Meteor velocities: a new look at an old problem

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Abstract.
Meteoroids that orbit the Sun encounter the Earth with speeds between 11 and 74 km/sec. However, the distribution of the velocities of meteoroids between these limits is not well known. The uncertainty is caused by the difficulty in measuring the true flux of meteors at the extrema of the velocity distribution. Whilst the most comprehensive measurements of meteor flux are those obtained using radio techniques, meteors with speeds > 50 km/sec occur at heights where the effects of initial radius of the trail and diffusion significantly reduce the radio reflection from the trails; on the other hand the high dependence of the collisional ionization probability on velocity (to the power ~3.5) significantly inhibits the detection of meteors with speeds < 20 km/sec. Recent developments in meteor radar systems are now making it possible to measure the velocity of meteors at the extrema of the distribution. For meteoroids ablating at heights between 100 and 120 km the speed of entry can be measured at 2 and 6 MHz using a radar with a 1 km diameter array located near Adelaide; these observations will commence early in 1995. In the meantime a 54 MHz MST radar is being operated at a pulse repetition frequency of 1024 Hz to search for the presence of interstellar (speed > 74 km/sec) meteors. Both these radars exploit the phase information available prior to the closest-approach (t_o) point.

Key words: Meteor velocities, radar meteor observations, space debris

1 Introduction

The measurement of the encounter speeds of meteoroids with the Earth's atmosphere is an essential feature of meteor astronomy, and optical and radio techniques are capable of achieving accuracies of better than 1%. In addition to the determination of the velocity characteristics of meteor showers, a number of distributions of the velocities of the sporadic population have been published (*e.g.*, faint photographic, McCrosky and Posen, 1961; radio meteors, Sekanina and Southworth, 1975; TV meteors, Sarma and Jones, 1985). McKinley (1961) presents a comparison of the radio meteor velocities measured at Ottawa and Jodrell Bank in the early 1950's.

Both the optical and the radar velocity distributions are significantly affected by the velocity dependence of the luminous and ionization efficiencies of ablating meteoroids. In addition, the techniques themselves have inherent selectivities that introduce velocity-dependent biases. Procedures for correcting the observed distributions to a given limiting mass have been applied to the optical data by Erickson (1968) and to the radio data by Sekanina and Southworth (1975).

In recent years the development of narrow beam VHF radars has opened up new possibilities for radar meteor astronomy and in particular for the measurement of meteor velocities. It is for this reason that a new look at the determination of the velocity distribution is appropriate.

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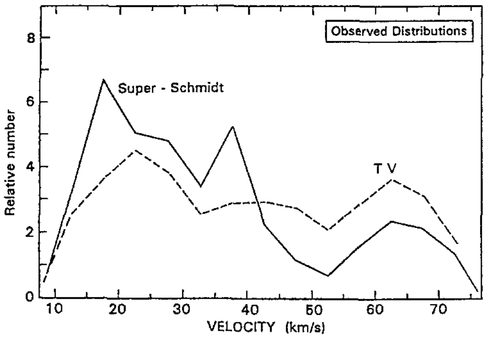


Fig. 1. Meteor velocity distributions as determined optically from 2500 faint meteors with a Super-Schmidt camera, and 454 TV meteors (magnitude range 3–8).

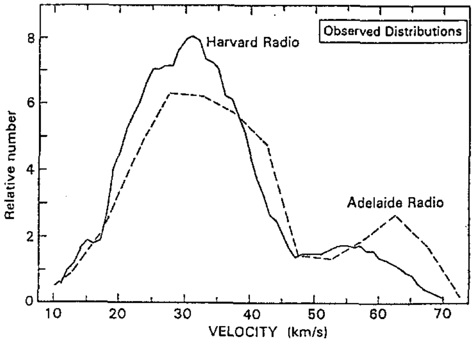


Fig. 2. Meteor velocity distributions as determined from radar data: Harvard Radio Meteor Project, 1968–69; Adelaide Radio Meteor Orbit Survey, 1960–61.

