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Atmospheric speeds of meteoroids and space debris by using a forward scatter bistatic radar

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Abstract. We describe a simple method for measuring the speeds of individual meteoroids and space debris by using the BLM (Bologna-Lecce-Modra) forward-scatter (FS) radar. The ionized trails left into the atmosphere may be distinguished each other due to the lower entrance velocities (7-10 km/s) of the small space debris with respect to those of normal meteoroids (11-72 km/s). Rise-time and diffraction techniques exploit the amplitude echo region of any FS echo respectively before and after the amplitude maximum, and are here used to obtain approximate scalar speeds . Normal accuracy in rise-time speeds is stated at better 10-12%. Coupled with precision trajectory information, precise velocities can be deduced by the BLM radar facility implemented by a five-element interferometric system whose design has been completed in 2007.

Key words. meteoroids, space debris, radar, speed measurements

1. Introduction

Accurate meteoroid and debris flux models are crucial for the design of space missions and the Earth's environment (Moussi et al. 2005). Analyses of material returned from space after prolonged exposure in LEO (Low Earth Orbits) and experiments in situ have widened our knowledge on millimeter- and micrometer-size particles of natural (meteoroids) and artificial (space debris) origin (Drolshagen 2001). For complete dynamical information it is essential to determine atmospheric speeds which for debris are on average from 7 to 10 km/s (as deduced from typical impact velocities in LEO) and for meteoroids, from 11 to 71 km/s (with an average around 17-20 km/s). If the atmospheric fluxes of meteoroid streams and background are well known, very little is known about the flux of space debris decaying into the atmosphere. It is felt that the meteoroid population has to be investigated in close connection with the space debris environment. Radar techniques, though able to detect smaller particle velocities, generally cannot achieve the same velocity accuracy as for photographic methods mainly utilized where

Send offprint requests to: G. Cevolani high precision heliocentric orbits are required. There are however many types of study where a limited accuracy of scalar speed may be sufficient, i.e. ablation coefficient, ionising efficiency and speed of formation of Fresnel zones using the echo amplitude fluctuations resulting from diffraction effects. Well formed oscillatory patterns are largely a result of the effects of body fragmentation, deceleration and train distortion due to atmospheric turbulence (Baggaley & Grant 2004).

2. The model equations: determination of speeds

Since 1995, the BLM (Bologna-Lecce-Modra) forward scatter (FS) radar system has been operating to study the atmosphere in the meteor region (70-120 km) and the physical/astronomical characteristics of meteoroids (Cevolani et al. 1995). The FS meteor radar utilizes a continuous wave transmitting frequency at 42.7 MHz and about 1 kw mean power and the transmitting station at Budrio (44.6°N) near Bologna and the receiving stations at Lecce (40.3°N) in Southern Italy and Modra (48.3°N) (Slovakia)(Fig. 1). Two distinct regimes exist in the detection of meteor trains by radar, these being the so-called underdense and overdense conditions. If the electron line density is sufficiently low ($q \leq 10^{14}$ el/m) the train is said to be underdense. A simple calculation of the peak received power from a typical FS echo indicates that most meteors with $q \geq 5x10^{12}$ el/m will be detected by the system, corresponding to m = 10^{-8} kg masses and $d = 100 - 200$ micron sizes.

In the case of a FS system (Fig. 2), one may observe considerably fainter and higher debris than in the case of a BS system. The total scattered field can be conveniently expressed in terms of Fresnel integrals C and S (Eq. 1) and the time variation of the scattering cross section of a plasma column can be described in terms of the generation of Fresnel intervals or the length of one-half of the first Fresnel zone, (f) (Baggaley et al. 1997). The center of the first Fresnel zone (the t_0 point) is at the point of tangency of the trail and an ellipsoid of revolution whose foci are at the transmitter and

