Modelling high-power large-aperture radar meteor trails

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Abstract

Despite decades of research, many questions remain about the global flux of meteoroids at Earth, their influence on the atmosphere, and their use as upper atmospheric diagnostics. We see high-power large-aperture (HPLA) radar observations of meteor phenomena called head echoes and non-specular trails as a valuable tool for answering these questions. In the past we conducted plasma simulations demonstrating that meteor trails are unstable to growth of Farley–Buneman gradient-drift (FBGD) waves that become turbulent and generate large B-field aligned irregularities (FAI). These FAI result in reflections called non-specular meteor trails. Using these and other results, we have developed a model that follows meteor evolution from ablation and ionization through the creation of radar head echoes and non-specular trail reflections. This paper presents results from this model, showing that we can reproduce many aspects of these large radar observations, such as the general altitude profile of head echoes and non-specular trails. Additionally we show that trail polarization due to E-fields or neutral winds causes a noticeable trail feature as well as may be responsible for trails lasting longer than about 1 s. We also demonstrate how such a model is a valuable tool for deriving meteoroid properties such as flux, mass, and velocity. Finally, such a model could also provide some composition information, and diagnose the atmosphere and ionosphere where meteors produce their trails.

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1. Introduction

Every day billions of meteoroids impact and disintegrate in the Earth’s atmosphere. Understanding this meteor flux is important for several fields of study from solar system evolution to imaging of gravity waves in the mesosphere. Yet, the basic properties of this global meteor flux, such as average mass, velocity, and chemical composition remain poorly constrained (Matthews et al., 2001; Cziczo et al., 2001). Many researchers study the physics and chemistry of meteor ablation but require better observational constraints to test their theories. Finally, several aeronomical phenomena and tools such as meteor radar, resonance Lidar, mesospheric airglow, polar mesospheric echoes, noctilucent clouds, and sporadic E, require meteor trails or their deposited metals or dust (Smith et al., 2000; Liu et al., 2002; Kelly and Gelinas, 2000; Rapp et al., 2003). Yet, researchers seldom separate a specific phenomenon’s inherent variability from changes in the input meteor flux. The modelling efforts presented in this paper are an attempt to better understand this meteor flux through observations of individual meteors using high power large aperture radars.

The remainder of this introduction describes some of the recent observational and theoretical advances made using large radars to study meteors. We then continue with the main focus of this paper, which is to present our
model of meteor evolution covering meteor entry from ablation and ionization, to plasma turbulence and complete diffusion.

2. New observations and interpretations

Over the past decade, scientists using tools such as high powered incoherent scatter radars and optical techniques made substantial progress in meteor research. These observations have prompted new simulations and theoretical developments that have resolved a number of longstanding issues. This paper incorporates some of these new theoretical developments into a model of meteor evolution and instability. The output of this model is simulated range–time–intensity (RTI) images of meteor reflection. Such a model allows us to better interpret radar observations and, as the remainder of this paper shows, has already been successful in reproducing many of the main characteristics of radar observations.

We begin by showing some of the observations we are interested in modeling. For this paper we present an example of ALTAIR observations of meteor reflections shown in Fig. 1. We chose this example because it has already been published by Close et al. (2002), and is one of the most detailed combined head-echo and non-specular trail observations that any contemporary radar is capable of making. For more information regarding the ALTAIR VHF and UHF radars see Close et al. (2000, 2002). (RTI) images such as displayed in Fig. 1 shows the tremendous amount of information contained within high power radar observations of meteors. These observations are far more complex than the comparatively simple low power observations of specular trails that require trail perpendicularity for reflection (for a review on such observations see Ceplecha et al. (1998)). High power radar meteor observations over the past decade have enabled researchers to explain a number of meteor features that were not previously understood. Modeling the physical processes underlying the phenomena shown in Fig. 1 is the focus of the meteor research presented here. The following paragraphs describe some of the general features of high power radar observations.

2.1. Head echoes

As a meteor enters the Earth’s atmosphere the particle heats up and atoms begin boiling off the surface in a process known as ablation. Depending on energy, the ablated particles are ionized upon collision with a neutral constituent, converting the tens of km/s linear velocity into a hot plasma (Jones, 1997). The ions thermalize after approximately 10 collisions, which takes between a tens of microseconds at 80km and as long as 1 ms at 110km (Jones, 1995). During this thermalization process the plasma density near the meteoroid could be very high allowing for overdense or scattering radar reflections. Researchers believe that a meteor head echo is the scatter of this dense plasma region that is continually regenerated at lower altitudes as the meteor descends. The result of these reflections appear as a diagonal line on RTI images as shown in Fig. 1. Recently many of the large radars, such as Jicamarca, ALTAIR, Arecibo, Millstone, MU, Sondrestrom and EISCAT have conducted studies of these head echoes (Close et al., 2000; Mathews et al., 1997; Chapin and Kudeki, 1994a; Zhou et al., 2001; Janches et al., 2000).

