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The Canadian Meteor Orbit Radar: system overview and preliminary results

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Abstract

This paper describes the Canadian Meteor Orbit Radar (CMOR) that has been in operation since late 2001. CMOR is a 3 station meteor radar operating at a frequency of 29.85 MHz near Tavistock, Ont. To avoid bias against fragmenting meteoroids that is inherent in the traditional multi-station method of Gill and Davies (Mon. Not. R Astron. Soc. 116 (1955) 105), we use a completely geometrical method similar to that used in the AMOR system (Quart. J. R. Astron. Soc. 35 (1994) 293) based on the interferometric determination of the echo directions and the time delays of echoes from two remote stations to obtain the trajectories and speeds of meteoroids. We describe the hardware and some of the software and present some preliminary results that provide a good indication of present capabilities of the system. Typically, we can measure 1500 individual trajectories, and hence orbits, per day with a mean accuracy of 6° in direction and about 10% in speed. A small subset of these for which it is possible to measure the speeds using Hocking's (Radio. Sci. 35 (2000) 1205) method yield speeds with a precision of about 5%. The purpose of this paper is to show that the radiants and speeds necessary for the computation of orbits are well measured rather than to discuss any orbital surveys.

Keywords: Meteors; Meteoroids; Interplanetary dust; Meteor radar

1. Introduction

Meteoroids are thought to be either the products of the decay of comets after planetary perturbations have brought their nuclei into orbits close enough to the Sun to produce appreciable sublimation, or the results of inter-asteroidal collisions. The dynamics of the population are far from being understood and the elucidation of the processes that govern the evolution and maintenance of the meteoroid complex is an exciting intellectual challenge of great practical importance since the impact of these small particles with space vehicles poses a significant hazard.

Large numbers of these small bodies impact the Earth's atmosphere everyday and can be observed as "shooting stars" after dark. In addition to leaving a luminous train as they ablate, they also leave a train of ionization which constitutes an effective reflector of radio waves. Such reflections enable radars to measure the meteoroid masses, speeds and trajectories. Although there are several other possible approaches to the determination of the characteristics of the meteoroid complex, meteor radar offers a very productive and cost-effective method of exploring the meteoroid population in an extensive region of inter-planetary space as

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has been demonstrated by Baggaley et al. (1994) and others.

Until the advent of the AMOR system (Baggaley et al., 1994), meteor orbit radars followed the basic design adopted by Gill and Davies (1955). According to Hawkins (1964), Gill and Davies' method was based on the idea of T.R. Kaiser of first determining the speed of the meteoroid by Fresnel diffraction amplitude oscillations and then to use this in conjunction with echo delay times measured on at least two remote receiver stations to determine the orientation of the meteor train. This method has two important disadvantages: only a small fraction of the echoes are suitable for analysis and the meteor selection criteria may introduce serious bias in the results of such surveys. It has long been known that many meteoroids fragment as they penetrate the Earth's atmosphere causing a significant "smearing" of amplitude oscillations of the echoes that makes them unsuitable for speed determination by the Fresnel diffraction oscillation method. It is therefore possible that such surveys may not be representative of the meteoroid population as a whole.

There have also been severe computational limitations in the past because of the amount of information produced by these radars. For example, the Harvard Radio Meteor Project (HRMP, see Hawkins, 1963) could only process 5 min of data out of every hour and produced only about 19,000 orbits over the period 1961–1965 and a similar number from 1968–1969. Technical advances in electronics and computers have gone a long way to correcting these weaknesses and provided a great impetus to develop a new generation of meteor orbit radars. The first of these was the AMOR radar (Baggaley et al., 1994) which produces over 1000 orbits per day of southern hemisphere meteoroids to a limiting radio magnitude of +14. The present paper describes the Canadian Meteor Orbit Radar (CMOR) located near Tavistock, Ont., which is at almost the same North latitude as AMOR is in the south. CMOR has a greater effective collecting area than AMOR but is much less sensitive and so is better suited to studying meteor streams since they tend to be relatively richer in larger particles than the sporadic meteoroid complex.

2. Design principles of CMOR

The pivotal idea behind the CMOR system was to avoid the use of the Fresnel diffraction method for determining the meteoroid speed and to use instead a purely geometrical technique similar to that employed by the AMOR meteor radar.

