LOW LATITUDE METEOR TRAIL ECHOES

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ABSRTACT

The meteoroids of mass 10^{-7} to 10^{-9}gm during Geminid meteor shower 2007 entered deep into the atmosphere and created large plasma density gradients. The range spread trail echoes (RSTE) are observed to be formed due to the meteoroids descending with moderate velocities. It has been noticed that there is a time delay for the formation of RSTE after the initial head echo recorded. The growth of RSTE may be attributed to the development of Farley Buneman Gradient Drift instabilities (FBGD). The meteoroids with mass range of few tenths of micrograms have exhibited the growth of RSTE. For different combinations of mass and velocity, RSTE were also recorded at even higher altitudes. The duration of RSTE are lower than that observed at mid and high latitudes. We have observed that meteoroids were able to generate the irregularities similar to that of type I irregularities (which are prominent at mid and high latitudes). It is reported that the meteoroids of significant mass has created large plasma density gradients which are sufficient enough to trigger such echoes.

Keywords: Meteoroid, Head Echo, Specular Trail, FBGD, Plasma density

INTRODUCTION

Every day, large number of grain size micro meteoroids ablate in the Earth's ionosphere - E region at an altitude of 80 – 120 Km destabilize the otherwise quite ionosphere (Williams and Murad, 2002). These meteoroids when enter the Earth's atmosphere, travel at velocities greater than 11.2 Km/s, collide with air molecules and owing to ram pressure, ablate completely creating a trail of plasma around them. This phenomena is sensible with the advance High Power Large Aperture radars (HPLA) operating at Very High Frequencies(VHF) and Ultra High Frequencies (UHF) which results in short duration back scatter echoes often referred to as Head echoes (Close et al., 2002; Janches et al., 2000, 2006; Mathews et al., 2001; Chau and Galindo, 2008; Dyrud et al.. 2008). Few milli seconds after the head echoes being recorded, meteor plasma trails expand and when the radar beam is pointed perpendicular to the expanding column the resultant backscatter from this trail is referred to as specular echo. The backscatter from the off perpendicular trails are termed as non specular trails [Close et al., 2002] or range spread trail echoes (Mathews, 2004). These trails are detected with both HPLA radars [Zhou et al., 2001; Close et al., 2002] and low power radars [Haldoupis and Schlegel, 1993; Reddi and Nair, 1998; Reddi et al., 1992]. With the aid of HPLA radars head echoes, electrodynamics of meteor trails, noctilucent clouds, polar mesospheric summer echoes and the interaction between the meteors and sporadic layers were studied, thus leading to a new research area in ionosphere studies. [Zhou et al., 1999; Gelinas et al., 1998; von Zahn et al., 2002; Plane, 2003; Haldoupis et al., 2007]. Haldoupis and Schlegel (1993) noticed large ion acoustic velocities of 320 ms^{-1} from meteor induced backscatter (MIB) echoes. The altitude dependent time delay between the head echo and trail was first coined by Reddy and Nair (1998) and further concluded that the seeding mechanism behind the detected field aligned irregularities as two stream plasma instability. Chapin and Kudecki (1994) hypothesized that gradient drift and two-stream plasma instabilities driven by electro jet electric fields caused these unique signatures. Oppenheim et al., (2000) and Dyrud et al., (2001) using plasma simulations and theory showed that for Farley Buneman /Gradient drift (FBGD) to grow, strong external electric fields are not necessary and further, they become turbulent and generate field aligned irregularities (FAI), and exhibit anomalous cross field diffusion [Dyrud et al., 2001]. With MU radar operating at 50MHz and ALTAIR radar operating at 160MHz & 422MHz, Zhou et al. (2001) and Close et al. [2002] respectively showed that meteor trails can be recorded with radar beam pointing perpendicular to the background magnetic field (B) (but not in parallel to B). While the other HPLA radars viz., EISCAT, Arecibo, and Millstone Hill, as they are not pointed perpendicular to the back ground magnetic field (B), couldn't frequently detect the non specular meteor trails. Zhou et al. (2004) using a simple model with a wavelength of 6.4 m, studied the aspect sensitivity of meteor trails, which assumes that trail turbulence is strictly field-aligned but localized spatially, making the turbulence sensible from a range of aspect angles. They found a significant contribution to the non specular trails even from the radar beams pointed off perpendicular to the magnetic field in addition to that from beams pointed perpendicular to the magnetic fields. For a FAI of 20m length, they showed that the power observed was 10 dB below when the beam pointed 6 degrees off perpendicular to the magnetic field direction. They further concluded that, the detect ability of non specular trails depends on incoming meteor's velocity, size, shape and its composition in addition to the radar specifications i.e. the frequency, polarization, direction of the incident electromagnetic wave.

