Polarization and scattering of a long-duration meteor trail

S. Close, 1 M. Kelley, 2 L. Vertatschitsch, 3 P. Colestock, 4 M. Oppenheim, 5 and J. Yee 1

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High-power, large-aperture (HPLA) radars have been used over the past two decades to characterize the plasmas formed both around and behind meteoroids as they enter Earth’s atmosphere. These plasmas, referred to as heads and trails, respectively, occur with relative frequency (peak head echo detection rate of ~1/s) but are extremely diverse and have been difficult to define in a general sense. One particular type of plasma, referred to as the nonspecular trail, occurs when the meteoroid travels quasi-parallel to the radar beam with the radar beam lying quasi-perpendicular to the background magnetic field. Reflection is believed to occur from field-aligned irregularities (FAIs) that form after the trail becomes unstable. While FAI scattering pertains to the majority of nonspecular trails that are short in duration, a subset of these trails, referred to as long-duration trails, still remains open to interpretation. In this paper we present a case study analysis of a long-duration, nonspecular trail and its associated head echo detected with the Advanced Research Project Agency (ARPA) Long-Range Tracking and Identification Radar (ALTAIR), which is an HPLA radar. These data are unique in that they are high resolution (with monopulse angles), dual frequency, and, most importantly, dual polarized, which allows for unprecedented insight into the scattering process from both heads and trails. First, we determine the velocity and mass of the parent meteoroid, which is a particle weighing more than a milligram and is one of the largest meteoroids ever detected by ALTAIR. Second, we determine the peak plasma density and polarization of the head echo and characterize the unique, yet strong returns in the opposite polarization, which may be due to multiple scattering centers within the range gate. Finally, we examine the polarization properties of the trail and discuss the first conclusive evidence of polarization flipping along the trail striations, which we believe corresponds to sharp gradients at the edges of the trail related to turbulent mixing of a dusty plasma that is elongating along the magnetic field. We look into a new idea, namely, the notion that some nonspecular echoes might correspond to a high Schmidt number, dusty plasma, as is found in and above noctilucent clouds. Our results show how polarized return can aid in scattering diagnostics and that single polarization radars must be used with caution for determining head and trail plasma densities given that some of the return can occur in the “unexpected” channel.


1. Introduction

When a meteoroid, defined as a small, solid extraterrestrial object, enters Earth’s atmosphere, it heats and ablates, emitting a large number of atoms at an altitude of between approximately 140 and 70 km. These ablated atoms subse-

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trails were done with low-power instruments [Sugar, 1963]. More recently, high-power, large-aperture (HPLA) radars, such as the Advanced Research Projects Agency (ARPA) Long-Range Tracking and Instrumentation Radar (ALTAIR), have been used to detect meteors. HPLAs observe meteors not typically seen by low-power instruments that often travel quasi-parallel to the radar beam; these include head echoes and nonspecular trails. Head echoes are the weak returns from the plasma immediately surrounding the meteoroid and moving at its velocity. Often, tens of milliseconds after the head echo vanishes, a more persistent echo returns from the nonspecular trail [Close et al., 2002]. These trails have also been referred to as range-spread echoes [Malhotra et al., 2008; Mathews et al., 2008], spread meteor echoes [Reddi et al., 2002], and turbulent trail echoes, and they typically endure for less than a few seconds. They have been detected using both HPLA radars [Chapin and Kudeki, 1994; Oppenheim et al., 2009] and, less frequently, low-power radars and are thought to result from Bragg scattering from field aligned irregularities (FAIs) in the trail [Heritage et al., 1962]; detection results from the growth of plasma instabilities. The time sequence associated with this process was summarized by Oppenheim et al. [2000], who showed that an ambipolar $E$ field (perpendicular to both the geomagnetic field and the trail) first develops, followed by a growth of plasma concentration waves on the edges of the trail that arise from the gradient drift/Farley Buneman instability and then, finally, plasma turbulence. This turbulence breaks the trail into multiple segments, which form FAIs that radars detect as nonspecular trails. Therefore, to observe this type of trail, the radar beam must lie close to perpendicular to the background magnetic field [Dyrud et al., 2001] but may be as far as 12° from perpendicular and still return strong signals [Dyrud et al., 2002; Zhou et al., 2004; Close et al., 2008]. Indeed Malhotra and Mathews [2009] and Mathews [2004] explain observations of range-spread trail echoes by invoking the pointing direction, whereby if two radars see the exact same trail, the duration and signal strength depends solely on the aspect sensitivity with respect to the radar bore site. While this explanation supports the majority of nonspecular trail detections, there are cases where the radar is not pointing anywhere near perpendicular to $B$ yet detects what appears to be a nonspecular trail with a long duration (more than a few seconds).

