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Accuracy of meteoroid speeds determined using a Fresnel transform procedure

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Abstract

New methods of determining meteor speeds using radar are giving results with an accuracy of better that 1%. It is anticipated that this degree of precision will allow determinations of pre-atmospheric speeds of shower meteors as well as estimates of the density of the meteoroids. The next step is to determine under what conditions these new measurements are reliable.

Errors in meteoroid speeds determined using a Fresnel transform procedure applied to radar meteor data are investigated. The procedure determines the reflectivity of a meteor trail as a function of position, by application of the Fresnel transform to the time series of a radar reflection from the trail observed at a single detection station. It has previously been shown that this procedure can be used to determine the speed of the meteoroid, by finding the assumed speed that gives a reflectivity image that best meets physical expectations. It has also been shown that speeds determined by this method agree with those from the well established "pre-t_o phase" method when applied to reflections with a high signal to noise ratio. However, there is a discrepancy between the two methods for weaker reflections. A method to investigate the discrepancy is described and applied, with the finding that the speed determined by using the Fresnel transform procedure is more accurate for weaker reflections than that given by the "pre-t_o phase" method.

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Keywords: Meteor; Radar; Fresnel; Transform; Speeds; Error

1. Introduction

Meteoroids ablating in the Earth's atmosphere produce ionisation that reflects radio waves. In radar observations of meteors, a "head echo" is produced by scattering from intense ionisation around the meteoroid, while a "transverse echo" is produced by the integrated reflection from the part of the trail of ionisation that is close to perpendicular to the radar beam. Such observations have been made for many years to measure both astronomical and atmospheric parameters. The speed of the meteoroid is a parameter of vital interest in meteor astronomy, and an accurate measurement of its value is essential in determining the orbit of the meteoroid. Radar facilities such as AMOR (Baggaley et al., 1994), dedicated to determining meteor orbits, measure the meteor speed to an accuracy of about 1%. Cervera et al. (1997) have shown that, in the case of meteor showers a precision of 0.5–0.8% in the speed measurement allows the pre-atmospheric speed of the shower meteors to be determined. The same authors have also shown that such measurements allow the density of the shower meteoroids to be estimated. The question as to the minimum signal-to-noise ratio required to give speeds with a precision better than 1% has as yet not been addressed, and a method of answering this question is the main thrust of this current paper.

A number of methods have been used to determine the speed of meteoroids from radar observations made at a single station. Hey and Stewart (1947) used the "range-time" method to measure the speeds of the small fraction of meteoroids for which a head echo could be observed

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while they traveled over many kilometres. Ellyett and Davies (1948) first used the "diffraction method", which can be applied to a fraction (about 10%) (Baggaley et al., 1994) of transverse echoes for which several Fresnel oscillations can be seen in the amplitude of the returned signal. In most cases the Fresnel oscillations are washed out by diffusion or fragmentation (Elford and Campbell, 2001). Two recent methods give speeds for a greater fraction of echoes by analysis of the reflected signal prior to the meteoroid reaching the "t_o" (or perpendicular) point. The "amplitude rise-time" technique (Baggaley et al., 1997) relates the speed to the rise time to maximum amplitude, but the speed is not as accurate as that derived from the "diffraction" technique. The "pre-t_o phase" technique (Cervera et al., 1997) uses the phase of the echo prior to the t_o point as a measure of the position of the meteoroid, and the technique produces speed results with low errors for most echoes, including those where the Fresnel oscillations are absent due to fragmentation or diffusion.

Elford (2001, 2004) has described a procedure for determining the radar reflectivity as a function of position along a meteor trail, by applying a Fresnel transform to the time series of the radar return recorded at a single detection station. To apply the transform, a speed for the meteoroid must be assumed a priori. During the development of this analysis procedure the outcome of the transform was examined visually and it was observed that the "image" optimised in appearance for a particular speed and deteriorated rapidly as the assumed speed was varied away from the 'optimum' value. In particular the steep rise from zero reflectivity expected at the position of the meteoroid was only seen for assumed speeds close to the optimum value. For echoes with large signal-to-noise ratios the optimum value was very close to that given by the "pre-t_o phase" technique.

