Multi-static, common volume radar observations of meteors at Jicamarca

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[1] Multi-static, common volume radar (MSCVR) observations have long been considered necessary for meteor observations, especially for the study of Range Spread Trail Echoes (RSTE). We present preliminary results - in the form of a case study - from the first MSCVR observations that were carried out at the Jicamarca Radar Observatory (JRO) in June 2007. A second antenna array, of similar sensitivity to a single JRO receive module, was constructed and operated at Carapongo, approximately 5 kilometers geomagnetically south of JRO. The JRO main array was used for transmission. Receiving was done using sub-arrays at JRO and with the array at Carapongo. The results provide new insights not only into the aspect sensitivity of RSTEs but also into the physical structure of the plasma giving rise to these echoes. These observations also establish a firmer basis for the modeling of the plasma processes that cause meteor trails to become field-aligned.
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1. Introduction

[2] Meteor observations using HPLA (High Power Large Aperture) radars emerged in the early 1990s as a powerful new tool providing valuable insights into the radio science of head and trail echoes, including RSTEs (see *Mathews* [2004] for review) in a field that was dominated predominantly by the study of specular or classical meteor echoes (see *Ceplecha et al.* [1998] for review). RSTEs, also known as non-specular echoes, have been observed since the 1940s but an exact explanation for the formation of these echoes has remained elusive. Two possible theories were put forward initially to explain the formation of these echoes - the ''Glint theory'' and the ''Blob Theory'' [*McKinley*, 1961]. The glint theory assumes that wind shear distorts the initially smooth and continuous trail in such a way that many points in the trail become perpendicular to the radar beam, thus forming various Fresnel scattering regions. The blob theory assumes that ionization is not created smoothly and continuously along the trail. It proposed that the line concentration of ionization varies along the trail, thus forming many scattering centers. RSTEs came back into prominence after their observation by *Chapin and Kudeki* [1994] using the Jicamarca radar. *Oppenheim et al.* [2000] proposed that Farley-Buneman/Gradient Drift (FBGD) instabilities can develop due to a meteor trail's self-generated ambipolar electric field and the polarization electric field present in the background ionosphere. *Dyrud et al.* [2001] showed that meteor trails are inherently unstable and the presence of external polarization E fields are not necessary for the formation of RSTEs. *Zhou et al.* [2001] showed that Field Aligned Irregularity [FAI] scattering—observed when the radar is pointed nearly perpendicular to the geomagnetic field—is necessary for the observation of these echoes. *Mathews* [2004] provided an in-depth modeling study of radio science issues concerning RSTEs.

[3] Most of the RSTEs observed with VHF radars last from a few milliseconds to less than 5 seconds. However, ever since the 1940s, a few RSTEs have been observed to last from over 15 seconds to as long as 15 minutes. Long-lived RSTEs have remained a subject of speculation and study ever since. *Malhotra et al.* [2007], based on statistical analysis of radar meteor data collected from the JRO 50 MHz radar, classified all meteor echoes over 15 seconds as long duration echoes and showed that an overwhelming majority of these long duration meteor echoes were obtained from scatterers located in the $\mathbf{k}\perp\mathbf{B}$ ($\mathbf{k}$ = radar wave vector, $\mathbf{B}$ = magnetic field) region of the radar (the $\mathbf{k}\perp\mathbf{B}$ locus±1 Fresnel zone at 100 km altitude) whereas the shorter duration RSTEs were found to occur from throughout the illuminated volume [*Malhotra et al.*, 2007, Figure 2]. This result implies that the initial irregularity structures in the meteor trails exhibit a wide scattering pattern and, given sufficient radar sensitivity, can be seen from anywhere in the radar beam whereas once the trail components significantly align along $\mathbf{B}$, they can be detected only within the $\mathbf{k}\perp\mathbf{B}$ region of the radar. This conclusion has far reaching implications to current interpretations of instability development in RSTEs as the location of the meteoroid trajectory relative to the narrow $\mathbf{k}\perp\mathbf{B}$ region strongly determines the observed RSTE properties such as onset time relative to the head-echo and trail lifetimes as functions of altitude. *Malhotra et al.* [2007] hypothesized that two identical, closely spaced, common-volume radars would observe the same RSTE event differently. That is, trail lifetimes, head-trail onset delay and trail structures are a function of the viewing geometry along the meteoroid trajectory. This is the subject of this paper.

