Interferometry observations of meteor trail irregularity using the Sanya VHF radar

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Abstract

An experiment of spatial domain interferometry observations of 3-m ionospheric irregularities at a low-latitude location in China was conducted using the Sanya VHF coherent radar. An additional antenna subarray for interferometry was constructed at the geomagnetically north of the main East-West antenna array of the Sanya radar. The main array was used for transmission. Receiving was done using the additional subarray and the main array. By employing the interferometry technique implemented at the Sanya radar, the spatial structure of 3-m irregularities responsible for a long duration range spread trail echo (RSTE) event was reconstructed. It was found that the spatial structure of the RSTE changed its shape from the strip-type elongated along the radar beam's boresight to layer-type in the vertical-meridional plane. Interestingly, the drifts of trail irregularities show a shear related structure above/below the altitude 97 km at which the trail echoes persisted for a long time of ~4 min. Possible causes for the generation and structural evolution of the long duration RSTE are discussed.

1. Introduction

As meteoroids enter the Earth's atmosphere, the surface particles and air molecules around the meteoroid quickly ionize, leaving behind a trail of ionization in its path. High-power and large-aperture (HPLA) radars often detect meteor trails when radio waves scattered by structures in turbulent meteor trail [1]. These trails are referred to as non-specular trail echoes [2] and range spread trail echoes (RSTEs) [3], and have been used to investigate the neutral winds [4-5]. The RSTEs, in general, are thought to be backscatterred from field aligned irregularities (FAIs) produced in meteor trails through the Farley-Buneman and/or Gradient drift (FBGD) instabilities [1], which are driven by the plasma gradient and ambipolar electric fields generated by the meteor subsequently got enhanced by the background electric field [6]. But for long lasting meteor echoes with lifetimes ranging from tens of seconds to several minutes, such as the trails observed by VHF/HF radars at middle latitudes, the generation mechanism is still not well understood. From the obvious change of RSTE Doppler velocity at different range bins, some investigators [7, 10] invoked the neutral wind shear driven instability as a possible candidate to account for the observed long duration RSTE events. Later, *Dyrud et al.* [6] demonstrated that the long duration meteor trails, which shown as a triangular shaped profile in radar range-time-intensity maps, are a natural consequence of the meteoroid ablation and plasma instability under the effect of strong wind or electric field. In this paper we provide a case study of long duration RSTEs detected by the Sanya VHF radar during an experiment of spatial domain interferometry. The possible mechanisms responsible for the observed long duration RSTE event are discussed. The overall analysis focuses mainly on the issue that how did the long duration trail irregularity structure change and what caused the changes.

2. The Sanya VHF radar interferometry experiment setup

The Sanya VHF radar, with an operational frequency of 47.5 MHz and a peak power of 24 kW, is sensitive

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to irregularities of 3-m scale size. Though the East-West baseline (for one dimension) of the radar has been utilized to investigate the zonal drifts of irregularities [5], it is difficult to uniquely determine the positions of irregularity scatterers in the illuminating region. Recently, we upgraded the Sanya radar system by placing an additional antenna subarray (only for reception) in the north of the main East-West array. The newly added subarray is comprised of 2×2 five-element Yagi antennas, similar to the subarrays aligned in the East-West direction. In this way, the position of scatterers within the radar beam can be obtained by measuring the phase difference between the signals received at three non-collinear separated antenna channels. For the present experiment, the radar was programmed with a PRF of 650 Hz and a pulse length of 6 μs. This corresponds to a range resolution of 0.9 km within the sampled range interval of 80–200.6 km. Received complex signals for each range bin and receiving channel were coherently integrated 4 times, and stored for offline interferometry analysis.