2 Observed velocity distributions

As examples of the meteor velocity (v) distribution determined optically we have shown in Fig. 1 the results from the Super-Schmidt observations of about 2500 faint meteors (McCrosky and Posen, 1961), and from 454 TV meteors (Sarma and Jones, 1985). The general bimodal distribution for both sets of data is astronomical in origin. The rapid fall-off in the number of meteors with velocities less than 20 km/sec is a consequence of the reduction in luminous efficiency with decreasing velocity.

Meteor velocity distributions deduced from radar data also show the bimodal characteristic, as is illustrated in Fig. 2. In these cases the distributions suffer two strong biases: (a) The rapid fall-off below 30 km/sec is due to the ionization efficiency of ablated meteor atoms varying as $\sim v^{3.5}$, and (b) The fact that trails from high velocity meteoroids are produced at greater heights, where rapid diffusion

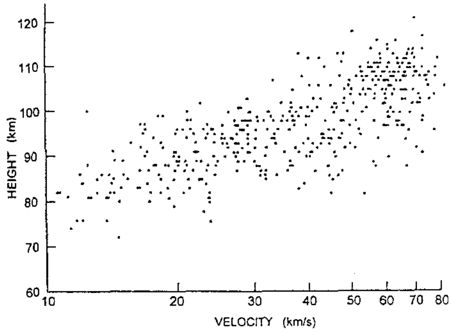


Fig. 3. Observed heights at maximum luminosity of 454 TV meteors (magnitude range 3–8) plotted against log (velocity, v).

of the trail causes severe attenuation of the radar echo. The general relationship between the height of a meteor and the velocity of the meteoroid is readily seen in Fig. 3 which is adapted from the results for the 454 TV meteors already mentioned.

3 Corrected velocity distributions

The production of light and ionization in meteor trails is highly velocity dependent and the reduction of the observed distributions to particles of a given mass is subject to considerable uncertainty. If the velocity dependence is written as v^n, the value of the exponent n is generally accepted as lying somewhere between 3 and 4. Erickson (1968) corrected a random sample of 286 meteors from the Super-Schmidt meteor velocity distribution given in Fig. 1 according to an expression derived by Jacchia *et al.* (1965), while Sekanina and Southworth (1975) corrected the Harvard Radio Meteor Project velocity distribution according to the ionizing efficiency given by Cook *et al.* (1972), *i.e.* v^4. The corrected distributions are shown in Fig. 4.

The optical and radio distributions reduced to a given mass show reasonable agreement up to a velocity of $\sim$35 km/sec, but at a velocity of 68 km/s they differ by a factor of $\sim 10^3$. At the greater heights rapid diffusion inhibits radar detection of meteors; Sekanina and Southworth also corrected the distribution for this effect and the correction is included in the result in Fig. 4. The wide discrepancy between these two results has remained known but unchallenged for more than twenty years.

Recently Taylor (1995) has pointed out that the actual correction applied by Sekanina and Southworth is not the value stated in their paper, and that when the corrected velocity distribution is revised the results appear as in Fig. 5. The revision increases the number of high velocity meteors by about two orders of magnitude. Fig. 5 also includes a corrected radio meteor velocity distribution derived by Nilsson (1962) from his meteor orbit survey of 1960–61 (Nilsson assumed an

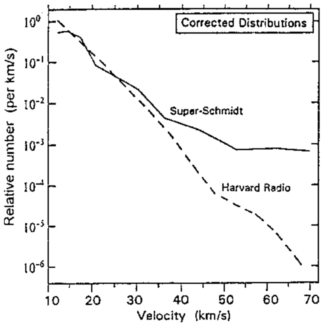


Fig. 4. Meteor velocity distributions corrected for luminous and ionizing efficiencies by Erickson (1968) and by Sekanina and Southworth (1975). There is obviously a major, previously unexplained, disagreement at $v > 35$ km/sec.

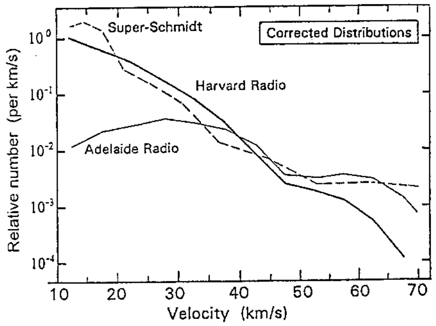


Fig. 5. Comparison of radio and optical velocity distributions, corrected for luminous and ionizing efficiencies, as appropriate. The Harvard radio distribution includes the revision by Taylor (1995) as discussed in the text.

ionizing efficiency varying as v^4, as did Cook *et al.*, 1972).

