ELEVATION, HEIGHT, AND ELECTRON DENSITY OF ECHOING POINTS OF METEOR TRAILS

By A. A. Weiss*

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Summary

Continuous and systematic operation of a C.W. equipment which measures simultaneously several characteristics of meteor echoes, including the location in space of the reflection point, provides the basic material for an examination of the geometry of detection of meteor trails by radio equipments and of the processes underlying selection of echoes for measurements of different kinds.

At least 60 per cent. of all echoes are distorted in some degree, presumably by atmospheric turbulence or by non-specular reflection. This and selection in height due to diffusion of the trail are the two most important selection processes.

The distribution of the echoing points of sporadic meteors, in zenith angle and in height, is compared with theoretical expectation. Height distributions found for Arietid and ζ-Perseid meteors agree with other measurements. The height distribution for the Geminid shower is unexpectedly narrow, a fact for which no satisfactory explanation can be advanced. Distributions of electron line densities at reflection points agree qualitatively with known mass distributions and trail shapes.

I. Introduction

Since 1952 a 27 Mc/s C.W. equipment for observation of meteors has been in operation at Adelaide. Full details of the original installation and aerial system will be found in Robertson, Liddy, and Elford (1953). With this equipment the following characteristics of selected meteor echoes may be measured simultaneously: (*a*) direction and slant range of reflection point on the meteor trail relative to the observing station, (*b*) line-of-sight velocity of drift of the meteor trail, (*c*) echo amplitude, (*d*) rate of decay of echo. The first two quantities are required for measurement of wind in the meteor region (Elford and Robertson 1953). The first alone suffices for measurement of the heights of the reflection points. From the rate of decay of the echo and the height of the reflection point the height-dependence of the diffusion coefficient and its absolute value can be established (Weiss 1955*b*). Electron densities follow from the echo amplitude and the position of the echoing point. In addition, the azimuth of the reflection point and the time of occurrence of each echo, whether suitable for detailed measurement or not, lead to results of direct importance to meteor astronomy (Weiss 1957).

In all these studies the fully automatic equipment is operated systematically in routine and continuous surveys. This is followed by reading of all echoes

* Division of Radiophysics, C.S.I.R.O., at Department of Physics, University of Adelaide.

suitable for wind measurement and culminates in the establishment of diurnal and seasonal variations in the parameters measured. One unforeseen consequence of this routine operation is the automatic availability of a precise location of each reflection point whenever any meteor parameter (not winds) is under study. This, coupled with the relatively simple aerial system and its cylindrical symmetry, permits a ready assessment of the dependence of meteor parameters upon the elevation and range of the reflection point. This is a distinct advantage, as these geometrical factors are of some consequence in the interpretation of radio data. With the very great majority of radio equipments such a detailed examination of the geometry of detection is impossible.

The present treatment is largely confined to aspects of the distribution in height of reflection points for both shower and sporadic meteors. Some measurements of electron line densities are also analysed. The prerequisite for such measurements is of course the aerial gain in the direction of the reflection point, but, in addition, a careful selection of echoes is of prime importance. The reasons for rejection of echoes as unsuitable for measurement of the position of the reflection point and the line density are so illuminating that a full discussion is considered appropriate.

II. Selection of Echoes for Measurement

The selection of echoes for wind measurement is a rather severe process, which results in rejection of over 80 per cent. of echoes recorded. The effects of this selection will be noticed repeatedly in succeeding sections. Records for September 1953 have been analysed in detail.

Of 4730 meteors recorded, only 872, or 18·4 per cent., were suitable for wind measurement. Reasons for rejection were ascertained from 4 days' records embracing 500 meteors, of which 98, or 19·6 per cent., were read; the details are summarized in Table 1. In amplification of the various categories of this table, the requirements for reading for winds may be stated: (*a*) the frequency of the Doppler beat pattern between sky and ground wave must not be too high or too low; if too high, the positions of maxima (or minima) on some or all of the five direction-finding aerials cannot be determined with sufficient accuracy, and if too low the echo decays or is terminated by the automatic camera sequencing unit before a sufficient number of Doppler cycles are traversed; (*b*) the duration of the echo must be sufficiently long to provide the requisite number of Doppler cycles; (*c*) echo amplitude must not be too large or too small, if too large the maxima of the beat pattern are cut off by receiver saturation; (*d*) the echo must not be severely distorted by turbulence, multiple centres, or other non-specular reflection; (*e*) the slant radar range must be recorded. Since for no echo satisfying criteria (*a*) to (*d*) did the slant range fail to record, (*e*) is not a limitation in practice. In effect, echoes are rejected for wind measurement only because the direction of the reflection point cannot be ascertained.