[5] McKinley and Millman [1949] were the first to observe four spectacular meteor trail echoes of the long-duration, nonspecular type. These trails were detected near Ottawa, Canada (45°N), and hence could not be due to FAIs, given the angle of the radar beam with the background magnetic field; that is, they were not due to plasma instabilities. In addition, Kelley [2004] reported a 5 min long echo over Poker Flat, Alaska, which also could not have come from FAI scattering. Remarkably, this same meteor trail was penetrated by an instrumented sounding rocket. The characteristics of the electron density spectrum in this trail and the fall speed of the echoing region suggest that this echoing region was a dusty plasma with a high Schmidt number, $Sc = v/D$, where $v$ is the viscosity coefficient and $D$ is the ambipolar diffusion coefficient in the dusty medium. High-Schmidt-number scatter is now accepted as the source of the enormous radar cross section (RCS) of the region [Cho and Kelley, 1993; Rapp and Luebken, 2004; Li et al., 2010] at and above the noctilucent cloud zone; these echoes are referred to as polar mesospheric summer echoes (PMSEs). However, an alternative explanation for the large RCS could be the thin metallic coating on the ice grains [Bellan, 2008], thereby removing the need to invoke a dusty plasma scenario, although a comment questioning this hypothesis was published by Rapp and Luebken [2009].

[6] Still, some long-duration trails may result from FAI scattering, as reported by Dyrud et al. [2007]. Dyrud and co-workers examined a trail detected by Jicamarca that lasted for over 4 min, with a characteristic “trail tail” showing decreasing altitude as time progresses. By applying an external electric field with a large (milligram) meteoroid, they reproduced the long-duration trail observed by Jicamarca without invoking a dusty plasma scenario. A trail tail may also be evidence of sedimentation as the dusty particles “settle” into the plasma medium.

[7] The two competing theories posed by Kelley [2004] and Dyrud et al. [2007] to explain their respective long-duration trails appear valid for their particular observations. However, as shown here, these theories do not fully describe all of the long-duration trails observed by various HPLA radars. In particular, ALTAIR observed what might be the longest duration, high-resolution meteor trail recorded to date. This long-duration trail has few similarities to the trails observed by Kelley or Dyrud et al. and cannot be fully described by either theory; it also may be similar in nature to the “radar bolide” event reported by Mathews and Malhotra [2010]. In particular, while the ALTAIR long-duration trail was observed perpendicular to the background magnetic field (unlike the trails observed by Kelley), it shows no trail tail (unlike the trails observed by Dyrud et al.) and, instead, contains dramatic striations that change in polarization. It is clear that no single theory to date can explain the diversity associated with long-duration trails, yet clues to the scattering mechanism may lie in new observations: namely, the dual-frequency, dual-polarized return of very high resolution data that currently only ALTAIR can provide.

[8] In this paper we provide a case study of a nonspecular, long-duration trail, detected by ALTAIR simultaneously at 160 and 422 MHz, with a strong return in both the right-circular (RC) and the left-circular (LC) polarizations. We use the high-resolution, polarized returns to help diagnose the scattering mechanism by comparing the theories put forth by Kelley [2004] and Dyrud et al. [2007]. Sections 1.1 and 1.2 describe the instrumentation and observation descriptions, respectively. Section 2 discusses the properties of the parent meteoroid and head echo. Section 3 reports the properties of the long-duration trail, including the role of a dusty plasma in providing nonspecular, non-FAI-related scatter. Section 4 summarizes and concludes.

1.1 Instrumentation
~7° at VHF and ~2.8° at UHF. ALTAIR receives both RC and LC energy and has four additional receiving horns for the purpose of angle measurement (both azimuth and elevation), which gives the position of an object in three dimensions by inclusion of its range and, hence, the three-dimensional (3-D) velocity and deceleration as well. ALTAIR is routinely calibrated for both signature (RCS) and metric (range, angles) data. In particular, ALTAIR tracks standard calibration spheres and will allow the spheres to trace out the ALTAIR beam pattern to calibrate the LC and RC signals as a function of position within the beam. This is an active calibration procedure that should eliminate polarized returns that depend on beam position, however, we cannot exclude that some residual anomalies remain. In summary, the in-phase and quadrature components are recorded for each of the four channels (LC, RC, AZ, EL) simultaneously at both VHF and UHF, providing 16 separate channels that may be used for diagnostics.

1.2. Observations

[9] Radar meteor data were collected at ALTAIR on 18 November 1998 during a 4 h period with fixed pointing in 2 min segments. ALTAIR showed a peak detection rate of 1.6 VHF head echoes per second during the time period of the Leonid shower; however, as previously reported [Close et al., 2002], the vast majority of these detections originated from the North Apex source and were classified as “sporadic.”