The measurement of the direction of the returned echo using a well-designed interferometer can compensate for the information lost by the neglect of the Fresnel oscillations. Many authors have shown (see, for example, McKinley, 1961) that for a back-scatter radar, the echo direction is orthogonal to the axis of the meteor train and this is known as the specular condition. The time delays of the echoes from the remote receivers can then supply the remaining information that allows the axis of the meteoroid trajectory to be determined. The speed of the meteoroid can then be extracted by combining the trajectory information with the time-delay measurements. Both CMOR and AMOR use this method of determining trajectories and speeds from a combination of interferometric and time-delay techniques but whereas the antenna system of AMOR illuminates only a narrow strip of the sky, CMOR affords almost all-sky coverage so that the geometry involved in the reduction of the CMOR data is somewhat more complicated than for AMOR.

Consider the main station and one remote receiver separated by a distance, D, as shown in Fig. 1. The initial echo is received at the main site, and at some slightly different time a second echo is received at the remote site. Depending on the geometry, the echo at the remote site may either precede or follow that at the main site. We will define the time delay, Δt, as being positive for an echo that is received after the main site echo. It is easy to show that for a meteor with speed v, if the range of the echo is much greater than that between the main and remote sites, the direction cosine, $\cos\xi$ (where ξ is the angle between the axis of the meteor trajectory and the vector from the main to the remote site) is given approximately by

$$\cos \xi \cong D/2v\,\Delta t. \quad (1)$$

The maximum error in this approximation is about 2% for $\xi = 45^\circ$ and $D = 8$ km with echoes from meteors at a height of 100 km.

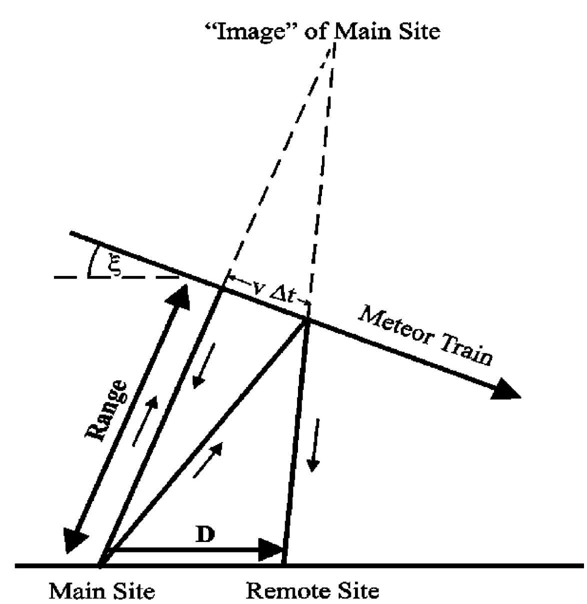

Fig. 1. Geometry of reflections on main and remote stations.

A second remote site is needed to make use of this information if v is not known. Two remote non-aligned sites allow the ratio of direction cosines to be determined. While this does not determine the direction of the train axis uniquely, it does confine it to a vertical plane (the time-delay plane) as shown in Fig. 2. The calculation is especially simple if the vectors from the main to remote sites are orthogonal and the normal vector $\vec{n}$ to the time-delay plane is given by

$$\vec{n} = \begin{pmatrix} \Delta t_2/D_2 \\ -\Delta t_1/D_1 \\ 0 \end{pmatrix}, \tag{2}$$

where D_1 and D_2 are the spacings to the respective remote stations which are assumed in this case to be along orthogonal axes. Similarly Δt_1 and Δt_2 are the delays times of the meteor echo observed at the two remote stations. If the remote stations are not located along orthogonal axes as is the case for CMOR, then

$$\vec{n} = \begin{pmatrix} \Delta t_2 \cos(\psi_1)/D_2 + \Delta t_1 \sin(\psi_2)/D_1 \\ -\Delta t_1 \cos(\psi_2)/D_1 + \Delta t_2 \sin(\psi_1)/D_2 \\ 0 \end{pmatrix}, \tag{3}$$

where ψ_1 and ψ_2 are the angles the vectors from the main station to the remote stations make with their corresponding orthogonal axes as shown in Fig. 3. Our Eqs. (2, 3 and 5) correspond to Eqs. (1, 2 and 4) of Baggaley et al. (1994).

A well-designed interferometer such as that described by Jones et al. (1998) can give an accurate and unambiguous determination of the echo direction, $\vec{e}$, with almost all-sky coverage. Because the specular reflection condition constrains the echo direction at the main site to be perpendicular to the train axis, we now have a second independent plane (the interferometer plane) containing the direction of the meteor train. The vector parallel to the axis of the train, $\vec{m}$, is the intersection of the time delay and interferometer planes as shown in Fig. 2. This is easily obtained from the vector product

$$\vec{m} = \vec{n} \times \vec{e} \tag{4}$$

and the direction of $\vec{m}$ is easily resolved by forcing its vertical component, m_3, to be negative so that the meteoroid approaches the Earth.

