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SOLVING LONG–STANDING METEOR MYSTERIES

A Dissertation in

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by

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ABSTRACT

Millions of meteoroids strike and disintegrate in the Earth's upper atmosphere every day and may be seen as visible or radar meteors. Although very few of the these foreign bodies actually make it to the surface of the Earth, they have been known to cause damage to satellites and are also the only known source (except for spacecraft debris) of metallic ions in the upper atmosphere, thus being responsible for various atmospheric phenomena. Despite these meteor echoes being studied using radars for close to a century now, some long–standing unsolved mysteries still remain in the field—what causes some of the meteor trails to last for so much longer compared with the other trails? Are meteors really responsible for the formation of Sporadic-E, an altitude–thin ionospheric layer? If yes, then why has there been no evidence of a direct relationship between the two despite numerous attempts since the 1930s? Using data collected from the Jicamarca Radar Observatory in Peru, we answer all of the above questions and solve these long–standing mysteries. Our results emphasize the importance of paying careful attention and due consideration to radio science issues while analyzing radar meteor echoes. It is found that the viewing geometry, i.e. the aspect sensitivity of meteor echoes, is also the primary constraint in observing long–duration meteor trails and almost all of the long duration echoes seem to originate from the $\mathbf{k}\perp\mathbf{B}$ region ($\mathbf{k}$ = wave vector, $\mathbf{B}$ = geomagnetic field) of the radar. This result is extremely significant because it raises questions about the observed durations of all Range Spread Trail Echoes (RSTE): the same meteor event could be simultaneously observed as a long duration trail (greater than 15 seconds) from one radar and a short duration trail from another radar. These claims are supported by

observations from the first-ever multi-static common volume radar observations of RSTEs. These results also provide new insights into the physical structure of the plasma giving rise to these echoes and also establish a firmer basis for the modeling of the plasma processes that cause meteor trails to become field-aligned while underlining the importance of carefully distinguishing event radio science as a prelude to specifying the role of these plasma processes.

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They say writing the first line of any dissertation is the hardest. Thank God I am done with it (with due apologies to Willie Nelson). It has taken me almost three years to do it (PhD, whatelse?) and as one approaches the destination (the Dr. in front of my name, whatelse?), one cant help but realize that like most things important in life, the journey actually matters a lot more than the destination. And as all meaningful journeys in life go, it is only the support of the people who care for you, the company of friends you make along the way and the mentors who guide you that make the journey successful and more importantly, worthwhile.

I would like to start by thanking and acknowledging the contributions of someone who fits all the above criteria, John Mathews who also happens to be my dissertation advisor. Thanks for giving me the opportunity John to get started on this frustrating, arduous yet always challenging and extremely enjoyable journey. Your support and encouragement go way beyond what one can expect from an advisor. I have learnt a lot from you (not only talking about science here) but without doubt, have a lot more to learn. Hopefully, this destination is just the beginning of many more journeys together.

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Professor Shirer, this has turned out to be a much more "readable" document. All the errors remaining are of course, totally the author's responsibility (yeah, that's me).

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Chapter I

Introduction

A **meteor**, commonly referred to as a “shooting star”, refers to the streak of light seen when a small object, known as **meteoroid**, enters the earth’s atmosphere. Not so very often, an exceptionally large meteoroid makes a transit through the earth’s atmosphere to the earth’s surface and comes to be known as a **meteorite.** The radiant of a meteor is the spot in the sky from where the meteoroid appears to be coming. In the case of a meteor shower, all the meteoroids appear to be originating from a common point. The advent of the highly sensitive HPLA (High Power Large Aperture) Radars has allowed us to study even the very small particles, known as micrometeorites, and we now know that non-shower meteors, also known as sporadic meteors, by far outnumber the shower meteors [Mathews et al., 2001]. Shower meteors by definition are due to a single comet, asteroid, or event and thus represent a modest, if sometimes spectacular, mass flux. Sporadic meteors represent all sources and thus a large mass flux. We focus on these sporadic meteors in our study.

Meteors and meteorites have been a subject of fascination for thousands of years (see Section 1.2). In the modern era, however the only reported fatality from a meteorite is an Egyptian dog in 1911, although there are doubts regarding the veracity of this report. The first instance of a human ‘hit’ in recorded history is that of an Albanian housewife on November 30, 1954 in Sylacauga, Alabama. A 4 kg stone chondrite meteorite hit Ann

Hodges while she was taking a nap after crashing through the roof and bouncing off the radio, thus giving her the dubious honor of being the only person on record to be hit by a meteorite. This meteorite is now on display at the University of Alabama. More recently, there have been reports of a 14-year-old boy being hit by a meteorite on June 12, 2009 but at the time of publication of this dissertation; the veracity of these reports is yet to be determined.

Figure 1. The one that finally made it!! Ed Howard, then Sylacauga mayor, Ann Hodges (the proud victim) and then Sylacauga Police Chief W.D. Ashcraft pose with the meteorite. The hole in the ceiling caused by the meteorite can be seen clearly. It bounced off the radio and struck Ann Hodges who was taking a nap at that time.
(Source: www.uanews.ua.edu)

1.1 Why study meteors?

Now that we know that meteorites mostly pose no direct threat to mankind (the dinosaurs might have a different tale to tell!), it becomes necessary to establish first why we need to study meteors at all.

Billions of meteoroid particles impact the Earth's atmosphere annually. The sheer magnitude of this flux makes it obvious that these foreign particles pose a grave threat to our space infrastructure. It is well established that the Perseids meteor showers were responsible for the destruction of the Olympus satellite of Japan in 1993. In order to avoid damage by the Perseus meteor shower in 1993, NASA postponed the launch of a spacecraft and also changed the pointing direction of the Hubble space telescope. In November 1999, China delayed the launch of its Shenzhou 1 spacecraft to avoid the Leonid meteoroid "storms". The afore mentioned incidents [MA Yue-hua et al., 2008] are an excellent illustration of why we need an accurate knowledge of not only the amount of mass flux of meteors but also its annual and seasonal dependence. It must be noted that the examples being given above illustrate only the effect of meteor showers. The mass flux from sporadic meteors or non-shower meteors is much more than that from meteor showers; hence they have a greater effect on our space vehicles. For example, the Hubble space telescope has 572 small craters as a result of the impact of meteoroids [www.space.com]. It is worth noting here that despite meteors being observed for centuries and seriously studied for well over two centuries, we still do not have a good estimate, or at least not one that most scientists agree on, of the amount of mass flux deposited by these foreign bodies in the earth's atmosphere. The annual mass flux as a result of these meteorites is estimated to be of the range of 2000 - 170000 tons [Ceplecha et al., 1998].

Apart from the effect on spacecraft and satellites, meteors also affect our space weather and are responsible directly or indirectly for various atmospheric phenomena. Meteors are the only source of metallic ions in the ionosphere (apart from space junk!). They also are speculated to be directly responsible for the formation and evolution of Sporadic-E, a thin metallic layer found in the E-region [85-130 km] of the ionosphere that is useful for radio communication. This layer is the subject of discussion in this document. Meteors also might play an important role in the formation of Polar Mesospheric Summer Echoes [PMSE], a subject of ongoing study [Bellan, 2008]. Meteor trails have long been used for the measurement of atmospheric waves and tides [see Ceplecha et al. (1998) for review]. An accurate calculation of meteor radiants and their distribution would provide valuable insights into the evolution of the solar system. In fact, it is even claimed that meteors and meteoroids striking the primordial oceans may have contributed carbon compounds that triggered the start of life [Furukawa et al., 2009].

As we show in this work, the role of meteors in the background ionosphere is still not appreciated fully. They are responsible for and can be used to explain some yet unexplained phenomena such as Quasi-Periodic Echoes [Malhotra, 2006].

There have been records of sightings of meteors from as long back as 1809 B.C. and it would be interesting to have a quick glance at some of these ancient observations and how the field evolved to come into its present state.

1.2 Ancient Records

“ The Lord cast down great stones from heaven”. ... Book of Joshua (10:11)

These ‘stones’ are later described as hailstones but it is quite possible that they might have been meteors [Olivier, 1925]. Perhaps, the earliest record of meteor occurrences is found in the Chinese and Japanese records (Imoto and Hasegawa, 1958), going back to 1809 B.C., which mentions, “many stars flew, crossing each other”. The first known annual record of a meteor shower, the annual Lyrid shower in this case, comes from the era of Chou Chuang Wang (687 B.C.), when the “stars fell like a shower”. These inexplicable large alien objects that occasionally “fell from the sky” were often held in awe and veneration by many races throughout the passage of time. Temples were built in Greece and Rome to house meteorites, and meteorites have also been found in the burial grounds of North Indian Americans and in an Aztec temple [Olivier, 1925]. Biot [1846] was the first to propose that these stones were of extra-terrestrial origin thus disproving the Academy of Science in France that had declared unequivocally that a meteorite was actually an earthly stone that had been struck by lightning. The impetus required for the study of this field was provided by the brilliant Leonid shower of 1833. An artist’s rendition of this shower is shown in Figure 2. This awe-inspiring spectacle that occurred on the night of Nov 12-13 caused the superstitious to believe that the Day of Judgment had arrived. More importantly, at least from our perspective, the event was observed by many with scientific training who concluded that all the streaks of light appeared to be coming from a common part of the sky, the constellation of Leo. Here, it is important to mention the name of Professor Olmstead of Yale University, one of the eye witnesses to this event, whose conclusions and analysis have not been able to withstand the rigors of time and the progress of science, but who helped establish meteor science as an essential part of astronomy. At this early point, most of the efforts were concentrated on establishing the presence of other periodic meteor showers and their radiant positions. Recollecting that a similar spectacle also was observed in November 1799, H.A. Newton, A.C. Twining and Schiaparelli, each independently, made a bold prediction that a similar spectacle would be observed in the 1866, a prediction that came true in the most spectacular fashion on Nov. 13, 1866 [McKinley, 1961].

This period did prove to be quite an exciting one for this young science. At the same time when the common man was being enthralled by the beauty of the Leonids in their full fury, a spectacle that we might never witness again, several scientists found out that the orbits of some comets bore a striking resemblance to those of some meteor showers. Several observations of many meteor showers at different time periods led to the conclusion that meteor showers are the debris of comets. The interest and the importance of meteors grew to such an extent that in 1848, a German physician named Mayer proposed a "meteoric hypothesis" to account for the conservation of the sun's energy. In 1890, Sir Norman Lockyer proposed that " all self-luminous bodies in the celestial space are either of swarms of meteorites or of masses of meteoric vapor produced by heat". This "meteor hypothesis" has, obviously, been long proven to be wrong but it demonstrates the interest and importance that was given to this 'new' field. McKinley [1961] provides an excellent review and goes into more detail of these exciting times for meteor science.

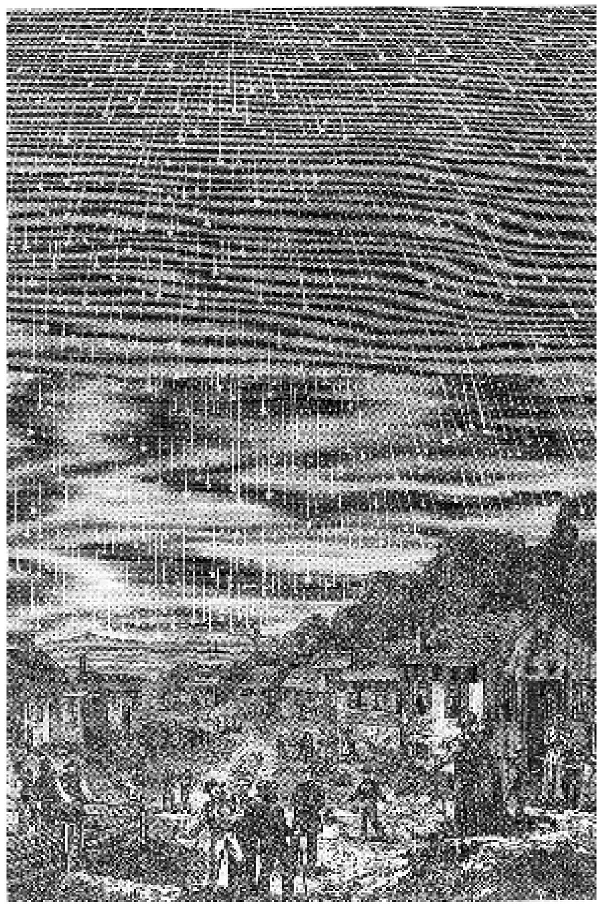

Figure 2. An artist's rendition of the awe-inspiring 1933 Leonids meteor shower.
(Source: The Heavens on Fire-The Great Leonid Meteor Storms by Mark Littman)

The advent of radars and the rapid development of their technology, especially during the Second World War, changed the field of meteor physics significantly and brought it to its present state today. In the next section, we look at this interesting and undoubtedly, the most significant period in the history of meteor physics.

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1.3 Radio Observations

Before we move on to the ‘radio history’ of meteoroids, it would be useful to classify the three different kinds of meteor echoes observed by radars, i.e. head echoes, trail or classical echoes, and range spread trail echoes (RSTE) [Figure 3].

The ‘**head echo**’ is observed from scattering associated with the plasma surrounding the meteoroid. A brief, and perhaps oversimplified description of this phenomenon is as follows. When a meteoroid descends through the Earth’s atmosphere, it heats up owing to air collisions. When this temperature reaches about 2000 K, surface particles quickly evaporate in a process known as ‘ablation’. These ablated particles quickly ionize and also ionize the atoms/molecules with which they collide, forming a ball of plasma around the meteoroid, the scattering from which is termed as the head echo. These head echoes, seen almost exclusively by High Power Large Aperture Radars (HPLA) have facilitated the measurement of the meteoroid radiant, velocity, deceleration and mass flux [Janches et al., 2000; Mathews et al., 2001]. Perhaps more importantly, helped to underscore the importance and sheer strength of sporadic meteors which are the meteors not found to be associated with any particular shower streams.

The ‘**trail echo**’ also referred to as classical or specular meteor echo is obtained from the scattering from the trail of ionization left behind in the path of the meteoroid. In order to observe these echoes, the radar beam has to be pointed perpendicular to the afore-mentioned trail of ionization, hence the name ‘specular echoes’. These echoes have been observed from low power classical meteor radars and have been used tradionally to

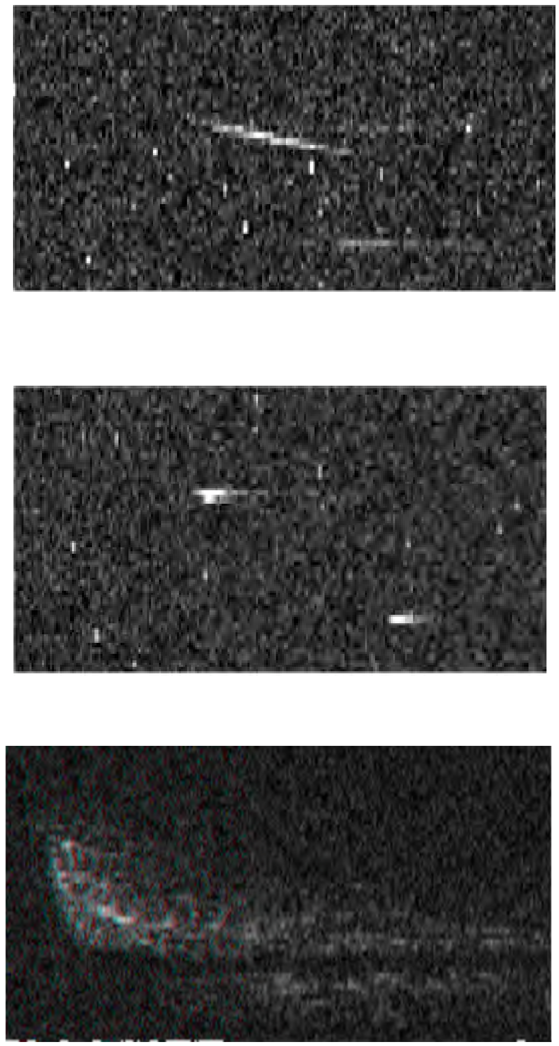

Figure 3 The three different kinds of radar echoes — (Top) the head echo, (Middle) the trail echo, and (Bottom) the RSTE — as observed from the MU radar.

calculate meteoroid velocity and to provide mass flux measurements along with background wind measurements. All these results have been put into some doubt with the increase use of HPLA radars in meteor observations [Mathews et al., 2001].

In this study, we are mainly concerned with the third kind of meteor echo, namely the **RSTE** [Range Spread Trail Echo]. These echoes are seen to last from a few seconds to over 15 minutes and are discussed in much detail.

Now, that we are done with the necessary classification of meteor echoes, we continue with our historical overview of meteors. The advent of RADARs in the second decade of the twentieth century, though the term as we know it today was not coined until 1941, revolutionized the entire ionospheric study and the study of meteors was no exception.

The effect of meteors on radio propagation was first suggested by Nagaoka [1929] and confirmed by Skellett [1931], although their explanation of the observed phenomena differed quite a bit. Nagaoka suggested that the ionization created by the meteor would be negligible compared with the already existing ionization in the E region. Thus the meteoroid would sweep away the electrons in its path, thereby reducing the electron density and causing a local discontinuity in the refractive index of the ionosphere. In contrast, Skellett [1931; 1932; 1935] held the view that a meteor adds rather than subtracts ionization, and he rightly came to the conclusion that meteors form a considerable source of ionization in the 100 km region. Head echoes certainly were observed during this period but display/technology was not adequate enough to recognize them.

On February 12, 1942, two German warships, the Schanhorst and Gneisenau, were able to make a dash through the English Channel to reach ports closer to Germany. Although this event may seem irrelevant to meteor research, their sailing caused great concern to the British Navy because the British radar system had been jammed during this incident, allowing the two ships to sail undetected by radio. James Stanley Hey was given the responsibility of explaining this incident. Because a subsequent jamming of the British radar occurred with no German bombing, Hey postulated that the loss of signal was an atmospheric, and not a German, effect. On looking into the matter further, Hey found that the jamming of the British radars coincided with the passage of a strong meteor shower and rightly concluded that the apparent jamming was due to the interference from meteors.

