110 echoes (1·3%) having dashed traces are quite distinct from those of the group with dotted traces, being distinguished from them both by the greater regularity and the longer period (about 1 s) of their fading. That these two disturbances are apparently different effects is further emphasized by their

Table 2

A COMPARISON BETWEEN THE INCIDENCES OF DISTURBED ECHOES AMONGST ALL PERSISTENT ECHOES AND AMONGST LEADER ECHOES

Type of Disturbance	Percentage of Disturbed Echoes	
	All Persistent Echoes	Leader Echoes
(*a*) Short period fading	38·0	25·3
(*b*) Weak beginning	0·5	1·5
(*c*) Range drift	4·0	10·0
(*d*) Long period fading	1·4	6·3
All types	40·5	37·4

different diurnal variations in relative incidence (Fig. 6). An analysis of the Adelaide wind records for wind shear yielded nothing which would help to account for these differences in diurnal variations.

It seems unlikely that the separate preliminary echo preceding 190 of the persistent echoes (2·4%) is in any way related to trail disturbance. This

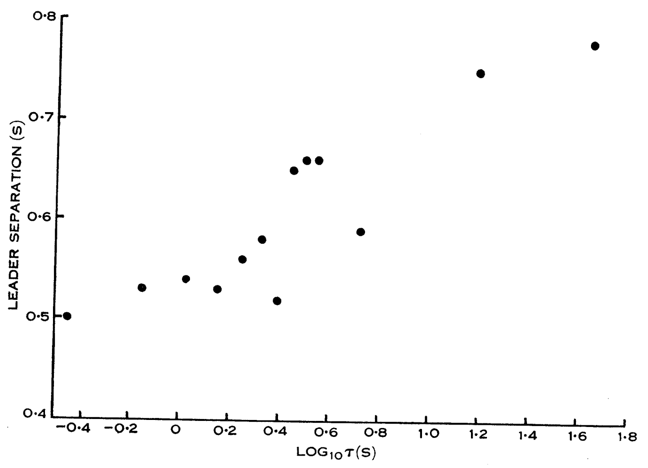


Fig. 7.—The average separation between preliminary leader echo and main echo as a function of echo duration τ.

supposition is strengthened by a comparison of the incidence of the four true disturbance types amongst those echoes with leaders, with that amongst all persistent echoes. The result is shown in Table 2. The only significant difference is the reduction, amongst echoes with leaders, of the relative number of echoes showing short-period fading, with a corresponding increase in all other types.

The time separation of the leader from the main echo has been measured for each leader echo. In Figure 7 the variation of average separation with subsequent echo duration shows that there is a slow but steady increase in leader separation with increase in duration. Figure 8 is a histogram giving the distribution of leader separations ; the mean separation is 0·34 s.

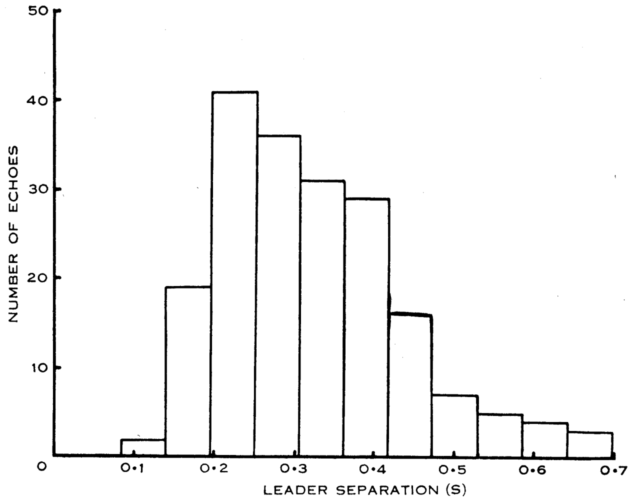


Fig. 8.—The frequency distribution of leader separations.

V. Conclusions

This survey has shown that for sporadic meteors whose trails have an electron line density $\alpha \geqslant 10^{13}$/cm (i.e. meteors brighter than visual magnitude +3) an unqualified power law such as (3) or (6) fails to describe the distribution of meteor echo durations. The departures from a power law are systematic and in the sense of an apparent increase in s with increasing meteor mass. It seems extremely unlikely that the whole of this increase is the result of trail disturbance affecting echo durations, as the removal of two-thirds of the expected number of disturbed echoes merely causes s to increase even more rapidly. Indeed, it is not impossible that the whole of the departure of the observed durations distribution for sporadic meteors from the power-law form may be attributed to the effects of the removal of electrons from the ionized columns by attachment to neutral air molecules.

From the arguments advanced in Section III (c) it may be concluded that if there is any seasonal or diurnal variation in the mass distribution of the brighter incident meteors it is scarcely significant.

This paper has posed a number of questions concerning the diurnal variations in the incidence of persistent echoes and in the various types of disturbed echoes which have been recognized. These questions can only be answered by a much more comprehensive recording of echo characteristics and waveform than has been possible with the simple equipment used in the present survey. In particular, the height of the echoing point, the velocity of the meteor particle, and the orientation of the trail will be required for each individual meteor, together with an understanding of the precise nature and effect of the distortion of the trail on the echo waveform and duration. A programme of observations fulfilling these requirements has been commenced at Adelaide.

VI. Acknowledgment

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