The final step is to recover the speed of the meteoroid from either

$$v = \frac{\vec{m}D_1}{2\Delta t_1} \quad \text{or} \quad v = \frac{\vec{m}D_2}{2\Delta t_2}. \tag{5}$$

The orientation of the trajectory and the speed of the meteoroid have now been found.

Since the range of the meteor echoing point from the radar is much greater than the separations of the remote from the main sites, the geometrical approximation made in Eq. (1) are extremely insensitive to the range so that the method can be used just as easily with a continuous wave system as with a pulsed meteor radar.

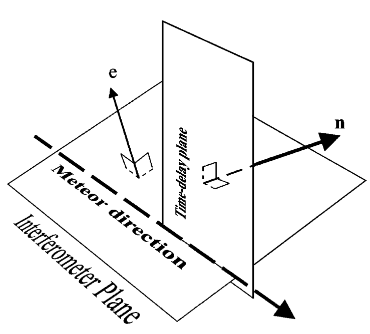

Fig. 2. The line containing the meteor directions is the intersection of the "interferometer plane" determined from the echo direction and the "time-delay plane" determined from the time delays of the echoes on the remote stations relative to the main station.

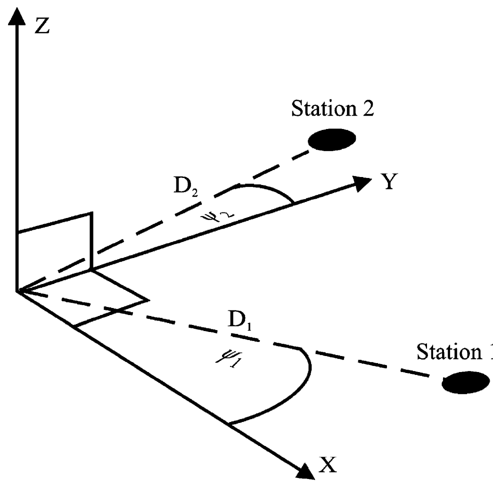

Fig. 3. Definition of the angles ψ_1 and ψ_2 involved when the vectors from the main to the remote stations are not aligned with the axes of the coordinate system.

3. Optimization of system configuration

Having decided that it is in principle possible to determine trajectories using only delay times and echo directions, we conducted numerical simulations to choose the system parameters that would optimize the performance of the system.

The numerical simulations were assumed underdense meteor trains with echoes having a realistic distribution of delay times. The ionization profile of the meteor train was taken to be identical with the luminosity profile as determined by Fleming et al (1993) for TV meteors of limiting magnitude of +7 which is typical of the meteors detected by CMOR at all three sites. We took the elevation angles of the echoes to be uniformly distributed between 20° and 80° and the azimuth angles to be uniformly distributed between 0° and 360°. The distribution of maximum ionization, q, of the trains was taken to be a power law

$$\mathrm{d}n \propto q^{-2}\,\mathrm{d}q, \tag{6}$$

which we considered to be representative of the meteor population as a whole.

The results of the system simulation are shown in Figs. 4–7. For a meteor to be detected on all three stations typically requires it to be 2.5 magnitudes brighter than for an otherwise similar meteor to be detected on just one station.

The choice of spacing for the remote stations is a compromise between optimizing the fraction of echoes observed on all stations, f, and the accuracy of the speed determinations. The likely error in the radiant directions is weakly dependent on the spacing when the spacing is greater than 4 km.

4. System hardware

CMOR is built around the SKiYMET meteor radar system produced jointly by MARDOC, Genesis Software Pty and Tomco Electronics Pty. and described by Hocking et al. (2001). The UWO meteor radar complex located near Tavistock, Ont. (43.264N, 80.772W) consists of three SKiYMET systems operating in synchronism at 17.45, 29.85 and 38.15 MHz. The three radars were used to determine the bias arising from the frequency-dependent attenuation of radar meteor echoes due to the destructive interference caused by the finite diameter of the ionization column known as the "initial radius effect" (Campbell-Brown & Jones, 2003). The radiant and speed determinations described in this paper were made at 29.85 MHz because of interference problems encountered with the 17.45 MHz and a lower echo rate at 38.15 MHz presumably due in part to the initial radius attenuation. Although the SKiYMET system was designed primarily for the measurement of winds in the meteor region of the

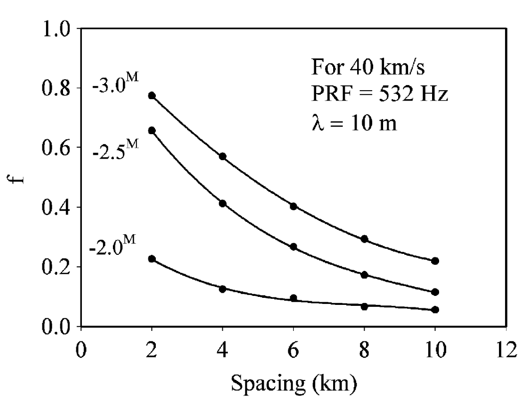

Fig. 4. Results of numerical simulation for determining fraction of meteors detected at the main site that yield orbits as a function of distance of remote stations from the main site and magnitude of the train relative to that which is just detectable at the main station.