The Harvard optical and radio distributions shown in Fig. 5 now agree to within a factor of ~2.5 for speeds from 20 to 55 km/sec. However there is still a large difference at the higher velocities. It seems likely on the basis of low MF radio observations of meteors (Steel and Elford, 1991) that the Harvard correction for the effect of diffusion is underestimated. In contrast the radio distribution of Nilsson agrees reasonably with the optical results for speeds above 30 km/sec, but shows a marked disparity at low velocities. There is no reason to conjecture that Nilsson's radio system and reduction procedures were biased against the detection of slow meteors. The difference, approaching two orders of magnitude at the lower velocity limit, remains unexplained.

4 Velocity measurements with a VHF radar

VHF radars operating at frequencies near 50 MHz, and originally designed to measure winds in the troposphere, have proved to be very useful meteor radars (Avery *et al.*, 1983; Nakamura *et al.*, 1991). Recently the VHF radar near Adelaide (Vincent *et al.*, 1987) has been upgraded to operate continuously as a meteor radar sharing time with its use as a tropospheric wind profiler. Some preliminary results regarding detection of the episodic June Librid shower have been published (Cervera *et al.*, 1993; Elford *et al.*, 1994).

The potential of the Adelaide system for measuring meteor speeds has only been explored in recent months, but the results are already quite outstanding. The parameters of the radar are as follows:

Frequency	54.1 MHz
Peak power	32 kW
Pulse length	13 μsec
Pulse repetition frequency (prf)	1024 Hz
Beam width	3°.2 FWHP
Beam direction	Azimuth: East and West (alternating) Elevation: 60°

A meteor echo is recorded when the amplitude exceeds a prescribed minimum value for a given number of pulse returns. Trails with line densities 10^{12} electrons per metre and greater are readily detected. The range and full signal (in-phase and in-quadrature components, which together render the amplitude and phase) of each pulse return are recorded and made available as time series. A typical record is shown in Fig. 6. Whilst the echo amplitude shows a large number of Fresnel oscillations, it is the phase variation during the commencement of the echo that is used for the velocity determination. The signal-to-noise ratio in the phase record can be enhanced by coherent averaging (*i.e.*, averaging the in-phase and in-quadrature signals separately) over a chosen number of pulses, typically between two and eight; the effect of two-point coherent averaging for this record is shown in Fig. 7. The speed is determined by converting from the echo phase information to the distance of the head of the trail (*i.e.*, the meteoroid location at any time) from the orthogonal point on the trajectory (the t_o point). That is, the phase variation gives us a measurement of the change in range from the radar site on a scale of metres, and a parabolic fit to that change in range renders the speed. By modelling, we have found that the reduction technique is accurate to about 0.5%. The speed of this particular meteor was 23.6 km/sec, and it was detected in the narrow radar beam at an altitude of 86 km.

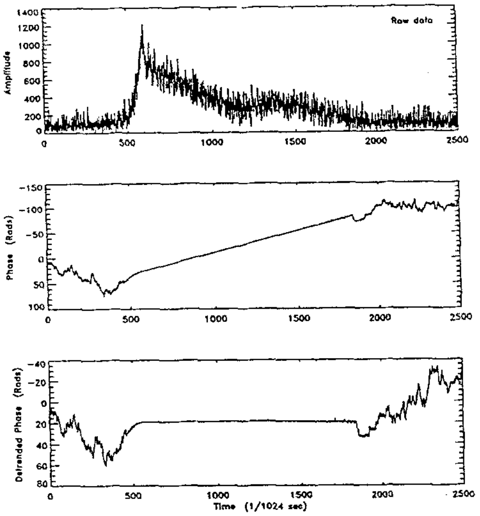


Fig. 8. A relatively long duration echo from a meteor at a height of 77 km, showing a steady phase change (centre diagram) over the life-time of the echo due to the bodily drift of the trail. In the lower diagram the effect of the bodily drift has been removed.