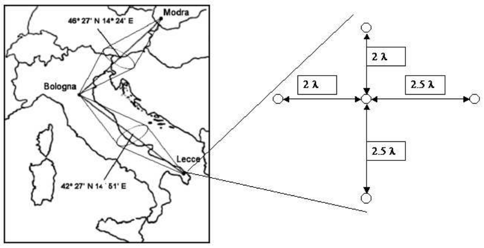

Fig. 1. The display of the BLM (Bologna-Lecce-Modra) radar system implemented by a radio-interferometer (to be installed in 2008 at the receiving station in Lecce), able to provide accurate speeds of meteoroids and space debris

receiver. The specular reflection in a FS system occurs at the t_0 point when the trail lies along a tangent to an ellipsoidal surface with the transmitter and the receiver stations in the foci. The condition is fulfilled at different distances of the reflecting point, but the system is most sensitive to trails which are nearly horizontal and directed along the transmission line (Hines et al. 1955). The choice of the reflecting point located closely to the middle of the transmission path (at the 'hotspots', i.e. zones of maximum concentrations of echoes) appears to be justified by observations.

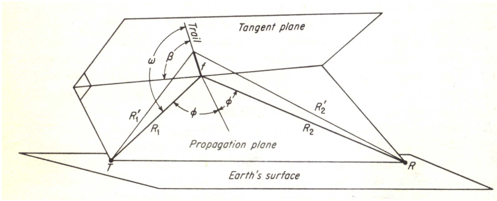

Fig. 2. The geometry of a forward scatter system (f: the length of one-half of the first Fresnel zone, zone of maximum reflection of the signal)

The received power P_r in the FS case is:

$$P_r \propto \frac{P_t \lambda^3 q^2}{R_1 R_2 (R_1 + R_2)} \frac{C_\omega^2 + S_\omega^2}{2} \quad (1)$$

where: P_t , the transmitted power; λ , the radar wavelength; q, the electron line density of the trail; R_1, the distance from the transmitter to the trail; R_2, the distance from the trail to the receiver; and

$$C_\omega = \int_{x_1}^{x} \cos \tfrac{\pi x^2}{2} dx \qquad S_\omega = \int_{x_1}^{x} \sin \tfrac{\pi x^2}{2} dx \tag{2}$$

are the conventional Fresnel integrals of optical diffraction theory. There is a convenient analogy between the generation of the echo in the radar case and the optical case of diffraction at a straight edge. As the body (meteoroid or debris) approaches the condition $x = 0$ (the t_0 point) there is a rapid increase of the signal power since an increasing number of half-period Fresnel intervals contribute to the reflected radiowave energy. The complex diffraction characteristics are very usefully described by a Cornu spiral (Fig. 3) with the Fresnel parameter x:

$$x = \frac{s}{f} \tag{3}$$

with s the physical distance traveled by the body and f:

$$f = \sqrt{\frac{\lambda R_1 R_2}{2(R_1+R_2)(1-\sin^2\varphi\cos^2\beta)}} = \frac{F(R_1,R_2)}{\sin\omega}$$
$$F(R_1,R_2) = \sqrt{\frac{\lambda R_1 R_2}{2(R_1+R_2)}} \tag{4}$$
$$\cos\omega = \cos\beta\sin\varphi$$

In the BS case is simply $f = \frac{(R_0\lambda)^{\frac{1}{2}}}{2}$.
The signal amplitude A in Fig. 3 b) is proportional to $(C^2+S^2)^{1/2}$ whose value is maximum (equal to 1.657) at $x = 1.217$.
The velocity of the body is:

$$V_i = \frac{\Delta s_i}{\Delta t_i} = \frac{\Delta x_i}{\Delta t_i}\frac{F(R_1,R_2)}{\sin\omega} \tag{5}$$

As the meteor approaches the condition $x = 0$ which is geometrically orthogonal in a BS system, there is a rapid increase of the signal power since an increasing number of half-period Fresnel intervals contribute to the reflected radiowave energy. To use the scattering cross section change prior to echo maximum, we require to quantify the magnitude of the amplitude increase over the Fresnel intervals prior to echo maximum. If n is the time measured in units of the pulse sampling interval τ, then normalizing the radar recorded echo amplitude A to the diffraction function, the body speed is in the FS case:

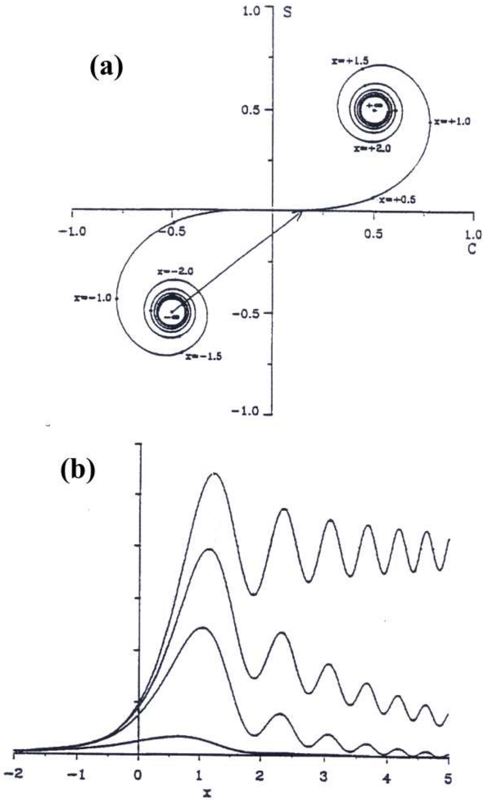

Fig. 3. (a) Cornu spiral representation as a function of the Fresnel integrals (C and S); (b) The Fresnel diffraction function representing echoes for cases of different diffusion rates (x = 0 designates the t_0 point))

$$V = \frac{1.657}{2\tau A_{\max}}\left(\frac{\Delta A}{\Delta n}\right)_{\max}\frac{F(R_1,R_2)}{\sin\omega} \tag{6}$$

Recently Baggaley and Grant (2004) obtained a reasonable estimate of the speed V_r (rise-time speed) in the BS case over the time interval from $1/e$ amplitude to echo maximum Δt given by (R_0 is the transmitter-trail distance):

$$V_r = \frac{1.35\sqrt{R_0\lambda}}{2\Delta t} \tag{7}$$

adapting the Eq. 7 to the FS case, we obtain:

$$V_r = \frac{1.35}{2\Delta t}\frac{F(R_1, R_2)}{\sin\omega} \tag{8}$$

3. Preliminary results

The FS transmitting and receiving antennas have an elevation angle $\alpha = 15°$ along the Bologna-Lecce direction and the effective collecting area of the system is about $6 \times 10^9 \mathrm{m}^2$ ($A_{\mathrm{eff}} = \pi \times 40 \times 50 \mathrm{~km}^2$).

Since the ionized trails are usually recorded in the height range of 60-140 km, only values of α equal to $10° - 25°$ are taken into account. This leads to mean values of the propagation angle $\phi = 65° - 80°$ and of $R_1 + R_2 = 710 - 760$ km. For typical values of $\beta = 45°$ we obtain values of $\frac{F(R_1,R_2)}{\sin\omega}$ very close to 1 (having the transmitting wavelength $\lambda = 7$m), see Tab. 1.

Table 1. Mean values of $F(R_1, R_2)$, $\sin(\omega)$, with $\omega \in \left[\frac{\pi}{2} - \phi, \frac{\pi}{2} + \phi\right]$ and the corresponding values of α (transmitting angle)

α	$F(R_1, R_2)$ (km)	$\sin(\omega)$	$F(R_1, R_2)/\sin(\omega)$ (km)
10°	0.78	0.69	1.13
15°	0.79	0.73	1.08
20°	0.80	0.75	1.07
25°	0.81	0.77	1.05