[10] Amplitude and phase data were recorded for each frequency and four receiving channels for altitudes spanning 70 to 140 km at VHF and 90 to 110 km at UHF. The beam width and the range sampling correspond to a total collecting area of 1502 km² at VHF and 58 km³ at UHF. The two ALTAIR waveforms used to collect the data were a 40 μs VHF chirped pulse (30 m range resolution) and a 150 μs UHF chirped pulse (7.5 m range resolution). We chose a linear-frequency-modulated chirped pulse to enhance our range resolution without sacrificing sensitivity. A matched filter was applied postdetection to down-sample the data streams with a 50 Hz pulse-repetition frequency, or 0.02 s interpulse period. Pulse-to-pulse Doppler processing was not pursued because the pulse-repetition frequency and the ALTAIR wavelength of approximately 2 m (VHF) and 0.7 m (UHF) give an unambiguous velocity interval of 0.048 km/s and 0.018 km/s, respectively. Using these waveforms, ALTAIR has a sensitivity of 64 and 81 dB at VHF and UHF, respectively, for a single pulse on a 1 m² target at 100 km range.

[11] For the nonspecular trail data, we computed the mean noise (at both LC and RC) in each 1 s interval for the full altitude extent at VHF and UHF. We then converted the raw amplitude and phase data to power and divided the entire 1 s data interval by the noise power. To correlate with the parent head echo (with speeds >11 km/s), we also corrected for range-Doppler coupling, which is a property of a chirp-type pulse and causes an offset in the apparent range of the echo.

2. Characterization of the Parent Head Echo and Meteoroid

[12] The head echo and long-duration trail were first detected at 21:22:58 GMT, or approximately 9:23 AM local time. The angle between the ALTAIR bore site and the background magnetic field was 89.9°, or approximately perpendicular to B. These data were collected simultaneously at VHF and UHF in both the LC and the RC channels and are shown in Figures 1 and 2, respectively. Note that the altitude shown in the images was computed by using the measured range at each point or pixel with the elevation of the ALTAIR radar beam. These altitudes do not include the monopulse elevation offset, since each point in the image will have a different monopulse elevation (and hence different altitude). Both the LC and the RC images are further segmented to help visualize the temporal evolution of the trail. We show 0.5 through 2 s (note the extended y axis in order to visualize the entire head echo) (Figures 1a and 2a), we present 0.5 through 10 s (Figures 1b and 2b), we show 0.5 through 50 s (Figures 1c and 2c), and we show 0.5 through 160 s (the entire trail) (Figures 1d and 2d). The head echo is first detected approximately 0.6 s into this data file and extends both above and below the altitude of trail formation, with the long-duration trail maintaining a constant altitude, unlike the trail tail observed by Dyrud et al. [2007]. The head echo traces out the VHF (and UHF) beam pattern exactly, confirmed by the monopulse data. Also visible in these images is what appears to be a specular trail formed at 86 km, which is visible in both LC and RC. Prior to the specular trail that formed between approximately 1.6 and 1.8 s, we see a slight slope to the signal between 1.38 and 1.58 s in LC, and 1.44 to 1.54 s in RC. This corresponds to quasi head echo scattering, meaning that the meteoroid is traveling perpendicular to the beam at this point but has not entered the first Fresnel zone. This type of scattering is a combination of higher-order Fresnel scattering and head echo scattering described by Close et al. [2004]. These types of echoes, while uncommon, are present in HPLA data sets and have been largely ignored, but may be an indication of fragmentation or a “terminal event” [Mathews and Malhotra, 2010]. Future work will focus on understanding this phenomenon. For the purposes of this case study, however, we believe that the presence of a specular trail occurring simultaneously with the long-duration trail, but at a lower altitude, is coincidental. However, we cannot exclude that these events are correlated. Finally, unlike for most nonspecular trails detected by ALTAIR [Close et al., 2008], we did not observe a time delay between the head echo and the trail. This time delay, initially described by Dyrud et al. [2001], is the time for the onset of turbulence that allows the radar to Bragg scatter at half the radar wavelength, but may be influenced as the plasma drifts into and out of the k-perpendicular-B direction. Although a lack of a time delay can be explained by invoking multiple scatterers, it immediately suggests that this trail exhibits atypical nonspecular trail properties. The head echo and parent meteoroid, which we believe shows a large fragmentation event, are described in this section.