[4] Figure 1 shows schematically that for two radars placed close to each other and looking at a common volume, a RSTE occurring at the $\mathbf{k}\perp\mathbf{B}$ region of one of radars (Radar 1) might be seen as a long duration event from that radar and a short duration event from the other radar (Radar 2) as it lies away from its $\mathbf{k}\perp\mathbf{B}$ region. This conclusion has important implications as current modeling

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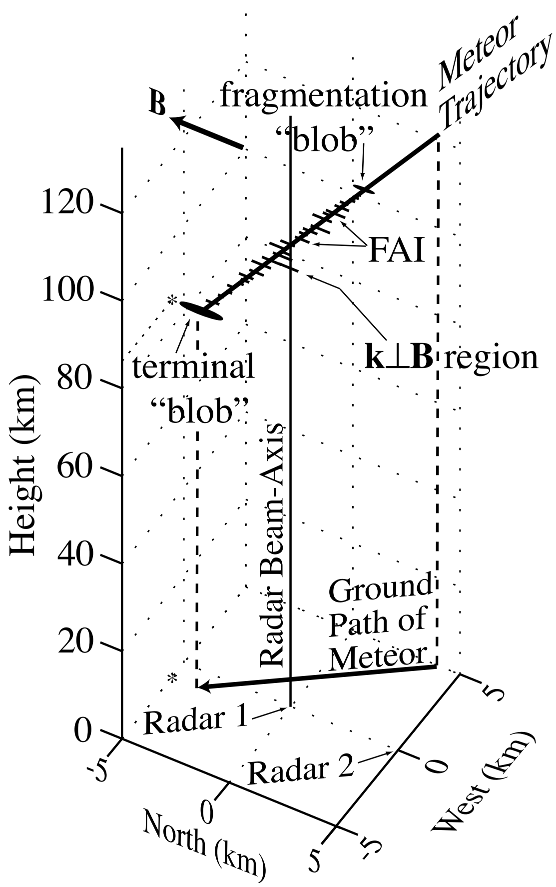

Figure 1. A RSTE occurring at the **k⊥B** region of Radar 1 might be seen as a long duration event from Radar 1 and a small duration event from Radar 2 as it lies away from its **k⊥B** region.

studies make extensive use of these observed radar parameters such as head-trail onset delay to understand and interpret trail instabilities. To test this hypothesis, we constructed another antenna array at Carapongo, ~5 km from JRO, to obtain a multi-static radar view of meteor events in the common volume of this radar system. In section 2 we present the experiment configuration. Our observations are presented in section 3. The results are discussed in section 4 and a summary of our investigations along with the future scope of study is provided in section 5. We would like to emphasize that these are the first-ever MSCVR observations of RSTEs. In order to fully determine and comprehend the physical significance of these new results, we present in this paper a case study of a few events that occurred in a short time “window” and that show some highly interesting features. A statistical analysis of our observations will be the subject of future papers.

2. Experimental Set-Up

[5] The results presented herein all derive from 14 June 2007 multi-static observations using the JRO 50 MHz VHF radar along with the Carapongo receive array. Transmission was done using the north quarter of the Jicamarca array while the signal was received at both the Jicamarca and Carapongo arrays. The JRO main array is centered at 11°57′05.18″ S, 76°52′27.43″ W and 507 m altitude. The Carapongo array was located at 11°59′56.51″S, 76°52′15.09″ W and 443 m altitude. These co-ordinates were obtained using GPS and Google Earth software. The horizontal separation of the two arrays was 5.27 km with the Carapongo array located 3.86° East of geographic south of JRO. The JRO antenna beam was pointed perpendicular to the geomagnetic field at JRO, at an angle of approximately 1.6° to the north-northwest from the vertical. The locus of points where the radar wave vector (**k**) is perpendicular to the Earth’s magnetic field (**B**) within ±1 Fresnel zones (a Fresnel zone is $\sqrt{R\lambda/2} \sim 550$ m at R = 100 km for 50 MHz Jicamarca radar) is denoted as the **k⊥B** region. The unique presence of the highly aspect sensitive Equatorial Electrojet (EEJ) scattering allows the **k⊥B** locus to be easily identified [*Kudeki and Farley*, 1989]. A 2 μs pulse with an inter-pulse period (IPP) of 1 ms was used, thus providing a range resolution of 300 m. In reception, three sub-arrays (1/64th) of the main antenna, each separated by a distance of six wavelengths, were used for our interferometric analysis. The 8 × 4 (4-element-dual linear polarization) Yagi antenna array located at Carapongo was so designed that it has very nearly the same sensitivity as one receiving module of the Jicamarca array. Theoretically, there should be at the most a 2dB gain difference between the two arrays. The Carapongo array was pointed vertically with ~10° beamwidth. A meteor event observed at the **k⊥B** region of the Jicamarca radar would be observed from Carapongo at an angle of ~85° w.r.t the magnetic field.