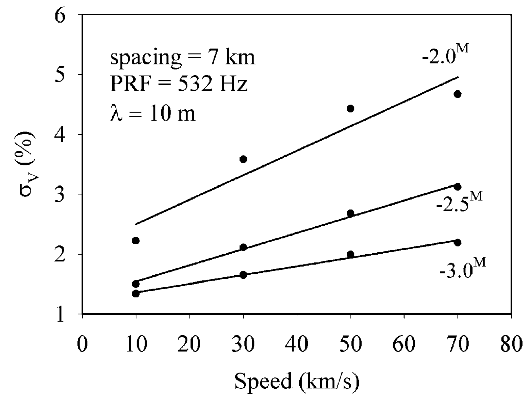

Fig. 5. Results of numerical simulation for determining the fraction of echoes that will yield orbits as a function of speed magnitude of the train relative to that which is just detectable at the main station. Spacing = 7 km; PRF = 532 Hz.

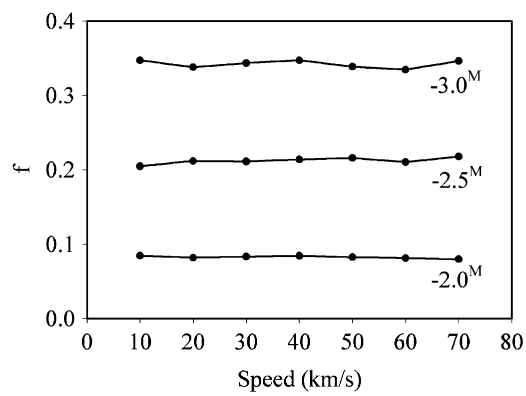

Fig. 6. Results of numerical simulation for determining likely error in speed as a function of speed and magnitude of the train relative to that which is just detectable at the main station.

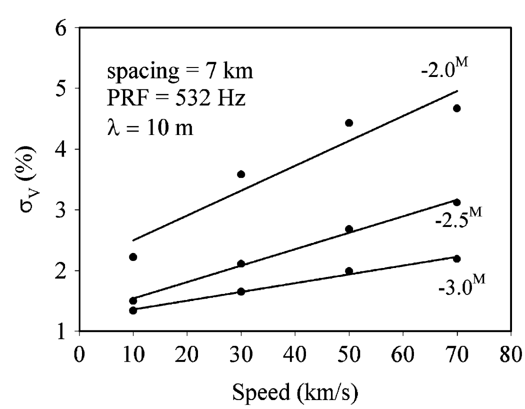

Fig. 7. Results of numerical simulation for determining the likely error in the direction of the trajectory, σ_θ, as a function of the electron line density assuming that the probable error in the determination of the echo direction is 1°.

atmosphere, it is very suitable for astronomical studies for meteors especially since it has all-sky coverage and is supplied with very useful software.

A key feature that makes the SKiYMET system suitable for our purposes is the 5-element interferometer described by Jones et al. (1998) that enables echo directions above 20° to be measured unambiguously to an accuracy of about 1°. The CMOR version of the SKiYMET radar was equipped with two additional receivers for use with the remote sites. The locations of the remote sites were chosen on the basis of the calculations described in the previous section. The Thames Bend site is 8.1 km distant from the main site and the Gerber site is 6.2 km, with the vectors from the main to remote sites being close to perpendicular at 96.8° as shown in Fig. 8.

One of the aims of CMOR was to get all-sky coverage so as to be able to access as much of the celestial sphere as possible. In the interests of simplicity, we chose vertically directed Yagi arrays for both transmitter and receiver antennas. No extra ground planes were used since numerical simulations indicated that they would have little effect for this antenna configuration. The transmitter antennas are all three-element Yagi arrays with a gain of 7.6 dBi, while the receiver antennas are two element but otherwise similar arrays with gain of 6.3 dBi. In each case, the reflecting element of the arrays was $\lambda/3$ above the ground. The antennas were aligned with the elements pointing 11° to the West of a N–S line so that the broad main beam was directed mainly E–W. Although there are nulls in the gain patterns along the axes of the antenna elements at zero elevation, the gain above 20° elevation is much more uniform. This represents the lower elevation detection limit for the majority of echoes.