The Leonids and Giacobinids meteor showers of 1946 provided further impetus for meteor research, the most important outcome of these being the discovery of the head echo by Hey and Stewart (1947) who also performed the first radio velocity measurement of meteor echoes. The first such reported echo is as shown in Figure 3. Meanwhile, considerable work had been done and progress had been achieved in the study of trail echoes. Pierce (1938) pointed out that for radar scattering to occur from a meteor trail, the trail must be perpendicular to the source, and the analysis of such a small wavelength, fresnel zone long column of ionization oriented perpendicular to the radar pointing direction at the closest point was carried out by Blackett and Lovell (1941). McKinley and Millman (1949) used this mechanism to develop a method for determining meteor shower radiants, successfully calculating the radiant of the Geminid meteor shower. They were also the first to point out that the head-echo moves with the speed of the meteoroid and has scattering characteristics similar to that of a point target. A few RSTEs or anomalous echoes also were observed during this time period and their existence was explained by the "glint theory" and the "blob theory", which we discussi in some detail in the next section.

McKinley and Millman (1949), Browne and Kaiser (1953) and McKinley (1955) propose different theories to explain the head echo. We do not go in detail of these theories because we are concerned mainly with RSTEs in this work, but the existence of these different theories is important to note because McIntosh (1962) pointed out that no consensus had been reached on the generative mechanism for the head echo despite 14 years of work. This along with various other factors including the release of McKinley (1961) – an excellent book on meteors that deals predominantly with trail echoes – and the funding scenario existing at that time, led to the focus being shifted from head echoes to trail echoes. It was not until the use of HPLA radars in meteor science in the nineties that head echoes came back into prominence.

The above two sections [1.2 and 1.3], largely taken from the author's master's thesis [Malhotra et. al., 2006], are in no way meant to be all-inclusive or exhaustive, but they do provide an idea of the rich and absorbing history of the field and also demonstrate the remarkable evolution of the field from one based largely on superstitions to a major scientific discipline.

1.4 Range Spread Trail Echoes

Range spread trail echoes (RSTE), also known as enduring echoes and nonspecular echoes, have been observed since the 1940s (Figure 4), but the exact explanation for the generation of these echoes still remains elusive. Two possible mechanisms were put forward to explain these echoes, "glint theory" and "blob theory" (McKinsey, 1961). The basic assumption behind the glint theory is that the ionization is produced continuously and smoothly behind the meteor trail. Wind shears distort the trail in such a way that many points in the trail become perpendicular to the radar beam, thus forming multiple Fresnel zones. This phenomenon is shown in Figure 5 (Top) .The blob theory, in contrast, assumes that ionization is not created smoothly and continuously on the trail and that the line density of ionization varies along the trail as shown in Figure 5 (Bottom), thus effectively forming multiple scattering centers. Both the above-mentioned theories, despite being remarkably simple in their explanation and yet being able to explain the majority of the observed features of RSTEs (especially true in case of blob theory as we see below), have never received their due in the community. After the 1950s, little work was done on these echoes because they were first upstaged by the specular trail echoes seen by the low power meteor radars and then later by the head echoes seen by the high power large aperture radars.

These echoes came back in prominence in 1994 (Figure 6) when they were observed by the Jicamarca radar (Chapin and Kudeki, 1994a), and they have been a subject of considerable study since then. In fact, these echoes had become so lost to the scientific community that the authors of this landmark paper failed to recognize that these echoes

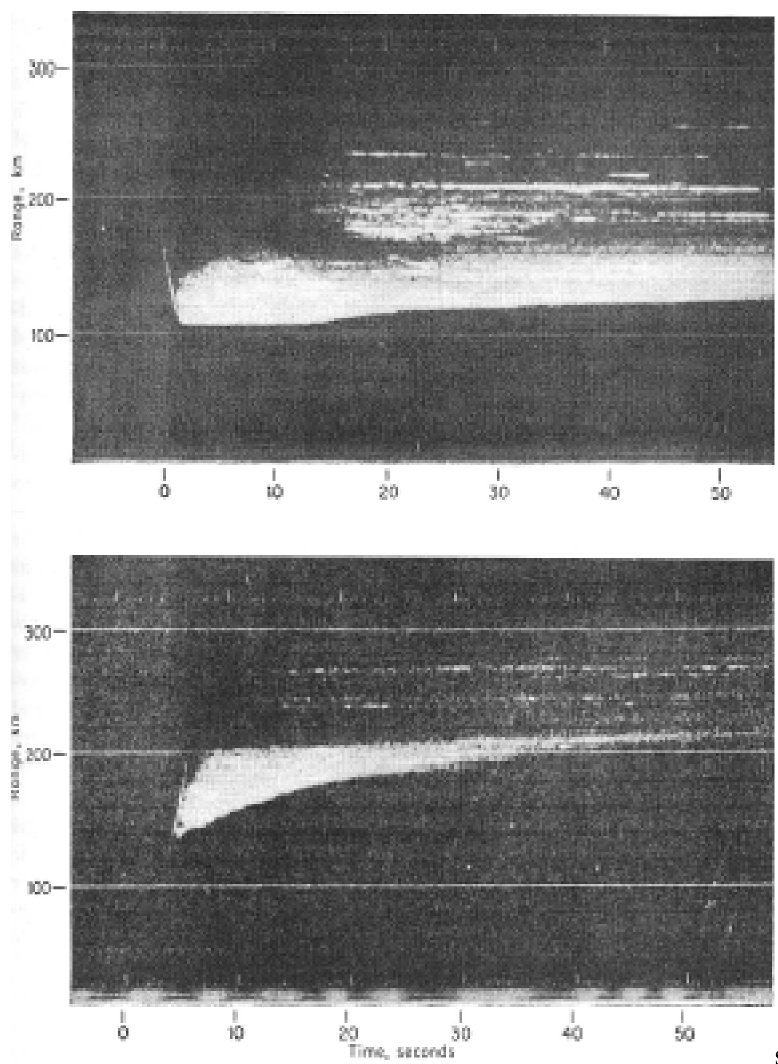

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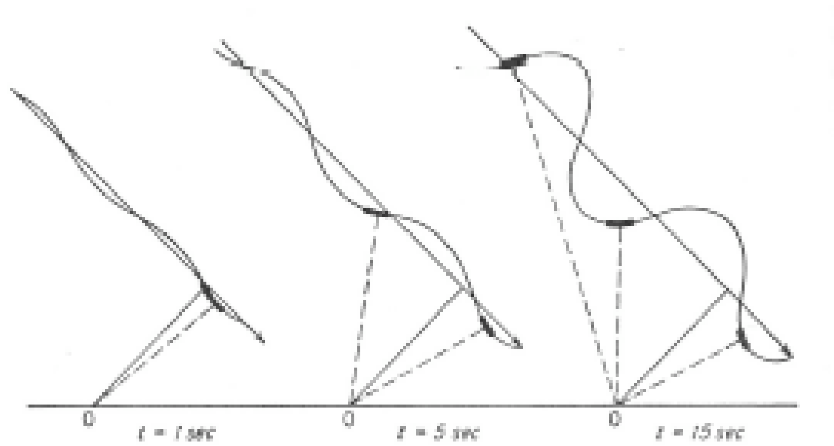
Figure 4. One of the first reported observations of range spread trail echoes
Source: Figure 1-7 [McKinley, 1961]



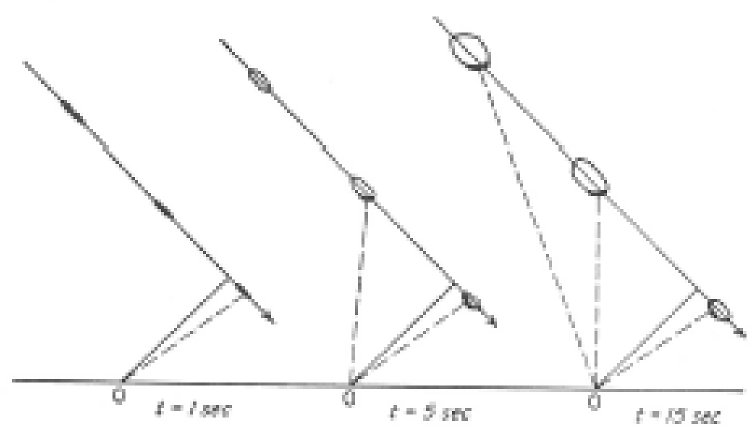


Figure 5. (Top) Wind-shear mechanism of formation of RSTE

(Bottom) Blob-theory postulate for formation of RSTE

Source: Figure 8-13 and 8-15 [McKinley, 1961]

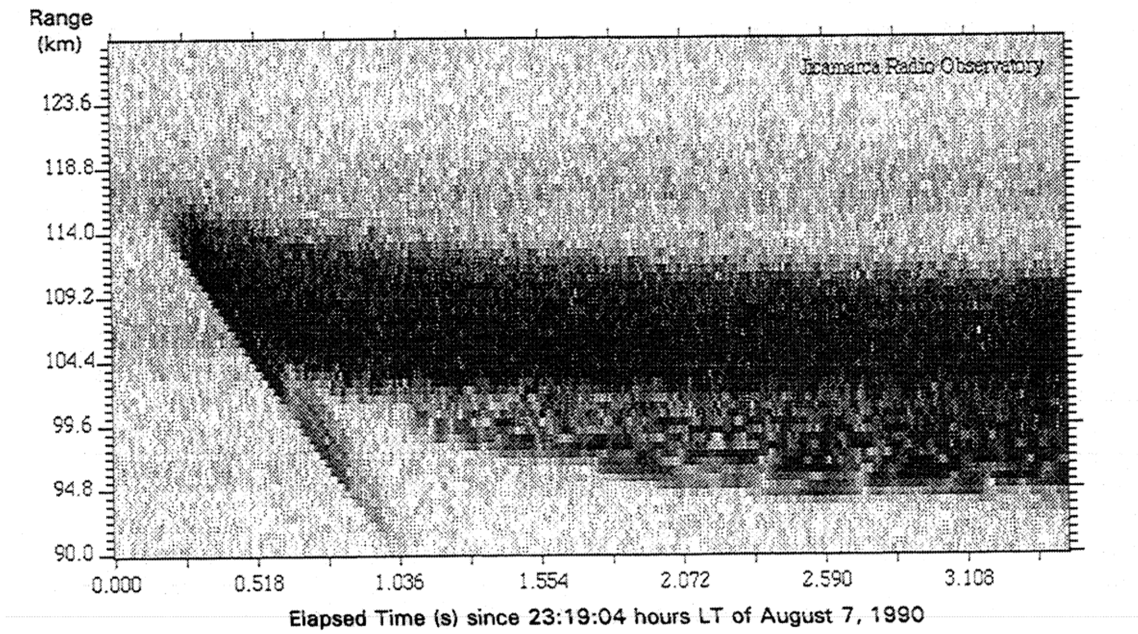


Figure 6. A RSTE observed by the Jicamarca radar (Chapin and Kudeki, 1994a).

had in fact been observed before in the 1950s. Chapin and Kudeki (1994b) attributed these unusual echoes to plasma instabilities incited by the equatorial electrojet along the meteor trail. The equatorial electrojet is an ionospheric phenomenon observed only at or close to the geomagnetic equator. This theory was found wanting however when these echoes also were observed from non-equatorial radars.. Dyrud et al. (2001) put forward the theory that meteor trails are inherently unstable within a confined altitude range [95 to 105 km], and so no external factors are required to induce plasma instabilities in meteor trails. A major breakthrough in our understanding of these echoes came about when they were observed with the 160/422 MHz ALTAIR radar (Close et al., 2002), but not with the much more sensitive Arecibo 430 MHz radar (Zhou et al., 1998), despite both these radars operating at similar frequencies. It was hypothesized that this difference could be attributed to the fact the ALTAIR radar was pointed perpendicular to the geomagnetic field (**B**) whereas the Arecibo radar was pointed at an angle of 45^o to **B** for the above referenced observations. Zhou et al. (2001) proved the above hypothesis by observing these echoes with the MU radar that was pointed perpendicular to **B** and also reported that almost all the head echoes observed in the $\mathbf{k} \perp \mathbf{B}$ geometry were followed by a range spread trail echoes, thus leading to the important conclusion that field aligned irregularity (FAI) scattering is essential to the formation of range spread trail echoes. Mathews (2004) provides an excellent in- depth study of the radio-science issues concerning range spread trail echoes.

In the next section, we provide a brief overview of our research efforts and also our motivation behind them.

1.5 Research Motivation and Overview

Range Spread Trail Echoes have been observed since the 1940s but still basic questions remain unanswered regarding the formation and evolution of these echoes and their effect on the background ionosphere. As stated above, RSTEs have been observed to last from a few seconds to occasionally even up to 30 minutes. What causes some of these echoes to last so much longer than the others? Is it due to a difference in the properties of the parent meteoroid or due to some change in the background atmosphere conditions? What causes RSTEs to be observed only in a confined altitude range? Are the blob theory and the glint theory, put forward as early as the 1950s and since long forgotten, still — the radio science — relevant? Questions also do remain on the exact nature of the scattering processes behind the observation of these echoes. A better understanding of these scattering issues would lend great insights into the development and evolution of these echoes. What is the effect of these meteor echoes on the background ionosphere, especially the Sporadic-E? It is widely accepted that metallic ions are responsible for the formation of Sporadic-E [Chandra et al., 2001; Doniy, 1971; Grebowsky et al., 1998; Naismith, 1956], and it is also well known that meteor ablation is the only source of metallic ions in this region of the ionosphere [Kelley, 1989]. So, one would naturally expect a direct relationship to exist between meteors and Sporadic-E. But despite numerous attempts in the past 70 years, no evidence has been found of a direct relationship between meteor ionization and Sporadic-E!! Why has there been no evidence of this relationship for so long, a relationship that seems to be so intuitive?

We answer all the above questions during the course of this dissertation. One of the main reasons why so many questions remain unanswered and why we still know so little regarding these echoes is that during the past sixty years, the research done on these echoes has been largely of a theoretical nature. We attempt to change this bias and present the most exhaustive observational results of these echoes to date from our campaigns carried out at the Jicamarca Research Observatory (JRO).

In Chapter II, we unravel the mystery behind the formation and evolution of long duration meteor echoes. Chapter III presents the results from the first ever multi-static common volume radar observations of RSTEs. Chapter IV deals with the effect of meteors on Sporadic-E. The future scope of our work is presented in Chapter V.

Chapter II

Long Duration Meteor Echoes

Most of the RSTEs last from less than a second to 5 seconds. Ever since the 1940s, however there have been observations of longer–lasting RSTEs, in some cases lasting for even more than 15 minutes. Figure 7 shows a RTI (Range Time Intensity) plot of a long–lasting RSTE observed in 1947 [Hey et al., 1947]. This observation in fact, almost certainly, is the first ever published RTI plot of any kind. What makes some of these trails last so much longer than other trails? Does the mass of the parent meteoroid have a prominent role to play or are the background ionospheric conditions the deciding factor when it comes to the duration of the trails? Why are the longer lasting trails so few in number? These questions still remain unanswered despite various efforts to come up with explanations [Bourdillon et al., 2005; Chapin and Kudeki, 1994a; Dyrud et al., 2005; Kelley, 2004; Mathews, 2004; Zhou et al., 2001] and still remain a subject of much speculation in the community. Bourdillon et al. [2005] comments "… such long enduring meteor events are exceptional and constitute a mystery". Kelley [2004] attributes such long–lasting trails to the reduction of electron diffusivity due to gravitational sedimentation of charged "dust" particles left behind a large ablating meteoroid. More recently, Dyrud et al. [2007] tries to explain these long duration echoes by studying how plasma instabilities could exist in the trail for so long a duration. Their reasoning is based on the assumption that plasma instabilities need to be present for the

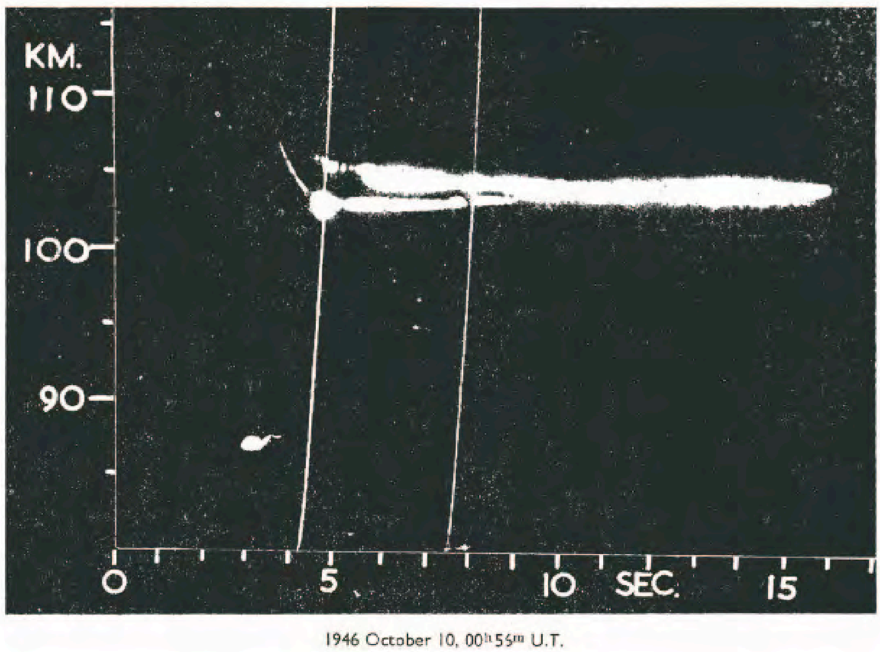


Figure 7. One of the first reported meteor head echoes (Hey et al., 1947) observed approximately between 3 and 4 seconds and between altitudes 103 and 107 kilometers. Also notice the RSTE following the head echo that lasts for well over 10 seconds. Film recording of radar signals in RTI format was developed during WWII.

radar to be able to observe these echoes. We examine the validity of this assumption below.

Using data collected from the Jicamarca Research Observatory (JRO) 50 MHz radar, we attempt to solve this long–standing mystery of long–duration meteor echoes. The results presented in this section and their implications also are presented in Malhotra et al. [2007a]. We start with an introduction to the JRO radar and what makes it unique and so useful for our study.

2.1 Jicamarca Research Observatory Radar

The Jicamarca Research Observatory radar is a 50 MHz radar located in the valley of Jicamarca near Lima, Peru [Figure 8]. The radar was constructed in 1960 and was one of the first–ever incoherent scatter radars (ISR) constructed. Incoherent scatter refers to the scattering from the thermal background fluctuations in the ionospheric electron concentration. It is the most basic form of scattering and is also referred to as thermal scattering. In order to detect these weak reflections from the background electron concentration, it is necessary for the radar to have an antenna of large aperture and a transmitter of high peak power. What makes the Jicamarca radar unique and useful in conducting ionospheric research is its location – the radar lies almost at the geomagnetic equator of the earth. Thus a variety of ionospheric and plasma phenomena that are unique to this region such as the Equatorial Electrojet only can be observed using this radar.