3. Observations

[6] In this section, we present the initial results from the first ever MSCVR observations of RSTEs. Figures 2a and 2b show RTI (Range-Time-Intensity) plots of long duration events and several short duration events observed from both JRO and Carapongo. The insets show the head-echo and the onset of the longest duration event. Various Figures 2a and 2b features common to both observing sites are labeled 1–4 in Figures 2a, 2b, 2c and 2d. We chose these long duration events as they show many interesting features as we go on to discuss later. The trail component occurring at 93–95 km (labeled 1) lasts for well over 40 seconds as seen in Figure 2a, thus we classify it as a long duration event per discussions by *Malhotra et al.* [2007]. Figure 2b shows the same events observed from Carapongo. The Carapongo trail (labeled 1) corresponding to the long duration RSTE at JRO (at 93–95 km) is seen to last for just over 15 seconds. Another trail component (labeled 2), just below 90 km altitude, is seen to last for almost the same duration (around 25 seconds) at both JRO and Carapongo. This RSTE component will be discussed in detail later.

[7] Figures 2a and 2b also show another meteor event (labeled 3), at 12 seconds and approximately 100 km, which lasts for around 20 seconds when observed from Jicamarca (Figure 2a) and only for ~ 4 seconds when observed from Carapongo (Figure 2b). This event is striking in that the apparent development of aspect sensitivity of the scattering is even faster (Note that diffusion is faster and so is instability development at higher altitudes) than for lower