2.1. Frequency Dependence and Meteoroid Mass

[13] Using data collected within the first second, including only head echo returns, the maximum VHF LC signal is 44.9 dB, while the maximum UHF LC signal is 33.7 dB at VHF. This 11 dB difference between UHF and VHF is similar to what we found for many head echoes in a previous study [Close et al., 2008]. The monopulse data indicate that the
maximum SNR of the signal occurs approximately at the center of each beam, with the peak UHF signal occurring 0.08 s and lower in altitude than the VHF signal. This is consistent with the scattering theory described by Close et al. [2004]. The head echo, however, shows strong return across multiple range gates at any one instant in time. For a single target contained within a range gate, we should observe one clear peak at each point in time with a shape that corresponds approximately to a sinc function (or Hanning window), which arises from application of the matched filter. In these images it is apparent that there are numerous “targets” (i.e., a distributed plasma) contained within the sinc function. This is illustrated in Figure 3a and the slice at 0.98 s in time is shown in Figure 3b. What is perhaps most telling is that there are two distinct peaks in Figure 3b. If we examine the monopulse offset, we find that the strongest signal (i.e., not noise) in the monopulse (both azimuth and elevation) occurs between the two peaks. This indicates that for distributed targets, the monopulse, which is a form of amplitude comparison and compares the signal strength in the various feed horns, must be used with caution but can be used as an added return for understanding the plasma distribution.

[14] The maximum head echo range rate corresponds to 65.1 km/s. The monopulse data show that this head echo traveled at an angle of approximately 10° from ALTAIR’s bore site. The 3-D velocity at the first detected altitude is 67.4 km/s, with a small deceleration (Figure 4a); we also determine that the head echo is traveling approximately 80° with respect to B.

[15] The mass of this meteoroid can be estimated either by using the SNR with a scattering theory [Close et al., 2004] or by assuming single-body ablation and calculating the ballistic parameter from the velocity and deceleration. A note of caution: While the scattering theory is largely immune to the effects of fragmentation and depends only on the total signal strength within a range gate, the single-body ablation model (i.e., the ballistic parameter) is only valid if we conserve momentum between the air molecule and one meteoroid. Since we believe this is a fragmenting event, we choose only to use the scattering theory to derive the mass. The

Figure 1. Head echo and nonspecular trail from an unusually long-duration tail collected at VHF in left circularity (LC) showing (a) 0.5 through 2 s, (b) 0.5 through 10 s, (c) 0.5 through 50 s, and (d) 0.5 through 160.
maximum LC RCS of the head echo was −5.2 dBsm (decibels relative to a square meter) at VHF and −39.2 dBsm at UHF, occurring at approximately 102 km altitude. The maximum RC RCS of the head echo was −7.2 dBsm at VHF and −41.4 dBsm at UHF. These data are plotted in Figure 4b. Combining both LC and RC returns, the maximum total RCS is −3.1 dBsm at VHF and −37.1 dBsm at UHF. This is the highest RCS of any head echo detected by ALTAIR to date and shows extremely large RC returns as well. For consistency with previous work, we use only the LC RCS in the spherical scattering theory developed by Close et al. [2004] to derive a peak plasma density of $4.0 \times 10^{15}$ el/m$^3$; this is considered overdense, meaning that the plasma frequency is much larger than the radar frequency. We can then estimate the meteoroid mass by assuming an ionization probability and mean molecular mass with the calculated plasma density. This method gives a maximum meteoroid mass of $4 \times 10^{-3}$ g. For comparison, the ballistic parameter method gives a ballistic mass of $6.9 \times 10^{-6}$ g (for a density of 3 g/cm$^3$) and $6.2 \times 10^{-3}$ g (for a density of 0.1 g/cm$^3$). Additional error in this ballistic mass exists because it requires an accurate deceleration, and this one derives from the second derivative of the fit to the range rate, a value with a substantial error. The typical particle detected by ALTAIR has a mass of approximately 10 μm; this particle is therefore one of the largest detected by ALTAIR during this collection period. Dyrud et al. [2007] noted that a large particle (milligram) is needed, in addition to an external electric field, to produce the long-duration trail observed at Jicamarca. However, as shown in Figures 1 and 2, the trail observed by ALTAIR shows no trail tail as verified through the monopulse (i.e., angle) data.