Here we present the electrodynamics of meteor trails recorded during the meteoroid showers which are observed over Gadanki (13.46^{0}N, 79.18^{0}E, 6.3^{0}N magnetic latitude).

Observations

MST radar located at Gadanki (13.46^{0}N, 79.18^{0}E, 6.3^{0}N magnetic latitude) has been operated in meteor mode. The Doppler spectra of meteor echoes have been recorded with different beam orientations i.e., E_{20}, W_{20}, Z_x (subscript 20 indicates 20^0 off Zenith angle) and N_{13} oriented at 13^0 towards North to record sporadic E produced during meteor shower. The technical details and system specifications are thoroughly discussed by Rao et al (1995). Four successive In phase (I) and Quadrature (Q) samples for each range bin were coherently averaged making the effective sampling interval of 4ms.

A meteoroid ablating in the upper atmosphere creates a narrow column of energetic neutrals and plasma. The neutral density is less than background ionosphere neutrals and plasma density created by meteoroid deposition is higher than background plasma. This column expands rapidly until slowed and cooled by collisions. The radius of the column at the point when it transitions from a rapid kinetic expansion to a slower diffusive expansion is called the initial radius of the trail and this initial radius is smaller than the mean free path length (Baggaley,1981). Non specular meteor trails were first reported by McKinley and Millman (1949) and were first described as Field aligned irregularities by Heritage et al., (1962) and more thoroughly by Chapin and kudeki (1994). Oppenheim et al., (2003a, 2003b) showed how these irregularities arise from instabilities driven by the plasma gradient and ambipolar electric fields generated by the meteor. This instability creates FAI which rapidly develops into plasma turbulence easily detected by large radars. Dyrud et. al (2001) showed that FBGD waves develop even if external electric fields are low or absent and also demonstrated that waves and turbulence cause anomalous diffusion much larger than the expected cross – field ambipolar diffusion indicating external E – region electric field or equivalently neutral winds can strengthen these instabilities but are not quite essential. When the trail echo exists, it almost always follows the head echo after a gap of greatly reduced signal strength. Dyrud et al., (2002) credited this gap to the time necessary for plasma instabilities to generate sufficiently large amplitude turbulence which enables trail measurement. Trail diffusion would occur at two distinctly different rates. When the trail density is high, the cross field diffusion rate is small. Later when trail density falls to only a few orders of magnitude above the background density, currents flowing in background plasma along the magnetic field are sufficiently large to cause the meteors to diffuse as if it were un magnetized. Thus the ambipolar field weakens and hence the driver for instabilities.

The back scattered signal of meteor trails can be differentiated from the other sources as many of the meteor trails exhibit a steep increase followed by an exponential decay and the doppler wave form is quasi – sinusoidal. Aided with MST radars, these meteor trails can be observed even after the post sunrise period and more frequently during pre sunrise period. These echoes, last for less than a split second but extend over two to three range bins showing that some meteor echoes cannot be considered as a discrete Fresnel reflection from a length of the trail equal to size of the first Fresnel zone (~1Km for 53MHz). The Doppler wave form could be close to a sinusoid in each range bin implying an equal doppler frequency in each range bin but necessarily it is not the same in successive range bins. During the Geminids meteor shower, 2007 on peak activity day and during peak hours of activity i.e. on 13th December in between 02:00 Hrs to 04:00 Hrs LT meteor trails were recorded with low mass indices.

Analysis

The electron line density and mass of the incoming meteor are estimated by following the model described by Stober (2008). By considering the processes of sputtering and evaporation of meteors in the meteor ablation model, meteor mass has been estimated precisely. Baggley (2002) stated the threshold temperature for meteor ablation to occur, Hill et.al., (2005) supported the above while studying the high altitude meteors and has found a threshold energy for impinging molecules to start the process of sputtering. In the three equation model these effects are included by a temperature dependent sputtering efficiency given as ;

$$\Lambda_s = Q\,(6\cdot 10^{-16})e^{\frac{T}{290}} \quad 1$$

The temperature gradient is given as

$$\frac{dT}{dt} = \frac{A_{cross}\,\rho_{air}\,v^3}{2\,C_3\,m}(1-\Lambda_s) - \frac{\varepsilon\,A\,\sigma_{SB}\,(T^4-T_0^4)}{C_3\,m} - \frac{A_{cross}\,C_1\,Q}{m\,C_3\,T^{\frac{1}{2}}}e^{\frac{-C_2}{T}} \quad 2$$