A frequency synthesizer unit provides the final amplifier stages of the transmitter with pulses of radio-frequency signal that have been shaped according to software instructions as to pulse repetition frequency (PRF), length and shape. Typically, we use a PRF of 532 Hz, a pulse length of 75 μs and tapered pulses to reduce the harmonic content of the transmitted signals. To ensure that the signals from all three stations share a common range bin in order to avoid needless complications in the analysis software, the pulse length was made somewhat greater than the extra path length encountered because of the separation of the remote stations.

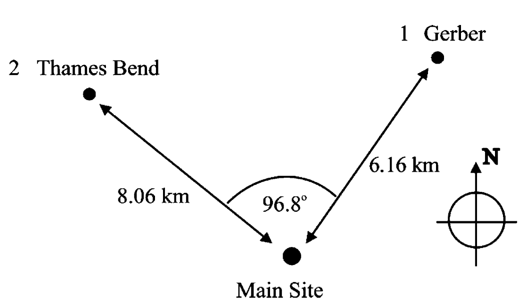

Fig. 8. Details of the UHF links between the main and remote sites.

The power amplifier consists of six 1 kW modules whose outputs are summed together in the combiner stage. The maximum duty cycle is 15% and the average power is limited to about 900 W and single-pulse mode used.

The transmitter power varies slightly with ambient temperature and humidity, and for this reason, the root-mean-square voltage delivered from the transmitter is monitored every 10 min and recorded in a file.

Each receiver antenna is connected to its associated receiver by a preamplifier situated at the antennas to make up for losses in the antenna–receiver cable. The received signal is mixed down to base-band and the in-phase and quadrature (I and Q) components are then digitized, buffered and finally transferred to the controlling computer. The bandwidth of the receivers is software-adjustable and typically was set at 25 kHz.

A meteor echo received by CMOR at the same level as cosmic noise at a range of 140 km is equivalent to a radio-meteor magnitude of $+8.9$ with cosmic noise temperature of 2.9×10^4 K.

The remote receivers capture the meteor echoes at 29.85 MHz. These signals are then converted to UHF close to 450 MHz and relayed back to the main site via UHF links and converted back to 29.85 MHz.

5. Analysis procedures

The basic echo detection and analysis algorithms used by the SKiYMET system are described in detail by Hocking et al. (2001). In this section, we provide a brief overview of the process adding those details that are specific to the CMOR system.

During observation runs, the first step in analysis of the data is to identify possible meteor echoes. A 4-point moving-average filter (also sometimes referred to as "4-point coherent integration") is applied to the I and Q channels which increases the sensitivity by about 6 dB so that the magnitude of a meteor signal with the same power as cosmic noise is about $+9.4^{\mathrm{M}}$. A further increase in sensitivity is also obtained by summing the amplitudes of the signals from each of the antennas in the interferometer. The resulting signal is monitored and when it exceeds the average value of the previous 10-point mean by eight standard deviations, the portion of the data stream of length 30 s surrounding that instant is saved to a file. This procedure effectively sets the triggering sensitivity of the system to 7.7 dB above cosmic noise putting the limiting magnitude at the main station at close to $+8.7^{\mathrm{M}}$. As discussed previously we need meteors about 2.5^M brighter than this—typically $+6.2^M$ magnitude to determine orbits.

Since the 30 s worth of data typically contains several meteor events, it is scanned repeatedly until they have all been identified. Possible meteors are then further scrutinized by a more sophisticated algorithm to reject both noise spikes and echoes from aircraft as well confirming that the event is not a remnant of a prior echo at the same range and that the rise and delay times of the echo are meteor-like. The consecutive samples of I and Q signals for each antenna are then entered into an array according to their range ("range bins") which is written to a file together with the details of the configuration of the system. It is also important to note that the recorded data are not subject to the 4-point coherent integration that is used for the detection procedure. Many of the echoes recorded at the end of these detection procedures have very low signal-to-noise ratios and the sophisticated digital signal processing algorithms such as those used in the SKiYMET software are required to extract the quantities of scientific interest. We also note that the SKiYMET system can also continuously record all the digital information acquired by the system in a "streaming" mode should the need arise.

The echo amplitude profiles often do not display the ideal exponential decay because of the effects of progressive distortion of the train by upper atmospheric winds. These effects complicate the measurement of the time delays. We are primarily interested in the instant the meteoroid passes the specular point and we have chosen to use the initial portion of the echo when the rate of increase of echo amplitude is greatest. The time differential of the echo amplitude is therefore much more useful than the amplitude itself as is shown in Fig. 9. There are many possibilities for determining the times associated with the peaks in the time differential. One simple procedure that gave excellent results in the numerical simulations is to find the centroid of that portion of the peak that exceeds half the maximum value. Other such algorithms have been discussed by Baggaley et al. (1994).