In the case of a backscatter (BS) radar the behaviour of rise-time speeds is quite consistent (Baggaley et al. 1997), confirming the method uncertainty as < 10%, whereas the uncertainty in each Fresnel speed is about $1 km/s$. Nevertheless, in our data only about 20% of records render a Fresnel speed, for the case where the diffraction pattern exhibited at least four Fresnel complete cycles. These oscillations can be suppressed by a number of factors, including fragmentation prior to, and during ablation, and rapid radial diffusion (which means the oscillations are rapidly damped out by decay of the amplitude of the returned signal). The rise-time speed technique also exploits the Fresnel amplitude time series but precisely utilizes the amplitude echo region up to and including the amplitude maximum. A parabolic fit is utilized to fix the position of maximum slope.

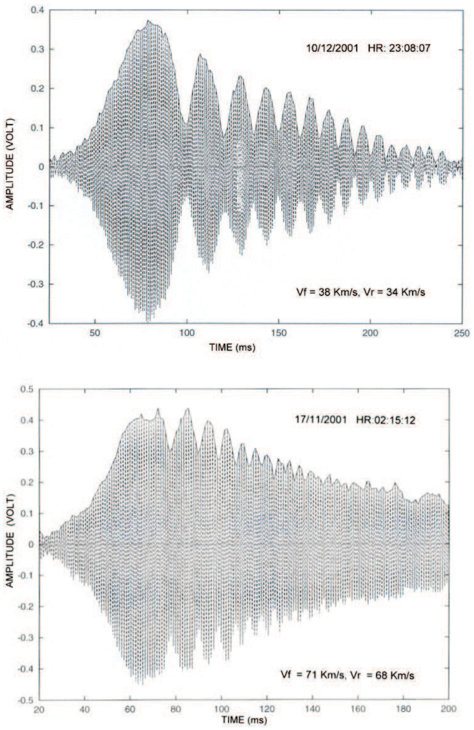

Fig. 4. Fresnel and rise-time speeds obtained for two radioechoes recorded by the BLM radar: (top) $V_f = 38$ km/s; $V_r = 34$ km/s (echo recorded on 10/12/2001, UT 23:08:07); (bottom) $V_f = 71$ km/s; $V_r = 68$ km/s (echo recorded on 17/11/2001, UT 02:15:12, probably associated to a Leonid meteor))

This is an interesting aspect since without knowing R_1, R_2 and ω, a random distribution of results should be expected. The Fresnel diffraction and rise-time methods can thus be useful not only to calculate the velocities but also investigate the characteristics of the experimental apparatus.

In Fig.4, two radioechoes exhibit the typical Fresnel figures. The Fresnel and rise-time methods furnish similar values of speeds for each echo: (top) $V_f = 38$ km/s; $V_r = 34$ km/s (a meteor recorded on 10/12/2001, UT 23:08:07); (bottom) $V_f = 71$ km/s; $V_r = 68$ km/s (a

Leonid meteor, recorded on 17/11/2001, UT 02:15:12)

4. Conclusions

Valuable rise time speeds can be obtained from the BLM radar utilizing the maximum gradients of the amplitude series up to peak amplitude echo measurements. In spite of distortion effects on the ionized trail and noise contaminating the echo profile, this technique is applicable to many more trails than the Fresnel oscillation technique, primarily due to its use of the echo amplitude preceding the peak, which is consistently identified in most trails. The rise time technique can typically make estimates of speeds that are good to an approximate uncertainty of 10 – 12%. To discriminate debris from meteoroids, speeds of even limited accuracy are welcome. Coupled with precision trajectory information, accurate velocities can be also deduced by the BLM radar facility implemented by a five-element interferometric system (to be installed at the Lecce receiving station in 2008), which consists of two orthogonal linear interferometers with a common central element (Fig.1). Test studies in 2007 have been carried out to perform ultimately the design of the interferometer to monitor the small space debris entering into the atmosphere. The ionization probability for collisional atoms of a small body entering into the atmosphere varies approximately as v^4 (Verniani 1974) and space debris are expected to reach their maximum ionization at lower altitudes because of their lower speeds.

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