It has been shown (Campbell et al., 2002) that this sensitivity to the correct speed can be exploited to use the Fresnel transform procedure to determine the speed of the meteoroid. For a given radar meteor echo the transform was applied for a range of assumed meteoroid speeds and the value that gave the optimum reflectivity image was taken as the 'true' value. Speeds determined in this fashion were compared with those given by the "pre-t_o phase" method and good agreement was found for echoes with relatively high signal-to-noise ratios (~30 db). On the other hand, for echoes with low signal-to-noise ratios (less than about 10 db) there were considerable discrepancies, with the Fresnel transform method generally giving larger speeds than the "pre-t_o phase" method. While some argument was put forward that the Fresnel transform method was better, this was not definitive.

In the work described here the two methods are compared by employing their application to cases where a meteoroid and its trail produce, simultaneously, a 'strong reflection' (high signal-to-noise ratio) in one rangebin and a 'weak reflection' (low signal-to-noise ratio) in an adjacent rangebin. This allows the application of both methods to weak reflections for which the speed (determined from the stronger echo) is known, so that the accuracy of both methods for weak echoes can be assessed.

2. Theory

The theoretical basis of the Fresnel transform technique has been published in detail elsewhere (Elford, 2001, 2004) so only a brief summary is given here. Fig. 1 illustrates a meteoroid at position H, travelling with speed v and leaving an ionised trail along the line HPO behind the meteoroid. The radar (wavelength λ) is at T, and the trail is perpendicular to the radar beam at position O, the "t_o" point. As the trail forms within the radar beam, the radio scattering recorded at T can be described by a complex time series $E(t)$. Assuming the speed of the meteoroid is constant, $x = vt$ and the Fresnel transform gives the reflectivity $A(y)$ as a function of distance y (measured as negative from the meteoroid at H) by the equation:

$$A(y) \propto v \int_{-\infty}^{\infty} E(t) \exp(-jk(vt + y)^2/R_o)\,\mathrm{d}t, \quad \text{where } k = 2\pi/\lambda. \tag{1}$$

The speed v is determined by applying the transform for different assumed speeds, to find the value that gives the most physically realistic reflectivity "image". The criteria for this are a rapid rise in the reflectivity at the position of the meteoroid, no contribution from ahead of this position, and minimal oscillations in the trail reflectivity.

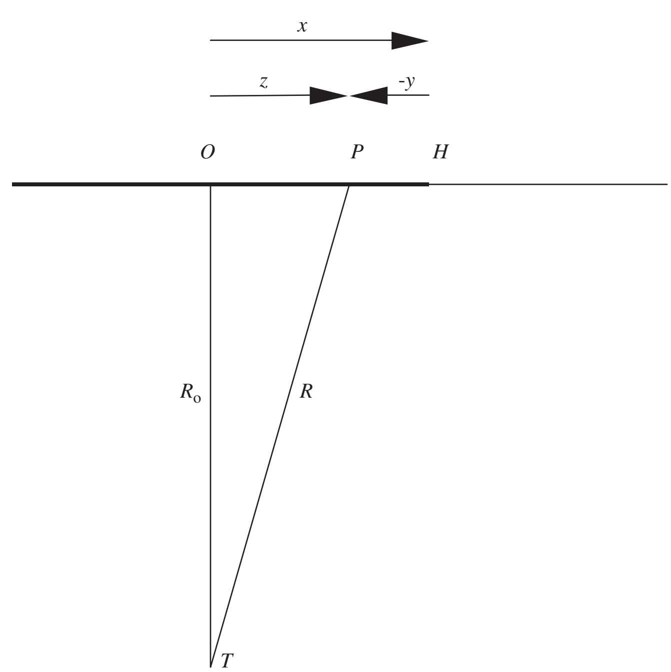

Fig. 1. Geometry of the trail and radar scattering.