How accurately do we need to measure the delay times as the remote stations? Since the direction of the meteor trajectory is determined from the intersection of the interferometer and time-delay planes we would expect that these should be measured to comparable accuracy. Comparison of echo directions determined independently with the 29.85 and 38.15 MHz radars, yields as mean error of 1.1° in the interferometrically determined echo directions, but it is not known how much of this is due to systematic differences such as uneven ground etc.

The following simple analysis provides an estimate of the orientation error resulting from the errors in delay–time measurements. Let us consider a simple system for which the remote stations are equidistant from the main station along the orthogonal axes. According to Eq. (2), a vector perpendicular to the time-delay plane has components in the horizontal plane proportional to $(\Delta t_2, -\Delta t_1)$ as shown in Fig. 10. The angular error in this vector is proportional to

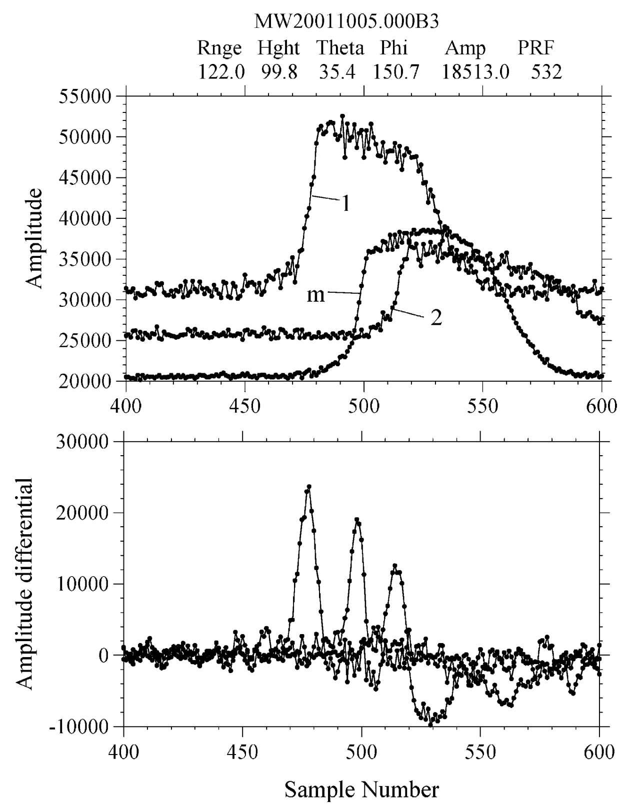

Fig. 9. Example of the (a) echo profiles and (b) the time differentials of the echo profiles received at the main (m) and remote stations.

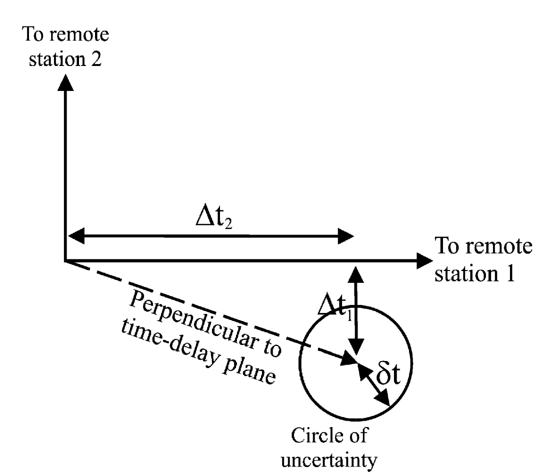

Fig. 10. The uncertainty in the orientation of the vertical time-of-flight plane is determined by the errors in the measurement of delay times of the echoes received at the remote stations relative to the instant at which the echo arrives at the main station.

$\delta t/\sqrt{\Delta t_2^2 + \Delta t_1^2}$, where δt is the measurement error in the time delay. Geometrical considerations show that the quantity $\sqrt{\Delta t_2^2 + \Delta t_1^2}$is given by

$$\sqrt{\Delta t_2^2 + \Delta t_1^2} = D\,\sin(elev)/2v, \quad (7)$$

where *elev* is the elevation angle of the radiant, v is the speed of the meteoroid and D is the distance of the main to the remote stations. With $elev = 45°$, $D = 7$ km, $v = 40$ km/s and a PRF = 532 Hz, we find that in order to measure the orientation of the delay-time plane to 1°, we must measure the time delay to about 1.25×10^{-3} s or to within 0.7 of a pulse interval. If time delays are measured more accurately than this, the likely error in the measured trajectory direction will be dominated by errors in the measurements of the echo direction over which we have little control. Thus, we should strive to measure the times to slightly better the 1 pulse and be content if we are able to measure trajectory directions within 2°.

