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Plasma distributions in meteor head echoes and implications for radar cross section interpretation

Robert A. Marshall[a,*], Peter Brown[b,c], Sigrid Close[d]

[a] University of Colorado Boulder, Department of Aerospace Engineering Sciences, 1111 Engineering Drive, 431 UCB, Boulder, CO 80309, USA
[b] University of Western Ontario, Department of Physics and Astronomy, London, Ontario, Canada N6A 3K7
[c] Centre for Planetary Science and Exploration, University of Western Ontario, London, Ontario, Canada N6A 5B7
[d] Stanford University, Department of Aeronautics and Astronautics, 496 Lomita Mall, Stanford, CA 94305, USA

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ABSTRACT

The derivation of meteoroid masses from radar measurements requires conversion of the measured radar cross section (RCS) to meteoroid mass. Typically, this conversion passes first through an estimate of the meteor plasma density derived from the RCS. However, the conversion from RCS to meteor plasma density requires assumptions on the radial electron density distribution. We use simultaneous triple-frequency measurements of the RCS for 63 large meteor head echoes to derive estimates of the meteor plasma size and density using five different possible radial electron density distributions. By fitting these distributions to the observed meteor RCS values and estimating the goodness-of-fit, we determine that the best fit to the data is a $1/r^2$ plasma distribution, i.e. the electron density decays as $1/r^2$ from the center of the meteor plasma. Next, we use the derived plasma distributions to estimate the electron line density q for each meteor using each of the five distributions. We show that depending on the choice of distribution, the line density can vary by a factor of three or more. We thus argue that a best estimate for the radial plasma distribution in a meteor head echo is necessary in order to have any confidence in derived meteoroid masses.

1. Introduction

The problem of determining the meteoroid mass flux input to Earth's atmosphere has persisted for decades (von Zahn, 2005; Plane, 2012); two orders of magnitude separate the high and low ends of the commonly-cited estimates (Murad and Williams, 2002). These differences arise due to different observational methods, but also due to a large number of uncertainties in assumed model parameters for each method. This makes the accuracy of individual meteoroid mass estimates quite uncertain, a problem compounded for many techniques by the ubiquitous effects of meteoroid fragmentation (Ceplecha et al., 1998).

We focus herein on plasma and meteoroid mass estimates derived from meteor head echoes observed with meteor radars. These measurements arguably suffer less biases from the effects of meteoroid fragmentation, though such effects are present in some head echoes (Kero et al., 2008). Meteor head echoes are frequently detected by High-Power Large-Aperture (HPLA) radars, and radar cross sections (RCS) can be determined in certain scenarios. Head echoes are radar reflections from the immediate dense plasma cloud surrounding the ablating meteoroid and appear to move with the meteoroid. Lower-Power, Broad Beam (LPBB) radars, designed to detect meteor echoes through transverse scattering, can detect the radial scattering from head echoes when comparatively larger meteoroids occur in the beam (Baggaley, 2002). Such systems tend to detect head echoes at the rate of one per hour (in the case of the Southern Argentina Agile Meteor Radar for example (Janches et al., 2014)) as compared to several or more per minute or per second as is typical for narrow-beamed HPLA (Close et al., 2004).

However, for either type of system, because of the plasma nature of the meteor head, the relationship between the measured RCS and the meteor plasma parameters is not straightforward. Close et al. (2004) and others relate the meteor head RCS to the electron line density q in the meteor, and then relate the line density to the meteoroid mass from:

$$m = \int \frac{q v \mu}{\beta} dt \tag{1}$$

where the integration is taken over the duration of the meteor. Normally, the velocity v is measured, and the mean molecular mass μ is assumed. The ionization coefficient β is summarized by Campbell-Brown et al. (2012) as a function of velocity, but is also a function of composition. A reliable description of β is still a topic of active research, though recent laboratory measurements (Thomas et al., 2016) are in

* Corresponding author.

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general agreement with earlier theoretical estimates (Jones, 1997), providing some confidence that values are known to modest accuracy, notably at speeds >20 km/s. The line density q is thus left to be determined. In prior work (Close et al., 2002, 2004), the plasma radial distribution is assumed to be either Gaussian or Parabolic Exponential (defined later in this paper), and a direct relationship between q and RCS is thus provided. However, these assumptions at the core of the technique used to invert meteoroid masses from the plasma radial distribution are worth further observational validation, a process which requires multi-frequency simultaneous observations of head echoes.

In this paper, we use results of numerical simulations of meteor head echo plasma radar (radial) scattering together with triple frequency radar data to constrain the plasma distributions of these meteor head echoes. The results show that the estimate of the line density q used to derive meteoroid mass is more complicated than previously thought, and that multi-frequency measurements of RCS are necessary to provide a best estimate of the plasma distribution.

2. Meteor head echo data

We analyze meteor head echo data from the Canadian Meteor Orbit Radar (CMOR), a triple frequency transverse scattering radar located near London, Ontario, Canada (Jones et al., 2005). CMOR has three identical radars operating simultaneously at 17.45, 29.15, and 38.45 MHz. The broad, all-sky beam has a transmit beam width of 30° and a receive beamwidth of 45° to the 3 dB points. The total system directivity is 14 dBi, with interferometric precision of order 1° for signals more than 10 dB above the noise floor (Brown et al., 2008). CMOR detects 1–2 head echoes per day at 38 MHz to as much as 10 per day at 17 MHz. However, only of order one head echo per week has three frequency detection at high enough signal to noise (at least 6 dB above the noise floor) at all three frequencies for measurements to be feasible and shows no significant signal interference or pulsations associated with fragmentation [e.g., (Kero et al., 2008)]. A total of 63 meteor head echoes observed simultaneously on all three frequencies are used in this analysis covering the period May 2006–December 2007. Fig. 1 shows an example head echo range-time-intensity plot from one of these events detected by the CMOR 17.45 MHz system.