2.2. Polarization Properties

Beginning from detection through 101.5 km, the VHF RCS peaks of the RC and LC signals appear to occur at the same relative time, with drops and peaks in LC coinciding with drops and peaks in RC, as shown in Figure 4b. Additionally, the VHF LC signal is stronger than the RC signal by only a few decibels relative to a square meter throughout the majority of this period, which is not consistent with scattering from a simple sphere. Beginning at 99 km the RC signal starts to dominate over the LC signal.
To explore further the polarization characteristics of the head, we plot the in-phase (I) and quadrature (Q) components of the head separately for both the VHF (Figure 5) and the UHF (Figure 6), which are, by definition, 90° out of phase with respect to each other. The VHF shows a striking feature: both the in-phase and the quadrature components of the LC and RC signals show an oscillatory behavior, with the LC and RC trending at the highest altitudes until 108 km, at which point the in-phase LC and RC components become exactly "out of phase" with each other. This pattern continues until the end of the trail, when it appears to begin to track again. The VHF quadrature components also match until approximately 110 km, at which point the LC and RC also become out of phase. The UHF, however, shows no such pattern in either the in-phase or the quadrature signals. This most likely indicates that the total path lengths of the RC and LC waves differ by an integral multiple of wavelength, which may point to internal reflection within the trail. The fact the UHF shows no such behavior could indicate either that the 1.9 m wavelength at VHF is an integral into the spacing of the scattering centers within the trail or, alternatively, that Faraday rotation, which has a much bigger effect on VHF, is manifesting within this very dense, long-duration trail.

Both the range-resolved data and the scattering behavior in RC and LC suggest multiple scatterers both within the radar range gate and in many range gates at one time, which is distinct from most head echoes. We believe that this is attributable to multiple meteoroid particles forming distinct plasma scattering centers at any one instant in time. Recent modeling results developed by L. Vertatschitsch (L. Vertatschitsch et al., Meteoroid head echo polarization features studied by numerical electromagnetics modeling, submitted to Journal of Geophysical Research, 2011) show that one reason for interesting polarization features could be attributed to fragmenting, or multiple plasma targets within a range gate [Mathews et al., 2010]. The model uses NEC-2, the Numerical Electromagnetics Code developed at Lawrence Livermore Laboratory. The program is freely distributed and uses the method of moments to solve for electromagnetic

Figure 3. (a) VHF LC data shown in Figure 2a zoomed to show an atypical head echo feature of multiple peaks at one instant in time. (b) The same data showing a slice at 0.98 s in time.

Figure 4. (a) Three-dimensional velocity (in km/s) and deceleration in (km/s²) as a function of altitude from a polynomial fit to the range rate and monopulse data. (b) LC and RC radar cross section (RCS; in dBsm) of the VHF and associated UHF data of the head echo.

Figure 5. VHF head echo in-phase and quadrature components of the LC and RC signal.
scattering problems whose geometry is made up of free space and wire or surface patches of perfect conducting material. This program is powerful and robust and serves the simplifications we have made to the meteoroid scattering problem well. We design a conducting sphere out of patches, much like looking at the globe with the latitude and longitude grid. This sphere represents the critical layer of plasma, the point where the plasma surrounding the meteoroid becomes so dense that scatter from our radar wave reflects like it is hitting a conductor. For meteoroids where this assumption holds, we can use the NEC-2 code to observe the scattering characteristics. We propagate a plane wave with RC electric field polarization and track the total power returned in both RC and LC polarization in the backscatter direction. From there, we add a second scatterer to simulate a fragmentation event where there are two meteoroids. When these scatterers are close enough, the model shows that we can observe RC polarization due to the wave propagation between the particles being strong enough to contribute to the total backscatter. The model can be generalized to multibody scatter and multisized scatter, can model phase, and can also show the monopulse channels as ALTAIR defines them.

[19] On the basis of the two-body fragmentation model already referenced, we can investigate the in-phase and quadrature VHF and UHF features seen. We understand that as two particles and their surrounding plasma drift apart, the geometry of their position relative to each other and relative to the radar bore site affects the phase in both the LC and the RC radar return. The LC phase, characterized by the in-phase and quadrature components of the received voltage, changes based on the displacement (in terms of number of wavelengths) between the two particles along the radar bore site. For the opposite polarization return the RC channel phase is affected by how many wavelengths fit between the two scatterers. A simple study, shown in Figures 7 and 8, displays the model results from a multiple-scattering event detected at both VHF and UHF. Two scatterers are drifting apart at a rate of 66 m/s and a 45° angle from the bore site. Figure 7 shows that as the particles begin close together (higher altitude), the in-phase and quadrature components vary together. As the particles drift farther apart (lower altitude), the in-phase and quadrature measurements begin to vary opposite each other. Figure 8 shows a UHF detection of the same fragmentation. We see the opposite trend in this particular streak: as the scatterers drift farther apart, we note that the in-phase and quadrature components begin to vary together. In a real event if the fragmented meteoroid passed through the main beam of the radar, picking out a piece of the modeled streak, we could easily see variation in the in-phase and quadrature streaks that match the streak described previously. The two-body scattering model, however, sug-

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Figure 6. UHF head echo in-phase and quadrature components of the LC and RC signal.