The errors in delay-time measurements also result in errors in the speed determinations. If the likely error in the timing determinations is the dominant source of error, then

$$\delta v/v = 2\delta t\, v/D\,\sin(elev), \quad (8)$$

where δv is the error in the speed determinations. When timing errors do not dominate, the accuracy of the speed measurements is largely the result of the error in the determination of the echo direction.

The SKiYMET software includes an estimate of the speed based on Hocking's (2000) implementation of the "pre-t_0" method (Elford et al. (1995); Cervera et al., 1997). Because the Hocking method (HM) requires fairly high S/N ratios, only a small fraction of the echoes, typically a few percent, meet the necessary criteria, but for these echoes it yields speeds accurate to about 5%.

Baggaley et al. (1997) have shown that it is possible to determine meteor speeds using the rise-time of the echo amplitude, but we have not yet implemented this method.

6. Orbit computation

Before the meteor trajectory and speed information can be converted to heliocentric orbital elements, several corrections are necessary. Baggaley et al. (1994) have found that deceleration in the Earth's atmosphere of the very faint meteors detected by AMOR may be corrected for by using the equation

$$v_\infty^2 = v_0^2 + 0.81 v_0^{1.6}, \quad (9)$$

where v_∞ is the mean out-of-atmosphere speed and v_0, the measured speed. When applied to CMOR observations of shower meteors, Eq. (9) gives values of v_∞ that are several km/s greater than those determined from the much more accurate photographic observations. By comparing our speed determinations for the major night-time meteor showers with those deduced from photographic observations, we find the following empirical expression for v_∞:

$$v_\infty^2 = v_0^2 + 1.82 v_0^{1.2}. \quad (10)$$

We have also noticed that the deceleration correction appears to depend on the shower so that even after applying Eq. (10), there is a residual uncertainty of about 2 km/s. We also make the standard corrections for the gravitational attraction of the Earth (zenithal attraction) and the rotation of the Earth (diurnal variation).

The corrected trajectory and speed can then be transformed into the heliocentric orbital elements. We make this conversion using routines from a program written by Ceplecha (1987) originally intended for the analysis of fireball observations which is more than adequate for the task.

7. Preliminary results

How well does CMOR perform as a meteor orbit radar? There are three questions that need to be asked. How many meteor echoes are suitable for determining orbits each day? What is the accuracy of the speed measurements and lastly, what is the measured accuracy of the radiant measurements?

In a typical day, CMOR detects 7000 meteor echoes at the main station. Of these, 1500 have sufficient information at all the three stations to enable an orbit to be determined. Of these, about 150 are sufficiently well behaved to yield HM speeds. Fig. 11 shows typical speed distributions of sporadic meteors produced by several meteor radar systems. It is clear that the time-of-flight (TOF) method produces many more high-speed meteor orbits than does the HM. Indeed, the TOF observations

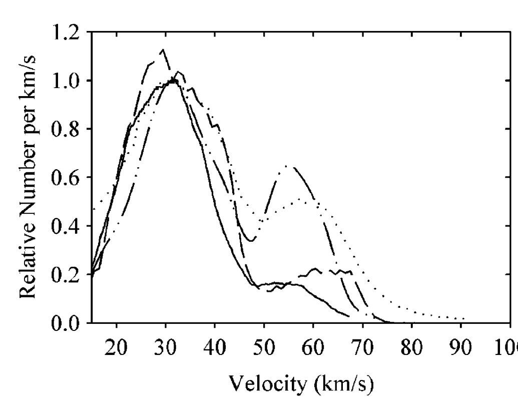

Fig. 11. Comparison of sporadic meteoroid pre-atmospheric speed distributions observed by several meteor radars. Solid line—HRMP; dash-dotted line—Jodrell Bank; dashed line—CMOR (HM); dotted line—CMOR (TOF).

are in good agreement with the Jodrell Bank while those obtained using the Hocking technique resemble the HRMP speed distribution.