A restriction on echo amplitude is essentially one imposed on the electron density in the trail at the reflection point, in relation to the aerial gain in this direction. Elimination of echoes on the grounds of distortion may be height-sensitive. A low Doppler beat frequency implies a small component of drift velocity in the line of sight. If this arises in a small actual drift velocity, echo selection will be azimuth-sensitive, perhaps mitigated by the diurnal changes in wind speed and direction. For reflection points close to the zenith, however, the line-of-sight wind component is always small, as the wind drift is essentially horizontal. Echo duration is related to the diffusion coefficient, which increases rapidly with height (Weiss 1955*b*); at 27 Mc/s height selection above 100 km may be severe. Since the height distribution of atmospheric and meteor parameters, found either from height correlations (e.g. winds, diffusion coefficients) or directly from the height distributions themselves, is one of the major contributions of meteor physics to the study of the atmosphere in the meteor region, selection of echoes by height is of considerable importance. It is one, moreover, to which every radio equipment is subject to an extent depending on the form of presentation of the echo and the operating frequency. Compared with this, selection in azimuth and in zenith angle is trivial.

TABLE 1

ANALYSIS OF ECHOES REJECTED AS UNSUITABLE FOR WIND MEASUREMENT

Type of Echo	Number of Echoes
Low Doppler beat frequency	60
High Doppler beat frequency	1
Echo decay too rapid	216
Low echo amplitude	45
High echo amplitude	14
Distorted echo waveform	66
Suitable for measurement	98
Total number of echoes	500

Of the 872 echoes for which reflection points could be located, echo amplitudes and hence electron densities were measured for 482. In the majority of cases rejection was associated with departures of the echo waveform from the smooth growth (persistent echoes only) and decay (all echoes) expected of a meteor trail dissipating by ambipolar diffusion in a quiescent atmosphere. Reference to Table 1 reveals 66 out of 164 otherwise readable echoes already rejected for distortion so severe that reflection points could not be located. We have here an additional 390 echoes (out of 872) which are less severely distorted. If these figures are representative, then at least 60 per cent. of all echoes are distorted in some degree by atmospheric turbulence, multiple reflection centres, or other non-specular reflection. This high rate may not apply without qualification to other equipments; indeed, less non-specular reflection and hence less distortion would be expected at higher frequencies. The importance of the result is that it emphasizes the danger of indiscriminate interpretation of echo amplitude and duration measurements on the basis of a theory of specular reflection by trails diffusing without distortion.

III. Zenith Angles of Reflection Points

(a) *Sporadic Meteors*

The distribution in zenith angle of the reflection points of sporadic meteors for September 1953 is illustrated in Figure 1. That this distribution is largely independent of the source distribution over the celestial sphere is shown by the absence of a marked diurnal variation (Weiss 1957) and the identical distribution found for March 1953.