The mass loss due to ablation is given as

$$\frac{dm}{dt} = -\frac{A_{cross}\,c_d\,C_1}{T^{\frac{1}{2}}}e^{-\frac{C_2}{T}} - \frac{\Lambda_s\,\rho_{air}\,A_{cross}\,v^3}{2\,Q}\,. \quad 3$$

Solving the equations enables us to calculate electron line density assuming Jones (1997) ionization efficiency

$$\beta = 9.4\cdot 10^{-6}(v-v_{thres})^2\cdot v^{0.8} \quad 4$$

Where threshold velocity v_{thres} defines the velocity below which certain atom can no longer be ionized by impinging meteors. Using Jones (1997), the electron line density along the meteor flight path is given by

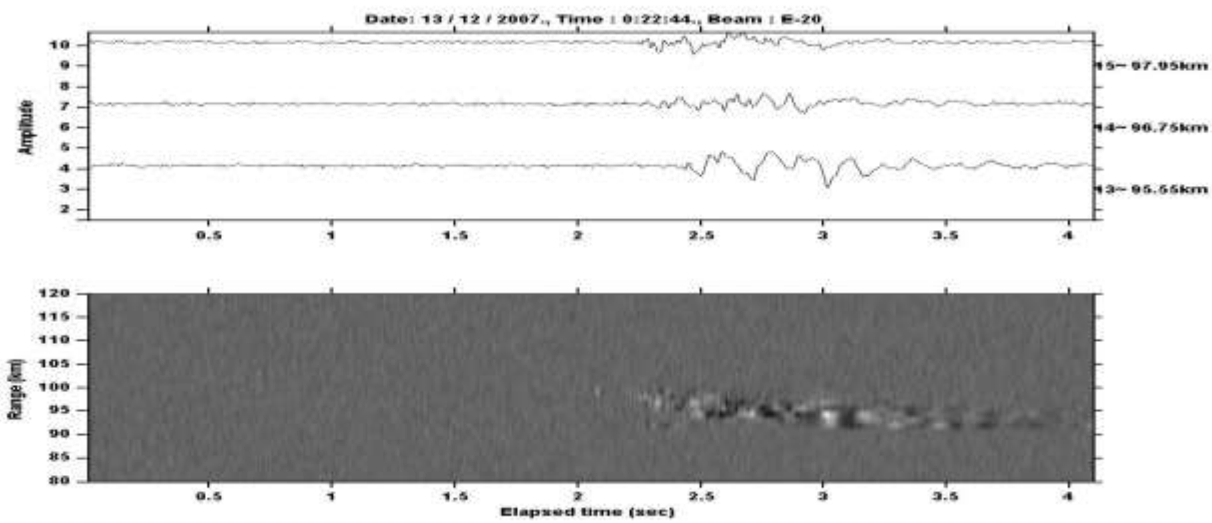
$$q = \frac{\beta}{m_a\,v}\frac{dm}{dt}\,. \quad 5$$

The three equation model is thoroughly discussed in Stober (2008) and we adopted the same for estimating the meteor mass. The constants appearing in the above relations were suitably taken from MSIS00 model.