To demonstrate these processes we constructed a cartoon diagram of the various stages of meteor evolution as shown in Fig. 2. The first panel of this cartoon demonstrates this head echo stage, and this paper will refer to the various stages presented in this figure as they arise. Several papers have been written addressing the scattering mechanism from the hot meteor plasma which results in a head echo (Close et al., 2004; Pellinen-Wannberg, 2004), and references therein. This paper does not attempt to address the head echoes scattering mechanism in any sophisticated manner as is shown later, but focuses primarily on the physics of the non-specular trails.

2.2. Non-specular trails

Chapin and Kudeki (1994a) were the first to present observations and interpretation of non-specular trails that suggested plasma instability as the cause for radio reflection. These observations were coincident with electrojet backscatter and were interpreted as a two-stream or Farley-Buneman instability driven by the
The presence of the electrojet E-field. Oppenheim et al. (2000) used plasma simulations and theory to show that meteor trails are Farley–Buneman gradient–drift unstable and that the linear instability develops into turbulence without a strong external E-field. Recently, using the steerable MU radar, Zhou et al. (2001) demonstrated that non-specular trails were easily detectable when the radar pointed perpendicular to B, while none were detected pointing parallel to B. These results provide dramatic support for the idea that non-specular trails are radio scatter from FAI. Finally, Dyrud et al. (2002) showed that the ~20 ms delay between head echo and non-specular trail (shown in Fig. 1) results from a turbulent trail timescale. This paper also demonstrated that only a portion of the trail is unstable and that characteristics such as meteor velocity, and composition dictate the location of instability. These results allow researchers to use non-specular trails to further diagnose meteor properties in completely new ways. For example, Oppenheim et al. (2003) has already applied this technique to resolve a long-standing discrepancy between observations and theory of trail plasma column radius, and Dyrud et al. (2004) estimated meteoroid velocity using non-specular trail altitude profiles.

3. Large radar meteor simulations

We constructed a model of the evolution of an individual meteor from atmospheric entry to trail instability and diffusion. By making some assumptions about trail reflectivity, the results of this model are used to create artificial radar RTI images for direct comparison with data from facilities like ALTAIR. The next few paragraphs describe how the model is constructed, and continues with a comparison between radar data of head trail pairs and results from the model. These are illustrated in Fig. 3 which shows our attempt to model the observation shown in Fig. 1. We would like to note that we chose Fig. 1 to present as the modeling case, not because it was matched perfectly with model results, but because it is representative example. This figure shows that many, but not all, trail features are currently understood.

3.1. Modeling a head echo

To create the artificial radar measurement, we start with models of meteor ablation and ionization from Lebedinets et al. (1973) and Jones (1997) respectively. The Lebedinets set of equations is for micro-meteoroids which takes as input an initial meteoroid mass, $m$, density, $\delta$, composition, velocity, and inclination angle about zenith.

The momentum equation tracks meteor velocity, $v$, as a function of path-length, $s$,

$$\frac{dv}{ds} = \frac{\Gamma Apv}{\delta^{1/3} m^{1/3}}.$$
The next equation, conservation of mass, follows the change in meteor mass as a result of ablation, and sputtering,

\[
\frac{dm}{ds} = \frac{4AK_1m^{2/3}}{\delta^{2/3}vT^{1/2}} e^{-K_2/T} - \frac{\Lambda_SApmt^{2/3}v^2}{2Q^{2/3}}.
\]

The remaining equation describes meteor temperature, and includes frictional heating, radiation, and loss of energy to ablation and sputtering,

\[
\frac{dT}{ds} = \frac{4A\rho v^2}{8C0^{2/3}m^{1/3}} (\Lambda - \Lambda_S) + \frac{4A\sigma(T_\text{atmos}^4 - T^4)}{C\delta^{0/3}\mu m^{1/3}} - \frac{4AK_1Q}{C\delta^{2/3}T^{1/2}m^{1/3}v} e^{-K_2}. \tag{1}
\]

In these equations, \(\Gamma\) is the drag coefficient, \(A\) is the shape factor, \(\rho\) is the atmospheric mass density, \(K_1\) and \(K_2\) are constants describing the evaporation rate, \(T\) is the temperature, \(Q\) is the energy of evaporation, \(\Lambda\) is the heat transfer coefficient, \(\Lambda_S\) is the sputtering coefficient, \(\sigma\) is the Stefan–Boltzmann constant, and \(C\) is the heat capacity. We also used the same values for constants and coefficients as Lebedinets et al. (1973) with the exception of the heat capacity \(C\). We find that \(C = 2.0 \times 10^8\) erg g\(^{-1}\) K\(^{-1}\) yields more realistic temperatures and altitudes of ablation.