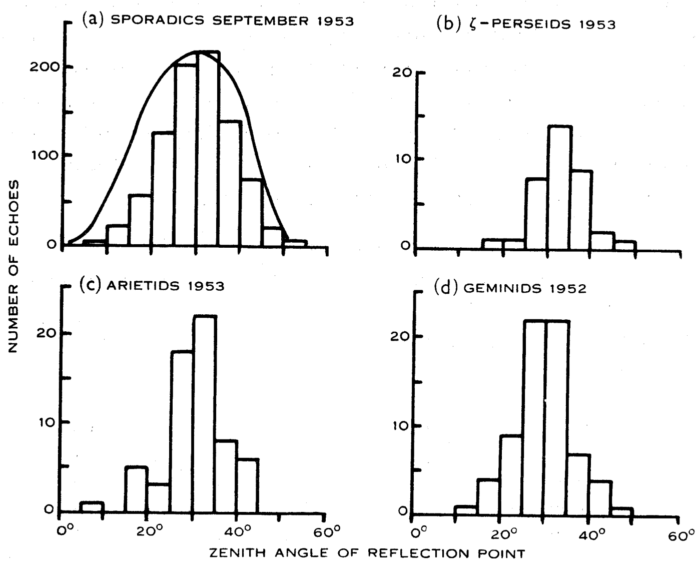

Fig. 1.—Zenith angles of reflection points of sporadic and shower meteors. The full line is the distribution predicted for a uniform sporadic radiant distribution.

This distribution may be compared with the prediction (Kaiser 1954*b*) for a uniform distribution of radiants on the geocentric celestial sphere. The number of echoes observed per unit zenith angle interval is

$$N_z = \text{const.}\ \sin^s z \cos^{(3s-7)/2} z\, S^{2(s-1)}(z), \qquad \ldots\ldots\ldots\ (1)$$

where z is the zenith angle of the reflection point, s the mass distribution parameter, and $S(z)$ the aerial polar diagram function (amplitude). In terms of power gains, $S^2(z) = (G_T G_R)^{\frac{1}{2}}$. For sporadic meteors $s = 2 \cdot 0$.

Aerial power polar diagrams for the major lobes of the transmitting and receiving aerials and the composite polar diagram appear in Figure 2. Small departures from rotational symmetry are introduced by the separation of transmitting and receiving stations, and by asymmetry in the north-south and east-west traverses of the individual polar diagrams, but the composite polar diagram should apply to the majority of echoes.

Function (**1**) is included in Figure 1 (*a*). The positions of predicted and measured maxima agree excellently, but the measured distribution is sharper than predicted. At small zenith angles this could be due to discrimination against small zenith angles through low Doppler beat frequencies (Section II). At large zenith angles, where the composite power gain is less than 10 per cent. of the maximum gain, the aerial polar diagram of Figure 2 is least accurate, and the discrepancy could be eliminated by an increase in aerial gain by a factor of 2 or so.

(*b*) *Shower Meteors*

Distributions for three showers are also given in Figure 1. These are all sharper than the distribution for sporadic meteors. All three showers transit low in the north at Adelaide, and the sharpness of the distributions must be sought in different source distributions for showers and sporadics. Echoes cannot be detected at zenith angles numerically smaller than the elevation of

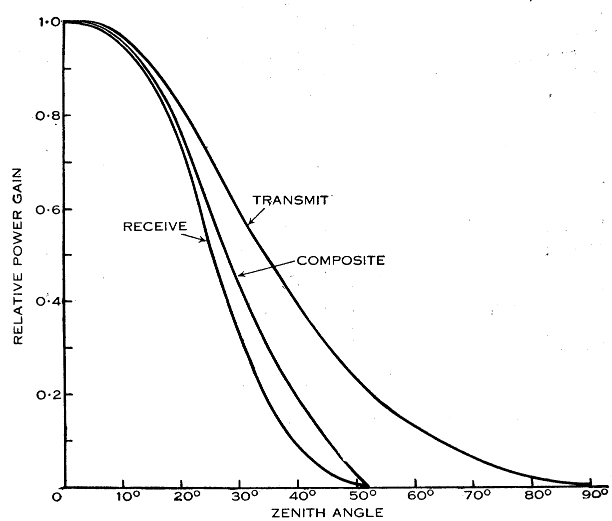

Fig. 2.—Power polar diagrams of the major lobes of the aerial system.

the radiant, if specular reflection is assumed. For radiants near the horizon the collecting area for showers with compact radiants is much more limited than for sporadic meteors, whose radiants may lie in any azimuth. Accordingly, shower meteors should give fewer reflection points at small zenith angles than sporadic meteors, as observed. At the other extreme, the limited elevation reached by shower radiants should result in a deficiency of reflection points at large zenith angles. This will not be very marked, as the equipment sensitivity falls off rapidly as the radiant elevation increases beyond 30°.