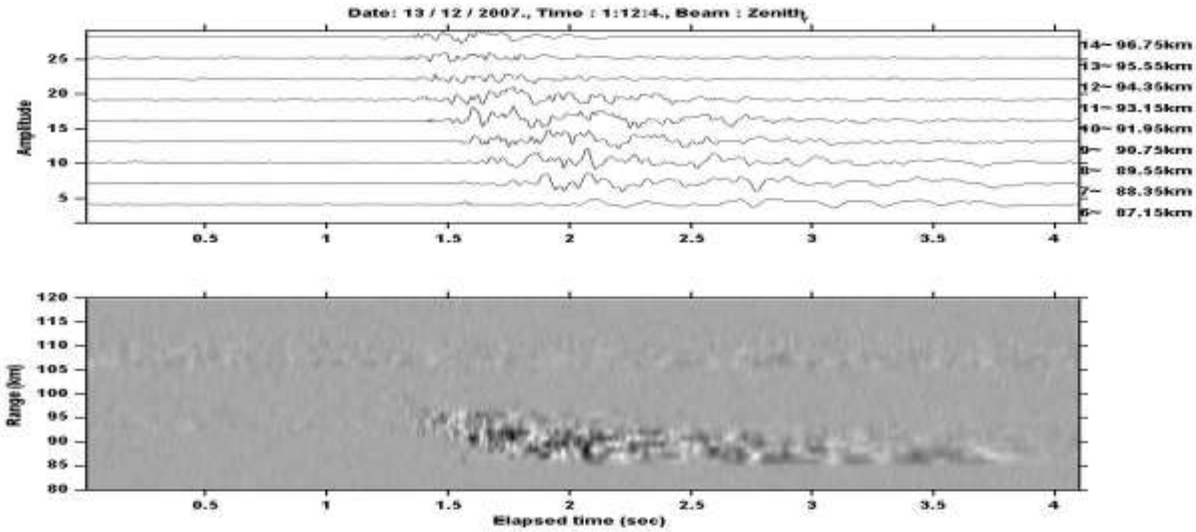
symbol	quantity/source	value/source
dv/dt	deceleration	-
dm/dt	mass loss due to ablation	-
dT/dt	temperature gradient	-
T	temperature	-
T_0	atmospheric temperature	$150-750K$
A	surface area	-
A_{cross}	cross section area	-
β	ionization efficiency	-
Λ_s	sputtering efficiency	-
σ_{SB}	Stefan-Boltzmann constant	$5.67\cdot10^{-8}W/m^2K^{-4}$
σ_a	ablation parameter	$10^{-8}s^2/m^2$
C_1	constants in Hunt et al. 2003	$6.92\cdot10^{11}kg/m^2s^{-1}K^{1/2}$
C_2	constants in Hunt et al. 2003	$57800...80000K$
C_3	constants in Hunt et al. 2003	$1\cdot10^3J/kgK^{-1}$
Q	constants in Hunt et al. 2003	$7\cdot10^3J/s$
C	heat capacity	$0.8...0.95kJ/kgK^{-1}$
m	meteor mass	$10^{-6}...10^{-14}kg$
m_a	mass of the ablated meteor species	$4.98\cdot10^{-26}kg$
v	meteor velocity	-
v_{thres}	threshold velocity	$5-8km/s$
c_d	drag coefficient	0.2..1.17
M_r	radio magnitude	-
ρ_{air}	air density	taken from MSIS00
ρ_{met}	meteor density	$1000...8000kg/m^3$
ε	emission	0.5...0.95

Results and Discussion

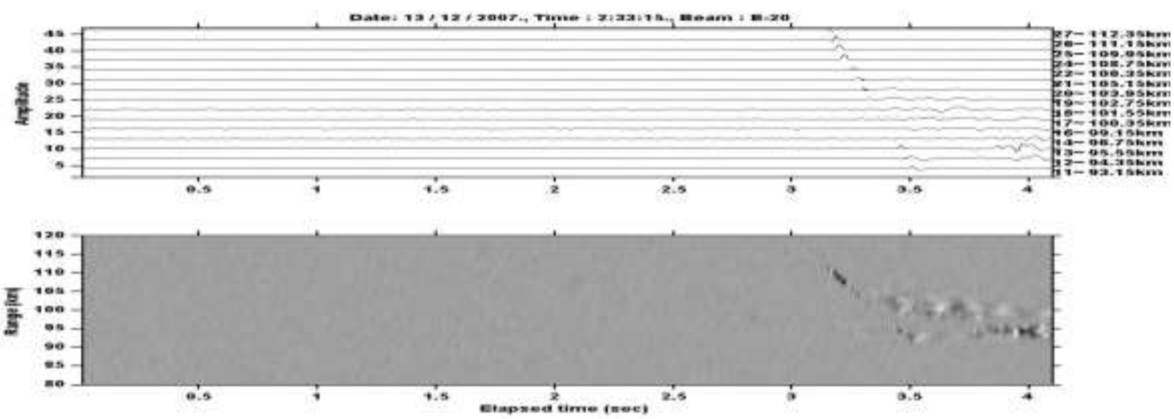
Depending upon the duration for which meteor trails have lasted, they were classified as long (> 1 sec), short (0.5sec – 1sec) and very short (< 1 sec) trails. Some of the long duration non specular meteor trails are discussed thoroughly along with the electrodynamics of their formation and existence figure 1. These long duration meteor trails were observed in the altitude



(a)



(b)



(c)