The Jicamarca radar has a square aperture of 84,000 square meters. It consists of two superimposed arrays of half-wave dipoles at right angles to each other. The dipoles are separated by a distance of one-half wavelength. The entire antenna is divided into quarters, with separate feed lines for the two superimposed arrays. Each quarter is subdivided further into 16 identical square modules, six wavelengths on a side, each containing 288 dipoles, making it a total of 18432 dipoles. An excellent description of the array is given in Ochs [1965].

This modular design of the array allows one to use multiple receivers for the reception of the scattered signals, thus making interferometry possible. This ability to perform interferometric analysis is what makes this particular radar so useful for our research as we see below in this chapter.

The results presented in this chapter all derive from observations at JRO performed on 1 and 7 June 2006. The antenna beam was pointed perpendicular to the geomagnetic field, i.e. at an angle of approximately 1.6° N from the vertical. The locus of points where the wave vector (**k**) of the beam is perpendicular to the Earth's magnetic field within ±1 Fresnel zones is denoted as the **k⊥B** region (a Fresnel zone is $\sqrt{R\lambda/2}$ ~ 550 m at R=100 km for Jicamarca). A major advantage of conducting these studies at JRO is that the presence of the highly aspect–sensitive Equatorial Electrojet (EEJ) scattering allows the **k⊥B** locus to be identified easily [Kudeki and Farley, 1989]. The north and south quarters (see Figure 9) of the Jicamarca antenna array were combined for transmission. In reception, sub-arrays ($1/64^{th}$) of the main antenna, as shown in Figure 9, were sampled independently for interferometric analysis of the echo signals. We utilize channels A, B, and C, each separated by a distance of six wavelengths, for our interferometric analysis. The transmitting half-power beamwidth is 1.1° north-south and 2.2° east-west, and the sub-arrays have individual full-width, half-maximum beamwidths of approximately 7°. The principle radar parameters for our observations are summarized in Table 1.

Figure 8 An aerial view of the Jicamarca Research Observatory

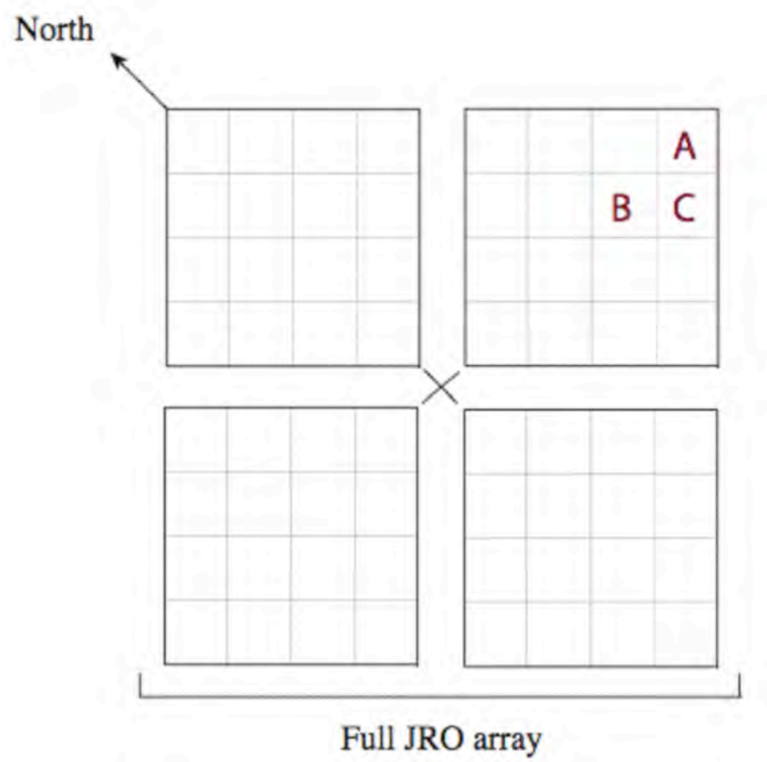


Figure 9 Experimental configuration for the observations carried out on 1 and 7 June 2006.

Table 1. Jicamarca 50 MHz radar parameters for the meteor observations of 1 and 7 June 2006.

Parameter	Value	Units
Frequency	50	MHz
Inter-pulse period	130.5	Km
Pulse width	5.85	Km
Barker code	13	Baud
Sampling rate	0.45	Km
Initial range	90	Km
Number of samples	77	
Number of channels used	3	
Transmitted peak power	2	MW

2.2 Observations and Analysis

Figure 10 shows the centroid position of RSTEs from a 15-minute period representative of our entire data set. This relative short period allowed us to assume the same background ionospheric conditions and, importantly, was taken during a time period when the equatorial electrojet was not present, although electrojet scattering before/after this period was used to confirm the locus of the **k⊥B** region. The equatorial electrojet scattering is often very intense and would mask many weak meteor events. The positions of the RSTEs were calculated using the interferometric technique introduced by Farley et al. [1981]. Because the basics of this approach have been repeated often in the literature [Farley and Hysell, 1996; Kudeki and Farley, 1989; Sahr et al., 1991], we do not go into the details here. In Figure 10, the black dashed line represents the **k⊥B** region at 100 kilometers for the Jicamarca radar. The dotted circle, indicating the angle in which the unambiguous meteor position can be calculated, has a radius of approximately 8.36 kilometers. The shaded region indicates distances of ± 2 Fresnel zones. It can be seen clearly that the longer–duration meteor echoes occur exclusively from scatterers in the **k⊥B** region. The shorter–duration echoes are well distributed throughout the beam although there is also a statistically significant preference for short duration RSTEs in the **k⊥B** region. That all the RSTEs occurring from the **k⊥B** region are not long duration echoes signifies that the mass/energy of the meteoroid also plays an important role in the formation of long duration echoes. The fact that all the long duration RSTEs occur from **k⊥B** region however leads us to believe that the aspect sensitivity associated with the

k⊥**B** geometry is the primary constraint for observing long–duration echoes. Additionally, it seems clear that some of the short–duration RSTE would be seen to be significantly longer–lived if viewed from the proper (**k**⊥**B**) geometry because there is nothing special about the **k**⊥**B** location as viewed from JRO—if JRO were moved geomagnetic east/west from the current location, we would expect statistically the same results. Again, we recognize the dependence of these echoes on other factors such as mass/energy of the meteoroid and possibly on the background ionospheric conditions. This dependence will be the subject of future work.

We conducted an interferometric analysis of all RSTEs over 5 seconds duration in our approximately 6 hour data set. Figure 11 gives the distribution of all such events for which unambiguous interferometric positions could be determined. Figure 11a shows a histogram of all such events occurring from the **k**⊥**B** region**,** defined in Figure 10, whereas Figure 11b shows the histogram, drawn on the same scale for comparison purposes, of all meteor echoes of duration greater than 5 seconds not occurring in the **k**⊥**B** region. It is clear from these figures that the majority of long–duration echoes – events over 15 seconds – occur in the **k**⊥**B** region. The two RSTE events with greater than 15 second duration not occurring in the **k**⊥**B** region were low–altitude events and are discussed in more detail in the next section.

Next we turn to specific examples of RSTE events. Figure 12a shows a Range (Altitude) Time Intensity (RTI) plot of a typical long-duration RSTE that lasts for over 30 seconds. Many examples of short-duration RSTE echoes also can be seen in the figure.

Figures 12b-12c show the position of this long lasting RSTE at various time intervals. In all these position figures, e.g., Figures 12b and 12c, the image on the right shows the evolution with respect to time and the image on the left shows the evolution with respect to range. The transmission beam pattern is included in these figures with the red contour showing a transmitted level of up to -10 dB. Figure 12b shows the position evolution of the head-echo associated with the Figure 12a (see inset) event and Figure 12c shows the evolution of the trail. Note that the head-echo intersects the **k⊥B** zone over ~100-104 km range interval—a range interval that corresponds to the longest lived components of the Figure 12a trail-echo. It is clear from this analysis that the scattering associated with the later part of the trail occurs exclusively from the **k⊥B** region even though the trail initially begins to form away from the **k⊥B** region. Although difficult to discern, the onset time of the trail-echo with respect to the head-echo varies along the meteoroid trajectory. This event occurs over a 97-108 km altitude range.

Figure 13 gives another example of a long duration RSTE that occurs over the 92-98 km altitude range, lasts for well over 25 seconds at the peak, and displays an onset time relative to the head-echo of over 1 second at the lowest altitude. Figure 13a shows the RTI plot of the event. The position of the head-echo associated with this long duration RSTE is shown in Figure 13b whereas Figure 13c shows the scattering region for the RSTE. As with the previous example, the later scattering is confined to the **k⊥B** region and becomes more and more localized with the passage of time. Note that this event has two distinct RSTE components that we associate with fragmentation below. As noted above, all but two of the 'long-duration' RSTE events observed (as summarized in Figure

11 and analyzed in the manner of the Figure 12 and 13 events) were found to have the long-duration part of the trail concentrated in the **k⊥B** region. These events are discussed below.

For comparison purposes, Figure 14a gives the RTI image of a typical 'short-duration' RSTE. It can be observed clearly from Figure 14b that the scatterers in this event are located far from the **k⊥B** region although in a well-illuminated part of the volume. However, this event also displays no apparent delay between the head- and corresponding trail-echo components and so might be grouped with the apparent fragmentation events discussed next. This event is discussed even further in the next section, as are the implications of these results to our understanding of trail plasma physics and radio science.

We also observe in our data set numerous examples of structured RSTEs showing two or more distinct regions (see Figure 13a) that we suggest are due to the meteoroid fragmentation events. Similar long-duration structured trails were also reported by Bourdillon [2005] who proposed the idea of a structured vertical wind shear in the lower E region trapping fragments of meteor trail plasma. We reject this interpretation here because other events that are nearby in time/altitude do not show this structuring. Importantly we find that these fragmented or structured RSTEs also can be explained via a radio science perspective, that is, based on where along the meteoroid trajectory relative to the **k⊥B** region the fragmentation occurs. Figure 15(a) is an example of such an event that, in total, occurs over 91-97 km altitude range with the head-echo first becoming visible at about 97 km. The RSTE is fragmented into three distinct regions, designated

(1), (2) and (3), respectively, in the figure. RSTE region (2) is seen to last for over 40 seconds, whereas the other two are shorter duration echoes—the upper part of the head-echo had no trail-echo component. Figure 15b shows the position of the head echo. Figure 15c-e show the scatterers associated with the fragmented parts (1), (2) and (3) of the trail respectively. The scatterers associated with the longer duration component of the trail—i.e., part (2)—are located exclusively in the $\mathbf{k} \perp \mathbf{B}$ region. Note that although the meteoroid trajectory passes through the antenna beam pattern, the three trail components do not correspond to the beam pattern and are thus considered to be part of the meteoroid processes.

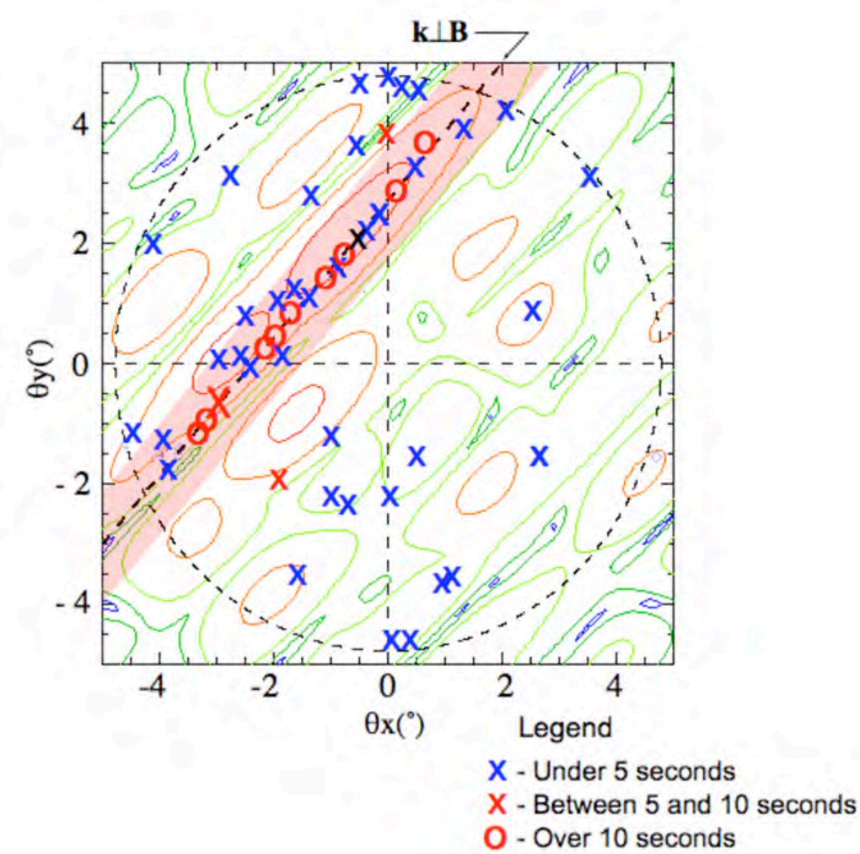


Figure 10. Centroid trail position of 50 random meteor events taken in a 15-minute time interval representative of our data set. The shaded red region has width ±2 Fresnel zones from the **k⊥B** region. It can be seen clearly that the longer–duration echoes derive exclusively from scatterers in the **k⊥B** region, whereas the shorter–duration echoes are seen throughout the illuminated volume but also occur with a statistical preference for the **k⊥B** region.

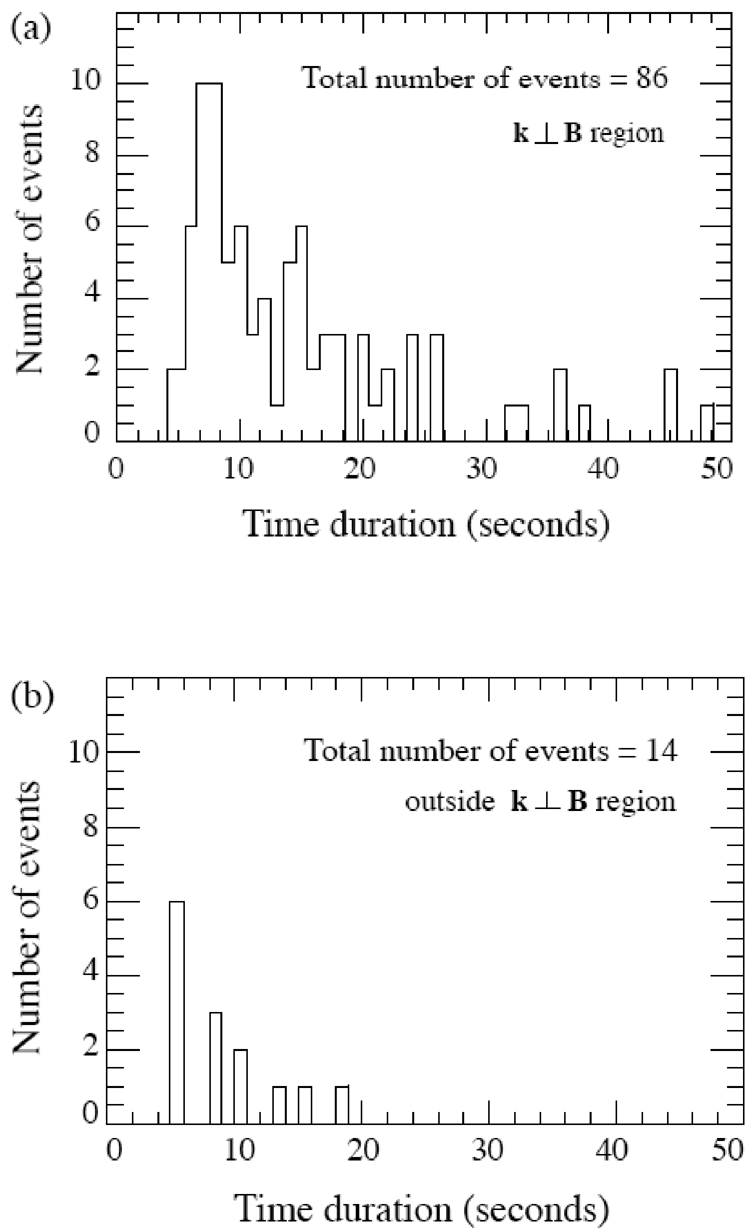


Figure 11. Histograms of all meteor trail events over 5–second duration in our approximately 6–hour data set. (a) All such events occurring in the **k⊥B** region shown in Figure 10. (b) All events over 5 seconds occurring away from the **k⊥B** region.