IV. Electron Line Densities

Figure 3 depicts distributions of echo amplitudes, relative to ground wave=1 (measured at the receiver output), for three groups of sporadic meteors and three showers. The differences between the groups of echoes are barely significant.

When echo amplitudes were measured, the form of each echo was noted. Two types of echo may be distinguished. The short, decay-type echo is characterized by an almost instantaneous rise to maximum amplitude, followed by an exponential decay; for such echoes the electron line density $\alpha < 2 \times 10^{12}$ electrons/cm. The other type, persistent echoes with $\alpha > 2 \times 10^{12}$, shows a slower rise to a flat maximum, followed by the exponential decay.

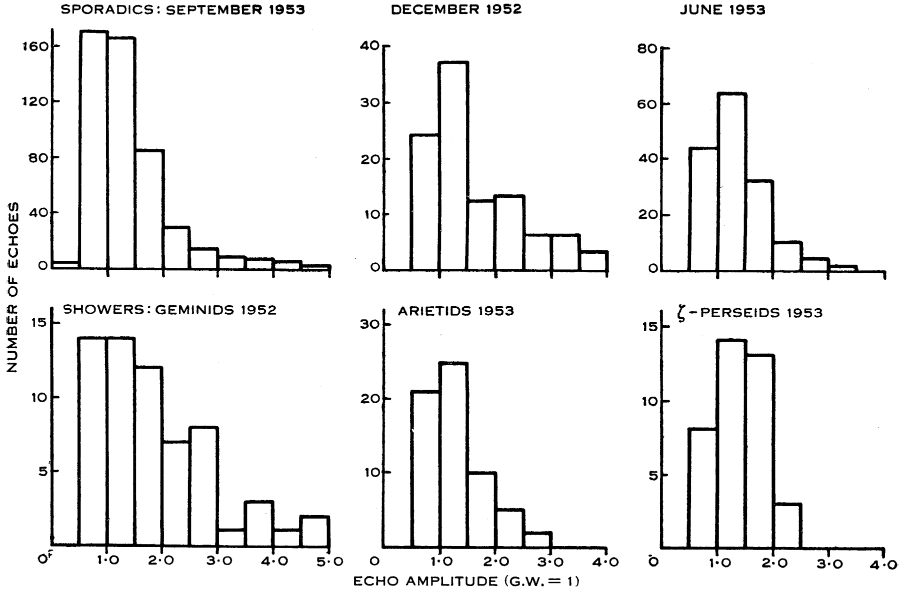

Fig. 3.—Distributions of echo amplitudes, relative to ground wave amplitude.

For short echoes, the line density is given by the Lovell-Clegg scattering formula

$$\alpha_S = (32\pi^2 R^3 \varepsilon / P G_T G_R \lambda^3)^{\frac{1}{2}} (mc^2/e^2), \quad \ldots\ldots\ldots\ldots \quad (2)$$

whilst for persistent echoes

$$\alpha_P = (54\pi^3 R^3 \varepsilon / P G_T G_R \lambda^3)^2 (mc^2/e^2). \quad \ldots\ldots\ldots\ldots \quad (3)$$

In these expressions, and for the equipment in question,

P = transmitter power = 250 W,
ε = echo power = 3×10^{-14} W minimum,
R = slant range to reflection point (m),
λ = wavelength = 11·2 m,
G_T = transmitting aerial power gain = 9·5 maximum,
G_R = receiving aerial power gain = 6·5 maximum.

With these equipment parameters, and echo amplitude A expressed in units of ground wave amplitude measured at the receiver output,

$$\alpha_S = 3A \times 10^9 (R^3/G_T G_R)^{\frac{1}{2}}, \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

$$\alpha_P = 50A^4 (R^3/G_T G_R)^2. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

R is now in kilometres and the product $G_T G_R$ is normalized to 100 max.