Figure 7. Modeled VHF head echo in-phase and quadrature components of the LC and RC signal.
suggests that the RC voltage levels should remain well below the LC levels for small particles. To achieve a magnitude similar to that shown in Figures 5 and 6, we would need a scatterer very large compared to the radar wavelength, reinforcing the large size estimates of the meteoroid, since the size of the meteoroid (in addition to the velocity and altitude of formation) correlates strongly with the size of the plasma [Close et al., 2004]. This simply modeled streak demonstrates that fragmentation, which is, in reality, limitless in its geometric complexity, could explain the phase results.

3. Characterization of the Long-Duration Trail

[20] We next examine the properties of the long-duration trail, including the polarization properties, frequency dependence, and scattering. Our goal is to test the two competing theories, namely, dusty trails and FAI scattering, to explain the long-duration trail shown in this paper.

3.1. Frequency Dependence

[21] The UHF trail is almost undetectable, as shown in Figure 9a (LC) and Figure 9b (RC), even though it is clearly still within the main beam of the UHF system. The wavelength dependence for the trail for the VHF and UHF LC returns using SNR \( \sim \lambda^x \) is \( x = 6.5 \). The much stronger wavelength dependence for the trail relative to the head was first shown by Close et al. [2004] and is consistent with results shown herein. Note that, again, while we used the bore-site elevation of the radar to compute altitude, we did not include the monopulse elevation, which would change the altitude scale at each point.

3.2. Polarization Properties

[22] The returns from this trail show a strong signal in both LC and RC, as noted earlier. Figure 10 shows two versions of the polarization ratio. In Figure 10a we plot the LC over the RC (i.e., polarization ratio), and in Figure 10b we show what is in effect the horizontal (\( x \)) over the vertical (\( y \)). In Figure 10a the return is dominated by RC in the first 10 s after the head echo forms. This is consistent across an entire slice in time. As time progresses the trail begins to form striations, with the polarization ratio becoming progressively more LC along a striation as time progresses and the altitude increases (though this altitude has not been corrected for monopulse). Figure 10b shows a similar dominance of the vertical (\( y \)) component in the first seconds after the meteoroid begins to ablate. Here the polarization ratio does not change along any one striation but instead shows a trend such that the trail shows more horizontal return (\( x \)) as the altitude decreases.

[23] Two obvious reasons for the polarized returns include (1) modification of the RF wave owing to the wave frequency, width of the plasma layer, collision frequency, or electron density (i.e., different cutoff frequencies) and (2) geometrical considerations, including multiple scatterers and elongation along a particular direction. We treat each of these separately.

[24] First, we consider polarization transformation due to variations in the trail plasma for a single-slab model. To convert the polarization from LC to RC, we need polarization-sensitive reflection coefficients, or

\[
\frac{|E_{\text{RC}}|}{|E_{\text{LC}}|} = \frac{\Gamma_O - \Gamma_X}{\Gamma_O + \Gamma_X},
\]

where \( \Gamma \) is the reflection coefficient for the \( O \) and \( X \) modes and \( E \) is the electric field for the RC and LC waves. Magnetization can cause mode splitting, so that the reflection coefficients are asymmetric. We want to estimate the rel-
The phase shift experienced by the $X$ or $O$ modes is just

$$\Delta \phi_{O} = 2 \frac{\omega}{c} \int_{0}^{x_{0}} \sqrt{1 - \frac{x}{x_{L}}} \left( \frac{\omega_{pe}x_{L}}{\omega} \right)^{2} dx = \frac{4\omega_{x}x_{L}}{3c} \left( 1 - \frac{\omega_{pe}}{\omega} \right)^{3/2}. \tag{5}$$

where $x_{0} = \frac{\omega_{pe}x_{L}}{\omega} = 1 - \frac{x}{x_{L}}$. Combining these results, we find for the overdense case (where the plasma frequency exceeds the radar frequency)

$$\Delta \phi_{O} - \Delta \phi_{X} = \frac{2\omega_{pe}x_{L}}{c}. \tag{6}$$

For a single-slab model, we can get a small amount of RC only because we are far above the cyclotron frequency and the $X$-$O$ modes are almost identical: thus there is little asymmetry. In reality, we can achieve nearly equal RC and LC only if we are radiating very close to the plasma frequency. Collisions do not help because we need to have the frequency close to the cyclotron frequency for collisional effects to have significant polarization dependence. If, however, we have a periodic array of thin, underdense slabs, there will be narrow stopbands; near the edges of these bands we can get any phase shift that we would like, given enough layers and the right spacing. A striated plasma, for instance, can provide multiple reflections, which enhances the asymmetry. This configuration may provide an RC enhanced by as much as a factor of 5 to 1. This may explain the primarily RC return in the seconds immediately after the trail forms.