There are several assumptions used in this model that should be noted. The drag coefficient is 1.0 which assumes the free flow regime. Since the meteor particle of interest are much smaller than the mean free path, this is likely a fair assumption. The shape factor, \(A = 1.21\), assumes spherical objects. Finally, the entire analysis requires that meteor temperature is constant throughout the body, which is a reasonable assumption for any meteor smaller than about 1 g. This requirement should be easily satisfied since we are modeling meteors smaller than 1 mg, which are believed to comprise the large majority of meteors that hit the Earth. Finally, the loss of mass as a function of altitude can then be used to estimate the number of deposited meteor particles in the atmosphere, given an assumed average meteor particle mass. While ablation models yield the number of evaporated meteor particles per meter path length, two crucial steps remain before the plasma parameters can be tested for stability. One must first calculate the probability that an ablated meteor particle becomes ionized. Second, since newly ionized meteor particles are extremely hot, a model is required to approximate the kinetic trail expansion, as hot meteor ions and electrons cool and expand to form a thermalized column of plasma.

There has been a fairly limited amount of research on what is known as meteor plasma \(\beta\), which is the coefficient of probability that an ablated meteor particle becomes ionized. Jones (1997) reviews the theoretical estimates for \(\beta\) which have the following form, \(\beta = k_i(v - v_i)^2\). Where \(v_i\) is the minimum velocity of a meteoric species that can produce ionization, and \(k_i\) is a species dependent constant. An additional characterization of \(\beta\) also reviewed by Jones (1997), results from empirical comparisons between radar and optical measurements of meteor trails produced by meteoroids faster than 30 km/s, and has the following form, \(\beta = 4.91 \times 10^{-6} v^{2.25}\). These two forms differ by as much as an order of magnitude depending on velocity. While this large discrepancy in ionization probability may be somewhat important for the study of head echoes, it is rather unimportant for the interpretation of non-specular trails as shown by Oppenheim et al. (2003). The reasoning behind this argument was shown to be that the growth rate for meteor trail FBGD is large and relatively constant for any meteor trail with a peak density greater than 10–100 times that of the background ionospheric plasma. Given this result, and a case we make later, that the estimated area of the head echo accounts for a large portion of head echo SNR variability, we use the \(\beta = k_i(v - v_i)^2\) equation in our model and in the results presented here.

These simple physics–based models predict the deposition of meteoric neutral and ionized particles as a function of altitude given an initial meteoroid velocity and mass. We use the resulting line-density (electrons per meter along the meteor’s path) to estimate where the radar would measure a head echo (Close et al., 2002; Janches et al., 2000; Pellinen-Wannberg et al., 1998; Mathews et al., 1997). We make an additional crude approximation for the scattering strength of the head echo shown in Fig. 3. We originally used the electron line density as a proxy for head echoes, but to improve the model and yet keep it as simple as possible, we have included an estimate for the area of the radio scatterer in the model. We approximate head-echo strength as proportional to \(n_e\Gamma_i^2\) where \(\Gamma_i\) is the initial radius. The altitude and velocity dependent estimate of the meteor plasma expansion radius from Bronshten (1983), is \(\Gamma_i = 2.845 \times 10^{16} v^6/n_{\text{atmos}}^{2/3}\). Though more sophisticated models exist for the scattering strength of the head echo plasma such as that published by Close et al. (2004), we conducted a study of head echo SNR using observations from Millstone hill radar, (Erickson et al., 2001), to show that a predicted \(\Gamma_i^2\) accounted for all but 30% of the variability in head echo SNR (dB). We hope to expand this study and publish the results in the near future.
Next, we will model the evolution of the meteor trail as the hot meteoric electrons expand outward and cool into a thermalized distribution of plasma in a non-uniform column. The second panel of Fig. 2 depicts the endpoint of this stage while our model accomplishes this analytically by using the initial radius $r_i$ from Bronshten (1983).