FIG. 1. LONG DURATION NON SPECULAR METEOR TRAILS

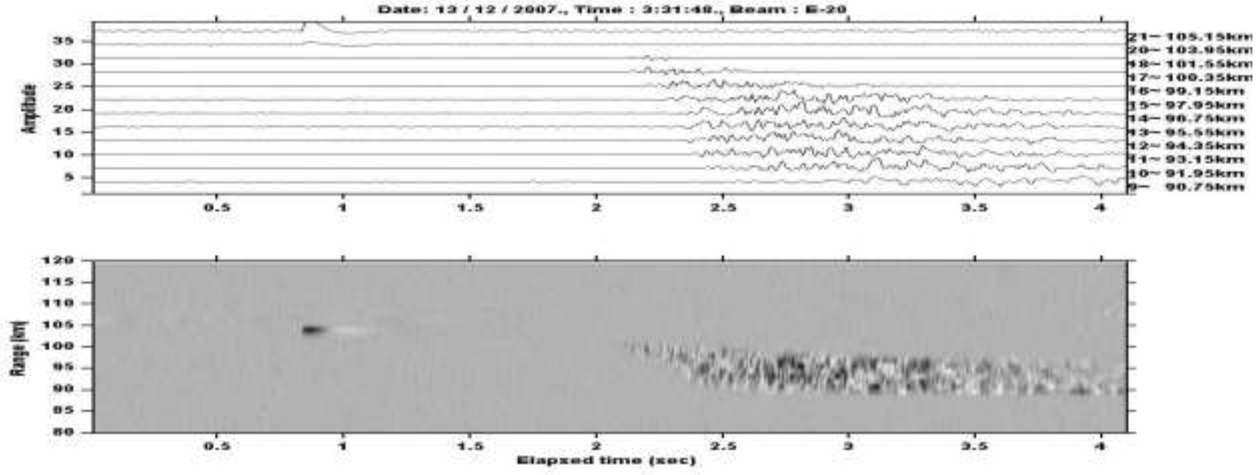
ranges below 100 Km. The duration for which these non specular meteor trails have sustained over this site of observations are confirming the results obtained by Dyrud et al (2011).These non specular trails have formed few fractions of seconds later the head echo being deposited. The expanded columns or trails will be formed within few micro seconds after the head echo is recorded and owing to the growth of turbulence within the trails. These non specular trails have lasted for more than 1.5 sec depending on the altitude of occurrence. Further the duration for which the trails survive depend on the velocity of the incoming meteors, its size, the background plasma density and also on the beam pointing direction. This is evident from figures 1(a), (b) &(c). The trails in the figure 1(a) & (b) have cut the beam nearly perpendicularly as a result long expanded columns were produced. Where as in 1(c), down the beam echo and the corresponding meteor has undergone sputtering or fragmentation as a result two separate head echoes followed by their spread trails were noticed. In figure1(c), we can also observe a second phase of ablation occurring at heights of 95Km. Such type of echoes are termed as low altitude trail echoes where the sputtering of the meteor took place leading to differential ablation.

During these night hours, the background plasma density is less and these meteors with higher masses descended to lower altitudes and created larger plasma density gradients. And for such plasma to detect as meteor trails require at least three orders of magnitude higher than the background plasma for radars to detect them as meteor trails (Dimant and Oppenheim, 2006a, 2006b). As soon as meteor plasma density falls below the required density threshold or approximates the background plasma density, they become undetectable for radars. According to the predictions of Dimant and Oppenheim (2006a, 2006b) when the trail density is sufficiently large, the cross field diffusion rate is small and when its density reaches low and few orders of magnitude above the background plasma, currents flowing in the back ground plasma along B_o becomes sufficiently large to cause the meteor to diffuse as if it were unmagnetized. This diminishes the driver for instabilities because of weakening of ambipolar field.