All decay-type echoes have been reduced using the Lovell-Clegg formula (4). This procedure gave very few decay-type echoes with apparent line densities $>2\times10^{12}$ electrons/cm. Since neither formula (4) nor (5) is expected to be accurate for intermediate type echoes with $\alpha\sim2\times10^{12}$, echoes classed as persistent, which included quite a few of intermediate type, were reduced using whichever expression (4) or (5) gave the greater line density. Line densities computed on

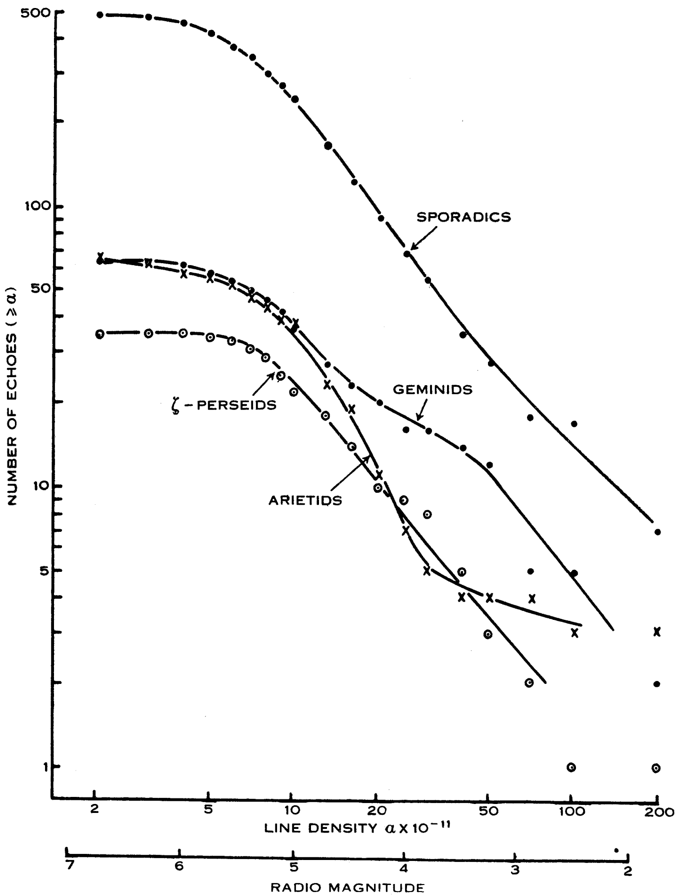

Fig. 4.—Distributions of measured electron densities (electrons/cm) for sporadic and shower meteors.

this basis may not be particularly accurate, but this procedure was justified in that it would accentuate any differences in the distributions of line densities which may exist between showers and sporadics and between showers *inter se*. A further source of inaccuracy in the computation of line densities for persistent echoes is the high powers to which the echo amplitude and the aerial gain are raised in (5).

Figure 4 is a double logarithmic plot showing the number of echoes for which line densities exceed or are equal to α. Radio magnitudes M_r, on the definition of Kaiser (1955), are also shown. For the reasons given above, the distributions in Figure 4 can only be regarded as qualitative. They do, however, show up directly the excess of bright meteors in the Geminid stream, and their marked deficiency in the Arietid stream, which is to be expected from the mass distributions found by Browne *et al.* (1956). Although it is not very well brought out in Figure 4, all three showers exhibit a decrease, relative to sporadic meteors, in numbers of meteors fainter than $M_r \sim 5$. This may be a geometrical effect,