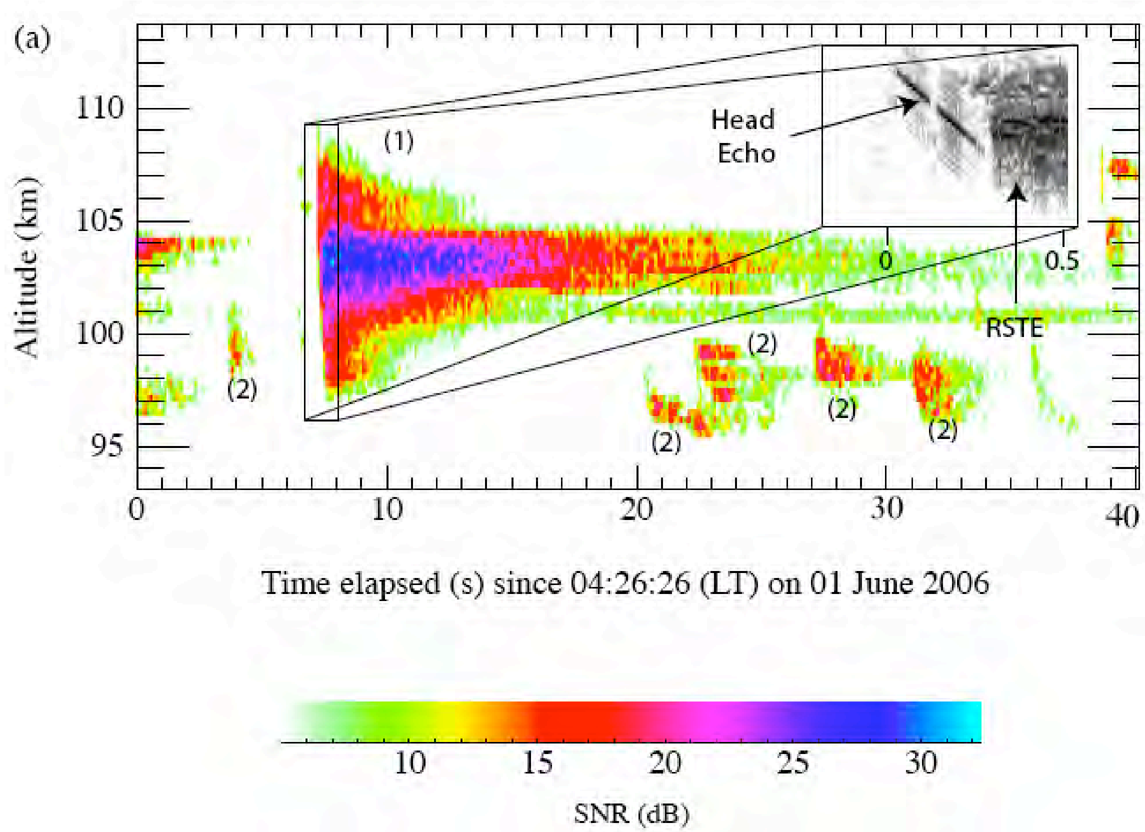


Figure 12. (a.) An RTI (Range Time Intensity) plot of a long–duration RSTE (Range-Spread Trail-Echo) (1). Notice the large number of short duration RSTEs (2) also present. (Inset) The head-echo associated with the RSTE can be clearly seen. Also note that the longest duration trail-echoes come from ~100-104 km altitude.

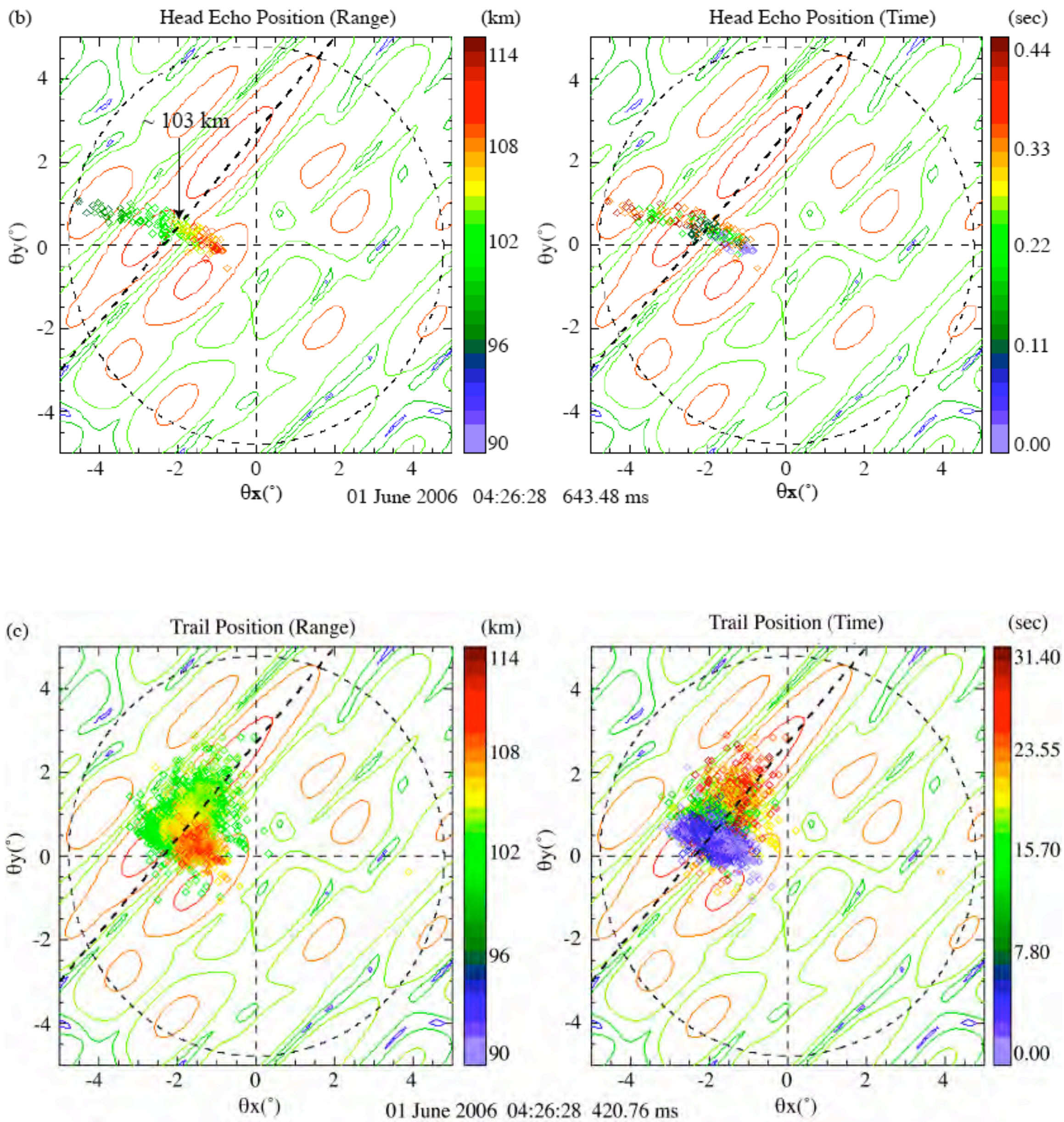


Figure 12 (b). The position of the head-echo. In all these images, the figure on the right shows position with respect to time and the figure on the left shows position with respect to range. (c) Evolution of the RSTE. Notice the trail begins to form away from the **k⊥B** region and the scatterers associated with the latter part of the trail occur exclusively from the **k⊥B** region and over a ~ 101-104 km range interval. Note that the trail drifts away from the location of the originating event.

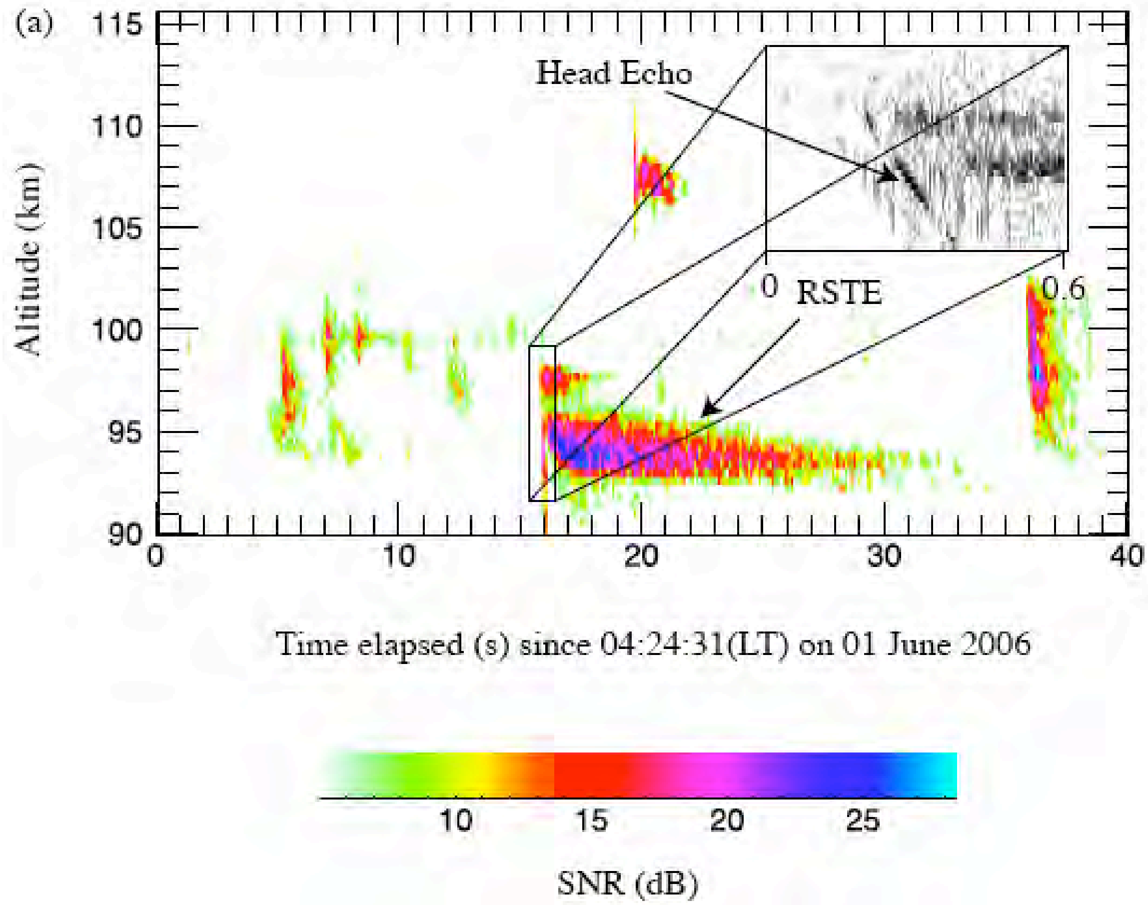


Figure 13. (a) RTI plot of another long-duration RSTE event occurring at a relatively low altitude. The head-echo corresponding to the originating meteoroid is readily apparent. Additionally, note the variation with altitude in onset time of the RSTE—an-oft noted phenomenon characteristic of RSTE events—but the delay is over 1 second at the lowest altitude.

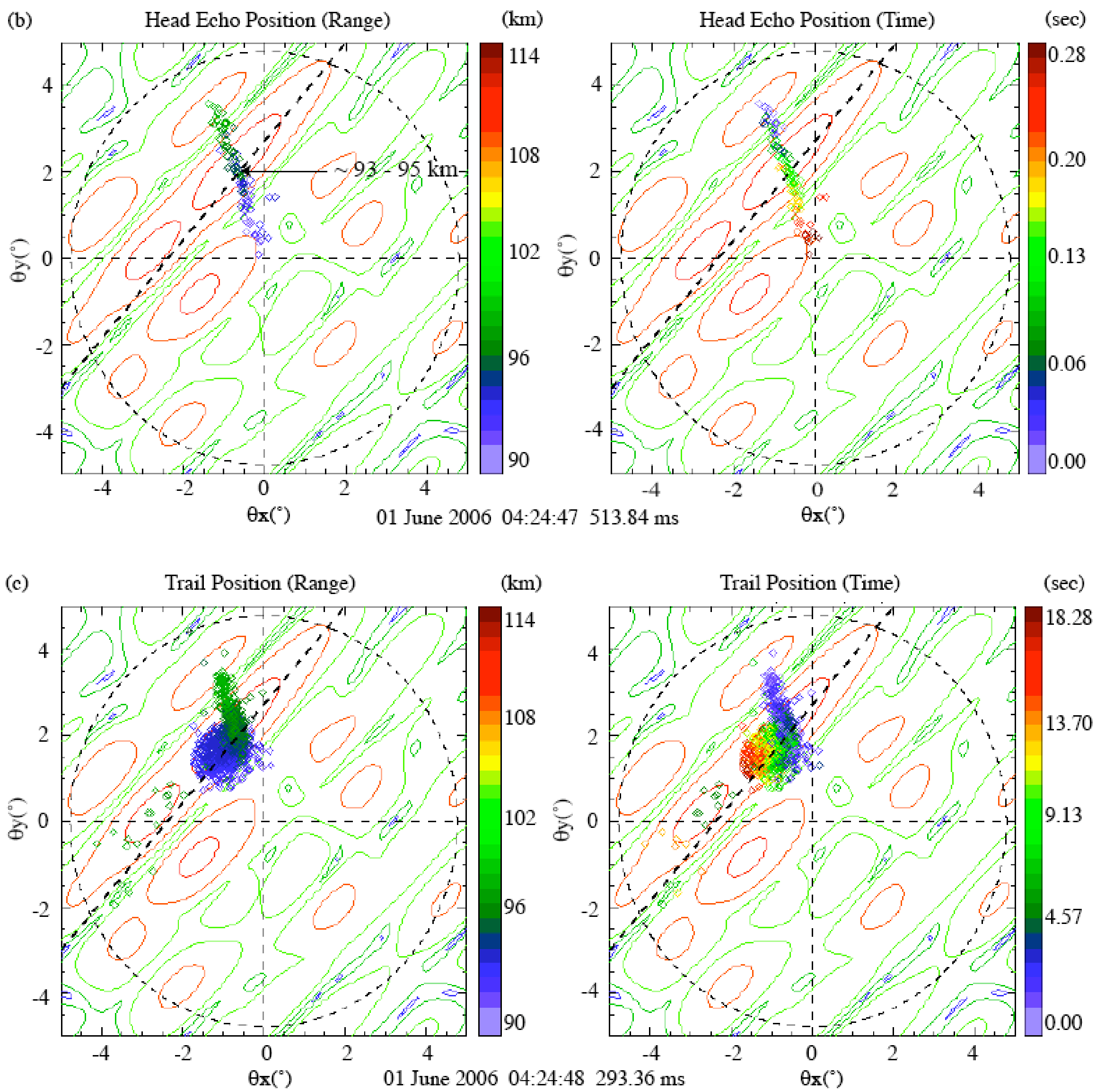


Figure 13. (b) Position of the head-echo and (c) Evolution of the trail. The meteoroid crossed the **k⊥B** region over the 93-95 km range. As with Figure 12, the trail starts to form away from the **k⊥B** region but the scatterers associated with the latter part of the trail that are responsible for the long duration of the trail occur from localized **k⊥B** region showing that longer duration RSTEs are highly aspect sensitive and occur exclusively from scatterers in the **k⊥B** region.

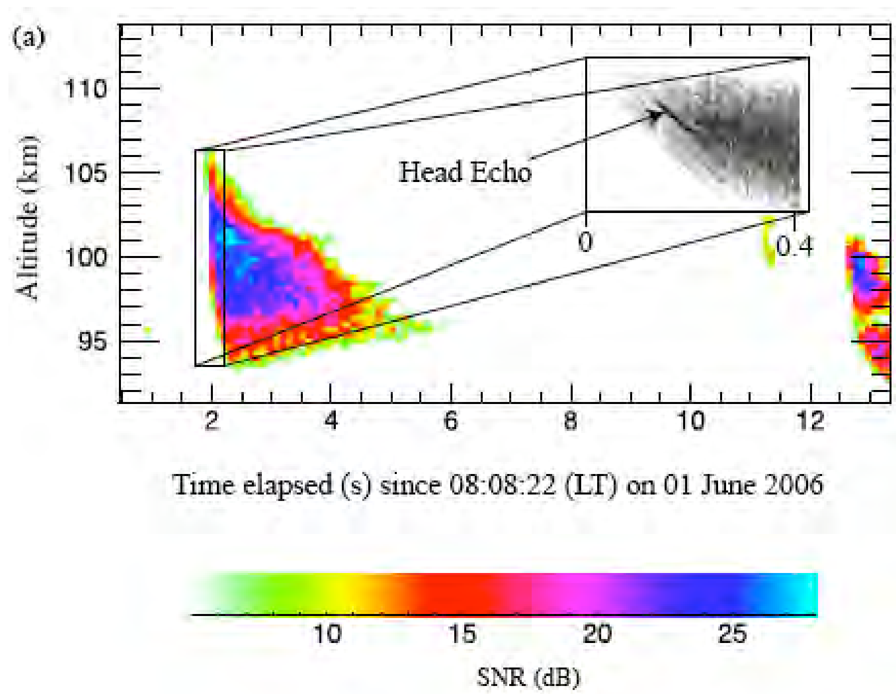


Figure 14. (a) RTI plot of a ‘short duration’ RSTE.

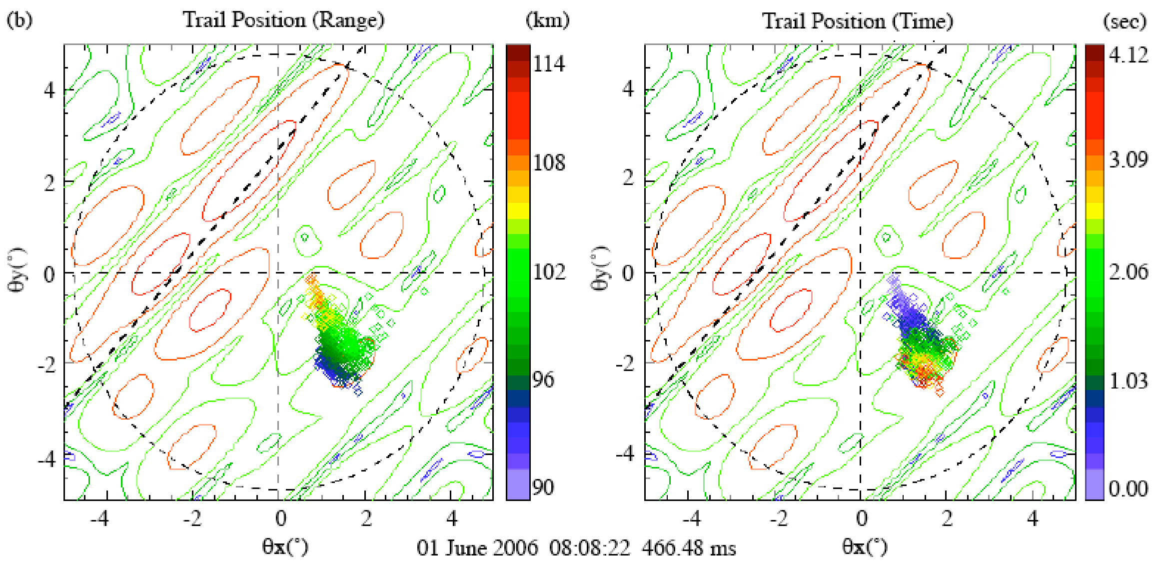


Figure 14. (b) The position of the panel (a) event. Note that this event occurs away from the **k⊥B** region, although in a well-illuminated part of the volume. This event shows no discernable onset delay between the head- and corresponding trail-echo regions.