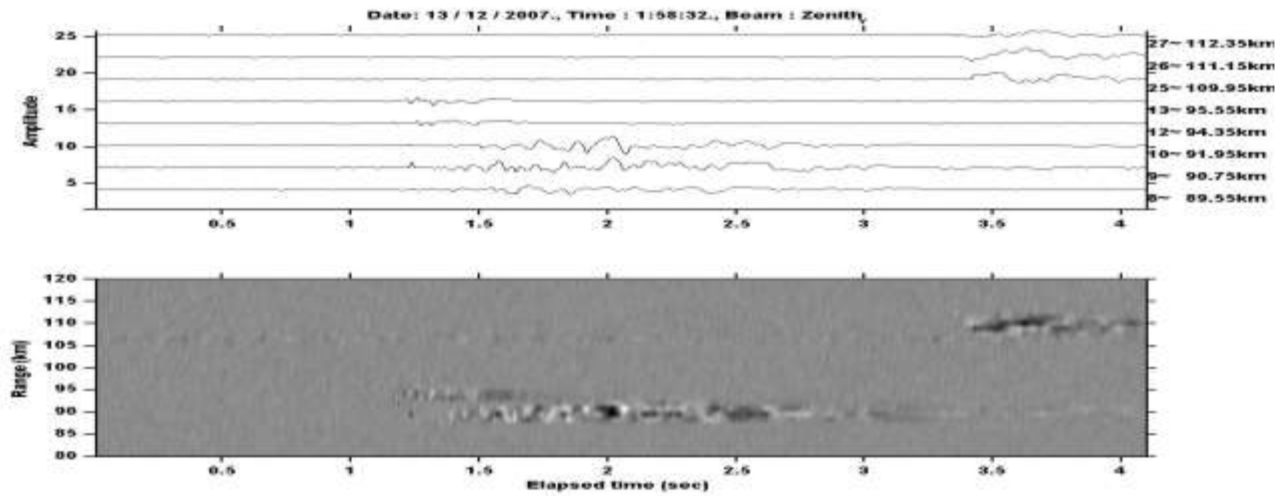
We can also notice that the trails at lower heights have persisted for relatively longer times than the trails at higher altitudes. At higher altitudes, above 98Km the local diffusion comes into play and the trail diffuse faster and reach a point where trail density gradient is too weak and hence the self driven ambipolar and polarization electric field and diamagnetic drifts are insufficient to drive FBGD instabilities thus loosing sensitivity much quickly. The critical drift speeds for meteor trails are often much higher than the ion acoustic speeds (Dyrud et al. 2005). At lower altitude portion of the trail, the gradient term in the meteor trail FBGD acts to damp the waves if the gradients are too steep, yet the polarization electric field drives the instability more strongly at lower altitudes since the polarization is proportional to ion collision frequency. Eventually, the gradients become weak enough, but density gradient term from the polarization term is still large enough, and the lower portion of the trail becomes destabilized. Thus the trail exists for relatively longer times. The trail durations observed with MST radar are in good agreement with those discussed in Dyrud et al. 2011.

Multiple echoes recorded in common volume are presented in fig. 2(a) – 2(c). The echoes appeared in common volumes might have originated from one single meteor and might have undergone fragmentation depending on their masses, entry speeds else might be because of different events. The trails appeared at lower altitudes sustained for longer times than the echoes appeared at higher altitudes. This shows that the lighter particles ablate at higher altitudes producing shorter echoes and the heavier ones ablated at lower altitudes produced longer trails. Thus the meteors of higher mass produced longer trails creating large plasma density gradients.

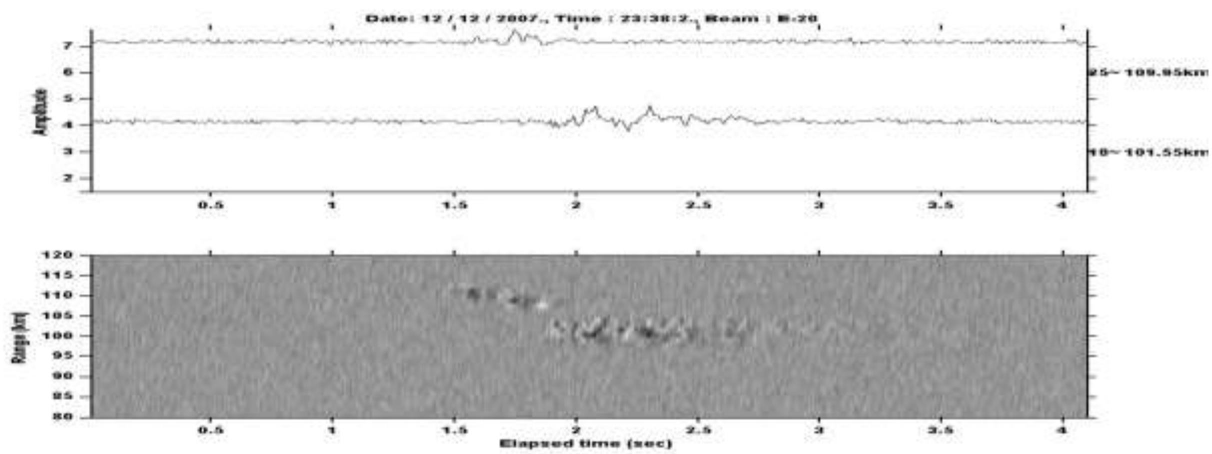
The meteor trails that appeared at and above 114Km (fig. 3) have lasted for extremely shorter durations i.e., not even about 0.1 sec. As soon as the echo was registered, it almost disappeared immediately without developing the trail. This might be due to either lighter meteors of microgram size or the meteors might have come with high velocities or extremely low velocities. A slower meteor with an entry speed of $15Kms^{-1}$ has less ionization and ablation which may not produce any trail or even if so, it will produce a very short trail. A meteor coming with an entry velocity greater than $55Kms^{-1}$ have very high kinetic energies and all of its mass becomes ionized at such high altitudes due to weak polarization electric fields above ~100Km and more rapid trail diffusion (Dyrud et al. 2011). The meteor entry velocities ranging from $25Kms^{-1}$ - $35Kms^{-1}$ only allows meteors to reach sufficiently lower altitudes where polarization electric fields become stronger yet still generate steep plasma density gradients (Dyrud et al. 2007). The observed line of sight velocities for the above displayed incoming meteors is found to be in the range of $24Kms^{-1}$ to $30Kms^{-1}$. In fig.3 very short duration echoes were displayed, where only head echoes are noticeable in fig.3(a) and 3(b) with the observed line of sight velocities of $16Kms^{-1}$ and $57.6Kms^{-1}$ respectively, which are well beyond the limits for trail