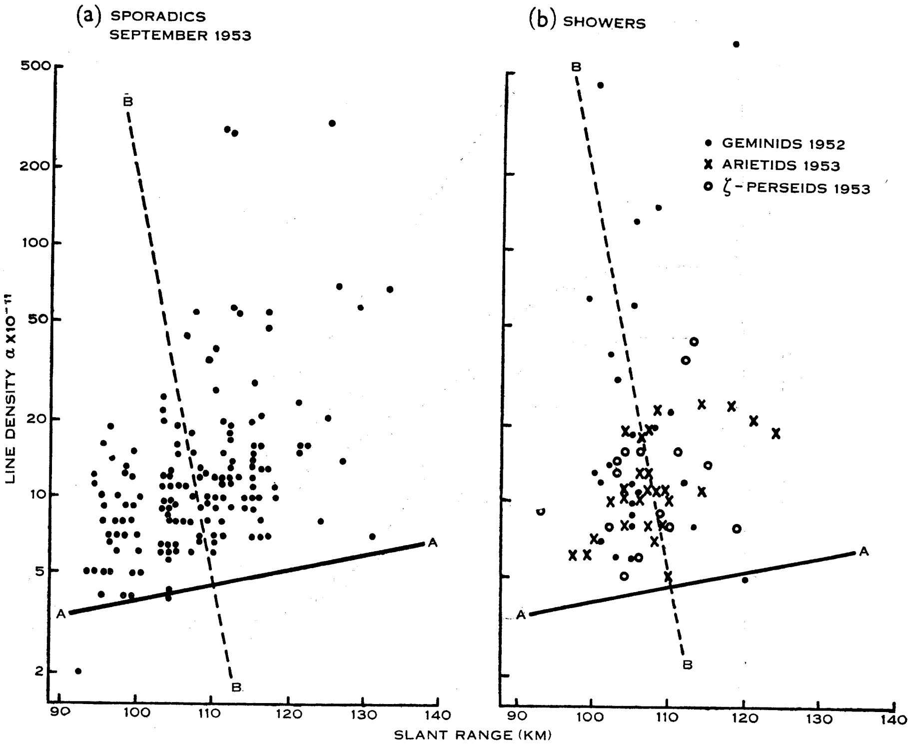

Fig. 5.—Range-electron density (electrons/cm) scatter diagrams for sporadic and shower meteors with $30 \leqslant z \leqslant 35$. *AA* is the locus of minimum detectable electron density, *BB* the locus of the points of maximum electron density in the trails, if atmospheric scale height = 7 km.

or it may indicate a real deficiency of faint meteors in these streams. Further observations, with larger samples extending to fainter meteors, will be needed to settle this point.

For sporadic meteors brighter than $M_r = 5 \cdot 5$, the empirical relation for the number of meteors with line densities $\geqslant \alpha$ detected by this equipment is

$$N(\geqslant \alpha) = \text{const. } \alpha^{-1 \cdot 33}.$$

In terms of radio brightness

$$N(\leqslant M_r) = \text{const. } 3 \cdot 40^{M_r}.$$

Finally, range-line density scatter diagrams for narrow intervals of zenith angle have been prepared. The one for $30 \leqslant z \leqslant 35°$ is reproduced in Figure 5. The curve *AA* is the limiting line density, corresponding to $A = \frac{1}{2}$, below which according to Figure 4 very few points should be situated. The measured line densities conform to this predicted relation between minimum detectable line density and slant range, and the agreement is equally good for other zenith angles. The line *BB*, whose position is arbitrary, is the locus of the points of maximum electron density of trails of meteors of constant velocity and radiant zenith angle. Its position, but not its slope, depends on these two quantities. For shower meteors, with narrow ranges of velocity and radiant zenith angle, there is a tendency for the points to concentrate to a locus of this form ; this is particularly so in the case of the brighter Geminids. It is the natural consequence of the distribution of electron density along the meteor trail, coupled with the rapid increase in numbers as the meteor mass decreases. For the fainter Geminids, indeed, the concentration to the locus of maxima is perhaps too marked ; a wide range distribution would be expected amongst the echoing points with lowest line densities, which should be situated near the extremities of the trails of more massive meteors as well as near the maximum points for the smallest meteors accessible to the equipment.

The position with respect to sporadics is not so obvious, because there is a spread in both velocity and radiant zenith angle which would have the effect of smearing out the locus of maxima into a band of considerable width.

V. The Sporadic Meteor Height Distribution

Figure 6 is a smoothed contour diagram of equipment sensitivity, which has been prepared from distributions of the slant ranges of reflection points falling within narrow intervals of zenith angle, for September 1953 sporadic meteors. The most probable height is a function of zenith angle, but the form of the height distribution is almost independent of this angle.

The collection zone, within which the equipment will detect meteors, is formed by rotating this cross section about the zenithal axis. Its volume is $1 \cdot 2 \times 10^6$ km^3.