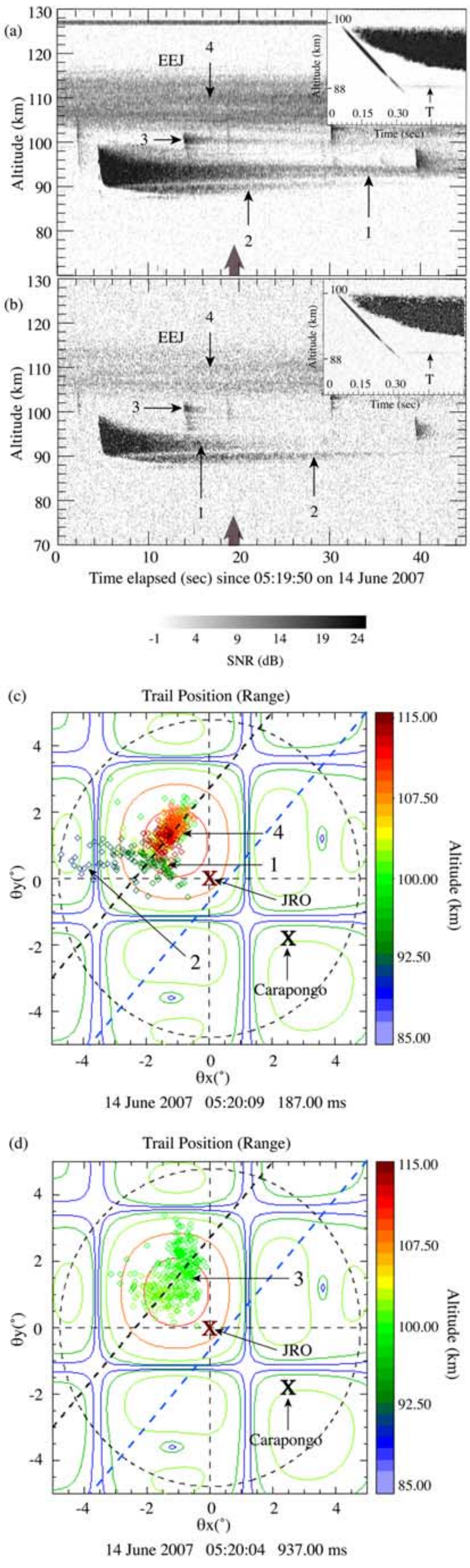

Figure 2. (a) RTI (Range-Time-Intensity) plot of long duration meteor echoes at JRO. The meteor trail labeled 1 lasts for well over 40 seconds. (b) RTI plot of the same event as observed from Carapongo. The corresponding long duration part of the trail (again labeled 1) lasts for just over 15 seconds. Also notice a lower altitude long duration trail at 90 km (labeled 2) lasting for approximately the same duration at both Jicamarca and Carapongo. The EEJ (labeled 4) can also be seen at altitudes 106–114 kms. Also note that event 3 is viewed as long duration at JRO and short duration at Carapongo. High resolution plots of the head echo are provided in Figure 2a (inset) Jicamarca and Figure 2b (inset) Carapongo. Here a faint return (labeled T) is associated with the ''terminal'' destruction of the meteoroid. Note also the different head-trail onset delay at JRO and Carapongo. (c, d) Position of the Figure 2a RSTE features with respect to range as observed from Jicamarca. The black dashed line represents the **k**⊥**B** region of the Jicamarca radar whereas the blue dashed line represents the **k**⊥**B** region of the bistatic system (Jicamarca and Carapongo). (1), (2), and (3) indicate the position of the trails labeled (1), (2), and (3) in Figure 2a respectively. (4) indicates the position of the highly aspect sensitive Equatorial Electro Jet (EEJ). It can be clearly seen that both the long duration trails at Jicamarca originate from the **k**⊥**B** region of Jicamarca.

altitude ''large'' event. It should also be noted that the highly aspect sensitive EEJ (labeled 4), observed at heights 104–116 km at both Jicamarca and Carapongo, is observed to be much stronger at Jicamarca (Figure 2a) than at Carapongo (Figure2b) due to the Jicamarca transmitting pattern being centered on the Jicamarca **k**⊥**B** region and having a first null near the bistatic **k**⊥**B** region (indicated in Figures 2c and 2d).

[8] Figures 2c and 2d show the interferometric positions of the RSTE components identified in Figures 2a and 2b. Event labels in Figures 2c and 2d correspond to those in Figures 2a and 2b. The positions of the scatterers were calculated using the interferometric technique introduced by *Farley et al.* [1981]. In Figures 2c and 2d the black dashed line represents the **k**⊥**B** region at 100 km for the Jicamarca radar and the blue dashed line represents the **k**⊥**B** region for the bistatic system (Jicamarca and Carapongo) at 100 km. The dotted circle, indicating the region within which the unambiguous meteor position can be calculated, has a radius of ∼8.36 km. The transmission beam pattern is also plotted with the red contour showing a transmitted level of up to −10 dB. In Figure 2c, the red points (labeled 4), representing comparatively the highest altitudes (see scales), correspond to the position of the scatterers responsible for the highly aspect sensitive EEJ. The green points (labeled 1) correspond to the position of the long duration meteor trail at Jicamarca observed at 93–95 km. In Figures 2c and 2d, one can clearly see that the scatterers responsible for the two long duration trails (labeled 1 and 3) lie exclusively along the **k**⊥**B** region of JRO but as noted from Figure 2b, these scatterers are observed to be highly aspect sensitive—resulting in shorter durations—when viewed from Carapongo. The viewing angle from the 100 km **k**⊥**B** region of