(a)

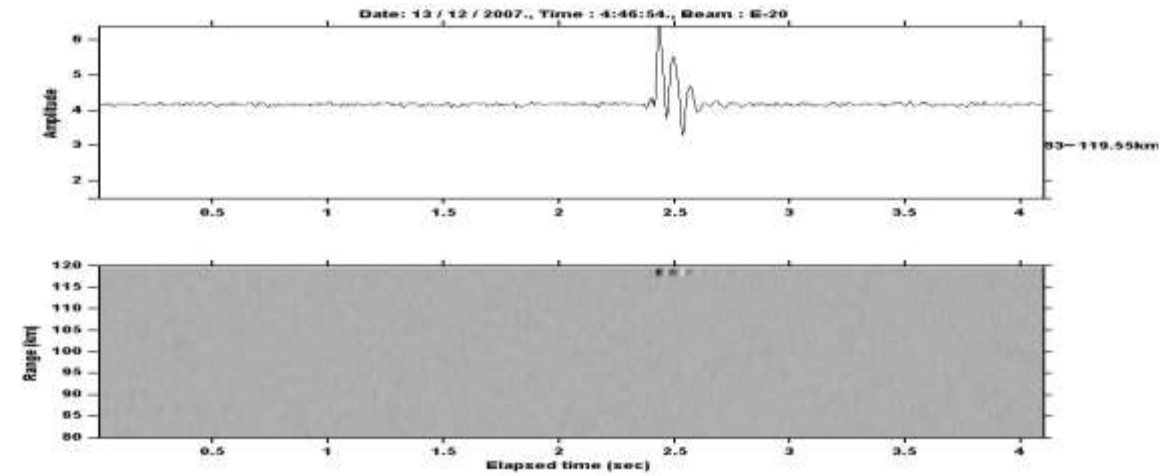


(b)

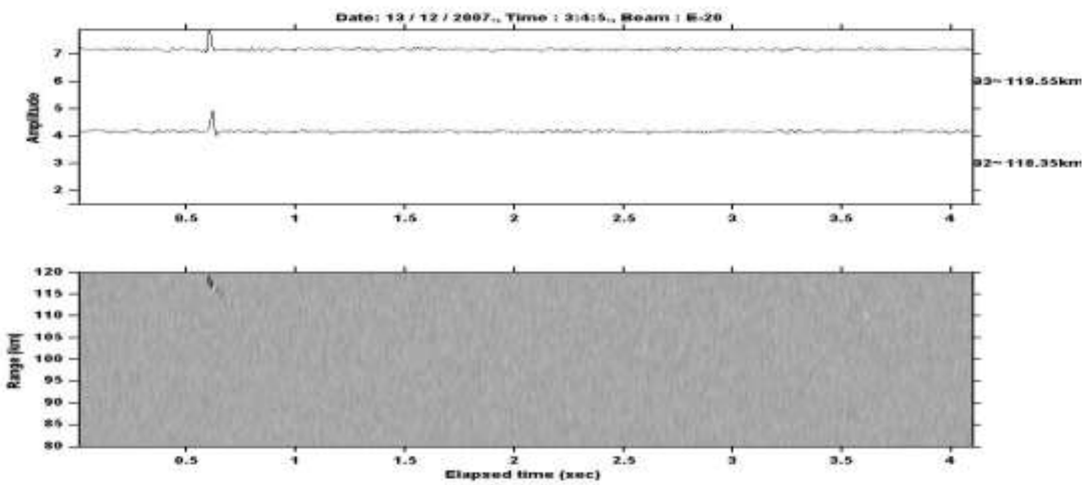


(c)

FIGURE 2. METEOR ECHOES OBSERVED IN COMMON VOLUMES AT DIFFERENT HEIGHTS



(a)



(b)

FIGURE. 3. SHORT DURATION METEOR TRAILS

formation as mentioned above and thus the trails are not observed. In the fig.3(a), only the trail is recorded at higher altitudes with no head echoes being registered and they too have sustained for extremely shorter periods of even less than 0.1 sec.