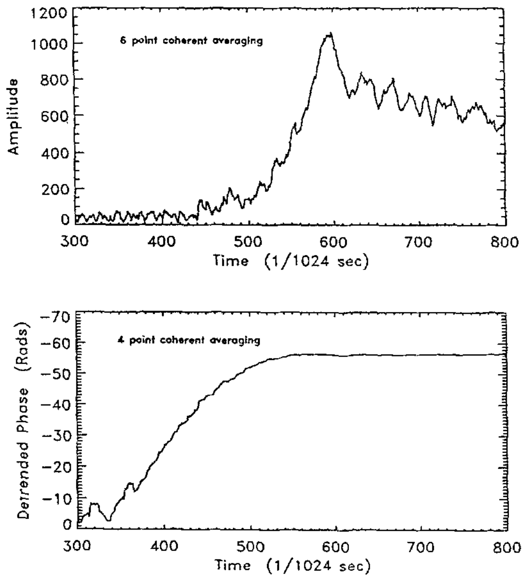
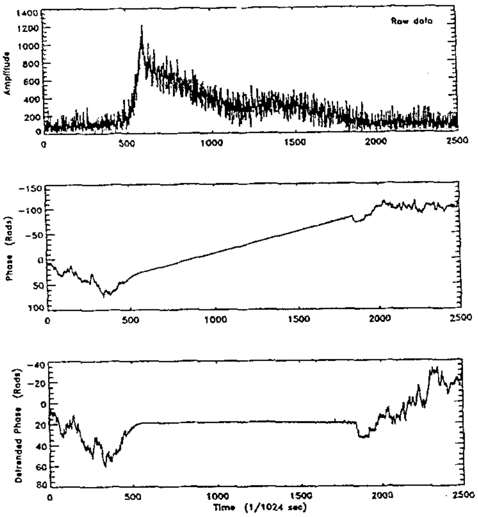


Fig. 9. The effect of coherent averaging on the echo shown in Fig. 8. The phase-time record between pulses 350 and 500 renders a meteoroid speed of 10.4 km/sec.

The improvement in the signal-to-noise ratio achieved by using the phase information is seen in the echo in Fig. 8. This relatively long duration echo shows a steady change in phase over about 1.4 seconds due to the bodily drift of the trail with the neutral atmosphere. In the lower plot in Fig. 8 the phase change due to the drifting trail is removed throughout the whole record and the behaviour of the phase variation during the commencement of the echo is enhanced by some coherent averaging as shown in Fig. 9. The fact that the phase variation shows a smooth coherent behaviour well before any echo is evident on the amplitude record is a feature of all the meteor radar data obtained with this system. This particular meteor had a measured speed of 10.4 km/sec. When the velocity measured between pulses 400 and 450 is used to predict the time of occurrence of the Fresnel oscillations on the amplitude record the observed minima occur significantly later than expected, consistent with strong deceleration of the meteoroid about the t_o point, leading us to suspect that this was a meteoroid arriving from a heliocentric orbit very similar to that of the Earth (so that it entered the atmosphere with a speed just above the Earth's escape velocity, 11.2 km/sec), but which was detected low down in its trail such that a significant drop in speed had occurred by then.

An alternative explanation for the record plotted in Figs. 8 and 9 could be that the trail was produced by ablating space debris. At this point of time we have no reason to prefer this possibility as the velocity is not inconsistent with the final stages of ablation of a very slow meteoroid travelling at an angle of 20°–30° to the horizontal. However the record clearly indicates that ablating space debris could easily be detected, in that this radar is capable of making accurate speed determinations for very slow meteors.

At heights above $\sim$105 km the radius of a diffusing meteor trail exceeds the wavelength for most meteor radars and the scattered signal is significantly attenuated. Also, the effective scattering length of the trail becomes too short to produce any Fresnel oscillations in the amplitude of the signal. An extreme example of this situation is shown in Fig. 10 where the ablation of the meteoroid and the rapid diffusion of the ionization has produced a moving-ball target that gives rise to a typical 'head echo.' The phase-time record now shows almost complete symmetry about the t_o point. At times less than about pulse 1425 and greater than about 1515 the rate of change of phase exceeds the Nyquist sampling frequency (512 Hz) and the record suffers from aliasing. Between these times the phase-time behaviour is parabolic about the t_o point, and in this particular case is interpreted as an ablating meteoroid with a speed of 59.2 km/sec. Also, it is clear from the diagram that the maximum amplitude occurs at the t_o point and this means that the axis of the antenna beam is orthogonal to the meteoroid trajectory. Assuming that the moving-ball target scatters isotropically and the ionization is approximately uniform along the part of the trail in the beam, the amplitude-time record can be interpreted as a cross-section of the polar diagram of the antenna beam. The angular width measured from the record confirms the theoretical value.