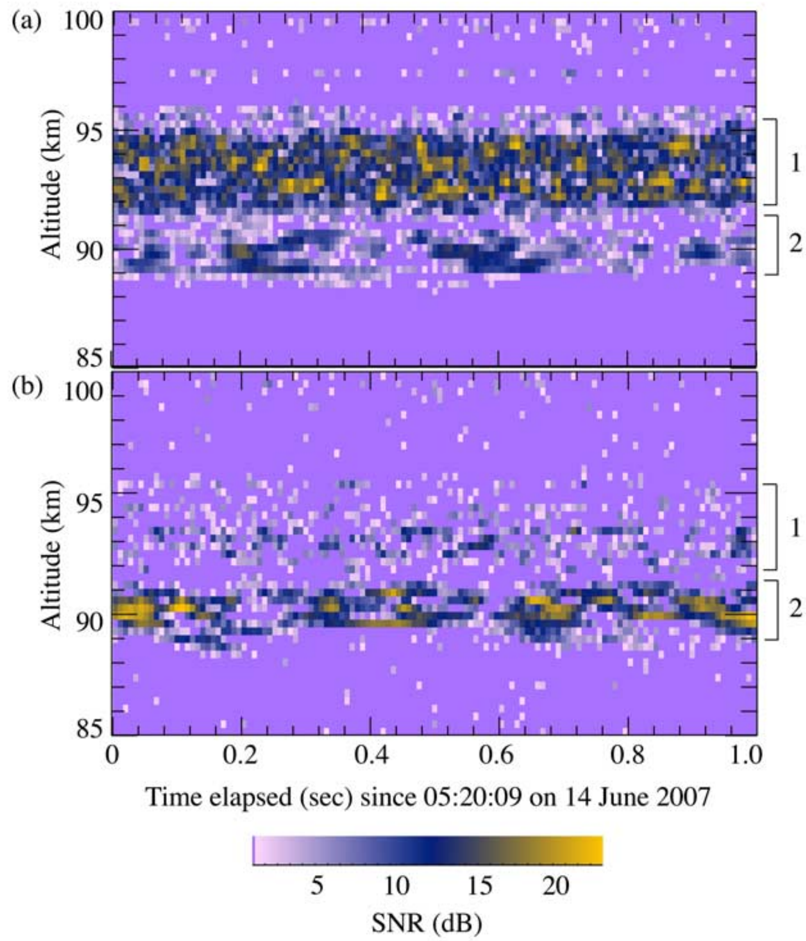

Figure 3. High-resolution RTI plot of a part of a trail for the meteor echo shown in Figure 2 at the time indicated by the arrow on the time axis, as observed from the (a) Jicamarca radar and (b) Carapongo radar. The difference in the structure of the upper long duration trail (93–95 km) and the lower-altitude long duration trail (90 km) can be clearly seen in the Jicamarca radar. The lower-altitude long duration is seen to be comprised of small blobs from both the radars.

JRO to Carapongo is 4.6°. The event component labeled 2 will be discussed in the context of the Figure 3 results.

4. Discussion

[9] *Malhotra et al.* [2007] hypothesized that if there were two identical radars placed very close to each other looking at a common volume, a RSTE occurring at the **k**⊥**B** region of one of the radars might be seen as a long duration event from that radar (provided the radar has sufficient sensitivity) and a short duration event from the other radar. Figures 2a and 2b give strong support to this hypothesis using the JRO/Carapongo multi-static radar system as we present a case study of two RSTE events occurring in the **k**⊥**B** region of JRO (Figures 2c and 2d) seen as a long duration events in Jicamarca (Figure 2a; events 1 and 3) and as short duration events at Carapongo (Figure 2b; events 1 and 3). As we noted earlier, there also exists a second long duration RSTE component—labeled 2—at ~90 km that is observed to have approximately the same duration at both Jicamarca and Carapongo. At 90 km altitude the viewing angle from the JRO **k**⊥**B** locus to Carapongo is ~5.1°. One might expect this trail to be located in both the JRO and bistatic **k**⊥**B** regions of the radars (dashed black and blue lines respectively) for this long duration trail to be seen as having about the same duration at both Jicamarca and Carapongo. But as shown in Figure 2c, this trail component (labeled 2) occurs far away from the bistatic **k**⊥**B** region of the radar and is ~2 km from the Jicamarca **k**⊥**B** region. Then the question arises why do we observe this trail as a long duration trail when it is clearly away from either the JRO or bistatic **k**⊥**B** regions and moreover, why is this long duration trail observed to be of almost equal duration from both Jicamarca and Carapongo. We answer these questions this with the help of Figure 3. Figure 3 is a high resolution, unaveraged RTI plot of a small portion of the same event showing the upper and lower long duration trails labeled 1 and 2 to correspond to the Figure 2 features. The time frame of the Figure 3 display is indicated by the thick arrow on the Figure 2 time axes. It can be clearly seen that the lower altitude long duration trail (labeled 2), which is observed to be of almost equal duration at both Jicamarca and Carapongo, is different in character from the upper RSTE (labeled 1). Specifically, the lower RSTE (2) appears to be comprised of a few (relative to the upper RSTE), slowly evolving, scattering centers that yield the observed "blobs".