Measurements were made of peak returned head echo amplitude at a common range and time where the returned power was at maximum for the 17 MHz frequency. The power calibration procedure follows the methodology given in Weryk et al. (2013). The resulting radar cross-section for our backscatter radar systems were found using the standard radar equation (eg. Skolnik, 2001):

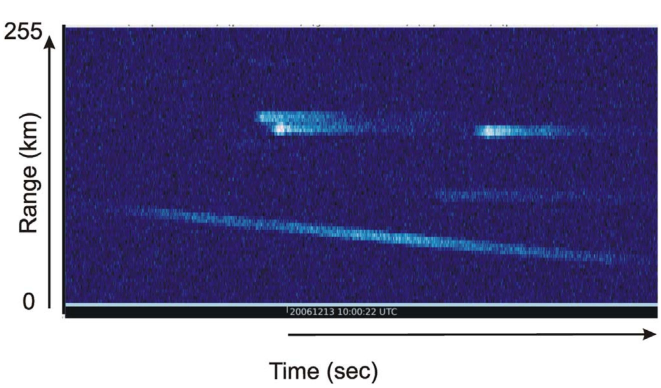

Fig. 1. An example of a head echo range (y-axis), time (x-axis), intensity (color coding) plot at 17 MHz. The horitzontal arrow along the time axis represents 1 s in time or 532 pulses. The horizontal lines at constant range represent transverse meteor echoes, while the sloping line running from a range of 96–54 km is a head echo. The individual echo returns have a range extent of approximately 12 km, equal to the width of the gaussian-tapered transmit pulse. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

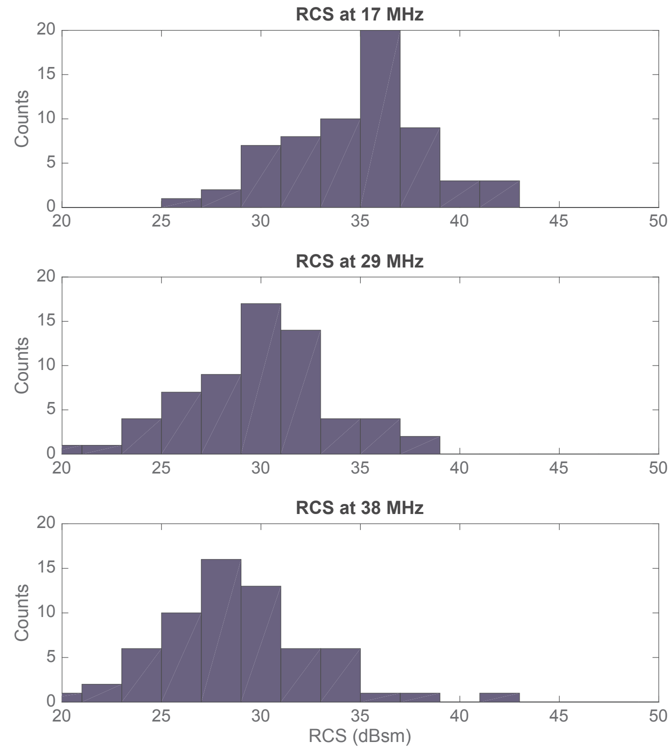

Fig. 2. RCS values derived from CMOR meteor head echo data at three frequencies. The shift to higher apparent RCS, in particular the minimal detectable RCS, at lower frequencies is in part due to the higher noise floor at 17 MHz than 38 MHz. This, in addition to wavelength dependent considerations, determines the final observed RCS distribution.

$$\sigma = \frac{(4\pi)^3 P_r R^4}{P_t G_t G_r \lambda^2} \tag{2}$$

where σ is the equivalent radar cross sectional area, P_r is the received power from the head echo, R is the range to the head echo, P_t is the transmitter peak power (in our cases these are all measured and ~6 kW), G_t and G_r are the transmit and receive gain in the direction of the echo and λ is the wavelength of the radar.

CMOR measures transmit power on a continual basis, with an accuracy of 5%, while the gain uncertainty is driven mainly by the uncertainty in interferometric direction, which is typically less than $2-3°$ for SNR >10, corresponding to a product accurate to 10%. The range is interpolated following the procedure in Weryk and Brown (2012) and based on direct comparison with simultaneous optical measurements is typically accurate to < 1 km, though in some cases this range error can be as large as 5–6 km for poor SNR echoes. It is worth noting that for this study the head echo ranges at 17, 29 and 38 MHz were estimated independently and the average deviations were < 0.3 km. The observed head echoes had very large RCS values compared to typical HPLA radar data, as expected for a LPBB system. Fig. 2 shows the peak RCS values for the 63 meteors analyzed here; some meteors show RCS above +40 dBsm at 17 MHz. As we will show, these high RCS values imply either very large meteor plasma radii or very high peak plasma density. If the meteor radius is related to the mean free path in the atmosphere, then it must be the case that the peak plasma density is high.

3. Numerical modeling

We use the Finite-Difference Time Domain (FDTD) meteor plasma scattering model of Marshall and Close (2015) to provide the relationship between meteor plasma distribution and RCS. The FDTD model simulates a broadband pulse scattering from an arbitrary meteor plasma