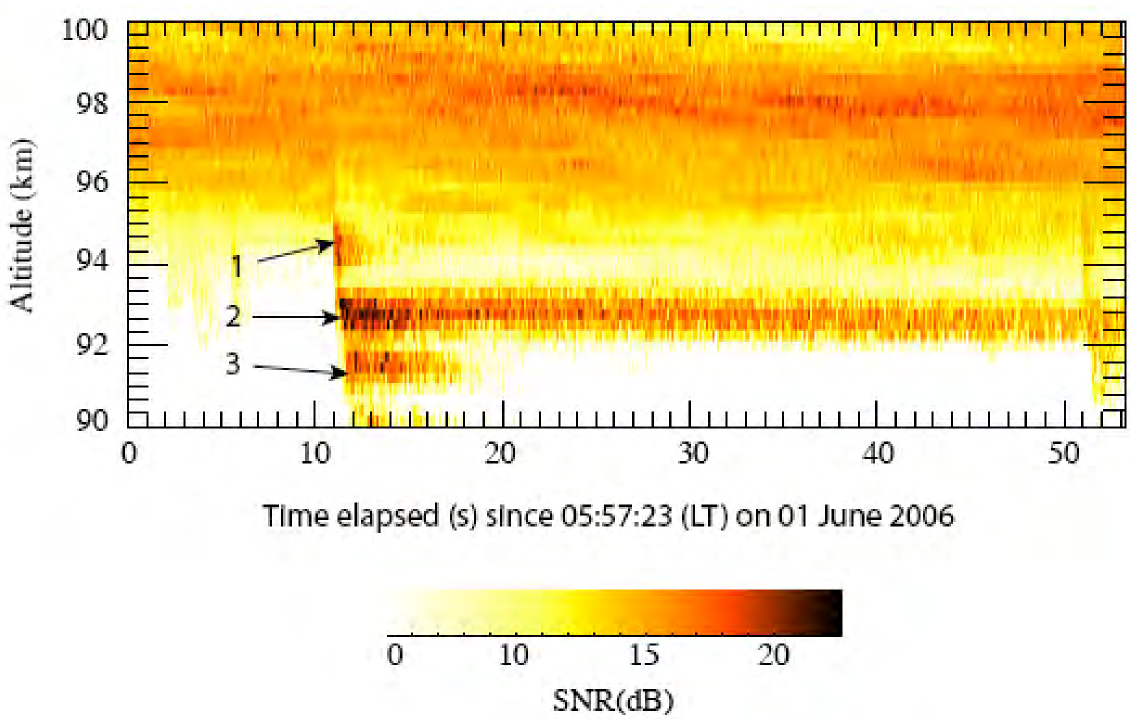
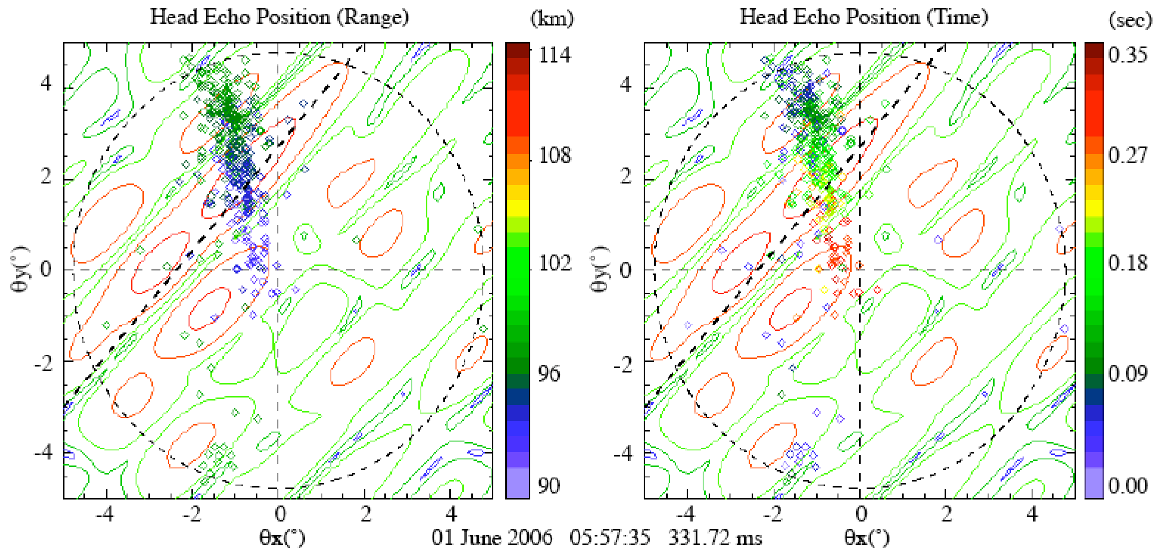


Figure 15. (a) RTI plot of a fragmented meteor echo. The meteor trail splits into three distinct parts, namely (1), (2) and (3). Equatorial Electrojet (EEJ) activity is observed above 95 km altitude.

(b)



(c)

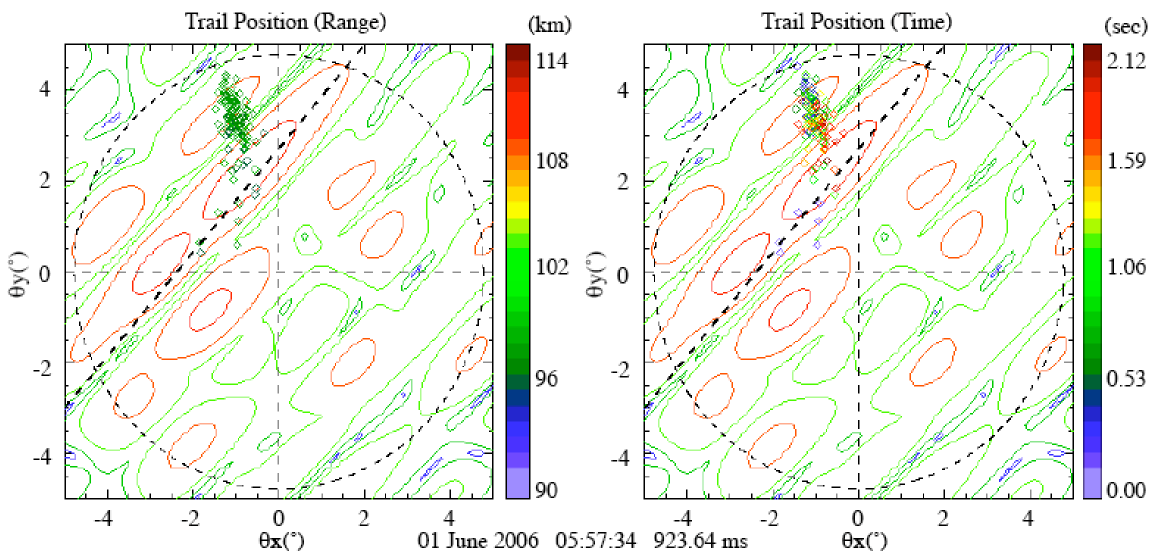
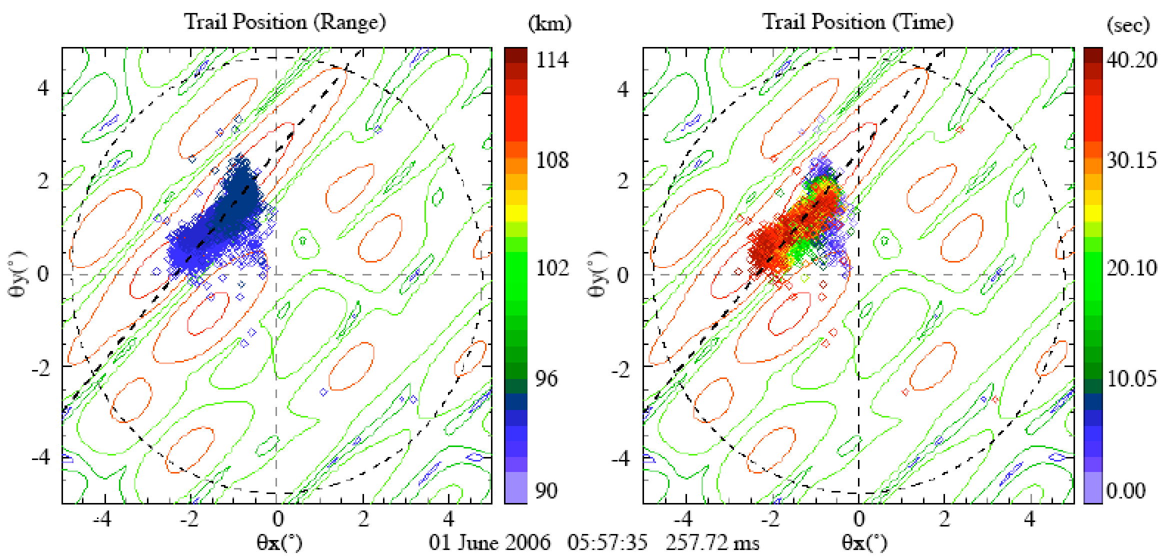


Figure 15. (b) Position of the head-echo shown in Figure 15(a). (c) Position of scatterers associated with part (1) of the trail.

(d)



(e)

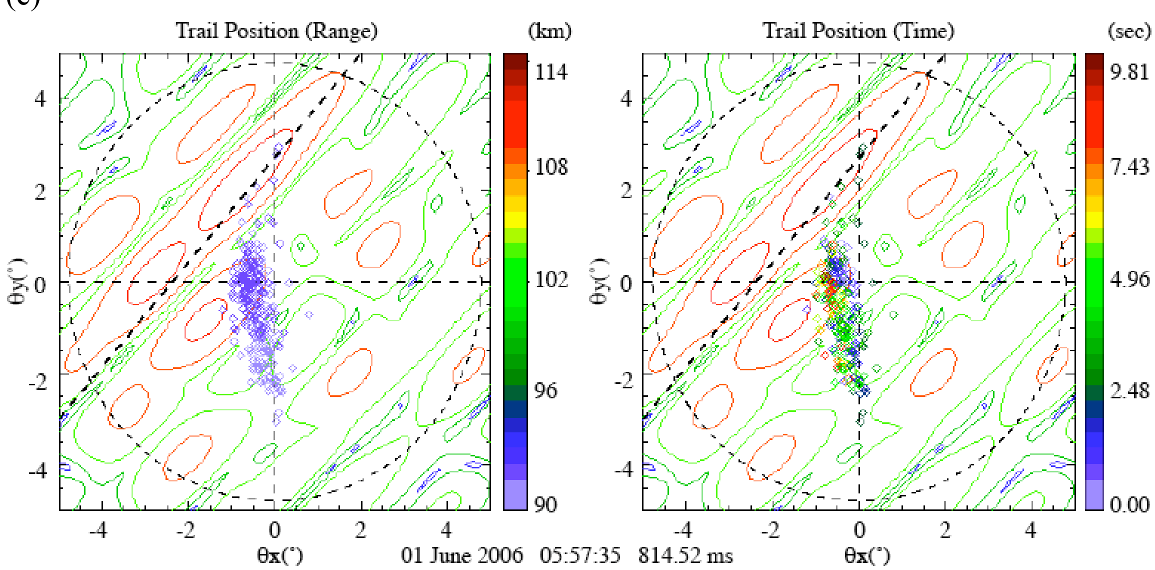


Figure 15. (d) Position of scatterers associated with part (2) of the trail. (e) Position of scatterers associated with part (3) of the trail. It is observed clearly that the scatterers for the longer duration component of the trail (d) occur exclusively in the **k⊥B** region unlike those responsible for shorter duration trail components (c,e). We interpret the three trail components as individual meteoroid fragmentation events that concentrate excess plasma in the three altitude regions.

2.3 Discussion

It is clear from our observations and statistical analysis that long duration RSTEs can be explained to a large degree from a radio science perspective and, to a certain extent, without detailed plasma physics considerations. That is, these results along with factors such as meteoroid fragmentation, radar sensitivity, and wavelength, impact possible plasma physics interpretations of RSTEs, especially as regards to RSTE onset delay relative to the head-echo and the altitudes over which RSTEs are observed. In particular, we find that the duration of the RSTE largely depends on the viewing geometry, given sufficient plasma, or to be more precise on the viewing geometry relative to the radar $\mathbf{k} \perp \mathbf{B}$ region. Mathews [2004] shows via simulation the effect of geometry on the interpretation of meteor FAI [Field Aligned Irregularity] scattering—our results are the first observational confirmation of these results. The basic conclusion from Mathews [2004] is that as the trail plasma progressively spreads parallel to the geomagnetic field – by ambipolar diffusion, winds, instability driven diffusion, or related mechanisms – and begins to fill a Fresnel zone, the radar scattering pattern becomes increasingly narrow – peaking in the backscatter direction only for those events in the radar $\mathbf{k} \perp \mathbf{B}$ region. Further, the time delay from the head-echo to onset of observed trail-scattering is associated both with the development of plasma irregularity structures in the meteor trail plasma—these structures are apparently intrinsic to the trails of fragmenting meteoroids—and with the transport time of the plasma from a location just outside the radar $\mathbf{k} \perp \mathbf{B}$ region to where the Radar Cross Section (RCS) of the developing FAI (Field-

Aligned Irregularity)-structure becomes sufficient to be seen in the **k⊥B** region. Also, within this perspective, we contend that more information concerning meteoroid and trail processes—e.g., fragmentation processes—can be inferred.

As summarized in Figure 10, almost all the long duration echoes we observed showed scattering concentrated from the radar **k⊥B** region, but the short-duration RSTEs were observed from throughout the illuminated volume. These observations can be explained as follows. The FAI-scatterers that develop in a trail that is far away from the **k⊥B** region do not present a large RCS to the radar. That is, we can observe RSTEs far away from the **k⊥B** region because the initial irregularities are less–aspect sensitive with a wider scattering pattern, while still presenting a relatively large RCS to the radar. As the scatterers field align, the scattering pattern narrows and the RCS in the direction of the radar decreases. As has been noted, it takes a very short time—a few milliseconds usually (the Figure 14 RSTE event appears to have occurred with no delay relative to the head-echo)—for the trail structure to develop, yielding the scatterers that progressively field align and become highly aspect sensitive, thus making most of the RSTEs observed away from the **k⊥B** region 'short–duration echoes'. That is, if we viewed many of these events with two, closely spaced, identical radars then we would find that some short-duration RSTEs seen from one radar would appear as long-duration events to the second radar. This point in emphasized in Figure 16 as we discuss next.

We observe the longest duration RSTEs only when the scatterers are located in the radar **k⊥B** region. That is, the meteoroid trajectory must pass through the **k⊥B** region or close to it in order for long-duration RSTEs to be observed by a sufficiently sensitive VHF/UHF radar. This reasoning of course assumes that the meteor trails derive from meteoroid events of sufficient mass and energy to produce the necessary plasma that then rapidly **B**-field aligns producing an FAI-structure that appears as an RSTE if the viewing geometry is satisfactory. It is most important to note that the viewing geometry typically varies along the meteoroid trajectory. That is, our results indicate that most of the RSTEs from meteoroid events of sufficient mass and energy likely would be seen as long duration echoes if viewed in the correct geometry as is explained with the help of Figure 16. In Figure 16, an RSTE, which lies in the $\mathbf{k}\perp\mathbf{B}$ region of radar located at point 1, will be observed as a long duration event from point 1, but the same event will be observed as a shorter-duration event from point 2 where the required geometric conditions are not satisfied. The Figure 16 RSTE could be an example of such a meteor event. For the Figure 16 event that occurs many Fresnel zones (a Fresnel zone is $\sqrt{R\lambda/2}$ ~ 550 m at R=100 km for JRO) away from the $\mathbf{k}\perp\mathbf{B}$ region, we contend that we observe the less aspect sensitive (wide scattering pattern) initial part of the trail and not the more aspect sensitive FAI structure that evolves later in the trail lifetime and that might be observed as a long-duration echo from a correctly situated radar for which the $\mathbf{k}\perp\mathbf{B}$ geometry is satisfied. Finally, it is interesting to note that the two long duration meteor trails observed away from the $\mathbf{k}\perp\mathbf{B}$ region (see Figure 11b.) occurred at low altitudes. In fact, only a part of the trail is visible over our lower range gate of 90 kilometers. Dyrud et al. [2002, 2005] report that non-specular meteor trails/RSTE are only unstable within a limited altitude range, confining these trails within an altitude range of 95-105 km, in contrast, we observe RSTEs over 90-110 km altitude range. These low altitude, long duration non-**k⊥B** RSTEs suggest a different formation and/or evolution mechanism for the formation of trail irregularities as contrasted with those at higher altitudes. One of the possible explanations for the occurrence of these events is that the trail irregularity structure at these low altitudes evolves much more slowly —with longer diffusion times —than those at higher altitudes yielding the longer duration for the low aspect sensitivity scattering stage. These low-altitude events are discussed in more detail in the next chapter.

2.4 Conclusions

The results presented in this chapter show that long–duration range spread trail-echoes (RSTEs) or non-classical meteor echoes can be explained to a large extent from a radio-science perspective. However the implications of these results regarding the physical processes by which trail-irregularities form are profound. The fact that almost all of the long duration RSTEs that we observe originate from the **k⊥B** region points to the interesting conclusion that the observed onset time and duration of most RSTEs is determined by viewing geometry as well as meteoroid mass, energy, and fragmentation processes along with radar sensitivity and wavelength; Figures 10-15 demonstrate these features. Note that viewing geometry can vary significantly along a typical meteoroid trajectory with part of the trail inside the **k⊥B** region and a larger trail component outside this region, thus yielding both variable onset delays to the RSTE and variable RSTE lifetime as a function of range. To further this interpretation, we contend that two identical, closely spaced radars would observe the same RSTE event differently—one radar may see a short–duration–only event, while the other radar may see a long duration component (or a mix of the two results plus different onset delays)—depending on how closely the meteoroid trajectory crossed through the common viewing volume relative to the **k⊥B** region for each radar. Our findings also point to immediate onset (zero-delay relative to the head-echo) RSTEs that may be due to meteoroid fragmentation and certainly raises questions about the formation mechanism of RSTEs at lower altitudes. As such, these results present considerable challenges to theories interpreting RSTE development in terms of the onset of Farley-Buneman/Gradient Drift (FBGD) instabilities.