The "blob-like" nature of these few scattering centers would clearly yield a wide scattering pattern resulting in lower aspect sensitivity for these "blobs". The low aspect sensitivity makes it possible to observe this trail for about the same duration at both Jicamarca and Carapongo even though it does not lie at the **k**⊥**B** region of either JRO or Carapongo. *Malhotra et al.* [2007] in their statistical analysis of long duration echoes using the same JRO main array also reported two long duration trails that were observed away from the **k**⊥**B** region of the radar. They noted that these trails were both low altitude trails (at ∼90 km) and commented that this might suggest a different mechanism for formation/and or evolution of RSTEs at lower altitudes. We note that this trail too occurs at a similar low altitude. *Dyrud et al.* [2002, 2005] report that FBGD instabilities in meteor trails develop within a limited altitude range, confining these trails within an altitude range of 95–105 km—but this RSTE, along with those referred to above from *Malhotra et al.* [2007]—is observed at an altitude of ∼90 km. This suggests a different formation and/or evolution mechanism for the trail plasma irregularities at these altitudes as contrasted with that at higher altitudes—a fact that is supported by the distinctive "blob-like" structure of these echoes as discussed above. A likely explanation is that the trail irregularity structure at these low altitudes evolves much more slowly—due to longer diffusion times—than those at higher altitudes thus yielding the longer duration for the low aspect sensitivity scattering stage. A more detailed study of these lower altitude, "blob-like" RSTEs will be the subject of future work.

[10] The insets in Figures 2a and 2b show high-resolution RTI plots of the head echo and of initial parts of the trail (component 1) as observed from both Jicamarca and Carapongo. It can be clearly observed that the onset-delay between the head echo and the trail echo is different in Jicamarca (Figure 2a, inset)—where it happens to be less—compared to Carapongo (Figure 2b, inset). This result has far reaching implications as the delay between the head echo and the trail is considered to be a signature property of the RSTEs [*Dyrud et al.*, 2002] - though *Malhotra et al.* [2007] showed that RSTEs with zero delay are also observed. In particular, the observed onset delay between the head-trail echoes has been used to put forward the theory that FBGD instabilities are responsible for the formation of RSTEs [*Dyrud et al.*, 2002]. Based on the duration of this observed time interval, taken as an average of 20 ms in the above mentioned references, this delay has been interpreted as the time taken for plasma instabilities to develop in the meteor trail. However as the insets in Figures 2a and 2b show that the duration of onset-delay is also highly dependent on the viewing geometry—ranging from ∼1 msec at 100 km altitude at onset as seen from JRO and a few milliseconds as seen from Carapongo—and hence careful consideration of the viewing geometry should be given before any conclusions can be reached on plasma instabilities based on onset delay.

[11] The (Figures 2a inset and 2b inset) show another interesting feature—the presence of a short, single altitude trail at roughly 88 km at both Jicamarca and Carapongo. This trail, labeled T, has (when examined at a very high resolution) a zero onset delay (between the head and the trail echo) at Jicamarca and seems to correspond to a fragmentation or "terminal" event, which the authors have also often observed in data collected from the Arecibo radar [*Mathews*, 2004] as well as from the Poker Flat AMISR radar [*Mathews et al.*, 2007]. This is apparently the first reported instance of these terminal events at JRO.

5. Conclusions

[12] We have reported the initial results—in the form of a detailed case study of two meteor events—from the first ever MSCVR observations of head echoes and Range Spread Trail Echoes. The results verify the hypothesis put forward by *Malhotra et al.* [2007] that if there were two identical radars close to each other looking at a common volume, a meteor echo (caused by a meteoroid of sufficient mass and energy) occurring at the **k**⊥**B** region of one of the radars might be seen as a long duration echo from that radar and as a short duration echo from the other radar. Our results also show that some of the long duration meteor echoes, especially those occurring at lower altitudes, appear to originate from lesser aspect sensitive "blobs" of plasma. This result might serve to confirm the conjecture by *Dyrud et al.* [2002] that the FB instability is collisionally suppressed at/below ∼95 km altitude. We will be presenting a statistical analysis of these echoes in the near future. This analysis will provide further insight into the formation of RSTEs. These "blob-like" echoes might prove to be quite significant as they force us to re-consider the 'blob theory' of formation of RSTEs proposed in the 1960s.We also show that the onset delay between the head-trail echoes—that is presented as a signature property in the current theory of RSTE (non-specular echoes) formation (due to development of FBGD instabilities)—is a function of viewing geometry. This implies that very careful consideration should be given to the viewing geometry before any conclusions can be derived on development of plasma instabilities based on the distance between the head echo and the trail echo.

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