The full line *AA* in Figure 6 is the mean height of the smoothed distribution. From the theory of the sporadic meteor height distribution (Kaiser 1954*b*), it may be deduced that for constant meteor velocity the relation between the mean height and the zenith angle of detection is

$$h_z = h_0 + H \ln \left[\cos^{\frac{1}{2}} z \sin^{-\frac{2}{3}} z (G_T G_R)^{\frac{1}{6}}\right]. \quad \ldots\ldots\ldots\ldots \quad (6)$$

h_0 is here regarded as an arbitrary constant, although its absolute value can be determined from the atmospheric, meteor, and equipment constants. Relation (**6**) will also apply if the velocity distribution of sporadic meteors is independent of the zenith angle of detection, which will be approximately true if observations are continuous. Expression (**6**) is plotted in Figure 6 as the line *BB* ; a value of $H = 7$ km has been assumed. Agreement between theory and measurement is poor, especially at small zenith angles, a fact which may have some bearing on the derivation of atmospheric scale heights from the widths of measured sporadic height distributions.

Trails detected at very small zenith angles must proceed from radiants close to the horizon. For these trails, which are very long, the zenith angle is no longer constant, because the Earth's surface can no longer be regarded as flat. Qualitatively, the effect of this changing zenith angle is to elongate, and so lower the ends of, the trails. Whether this is sufficient to lower the measured mean height to the extent shown in Figure 6 can only be settled by calculation. In any case it is unlikely to afford an explanation of the discrepancy for $z > 10°$.

Although it is not evident in Figure 6, the upper portions of the sensitivity contours must be influenced by cut-off due to high rates of diffusion. The cut-off is independent of zenith angle, which is not unexpected. Although it is not attempted here, a careful analysis of the form of the height distributions and of the scatter diagram of diffusion coefficient versus height would undoubtedly enable the nature of the diffusion cut-off to be established.

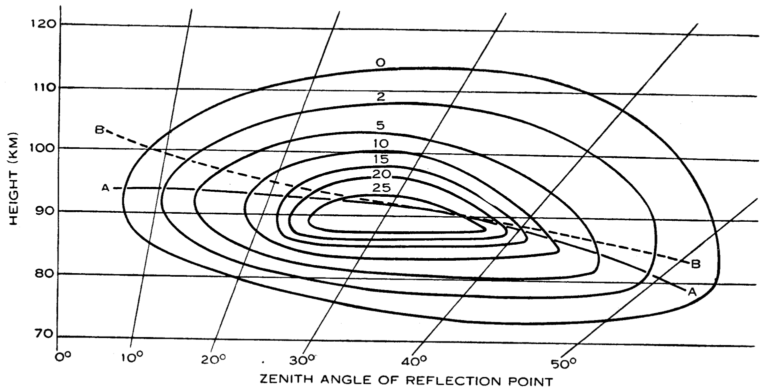

Fig. 6.—Zenith angle-height contours of equal equipment sensitivity. The numbers against the contours are relative sensitivities. The line *AA* gives the observed mean height, *BB* the mean height predicted for a uniform distribution of sporadic radiants.

VI. Shower Meteor Height Distributions

Height distributions for three showers are reproduced in Figure 7. Distributions for the Arietids and the ζ-Perseids are based on echoes selected by the geometrical method described by Weiss (1955*a*). That for the Geminids was determined by subtraction of the distribution for sporadic meteors on neighbouring days from the distribution for mixed sporadic and Geminid meteors found over the times of shower activity. Rather smaller samples of echoes for 1952 and 1953, known by the geometrical selection method to be Geminids, gave identical distributions.

The r.m.s. deviations for Arietids and ζ-Perseids are respectively 5·10 and 7·16 km. The theory of the shower meteor height distribution (Kaiser 1954*a*) relates these r.m.s deviations to the mass distribution parameter *s* and atmospheric scale height *H*. With $H=7$ km we find $s=2\cdot6$ for the Arietids and $s=1\cdot9$ for the ζ-Perseids, in the range of brightness $3 \leqslant M_r \leqslant 6$. These values of *s* are consistent with the line density distributions of Figure 4, if we accept $s=2\cdot0$ for sporadic meteors, and also with the values given by Browne *et al.* (1956).