Dyrud et al. [2002] adopts a mean delay of 20 msec between the head-echo and RSTE onset based on 16 example events observed using the ALTAIR 160 MHz radar and uses this result plus the altitude distribution of the RSTEs to support a plasma instability model for the trail evolution. Specifically, Dyrud et al. asserts that the meteor trails are Farley-Buneman gradient drift unstable only over a limited altitude range that depends on the mass and energy of the meteoroid. We observe RSTEs throughout the meteor zone (90-115 km in this case) with onset delays that depend on viewing geometry and on the radar sensitivity to a particular event. We additionally observe zero onset-delay events or event components. Dyrud et al. [2004] invokes the Dyrud et al. [2002] approach to propose a method of deriving meteor velocity from the properties of the observed RSTE, but does so without recognizing the relationship of the RSTE properties to the $\mathbf{k}\perp\mathbf{B}$ region. Here they used a sample of six meteor events from the ALTAIR radar with their Figure 1 giving the archetypal event. We note that their Figure 1 event actually appears to display a small region of no delay or at least comparatively very little delay between the head- and trail-echoes corresponding, we conclude based on our results, to the $\mathbf{k}\perp\mathbf{B}$ region or possibly to a fragmentation event giving immediate rise to a scattering region. Dyrud et al. [2005] invokes the same event on the way to modeling radar meteor trails (RSTEs) again without detailed utilization of the geometry of the meteoroid trajectory relative to the $\mathbf{k}\perp\mathbf{B}$ region. Dimant and Oppenheim [2006] note in their introduction that "Nonspecular meteor echoes observed by HPLA VHF or UHF radars like the one shown in [their] Figure 1 typically originate from trails where the radar points close to perpendicular to the geomagnetic field." They however do not take into consideration the fact that the detailed properties of an observed RSTE event depend critically on the geometry—as demonstrated herein—and thus their predictions need to be mapped to appropriate geometries. We conclude that although it seems reasonable that Farley-Buneman/Gradient Drift instabilities play a role in RSTE formation and evolution, the complexities of RSTE dependence on "radio science" issues and on altitude significantly clouds the issue. Indeed, it remains possible that plasma instabilities are not necessary to explain at least some of the observed events. That is, that normal parallel-**B** diffusion and irregularities in the trail plasma production owing to meteoroid fragmentation/ablation properties may give rise to the irregularities that appear as RSTEs to the radar.

Common-volume, multi-static, multiple- frequency radar studies would go a long way in resolving most of these issues. These multi-static common volume radar observations form the subject of the next chapter.

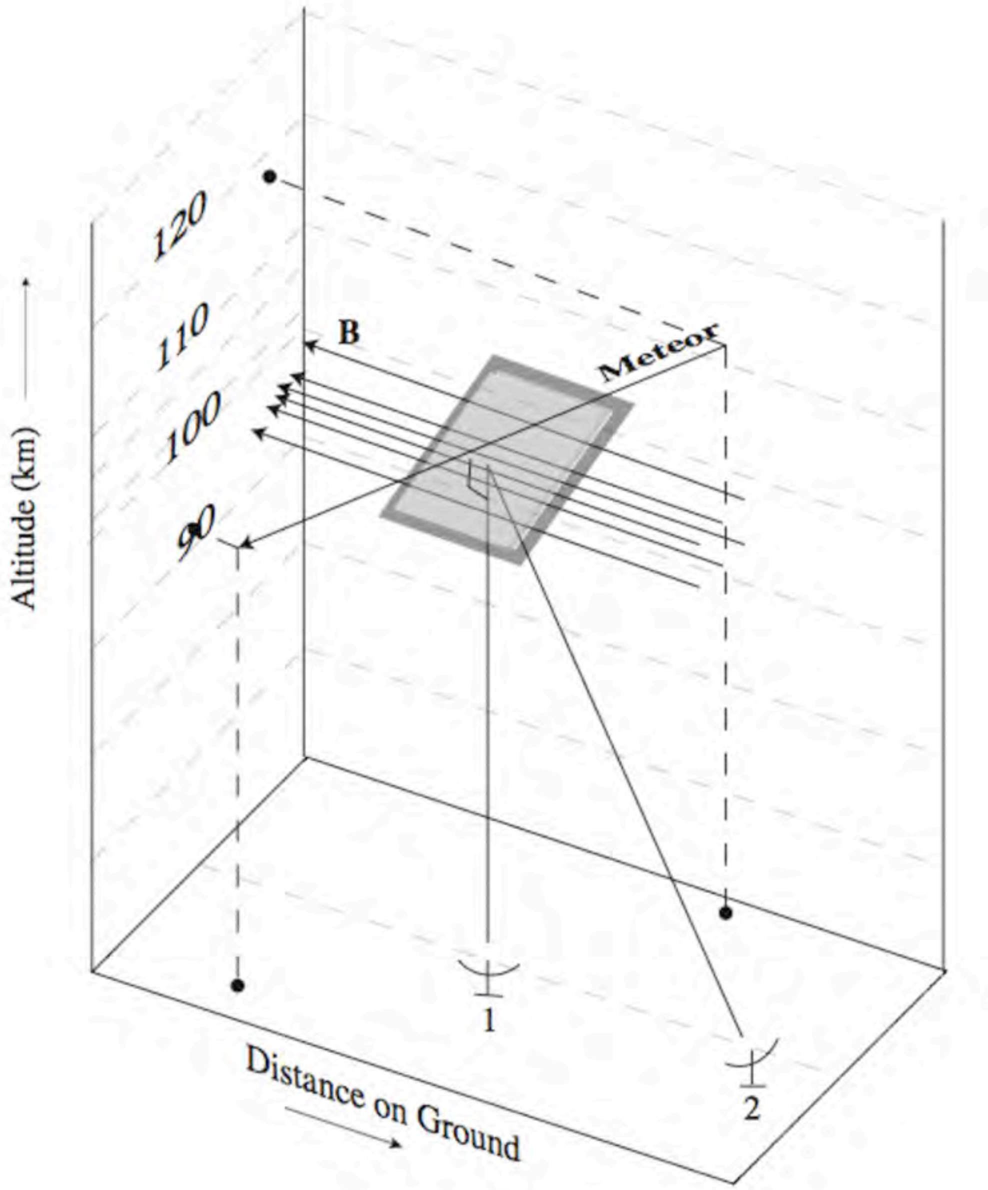


Figure 16. An RSTE might be seen as a ‘long-duration’ echo from radar at position 1 for which it lies in the **k⊥B** region and simultaneously be observed as a ‘short-duration’ echo from a radar located a position 2 for which it lies away from that **k⊥B** region.

Chapter III

Multi-static common volume radar observations

In the last chapter, it was found that an overwhelming majority of the long duration meteor echoes are obtained from scatterers located in the **k⊥B** (**k** = radar wave vector, **B** = magnetic field) region of the radar (the **k⊥B** locus ± 1 Fresnel zone at 100 km altitude) whereas the shorter duration RSTEs are found to occur from throughout the illuminated volume. On the basis of these results, it was 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. Figure 17 shows schematically that for two radars placed close to each other and looking at a common volume, a RSTE occurring at the **k⊥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) because it lies away from its **k⊥B** region. This conclusion has important implications because current modeling 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, a second radar with viewing volume common to the Jicamarca radar was constructed in Carapongo, a location approximately 5 km geomagnetically south of Jicamarca. The results from these multi-static common volume radar (MSCVR) observations, the first of its kind when it comes to RSTE observations, are presented in this chapter. These results are also reported in Malhotra et al. [2007b]. 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.

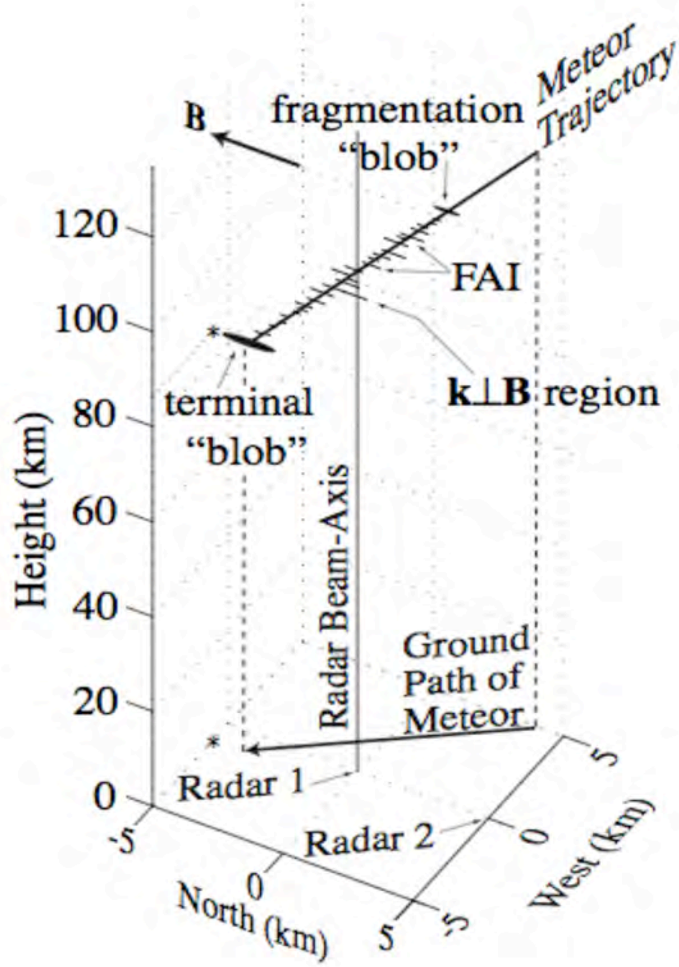


Figure 17. A RSTE occurring in the **k⊥B** region of Radar 1 might be seen as a long duration event from Radar 1 and a small duration event from Radar 2 because it lies away from its **k⊥B** region.

3.1 Experimental Set-up

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 and the signal was received at both the Jicamarca and Carapongo arrays. The JRO main array is centered at 11^0 57′ 05.18″ S, 76^0 52′ 27.43″ W and 507 m altitude. The Carapongo array was located at 11^0 59′ 56.51″ S, 76^0 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 3.86^0 East of geographic south of JRO. The JRO antenna beam was pointed perpendicular to the geomagnetic field at JRO, at an angle of approximately 1.6^0 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 $\sqrt{R\lambda/2}$ ~ 550 m at R=100 km for 50 MHz Jicamarca radar) is denoted as the **k⊥B** region. 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 ($1/64^{th}$) 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 $\sim 85°$ with respect to the magnetic field.

3.2 Observations and Analysis

In this section, we present the initial results from the first ever MSCVR observations of RSTEs. Figures 18 (a) and (b) show RTI 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 Figure 18 (a) and (b) features common to both observing sites are labeled 1-4 in Figures 18 (a-b) and 18 (c-d). We chose these long duration events as they show many interesting features as we discuss below. The trail component occurring at 93-95 km (labeled 1) lasts for well over 40 seconds as seen in Figure 18a, and so we classify it as a long duration event per discussions in the last chapter. Figure 18b 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 is discussed in detail below.

Figure 18 (a-b) also shows another meteor event (labeled 3), at 12 seconds and approximately 100 km, that lasts for around 20 seconds when observed from Jicamarca (Figure 18a) and only for ~ 4 seconds when observed from Carapongo (Figure 18b). 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 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 18a) than at Carapongo (Figure18b) owing 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 Figure 18c-d).

Figures 18c and 18d show the interferometric positions of the RSTE components identified in Figure 18 (a-b). Event labels in Figure 18 (c-d) correspond to those in Figure 18 (a-b). In Figures 18c and 18d, 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 also is plotted with the red contour showing a transmitted level of up to -10 dB. In Figure 18c, 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 Figure 18 (c-d), 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 18b, 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 JRO to Carapongo is 4.6°. The event component labeled 2 is discussed below in the context of the Figure 19 results.

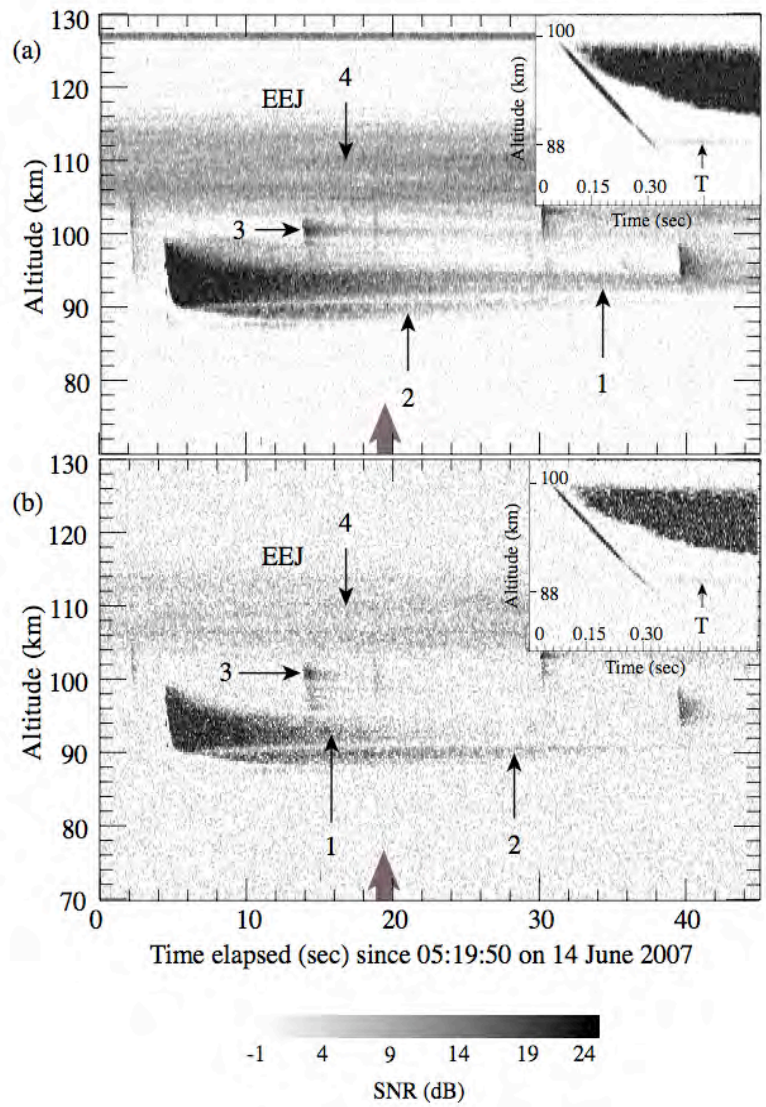


Figure 18 (a) RTI (Range-Time-Intensity) plot of long duration meteor echoes at JRO. The meteor trail at labeled 1 lasts for well over 40 seconds. (b) RTI plot of the same event as observed from Carapongo. The corresponding long duration part of the trail (again labeled 1) lasts for just over 15 seconds. 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 km. Also note that event 3 is viewed as long duration at JRO and short duration at Carapongo. The insets in (a) and (b) show high resolution plots of the head echo at Jicamarca and Carapongo respectively. 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.

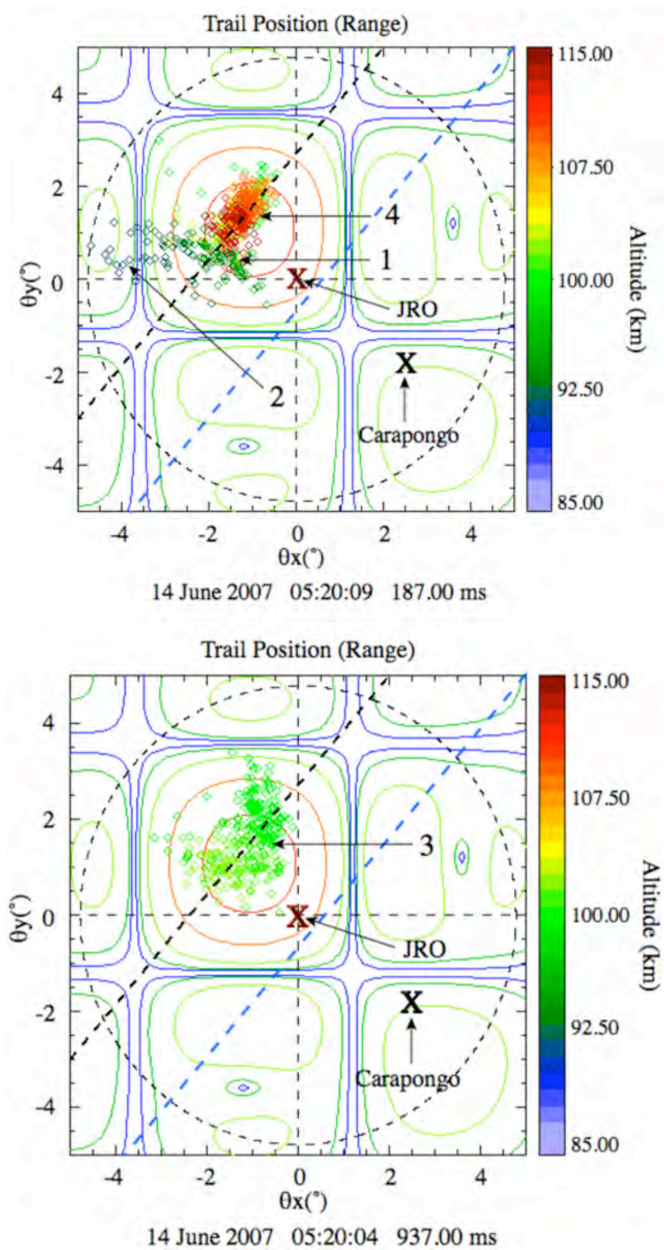


Figure 18 (c) and (d) Position of the Figure 18a RSTE features with respect to range as observed from Jicamarca. The black dotted line represents the **k⊥B** region of the Jicamarca radar whereas the blue dotted line represents the **k⊥B** region of the bistatic system (Jicamarca and Carapongo). Here (1), (2) and (3) indicate the position of the trails labeled (1), (2) and (3) in Figure 18a respectively. Also, (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.

3.3 Discussion

In the last chapter, we hypothesize that if there were two identical radars placed very close to each other and looking at a common volume, an 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. Figure 18 (a-b) gives strong support to this hypothesis using the JRO/Carapongo multi-static radar system. Here we present a case study of two RSTE events occurring in the **k⊥B** region of JRO (Figures 18c and 18d) that are seen as long duration events in Jicamarca (Figure 18a; events 1 and 3) and as short duration events at Carapongo (Figure 18b; events 1 and 3). As we noted above, 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 (dotted black and blue lines respectively) for this long duration trail to be seen as having about the same duration at both Jicamarca and Carapongo. As shown in Figure 18c however, 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.