### 3.2. Modeling non-specular trails

Now that we have modelled a meteor trail plasma column we can predict where such a trail will produce non-specular echoes based on a simple, but well tested assumption: meteor trails become Bragg reflective at altitudes where the trail is unstable to plasma waves and remain reflective until the trail diffuses to the extent that the plasma becomes stable and the waves die down (Dyrud et al., 2002, 2004). As discussed in these papers, the meteor trail FBGD instability differs from that derived for E-region applications in few important ways (Fejer et al., 1984). First, no approximations regarding the growth rate in comparison to the real frequency or ion collision frequency can be made and the full quadratic dispersion relation must be solved. Second, the diamagnetic drift can be as large as the trail $E \times B$ drift and must be included as part of the driving drift. We also note here that we use 2-D linear-local solution with kinetic ions (to calculate realistic growth rates and wave numbers due to landau damping) and mass-less fluid electrons.

The simulated non-specular trail shown in Fig. 3 is produced by continually testing a diffusing plasma column for stability. The model assumes that a radar is looking in the perpendicular to $B$ direction in order for reflection. While unstable we expect reflection from meteor trail FAI, and since diffusion rates in the E-region are so rapid ($10^5 - 50 \text{ m}^2 \text{s}^{-1}$), when no longer driven, we expect meteor trail density irregularities to diffuse away in much less than one second. Examination of Fig. 3 shows that the non-specular trail does not occur over the same altitude range as the head echo, a consequence of the idea that only a portion of the trail is unstable as demonstrated in Fig. 2 and discussed in Dyrud et al. (2002). The non-specular trail appears on the plot after a preprogrammed 20 ms delay, based upon the simulation results from Dyrud et al. (2002). The duration of the trail is dictated by the local diffusion coefficient. We use the parallel to $B$ diffusion coefficient for the E-region ionosphere as suggested by Dyrud et al. (2001). This paper showed that, despite trail orientation, instability driven anomalous diffusion causes trails to diffuse at the parallel rate in all directions, a feature confirmed by specular trail observations (Galligan et al., 2003). Using the parallel rate also reproduces the pattern of decreasing trail duration with increasing altitude, which is a common feature of non-specular trail observations (Dyrud et al., 2002; Zhou et al., 2001).

The meteor generating this head echo and non-specular trail had a known velocity of 63 km/s as calculated from the head echo range rate. Initializing the model with this velocity into generates a non-specular trail altitude span that matches the observed span to within about 2 km. Dyrud et al. (2004) discusses this altitude variation of non-specular meteor trails as a function of velocity. We could not, however, accurately reproduce the actual altitude of the observed trail with an iron dominated ion composition. Our model predicts that this trail, if composed principally of iron, would produce an echo beginning at 110 km, while the observed trail begins near 102.5 km. The model run shown here was produced using a lighter assumed trail ion weighing 22 amu. A lighter ion of 12 amu moves the top of the trail down to 102.5 km, but it is unlikely, but possible that a meteor trail would be composed of a mixture of $H^+$ and $O^+$ such as produced by a disassociated water trail or perhaps a multiply ionized plasma such as $mg^{++}$. Yet, this demonstrates the promise of combined head echo and trail modelling for using radars to actually sense the composition of deposited meteor particles. This may be the only technique available for measuring the composition of small meteors, since they neither generate sufficient light for spectral studies nor does any material reach the ground where it can be analyzed. Our model indicates that further theoretical work needs to be done before one can conclusively draw conclusions about meteor and meteoroid composition from non-specular trails.

By now the reader has noticed that while Fig. 3 produced many of the features shown in Fig. 1, such as the altitude span of the head echo and non-specular trail, a number of the features are not represented by the model. A feature that we are not able to model is the very flat-top nature of the observed trail. This is the only time we have seen such an observation, which is perhaps due to fragmentation at that altitude. Careful examination of Fig. 1 reveals that, except for the flat-top portion of the trail, the rest of the trail has the same round shape with altitude as modelled in Fig. 3. Two additional features are that the delay between the head echo and non-specular trail is constant with altitude except at the lower portion of the trail which shows a delay linearly increasing with decreasing altitude, and that the modelled trail lasts only about 0.2 s instead of the observed 0.4 s. This delay feature is seen in many non-specular trails, not only by ALTAIR but other radars as well such as Jicamarca (Chapin and Kudeki, 1994b). We have recently reproduced such a feature by including the effects of a background electric field or a neutral wind in our model.