For the Geminids, the r.m.s. deviation is 5·17 km, leading to $s=2\cdot5$. This value is consistent with the indication in Figure 5 that Geminid meteors are detected only near the points of maximum electron density in the trails; it is, however, very much larger than the values, 1·45 and 1·62, given by Browne *et al.* for fainter Geminids. This discrepancy is obvious from the very much broader height distribution measured at Jodrell Bank, and would be larger still were it not for the long tail of our distribution. No ready explanation suggests itself, but it must be due to failure to detect, or to measure, echoing points lying near the ends of the trails. Very low and very high heights of detection presumably arise in long trails of bright meteors seen at either extremity. It may be true that the Geminid trails, because of a larger proportion of bright meteors, are on the average much longer than for the other showers with steeper

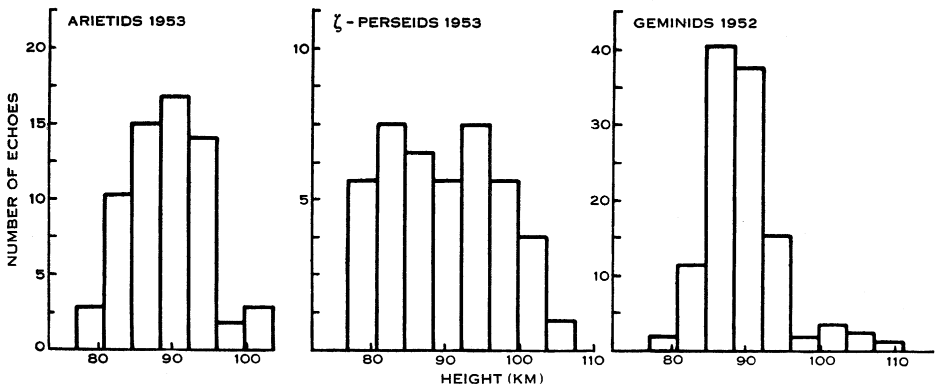

Fig. 7.—Height distributions of echoing points of shower meteors.

mass distributions. Near the beginning of a trail, $d\alpha/dh$ is proportional to $\exp(-h/H)$, hence a small decrease in equipment sensitivity, say due to cut-off by diffusion, will shorten the detectable length of trail very much more for a bright meteor than for a faint meteor. Now the height gradient of the diffusion coefficient for the Geminid meteors is about twice as large as that for the other showers and for sporadic meteors (Weiss 1955*b*; this result is also confirmed by measurements on the 1953 Geminids), so that Geminids should be abnormally sensitive to cut-off by diffusion. This could well explain the lack of high Geminids, but none of the selection processes considered in Section II should operate differentially on the lower portion of the height distribution. Perhaps the cause of the discrepancy is associated with the low elevation ($<25°$) of the Geminid radiant at Adelaide.

VII. Conclusions

Continuous recording, with the one equipment, of those characteristics of meteor echoes necessary for the location of the reflection point in space, and for measurement of echo amplitude, form, and rate of decay, permits a detailed examination of the principles underlying the selection of echoes for measurement, of the geometrical aspects of meteor detection, and of the influence of the selection process on the geometry of detection. With few exceptions, the manner in which the equipment responds to meteor trails agrees with theoretical expectation. The agreement between observed and expected distributions of electron densities, both in number and in height, engenders considerable confidence in the outcome of systematic studies of this kind, provided that a careful selection of echoes is first made on the basis of echo characteristics. Of the selection processes, selection of echoes in height is likely to prove the most troublesome. It not only affects the number-height distributions, which contain information on the atmospheric properties and the manner of ablation of a meteor particle in its flight through the atmosphere. Its influence can extend to the determination of height gradients of such quantities as the diffusion coefficient, in the form of incomplete scatter diagrams.

The conclusions regarding the high incidence of turbulent or other distortion in meteor echoes and the distribution of measured electron densities cannot be regarded as final. In their present state they do little beyond demonstrating the potentialities of the type of C.W. meteor equipment still under development at Adelaide. With the addition of a single simple outstation to the present equipment, comparison of echo amplitude and form can be made at two precisely known points on the trail of a shower meteor whose radiant position is already known. Further addition of accessory equipment for velocity measurement and (for some applications) of a second outstation, will render accessible the much more numerous sporadic meteors.

VIII. Acknowledgments

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