[25] Second, we consider that the explanation for the curious polarization features pertains to geometrical considerations, including multiple scatterers and elongation. With regard to multiple scatterers, if the incoming wave reflects twice off of a perfect conductor, the wave will transition from RC to LC, and back to RC before being received. With regard to elongation, an object that is large compared to a wavelength in all directions (e.g., a flat plate or a sphere) will flip an RC wave to LC. If, however, the object is elongated in one particular direction, such as a wire or a line, then the radar will see equal parts LC and RC. To diagnose the polarized trail for a geometrical explanation, we can examine the monopulse, which provides the elevation and azimuth as a function of altitude and time at each point. We apply the monopulse to the detected range to convert this to an $x$-$y$-$z$ coordinate system, which is shown in Figures 11a and 11b. Figures 11a and 11b show the trail positions at 20 s color-coded for altitude and the absolute elevation off bore site, respectively, as if looking straight down the radar’s bore site. The bore site and magnetic field crossings ($k$-$B$ crossings) are also included in $5^\circ$ increments, with the dashed black line being the perpendicular intersection between the bore site and the magnetic field. In
Figure 11a the altitude follows a general trend of decreasing as the position moves from the positive \(x-y\) quadrant to the negative \(x-y\) quadrant, with no general trend as the trail moves toward the center of the radar from any direction. Additionally, points with similar altitudes seem to spread out along the \(k-B\) crossings, positive and negative \(x\), as the trail moves across the beam. In Figure 11b the absolute elevation off bore site decreases as the trail approaches the center of the beam from any direction. Since both images are plotted for the same time, the conclusion can be drawn that, even if the altitude is continually decreasing, the elevation off bore site can be either increasing or decreasing. Therefore, even though earlier plots show the elevation off bore site following an increasing altitude contour, the actual altitude of the trail should not be mistaken to also be increasing. Note that the scales for the \(x\) and \(y\) axes are far too large to be within the physical radar beam at these altitudes. These large values are due to the trail diffusing across the different lobes of the beam and necessitating a more complex correction analysis of the phase wrap, which has been left for future work. Nevertheless, there is clearly a large geometric correlation between the geometric properties of the trail at any one point in time and the polarization structure along a striation. In the immediate times after passage of the meteoroid, the trail has a high density, with multiple reflections within a range gate. This corresponds to a high RC signal. As the trail diffuses and becomes more beam centered, the typical reflection scenario of a primarily LC return emerges as a more “line-like” reflection takes place.

### 3.3. Scattering

#### 3.3.1. Field-Aligned Irregularity Scattering

[26] This is the longest trail ever measured with an HPLA radar that also finely resolves the head echo. The richness of this data set provides a number of clues to the underlying physics. The weak but existent UHF signal indicates that a cascade process drives waves’ energy down to 36 cm in size; however, note that it is not necessary to invoke FAI scattering if we do indeed have an inhomogeneous plasma with discontinuities arising from fragmentation [Malhotra et al., 2008]. The total power appears to fall off faster than \(f^{-2}\) and, as noted earlier, is much closer to \(f^{-6}\) [Close et al., 2008], unlike scattering from PMSE, which, in the limit of very large Schmidt numbers, is closer to \(f^{-3}\).
Assuming that the streaks extending from 25 to 170 s in Figures 1 and 2 are localized turbulent plasmas, we can determine their velocities. The lower set of streaks travels at 27 m/s. Since the radar has an ∼3° elevation angle, this would imply a Y horizontal velocity or some combination of vertical and horizontal velocities. These are plausible wind velocities given our understanding of neutral dynamics at these altitudes.

The difficult question about these trails is the following: What sustains plasma density irregularities with 0.9 m and 36 cm wavelengths for over a minute, as is necessary to create these trail reflections? Typical non-specular trails disappear within a few seconds and the longest trails vanish within 30 s. The collisional mean free path at 100 km is of the order of 15 cm and climbs rapidly with altitude, meaning that one expects 0.9 m and 36 cm structures to dissipate quickly. The most abundant source of free energy, which could maintain these irregularities against the homogenizing influence of diffusion, derives from the steep density gradients on the edge of the trail, as it does for shorter trails. However, unlike for shorter trails, this trail persists long enough for chemical processes to become important. We know that ozone can play a role at lower altitudes (below 95 km) after about 2 s. Also, dust can begin forming within a few seconds [Saunders et al., 2007]. It is possible, although not definitive, that this dust can help sustain short wavelength irregularities. Also, these trails show this odd, streak-like behavior, indicating localized regions of turbulent plasma surrounded by quiet plasma, possibly analogous to the persistent trails with gaps in them reported by Kelley and Makela [2001].