The precise cause of the loss of sensitivity of the Hocking technique for speeds above 45 km/s has not been identified, but it is likely that the result of the selection criteria be employed to identify suitable echoes as well as selection against fragmenting meteoroids. It is possible that none of the methods is free of a speed-dependent bias. The simulations described previously, suggest the fraction of meteor echoes that produce orbits, does not vary appreciably with speed. The form of the speed distribution has been well-established and the underlying reasons known for decades (Davies and Gill, 1960). The lower speed peak is associated with the helion/antihelion sporadic meteor sources while the higher speed peak is produced predominantly by meteors from the apex source (see e.g. Jones and Brown, 1993). In a comprehensive analysis of radio-meteor rate observations over several years in both Ottawa (Canada) and Christchurch (NZ), Brown and Jones (1995) showed that the apparent strengths of the helion, antihelion and apex sources are approximately equal which would suggest the ratio of the two maxima is of the order of 2, as is in fact the case for the CMOR observations in Fig. 11.

We estimate the accuracy of the speed measurements from the observed scatter in the measured speed of shower meteors on the assumption that the measurement errors are much greater than the intrinsic scatter. If this assumption does not hold, we will overestimate the error in the speed determinations. The typical error for the TOF method is about 10% while that for the HM is about 5%. The TOF speeds appear to be a slightly less (-0.1 km/s) than the HM speeds but this may be not be significant. In any case, this is much smaller than the measured scatter and can safely be ignored for the present.

We now turn our attention to the accuracy of the measured radiants. Fig. 12 shows a plot of the radiant distribution for meteor orbits measured during the 2002 Quadrantid shower. The root-mean-square (r.m.s)

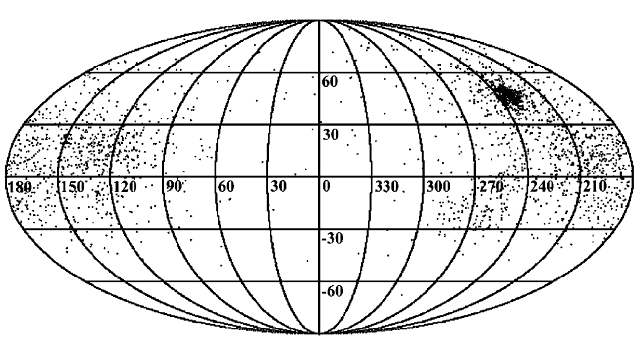

Fig. 12. Observed distribution of radiants 4 January 2003 during the Quadrantid meteor shower.

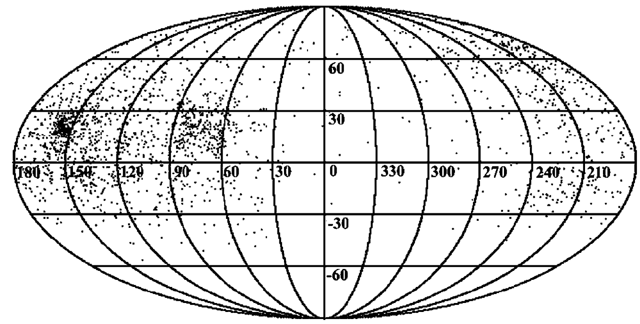

Fig. 13. Observed distribution of radiants 19 November 2002 during the Leonid meteor shower.

scatter in directions of the Quadrantid radiants ($RA \cong 231°$, $Dec \cong 50°$) is of the order of 6°. A similar plot of the distribution of the radiants observed during the 2002 Leonid shower is presented in Fig. 13. Even though the HM speed determinations are significantly better than those obtained by the TOF method, this does not translate into more accurate radiant determinations since they depend on the accuracy of the time delay measurements. The uncertainty in the delay time should be reflected in the uncertainty in the orientation of the time-delay plane and hence the trajectory direction. The considerations presented previously allow us to estimate the likely error in the measurement of the time delays. Putting $\delta v/v = 0.1$ we find $\delta t = 0.007$ s or 3.7 pulses which correspond to an uncertainty in the angular measurement of about 6° as is in fact observed. This confirms that our first priority ought to be to increase the accuracy of the time-delay measurements.

8. Conclusions

CMOR has shown itself to be a productive system for measuring meteor radiants and speeds. It has the potential to provide reliable orbits once the problem of the correction for atmospheric deceleration has been solved. The accuracy of the orbital elements awaits improvements in the time-delay measurements since these are the main sources of uncertainty. Simulations originally performed to test the system concept and to provide the initial choice of system parameters show that ideally we should be able to measure speeds to an accuracy of about 5% and directions to about 2°. However, the numerical simulation was based on the assumption that all the meteors are underdense. In practice, many of the observed echoes are overdense with durations that are significantly greater than those of underdense echoes. This increased echo duration provides time for additional specular reflection points to appear along the train as it is distorted by upper atmosphere winds. Instead of having a sharp rise followed by a relative gentle decay, the echo amplitude often shows several maxima that can result in a wrong measure of the delay time. While the present software attempts to minimize such effects, it is not yet always satisfactory and a great deal of work needs to be done to find a good solution to this problem.

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