The question arises as to why 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 with the help of Figure 19. Figure 19 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 18 features. The time frame of the Figure 19 display is indicated by the thick arrow near 20 sec on the Figure 18 time axes. It can be seen clearly 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 composed 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.

In the last chapter, while presenting the statistical analysis of long duration echoes using the same JRO main array, we also report two long duration trails that were observed away from the **k⊥B** region of the radar. Both these trails were low altitude trails (at ~ 90 km), and we commented that this location might suggest a different mechanism for formation/and or evolution of RSTEs at lower altitudes. We note that the trail in Figure 19 also occurs at a similar low altitude. Dyrud et al. [2002, 2005] report that FBGD [Farley Bunemann Gradient Drift] 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 the last chapter, 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. Also, electrodynamic instabilities may be suppressed by collisions. A more detailed study of these lower altitude, "blob-like" RSTEs will be the subject of future work.

The insets in Figure 18 (a-b) 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 observed clearly that the onset-delay between the head echo and the trail echo is different in Jicamarca (Figure 18a-inset)—where it happens to be less—compared with Carapongo (Figure 18b-inset). This result has far reaching implications because the delay between the head echo and the trail is considered to be a signature property of the RSTEs [Dyrud et al., 2002] – although in the last chapter, we 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 Figure 18a and 18b 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.

The inset figures 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 fragmentation or "terminal" events, which have also been often observed in data collected from the Arecibo radar [Mathews, 2004]. This figure is apparently the first reported instance of these terminal events at JRO.

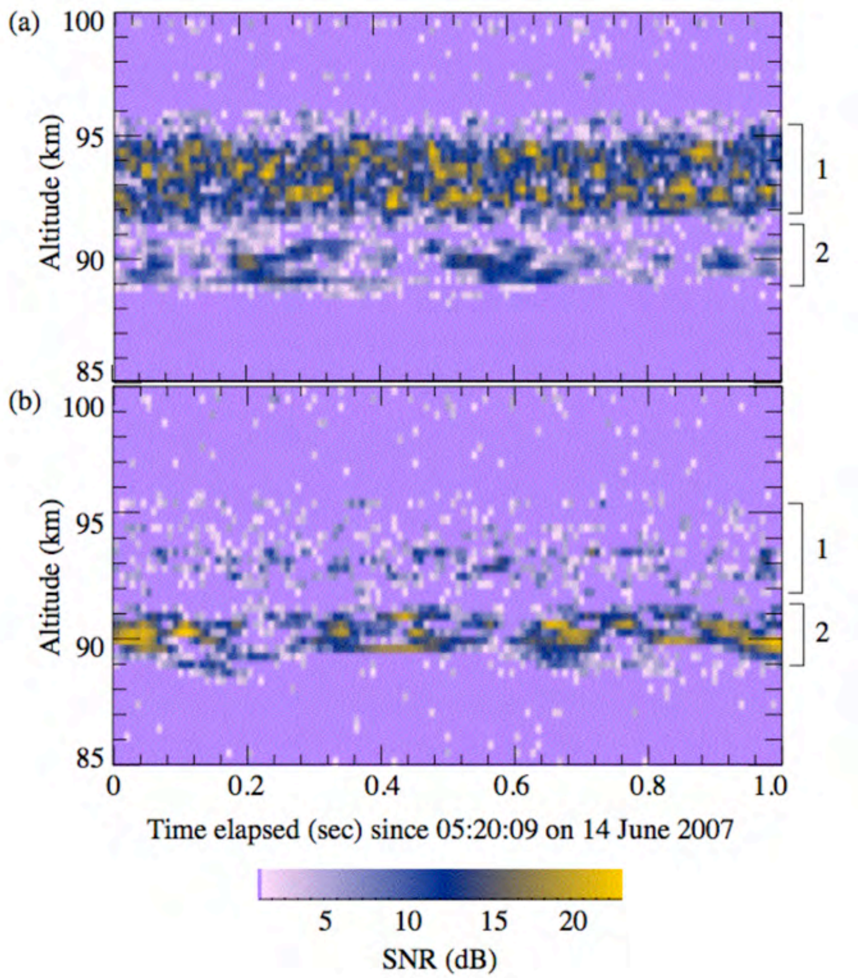


Figure 19 (a) and (b) High-resolution RTI plot of a part of a trail for the meteor echo shown (at the time near 20 sec indicated by ↑ on the time axis) in Figure 18 as observed from the (a) Jicamarca radar (b) Carapongo radar. The difference in the structure of the upper long duration trail (93-95 km) and the lower-altitude long duration trail (90 km) can be seen clearly in the Jicamarca radar. The lower-altitude long duration is seen to comprise of small blobs from both the radars.

3.4 Conclusions

We have reported the 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 in the last chapter that if there were two identical radars close to each other looking at a common volume, then a meteor echo, caused by a meteoroid of sufficient mass and energy, occurring at the $\mathbf{k} \perp \mathbf{B}$ 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. 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 result implies that careful consideration should be given to the viewing geometry before any conclusions can be derived on the development of plasma instabilities based on the distance between the head echo and the trail echo.

Chapter IV

Effect of meteor ionization on Sporadic-E

Sporadic-E (defined here as altitude-narrow E-region layers that last tens of minutes) is arguably the most famous and well-studied E-region layer [see Mathews (1998) for a review], being first observed by ionosondes in as early as the 1930s. Since then, this mid–latitude, E-region phenomenon has been observed and studied extensively using ionosondes, radars, and rockets. Extensive progress has been made in the study of this layer, and the windshear theory – first proposed in the 1960s – has withstood the test of time and remains the most widely accepted theory for the formation of this layer. In order to explain the observed long lifetimes and altitude narrowness of this layer, it has long been accepted that this layer is composed of metallic ions. And meteors are widely accepted to be the only source of metallic ions in the E-region of the ionosphere. So, it would seem logical that meteors are responsible for the formation of Sporadic-E. In fact, it was all the way back in 1938, that Pierce put forward this idea that meteor ionization is responsible for the formation of Sporadic-E. To date i.e. in over 70 years however, no evidence has been found of a direct relationship between meteor ionization and Sporadic-E!!

This lack of evidence is clearly not due to the lack of effort – if anything, various studies on finding a relationship between meteors and Sporadic-E have just made the problem more confusing. Here are just a few examples - over the years, there have been many reports of high to low correlation between the meteor shower activity and Sporadic-E [Chandra et al., 2001; Doniy, 1971; Grebowsky et al., 1998; Naismith, 1956] to absolutely no correlation between meteor shower activity and the occurrence of Sporadic-E (Baggaley and Steel [1984] using 30 years of observational data) to even an inverse relationship between the meteor activity and the occurrence of Sporadic-E [Kotadia and Jani, 1967]!

One of the reasons why such diverse results were obtained in all the previous attempts to study this relationship was that they all assumed that meteor showers were the cause of Sporadic-E. Based on this assumption, an attempt was made to correlate the occurrence of meteor showers with the observations of Sporadic-E. Now however, with the use of the very sensitive HPLA radars for meteor studies, we know better, that the non-shower or sporadic meteors far outnumber the shower meteors. So, one does not need to be dependent on meteor showers for observing Sporadic-E. The sporadic meteor activity continues in full force all year round. No wonder all the earlier studies found all possible correlations between meteors and Sporadic-E.

But the overwhelming presence of sporadic meteors, however poses another, in fact more challenging problem. HPLA radar observations of Sporadic-E have shown that Sporadic-E is in fact totally “unsporadic”. If one has a powerful enough radar then one can observe Sporadic-E all the time, thus making the word a misnomer. The ubiquitous presence of Sporadic-E makes sense although because sporadic meteors, as stated earlier, are present all year round. Unfortunately this ubiquitous presence complicates the problem of finding a direct relationship between meteors and Sporadic-E. It would be so much simpler if we could just possibly turn off the meteors for a little while, see the Sporadic-E disappear and then turn on the meteors again and then see the Sporadic-E appear again.

What complicates this problem even more for us is the fact that Sporadic-E has never been observed at the geomagnetic equator, even with the sensitive Jicamarca radar. Relatively little progress has been made in the study of equatorial Sporadic-E when compared with the study of mid-latitude Sporadic-E. The argument for not observing Sporadic-E at the geomagnetic equator has been that at the geomagnetic equator, owing to the geomagnetic field lines being totally horizontal, the electrons would not be able to follow the ions, which is necessary for the formation of this layer. It should be noted that, however, Jicamarca does not lie exactly at the geomagnetic equator but at $\sim 1^{o}$ dip angle.

It is obvious from the above discussion that finding a relationship between meteor ionization is a challenging task and something that has remained an unsolved problem in the community for too long. Some of the questions that remain unanswered are:

- Can Sporadic-E be observed at Jicamarca at all??
- If yes, then why has it not been observed at all in the past 40 years??
- Is there a direct relationship between meteor ionization and Sporadic-E?? Yes!! But how do we find it??

In this chapter, we answer the above questions and to solve the long standing mystery regarding the relationship between meteors and Sporadic-E. We present in this chapter what we believe to be the first Sporadic-E observations from JRO. The structure and characteristics of these equatorial Sporadic-E layers is compared with their mid-latitude counterparts. We also demonstrate the immediate effect of meteor-produced ionization on the formation and evolution of the equatorial Sporadic-E layer. The results of this chapter also form the basis for Malhotra et al. [2008].

4.1 Experimental Set Up

The results presented herein all derive from observations at JRO carried out on 7 June and 10 August 2006. The north and south quarters of the Jicamarca array were combined for transmission. A 39 μs 13–Baud Barker coded pulse was transmitted on both the days with an IPP (Inter Pulse Period) of 870 μs on 7 June and 900 μs on 10 August. In reception, three subarrays (each 1/64th of the main antenna) were sampled independently at a sampling rate of 3 μs to conduct interferometric analysis of received echoes, thus providing a 450 m range resolution. For 10 August observations, the radar beam was pointed vertically, hence away from the **k** ⊥ **B** region of the radar (JRO is located at ~1^o dip angle), to minimize interference from EEJ. The **k** ⊥ **B** region can be observed through the sidelobes however, and hence the EEJ can be clearly observed as shown in figures later. For the 7 June observations, the antenna beam was pointed perpendicular to the geomagnetic field, i.e. at an angle of approximately 1.6^o N from the vertical. More details on the parameters for the 7 June observations can be found out in Section 2.2 of this document.

4.2 Observations and Analysis

Figures 20(a) and 20(b) show RTI (Range Time Intensity) plots of our data collected on 10 August and 7 June respectively. In Figure 20(a), the Sporadic-E, a narrow E-region layer lasting tens of minutes, can be seen beginning at 0300 hours at ~98 km and lasting for ~1.5 hours before reappearing at ~ 0545 hours. The EEJ can also be seen at heights varying from 98-114 km altitude. In Figure 20(b), the layer can be observed sporadically beginning at 0553, 0618, 0633 and 0713 hours. The layer can also be observed in early morning hours when there is a very strong EEJ present i.e. beginning at 0713 hours. It should be noticed that although the occurrence of the convergence layer has an obvious correlation with the EEJ in Figure 20(b), there is no such correlation to be seen in Figure 20(a). Figure 20(c) is a high-resolution RTI plot of the Sporadic-E layer observed in Figure 20(a) over a shorter period. The effect of the large number of meteor echoes occurring in this time period on the Sporadic-E can be observed easily on this layer that is seen to descend clearly in altitude by about 1 km over this period, a characteristic of these altitude narrow layers.

Figure 21 shows the position of the layer shown in Figure 21(c) obtained via interferometry analysis of the layer at a time period when there was no "interference" by the meteor echoes. The black dashed line represents the $\mathbf{k} \perp \mathbf{B}$ region of the Jicamarca radar at 100 km. The dashed ellipse indicates the region within which unambiguous echo position can be calculated. The contours represent the transmitting and receiving patterns of the JRO radar. Calibration is done using the highly aspect sensitive EEJ [Kudeki and Farley, 1989] and long-duration meteor echoes [Malhotra et al., 2007a; b]. It can be clearly observed in Figure 21 that the scatterers responsible for the Sporadic-E radar signature lie in the $\mathbf{k} \perp \mathbf{B}$ region of the radar.

Figures 22 and 23 show the direct effect of meteor ionization on Sporadic-E, the first-ever results showing this relationship. In Figure 22, the effect of the meteor echo occurring at ~10 seconds on the Sporadic-E can be observed easily. The ionization produced by the above-mentioned meteor event can be seen strengthening or reinforcing the Sporadic-E return. Figure 23(a) shows another RTI plot depicting the effect of meteor induced ionization on the Sporadic-E, although in this case the relationship is not as obvious as that shown in Figure 22. We utilize interferometry to study this relationship. Figures 23(b) and 23(c) are interferometry plots, similar to Figure 21. Figure 23(b) shows the position of the scatterers associated with the initial 2 seconds of the meteor trail is duration. It can be seen that the meteor echo starts well away from the $\mathbf{k} \perp \mathbf{B}$ region of the radar and hence, as shown by Figure 21, lies well away from the Sporadic-E return. Figure 23(c) shows the position of the scatterers associated with the latter part of the trail, a 12 second time period starting from 04:19:31 hours. One can observe that as time progresses, the scattering associated with the meteor trail originates exactly from where the layer was observed [Figure 21]. Thus, it can be concluded that in this case too, meteor ionization affects the Sporadic-E, although the effect is not as easily noticeable as in Figure 22. Numerous other such examples are available.

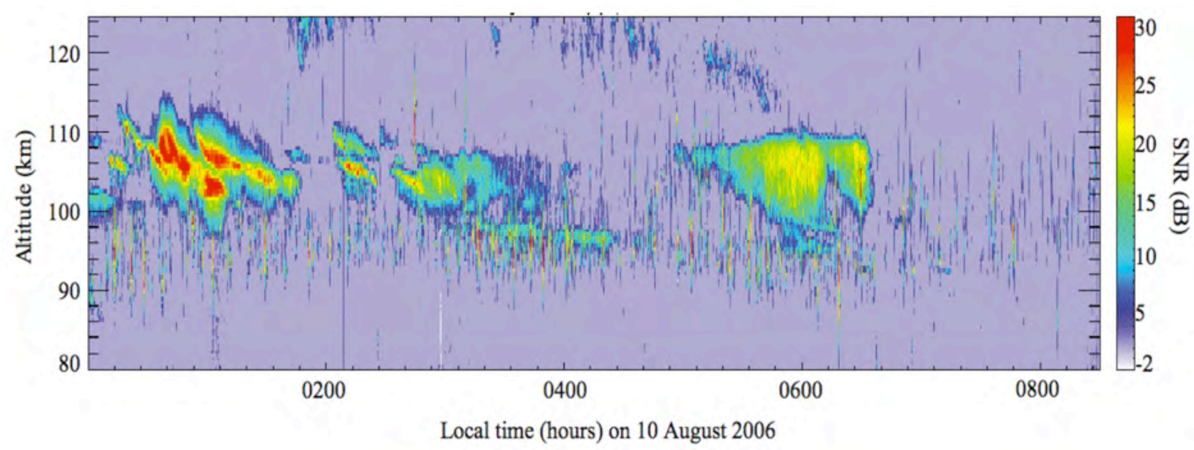


Figure 20. RTI (Range-Time Intensity) plots showing the presence of Sporadic-E (SpE) over Jicamarca. (a) SpE can be observed easily beginning at 98 km altitude at 0300 hours and then again at 0545 hours on 10 August 2006. The layer is seen to descend in altitude over time.

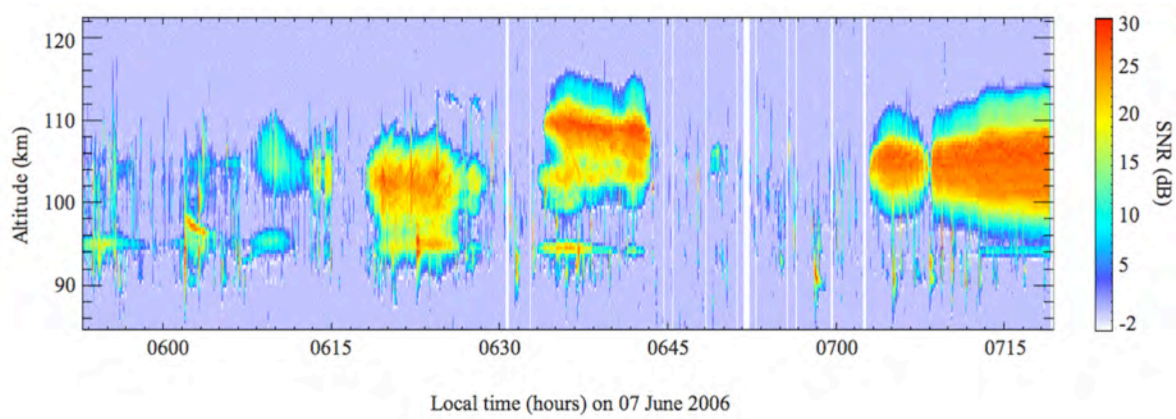


Figure 20 (b) SpE as observed from JRO on 07 June 2006.

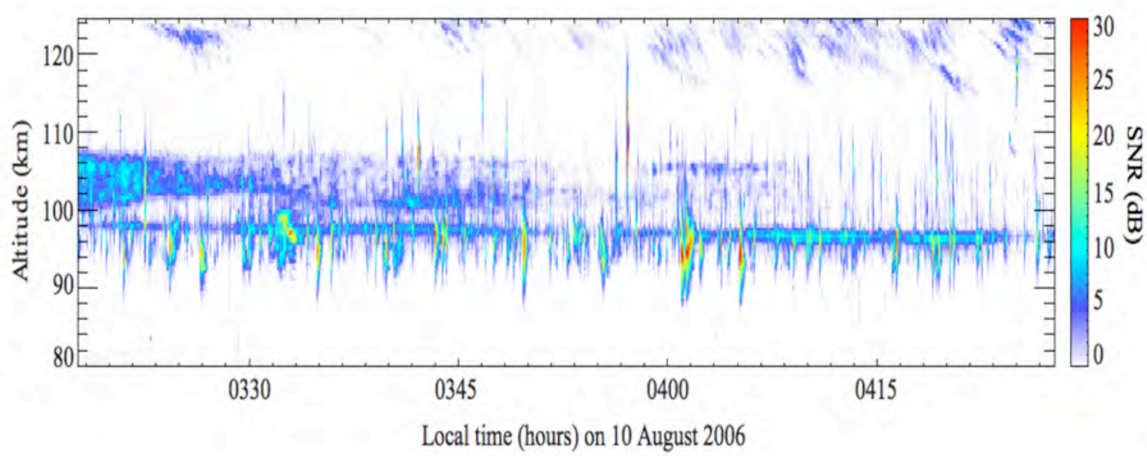


Figure 20 (c) High-Resolution RTI plot of the SpE observed in Figure 20(a) over a shorter time period.