Oppenheim et al. (2000) described the effects of a background field or wind on a meteor trail. A horizontal
wind blowing across a meteor trail will cause a trail polarization electric field that will bolster the trail ambipolar electric field and influence trail instability. Oppenheim et al. (2000) showed that the 1-D trail electric field perpendicular to the trail axis takes the following form:

\[ E = \frac{m_i}{e} \left( -\frac{\delta n}{n} v_i \frac{E_{\text{background}}}{B} + \frac{kT_i}{nm_i} \frac{\delta n}{\partial x} \right), \]

where the first term represents this polarization field and is proportional to the ion collision frequency, \( v_i \), the perturbed electron density, \( \delta n \equiv n - n_0 \), and \( E_{\text{background}} \). The second term is the ambipolar electric field resulting from the trail density gradient, where \( x \) is the direction perpendicular to the trail and \( E_{\text{background}} \). We point out that both the ion collision frequency and the peak density tend to increase with decreasing altitude, so this term becomes more important at lower altitudes.

Fig. 4 shows a simulated trail with the exact same conditions as 3 except with the inclusion of this polarization field resulting from a 20 m/s horizontal wind. This addition changes the predicted region of trail instability. We note here that the modelled \( \delta n \equiv n - n_0 \) begins near 10,000 and weakens during diffusion. Further, this drop in trail altitude creates an effective time delay between head and trail which increases as altitude decreases. This increasing delay is a commonly observed feature of head/trail pairs which we now believe is understood.

The reason a wind or E-field produces this feature is as follows. A gradient term in the meteor trail FBGD instability acts to damp the waves if the gradients are too steep, while the polarization field drives the instability at low altitudes. So after the gradients become weak enough, yet \( \delta n \) from the polarization term is still large enough, the lower portion of the trail becomes destabilized. This attribute of meteor trail stability is exciting indeed, and may, with further study, allow these types of observations to diagnose E-region electric fields and mesopause neutral winds. While such effects may complicate using non-specular trail altitude for composition studies as suggested above, these effects should be separable. Wind and E-fields should only influence the lower altitude of a non-specular trail, while meteor velocity and composition play a role in both the upper and lower altitude limits of non-specular meteor trails.

The inclusion of the effects of winds has made the trail last longer at most altitudes but too long between about 90 and 95 km. This extended portion of the trail is not seen in Fig. 1. There could be several reasons for this. While the main portion of the trail shown here has a peak growth rate for wavelengths at 10's of cm, the extended portion of Fig. 4 has a peak growth rate (not shown in this figure) at a few meters. Also, ALTAIR observes meteors located outside the electrojet and, therefore, we expect the polarization E-field in this region to be typically considerably lower than in the region measured by the Jicamarca radar. Additionally, the ALTAIR radar was pointed near 1° off perpendicular to B for these observations, which may indicate that this extended portion resulting from winds due to the change in wavelength may have a much different aspect sensitivity than the main part of the trail, which is primarily driven from the ambipolar field and diamagnetic drift of the trail. This interpretation is strengthened by observations of extended trails (longer than 1 s) by MU and Jicamarca observations, when these radars are pointed exactly perpendicular to B (Zhou et al., 2001; Chapin and Kudeki, 1994b).

4. Summary

Large radars give us a new tool for investigating meteor and E-region physics. By applying relatively simple theoretical models we can explain much of the observational data and we have made great strides in understanding this interaction as the model shown here demonstrates.

This model starts with ablation and ionization models to determine the characteristics of the plasma trail created by a given meteoroid. It then uses a simple analysis of plasma density and neutral atmospheric density to predict head echo reflection strength. Then our models apply the threshold criterion from a highly simplified linear meteor trail Farley–Buneman gradient-drift (FBGD) instability theory to predict where and when trails develop B-field aligned irregularities (FAI). These FAI result in the reflections called non-specular meteor trails. By combining these ideas we simulate

![Fig. 4. Simulated VHF head echo and non-specular trail for the meteor observation with same properties shown in Fig. 3 with the inclusion of a 20 m/s horizontal wind blowing across the trail.](image-url)
large-aperture radar observations of meteor evolution from head echo to non-specular trail reflections. This paper shows that this model reproduces many aspects of the radar observations, such as the general altitude profile of head echoes and non-specular trails, including a common, but until now unexplained, low-altitude delay between head and trial. We believe such a model may become a valuable tool for deriving meteoroid properties such as number, mass, velocity, and provide some composition information. Finally, because meteor ablation and instability depended on atmospheric properties such as winds, density, and temperature, head-echoes and non-specular trails may prove useful as remote atmosphere and ionosphere profilers.

References