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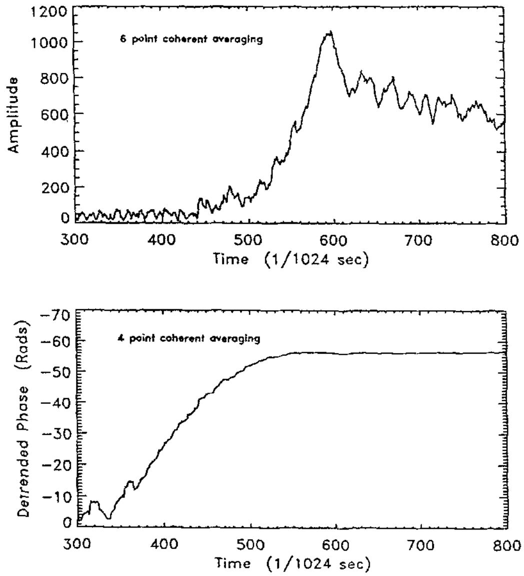

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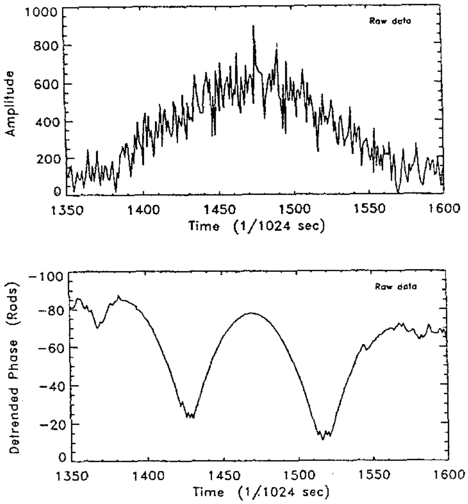

Fig. 10. Amplitude and phase variation associated with a 'head echo' from a meteor at a height of 96 km. The meteoroid velocity is 59.2 km/sec. Aliasing occurs in the phase records before pulse 1425 and after pulse 1515. The amplitude variation is due primarily to the polar diagram (narrow main beam) of the antenna.

The most significant point about the record shown in Fig. 10 is that for most other meteor radar systems this echo would have been passed over as of little significance. In contrast to the amplitude-time behaviour, the variation of the phase with time is a rich source of information leading to some precise measurements. The exploitation of such phase information means that a much greater fraction of the high altitude, high velocity component of the meteor population is accessible to radar studies and, in particular, to measurement of velocities. With a system prf of 1024 Hz, geocentric velocities well in excess of the solar system limit of 74 km/sec are measurable using this technique, even though, due to pulse aliasing, the Fresnel oscillation method cannot access such speeds to produce accurate speed determinations.

5 Velocity measurements at 2 MHz

To fully explore the velocity distribution of meteors at heights above 110 km using radio methods requires observations at low frequencies, below 10 MHz. We proposed to use the upgraded 2 MHz radar system near Adelaide for this purpose. This system is now capable of both transmission and reception on its 1 km array with a beam directed at least 30° from the zenith.

A trail at a range of 140 km and extending about 6 km back from the t_0 point covers about three Fresnel zones at 2 MHz, and this is sufficient for a determination of the speed of the meteoroid if the polarization of the radio waves relative to the trail axis can be estimated. The latter is anticipated to be available from amplitude measurements using the array in its dual orthogonal polarization mode. For the system operating at a prf of 100 Hz a trail formed at a speed of 70 km/sec will be sampled about eight times prior to the t_o point. It is considered that this is sufficient to determine the meteoroid speed to within 5%. Thus we will be able to measure the speeds of meteoroids ablating at very high altitudes, above the echo ceilings of conventional VHF meteor radars.

Acknowledgements

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