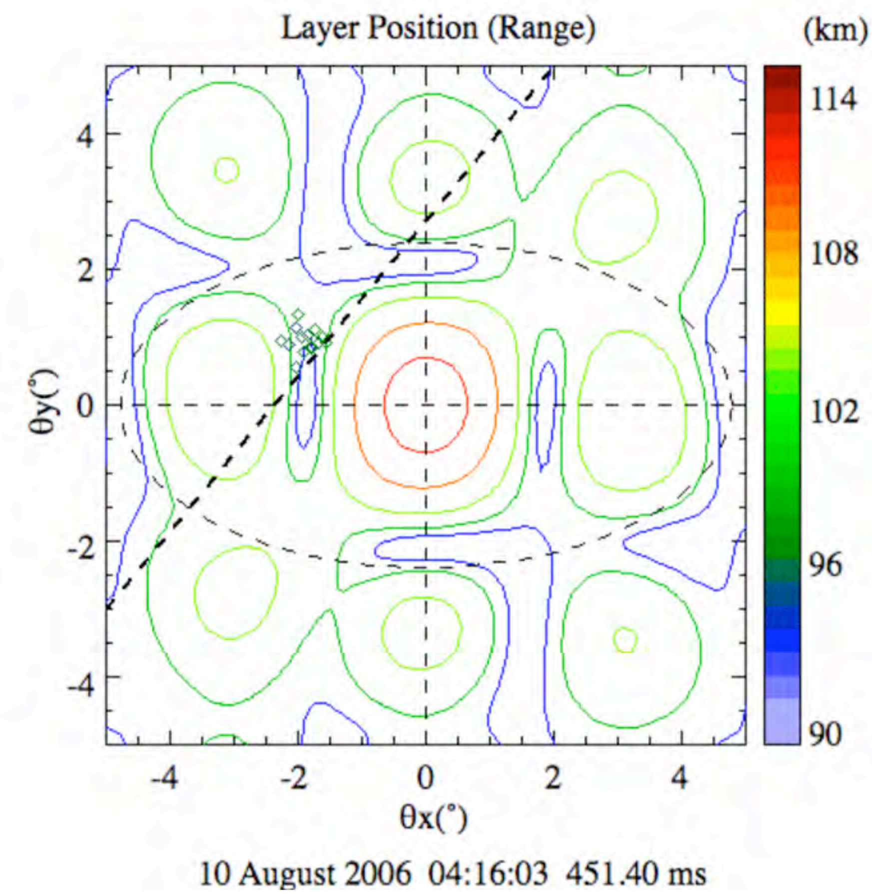


Figure 21. Interferometry plot showing the positions of the scatterers responsible for the Sporadic-E radar signature observed in Figure 20(c). The black dashed line represents the **k** ⊥ **B** region of the JRO radar at 100 km. It can be observed clearly that the scatterers lie in the **k** ⊥ **B** region of the radar.

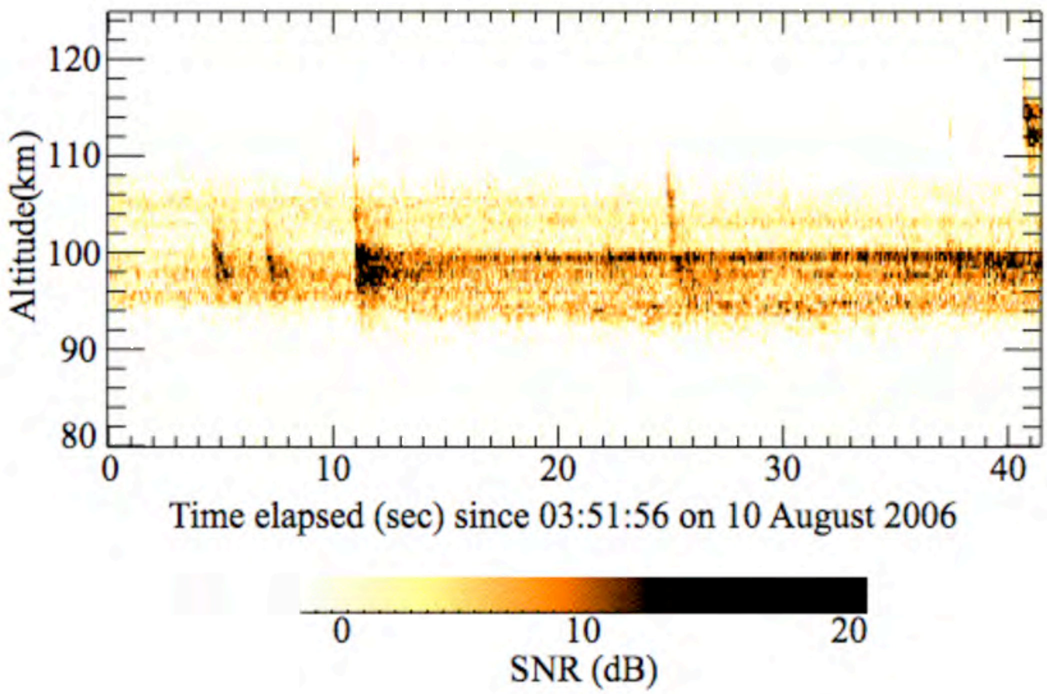


Figure 22. RTI plot showing a direct relationship between meteor–induced ionization and Sporadic-E. The ionization produced by the meteor event occurring at ~ 10 seconds can be clearly seen strengthening the Sporadic-E return.

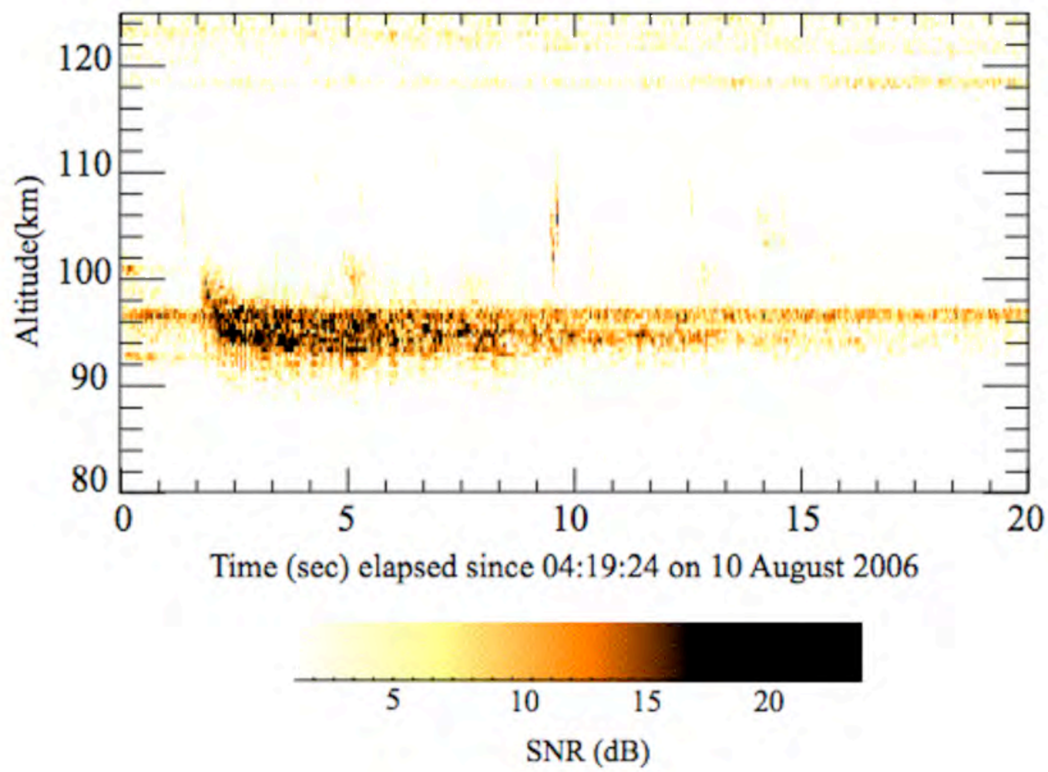


Figure 23. (a) RTI plot showing direct relationship between meteor ionization and Sporadic-E.

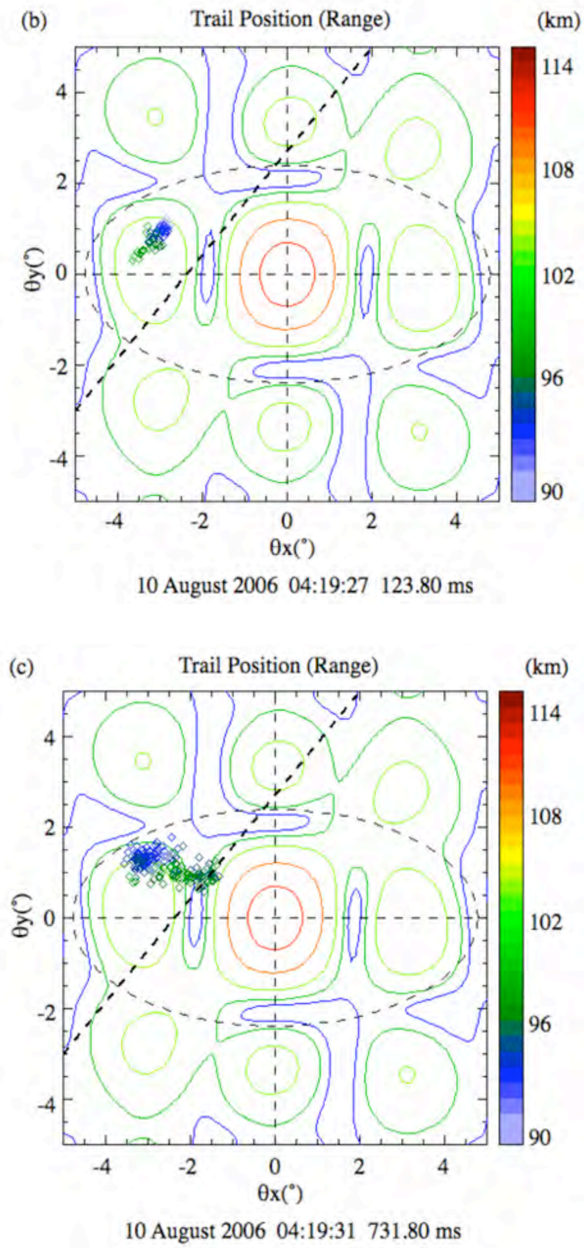


Figure 23 (b) Interferometry plot showing the position of the scatterers associated with initial 2 seconds of the meteor trail. The meteor echo starts well away from the **k** ⊥ **B** region of the radar, and hence away from the Sporadic-E return. (c) Position of the scatterers associated with a 12–second time period of the trail starting from 04:19:31 hours. As time progresses, it can be clearly observed that the scattering associated with the meteor trail originates from the position of Sporadic-E return (Figure 21).

4.4 Discussion

Figure 20 (a)-(c) show the first observations of Sporadic-E by the JRO 50 MHz radar, and quite possibly by any radar located near the geomagnetic equator. As noted above, windshear theory is the widely accepted explanation for the formation of Sporadic-E. Simply stated, the windshear theory refers to the vertical component of the ion motion in response to the Lorentz Force ($\mathbf{F}_{ion} = q_{ion} (\mathbf{v}_{ion} \times \mathbf{B})$; where q_{ion} is the ion charge, $\mathbf{v}_{ion}$ is the ion vector speed, and large-scale electric fields are taken to be absent) where the long-lived metal ions are taken to be collisionally embedded in the neutral wind that is responding periodically to tides and/or acoustic gravity waves (AGWs). In particular, convergent vertical ion motion occurs when there is a westward wind above and an eastward wind below. A correspondingly large wind shear also yields ion convergence. Most often the necessary convergence is taken to be the result of tides or acoustic-gravity waves that have a downward phase speed yielding the oft–observed slow vertical descent of the resultant ion layers.

The layer shown in Figure 20(a), also shown at a larger time scale in Figure 20(c), shows a descent with time at the rate of 0.53 m/s. This descent, as stated above, is a well-known feature of mid-latitude Sporadic E attributed to the influence of diurnal and semi-diurnal tides on the layer [Mathews, 1976; Whitehead, 1989]. There is no reason for these tides, which are known to influence Sporadic-E layers observed by the Arecibo ISR [18.3° N, 66.75° W] [Mathews and Bekeny, 1979; Mathews et al., 1997] not to influence the Sporadic-E layers observed using the Jicamarca radar when both the Arecibo and

Jicamarca ISRs lie at similar latitudes in the geographic northern and southern hemispheres respectively. The layers observed in Figure 20(b) do not show any noticeable descent with time.

The altitude at which the equatorial Sporadic-E is seen to first appear in Figure 20(a), 98 km, agrees well with the altitudes at which the mid-latitude Sporadic-E is observed and also happens to be a preferred altitude for the formation of mid-latitude Sporadic-E [Whitehead, 1989]. Obviously, the presence of EEJ would make it difficult to observe Sporadic-E at higher altitudes at Jicamarca.

While discussing the wind-shear theory, Kelley [1989] points out that at the dip equator i.e. when the magnetic field is perfectly horizontal, the highly magnetized electrons would not be able to move perpendicular to **B** to join the converging ions, thus leading to the building up of a huge space charge electric field and bringing the plasma accumulation process to a halt. As they point out however, even a slight dip angle would allow the electrons to move along the field lines from a region of ion divergence to one of ion convergence, thus allowing the building up of layers. This point becomes important because the JRO radar is not located exactly at the geomagnetic equator, but at a $\sim 1^{o}$ geomagnetic north dip angle. It should be noted that there have been reports of Blanketing Sporadic-E observations using ionosondes attributed to horizontal wind shears from similar geomagnetic dip angles [Reddy and Devasia, 1973]

Figures 22 and 23 are the first–ever results showing a direct relationship between meteors and Sporadic-E. Although it has been established for a long time that long-lived metallic ions are necessary for the formation of Sporadic-E, until now no direct relationship has been found between meteor–induced ionization and Sporadic-E. One of the main reasons why we are able to observe this relationship [Figures 22 and 23] is the different scattering mechanisms responsible for observing the Sporadic-E at different regions. Mid-latitude ISRs observe Sporadic-E by means of incoherent scattering whereas Sporadic-E is observed over Jicamarca by means of $\mathbf{k} \perp \mathbf{B}$ (FAI-like) scattering [Figure 21]. This scattering mechanism allows us to study clearly the effect of meteors while they "paint" the convergence layer. Also, the interferometric capabilities of the Jicamarca radar allow us to observe the transport and effect of meteor induced ionization on the Sporadic-E — Figure 23 being a case in point.

We would also like to lastly note the occurrence of descending higher altitude layers in Figures 20(a) and 20(c) which bear a remarkable structural similarity to intermediate layers observed at mid-latitudes [Mathews, 1998]. On conducting interferometric analysis on these layers, we find that these layers are also highly field aligned. Unfortunately, the lack of appropriate height ranges in our present data sets hinders further study of these layers, and they will be a subject of future study.

4.4 Conclusions

We report the first-ever observations of Sporadic-E from the JRO 50 MHz radar, and quite likely the first such observations from any (non-ionosonde) radar located close to the geomagnetic equator. These layers show a descent in time similar to that observed in mid-latitude Sporadic-E, thus pointing to the influence of tides on these layers. These layers also are observed to occur at similar altitudes as their mid-latitude counterparts. The Equatorial Sporadic-E is observed via $\mathbf{k} \perp \mathbf{B}$ (FAI or Fresnel) scattering whereas incoherent scattering is responsible for observing mid-latitude Sporadic-E. These layers observed at Jicamarca appear to be “truly” sporadic in nature but this might purely be a function of the observing instrument. We also have reported the first-ever results showing a direct relationship between meteor ionization and Sporadic-E, something that has been a subject of much speculation and mystery in the community for many years.

Chapter V

Future Work

During the course of this work, we have solved some long standing meteor mysteries, in some cases such as the Sporadic-E, mysteries dating as back as 1930. We have shown that observation of long duration meteor echoes, observed but unexplained despite various attempts since the 1940s, can be explained to a large extent, if not fully explained, purely from a radio science perspective. The fact that almost all the long duration RSTEs that we observe originate from the $\mathbf{k} \perp \mathbf{B}$ region of the radar, a completely “man-made” region, makes one wonder how many of the observed meteor echoes are actually long lasting i.e. last for over 15 seconds. Significantly the same long duration meteor echo could be observed as a short duration echo from a second radar if it lies away from the $\mathbf{k} \perp \mathbf{B}$ region of the second radar as shown in Chapter 3. Also, the effect of mass of the parent meteoroid on the duration of the meteor echo, if any, should be well studied. Any such work should give primary importance to the radio science aspects of the study owing to reasons outlined throughout this document.

Our multi-static common-volume radar observations performed at Jicamarca-Carapongo have shown that other observed meteor properties such as the onset delay between the head echo and the trail are also a function of the viewing geometry. The duration of this onset delay has been used to invoke plasma instability theories in explaining the formation and evolution of RSTEs. We have shown however, that this delay is also a variable depending on the viewing geometry. Hence once again, due consideration should be given to viewing geometry and radio science issues before reaching to any conclusions based on this delay. More multi-static common-volume radar observations using different frequency radars would go a long way in giving us a better understanding of all the radio science issues and also the scattering processes involved in these trails.

We also have been successful in reporting not only the first observations of Sporadic-E from the Jicamarca radar but also in presenting the first ever proof of a direct relationship between meteor–induced ionization and Sporadic-E, a subject of much work and speculation in the community for over 70 years. More observations of the layer need to be carried out in order to study the diurnal and seasonal variability of Equatorial Sporadic-E and also to study the effect of the Equatorial Electrojet on the layer, if any. Also, a similar study needs to be performed to find out the effect of meteor ionization on the formation and evolution of Polar Mesospheric Summer Echoes, if any, which has been the subject of much debate over the past few decades.

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