For the event presented in figure 1(c), the mass of the meteoroid is obtained as 2.27E-06 gm and the observed electron line density is 1.7E+16ele/m. The observed electron line density is atleast 100 times greater than background electron line density. For the rest of the events presented in figures 1(a), 1(b), 2(a), 2(b),2(c) and 3(a), 3(b) their respective masses were estimated as 1.18E-06, 2.22E-07, 4.58E-08 ,7.36E-07, 9.72E-08, 5.47E-08,1.28E-06 gm and the corresponding electron line densities are 1.05E+17, 2.46E+16, 9.27E+15, 1.61E+17, 1.49E+15, 1.01E+16, 4.06E+16 ele/m respectively. The doppler velocity of the meteoroid presented in fig 1(c) and corresponding doppler shift were typically different from those echoes which are common at low latitude sites. This exhibited phenomenon is entirely attributed to the meteors. For meteors to exhibit such back scattered echoes it has to develop electron line densities which are atleast 70 times greater than the background plasma. The meteoroid presented in fig.1(c), because of its heavier mass, could generate the plasma sufficiently larger than the above said threshold condition. Thus the generated plasma creates large gradients in ionosphere. A meteor trail distorts an otherwise uniform electric field due to the following. A dense plasma trail has a much higher conductivity than the ambient E-region ionosphere, especially at night time. The component of a strong external DC electric field along the trail axis induces a strong current within the trail that cannot be closed in the ionosphere and must stop at the trail edges. As a result, the trail edges acquire net electric charges that partially cancel the external electric field within the trail. At the same time, far from the trail, the external electric field remains nearly undisturbed, creating a large potential difference projected onto the trail length. This leads to the formation of a transitional zone between the far ionosphere and the nearly equi potential meteor trail. The transitional zone between the two different plasma density distributions contains spatially inhomogeneous electric fields which increase dramatically near the meteor trail edges. These induced fields may drive plasma instabilities which give rise to plasma density irregularities responsible for non-specular radar echoes. Additionally, the field induced near the trail edges can have a significant component along the magnetic field. This field can energize electrons dramatically. Polarization electric fields near the trail edges give rise to electric currents which flow from the ionosphere into the trail on one side of the trail and flow out into the ionosphere from the other side. This effect results in a net trail current which complements the current loop associated with the trail diffusion (Dimant and Oppenheim, 2006a). Unlike the induced electric fields that decrease as the trail diffuses, the polarization trail current stays roughly the same while the trail density remains sufficiently large. Qualitatively, the meteor FBGD instability is similar to the FBGD instability responsible for auroral and equatorial electrojet radar echoes and becomes unstable when the electron drift (gradient and E ×B drift) speed exceeds a modified ion acoustic speed. The FB instability near the trail surface can be excited by the induced electric field even if the external electric field is well below the FB threshold provided moderate dense trails whose internal plasma density exceeds the background plasma by 70 times (Dimant et.al 2009). Thus there were the rare appearances of meteor induced backscattered echoes which are similar to type I echoes of mid and high latitudes.

CONCLUSIONS

The electrodynamics of range spread meteor trails observed at different heights are discussed and are attributed them to the growth of FBGD within the meteor trails. Meteors of mass 10^{-4}gm to 10^{-8}gm could create electron line densities in the range of 10^{16} to 10^{14} ele/m, which is at least 70 times greater than the quiet time background ionosphere plasma at night times at low latitude regions like Gadanki and is sufficient for the generation of FBGD waves within the meteor trails which in turn induce electric fields of few V/m, perpendicular to the geomagnetic fields and drive the instabilities and leading to the diffusion of the trail. Thus the range spread trail echoes are the consequences of FBGD instabilities triggered within the meteor trails. The gap between the head echo and the trail is attributed to the time lapsed for the FBGD to build up. It is also observed that down the beam echoes have survived shorter than those which cut the beam nearly perpendicularly. Echo durations of range spread trail echoes observed with MST radar have survived for longer times at lower altitudes and immediately disappeared at higher altitudes above 110 Km and are in good agreement with those predicted by Dyrud et al. 2011. The meteor echoes which have appeared in common volume is an interesting study, as it has been noticed the cases of meteor fragmentation.

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