3.3.2. Dusty Trail Scattering

The event studied in this paper is certainly unique, although not unprecedented. Comparison with the four McKinley [1961] long-duration echoes shows that FAI scattering was responsible. In the next paragraphs we review this type of scatter and the role of meteor trail reflections. The most abundant source of free energy, which could maintain these irregularities against the homogenizing influence of diffusion, derives from the steep density gradients on the edge of the trail, as it does for shorter trails. However, unlike for shorter trails, this trail persists long enough for chemical processes to become important. We know that ozone can play a role at lower altitudes (below 95 km) after about 2 s. Also, dust can begin forming within a few seconds [Saunders et al., 2007]. It is possible, although not definitive, that this dust can help sustain short wavelength irregularities. Also, these trails show this odd, streak-like behavior, indicating localized regions of turbulent plasma surrounded by quiet plasma, possibly analogous to the persistent trails with gaps in them reported by Kelley and Makela [2001].

In the presence of charged dust or ice particles, the ambipolar diffusion coefficient is reduced drastically [Verniani, 1969; Cho and Kelley, 1993; Rapp and Luebken, 2003; Li et al., 2010]. We believe the dimensionless Schmidt number is increased by factors of up to several thousand. In such a medium the viscous subrange in turbulence theory is replaced by a viscous-convective subrange, which pushes the inner scale to wave numbers over an order of magnitude larger than the Kolmogorov microscale. The concept that the spectrum of a passive scalar mixed by turbulence could be far different from the driving medium was first proposed by Batchelor [1959] and is a well-established theory [Tennekes and Lumley, 1972]. First applied to PMSE by Kelley et al. [1987], the idea is by now well established [Bellan, 2008; Genge, 2008; Rapp et al., 2010]. The cross section at VHF can be 70 dB higher in the polar summer than in any other season of latitude.

Rosinski and Snow [1961] showed that ablating meteoroid material can coalesce into smoke and dust particles at the nanometer scale, forming Earth’s dust layer. In the polar summer these particles grow to 50 nm by accumulating an ice layer. This size is large enough to cause lidar Mie scatter and UHF radar scatter [Röttger et al., 1990; von Cassart et al., 1999; Nicolis et al., 2009; Varney et al., 2009]. Large meteor showers can produce large particles, as confirmed by visual observation of forward scatter from meteor trails and the rocket penetration already mentioned. Both of these observations indicate particles greater than 10 nm in radius immediately after the impact. The long-duration echo reported here was most likely created by a particle greater than 1 mg, as noted earlier.

We turn now to the curious polarization observations to diagnose the scattering. The striated nature of the echo provides a clue. These indicate that the target is very structured, possibly by a combination of gravity waves and anisotropic turbulence. If a striated region of dusty plasma is interrogated by an RC wave, it can be considered as a superposition of two linearly polarized waves. When such a wave interacts with a localized quasi-line of dusty ionization, it will scatter a signal that is linearly polarized; the signal can then be written as a superposition of circularly polarized waves. Upon reception, one or both RC and LC waves will be received. As noted earlier the monopulse data both support the curious polarization returns and suggest a possible dust trail scatter.

4. Summary and Conclusion

We have investigated the properties of a long-duration meteor using the dual-frequency, dual-polarization waveforms transmitted by ALTAIR. The trail was formed by a fast-moving large (~1 mg) meteoroid traveling nearly parallel to ALTAIR’s bore site. Both the head echo and the trail shows curious polarization features. In particular, the head echo shows nearly equal SNRs in both the LC and the RC channels, with a multipeak signal across many range gates. Both of these findings are inconsistent with the majority of head echo returns, though they are not entirely unique. The trail extends for over 160 s, which is distinctive in and of itself; however, it also shows strong returns in both LC and RC as well. We believe that the head echo may be exhibiting multiple scattering within a range gate, which is supported by the model presented here. This would manifest as strong returns in both polarization channels. Additionally, we believe that the trail may have a strong dust component and also show multiple scatterers within a range gate, manifesting as a strong RC. As the trail expands and diffuses, a particular striation becomes aligned with the background magnetic field, returning the polarization to a typical scenario of primarily LC return. Nevertheless, FAI scattering may still be responsible if we invoke a strong enough background electric field, but the field must be relatively localized spatially and temporally, again, given the unique nature of this trail among the many detected by ALTAIR during the time period.

Our future work will include examining the polarization ratios of non-specular trails using a more extensive data set and determining diffusion coefficients for all of our trails, both specular and non-specular.

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