3. Observational results

Figure 1a shows the range-time-intensity (RTI) plot of the backscattered signal power detected by the Sanya VHF radar in the morning 23:00-24:00 UT (0630-0730 LT) on 20 August 2013. Figures 1b and 1c show higher temporal resolution RTI images during two time intervals, respectively. As is evident from Figure 1a, tens of thin and short vertical streaks covering several range bins that represent the radar returns from meteor trails were observed. Most of the trail echoes lasted for less than 15 s, while one trail (as was named long duration RSTEs) maintained a distinct signature during the period 23:27-23:31 UT. In this case, the long duration RSTEs possess a triangular shaped altitude-duration profile, where the radar returns initially span slant ranges from 100-130 km. The trail at lower and upper altitudes lost its reflectivity as time proceeds and finally concentrated around the range interval 105-110 km. Such a feature is consistent with the trail echoes observed at Jicamarca [1]. Another notable feature shown in Figures 1a-1b is that the long duration RSTE is fragmented into two distinct regions, RSTE region A1 and A2, lasted for about 30 s and 4 min, respectively.

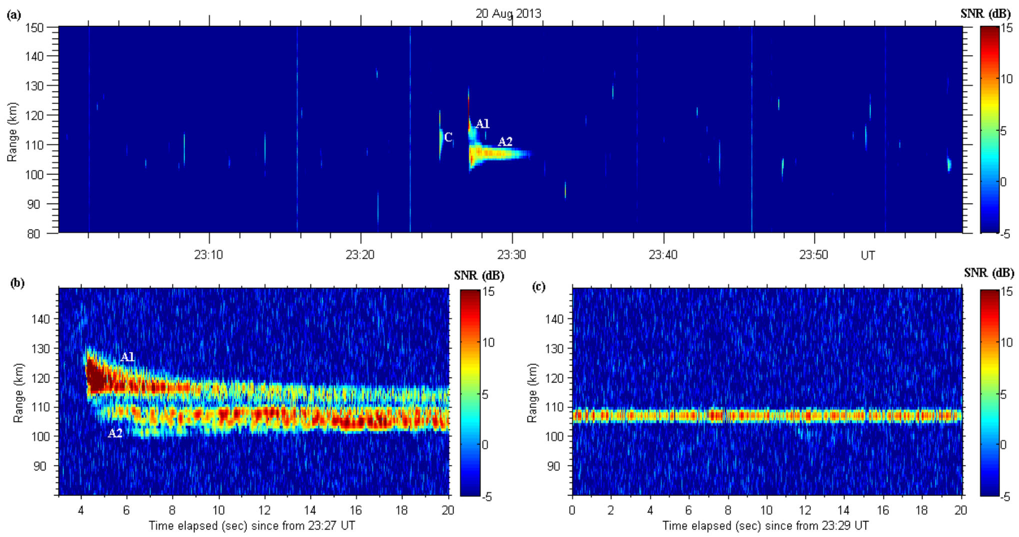

Figure 1. Range-time-intensity (RTI) maps of meteor induced backscatter echoes

Figure 2 shows the reconstruction results of the long duration RSTEs projected on the vertical-meridional plane during different time intervals. Two straight lines tilted from lower left to upper right in each panel represent the elevation angles 64º and 65º, respectively. Different colors in the echo patterns represent different range bins. From the top planes of Figure 2, it can be clearly seen that the trail irregularity echoes are aligned along the radar beam's boresight in the vertical-meridional plane during the early phase. This indicates that the trail echoes aligned as a stripe-type in the plane come exclusively from the **k**⊥**B** region. By using a large amount of RSTE observations from HPLA radars, *Malhotra et al.* [8], and *Close et al.* [9] demonstrated the majority of long duration echoes come from the region of **k**⊥**B**. Another significant feature to be noted in Figure 2 is that, the trail echoes below (above) the range bin 107 km (altitude 97 km) seem to displace away from the region of **k**⊥**B** as time proceeds. The trail irregularity structure changed its shape from the initially formed strip-type to layer-type. Notably, the bottom panels of Figure 2 show that the RSTEs in different range bins (color-coded) finally situated near the altitude 97 km. After that, the trail echoes coming from the direction of off-perpendicular to **B** decayed and diminished, whereas the echoes in the **k**⊥**B** region continued to exist for a longer time of 4 min.

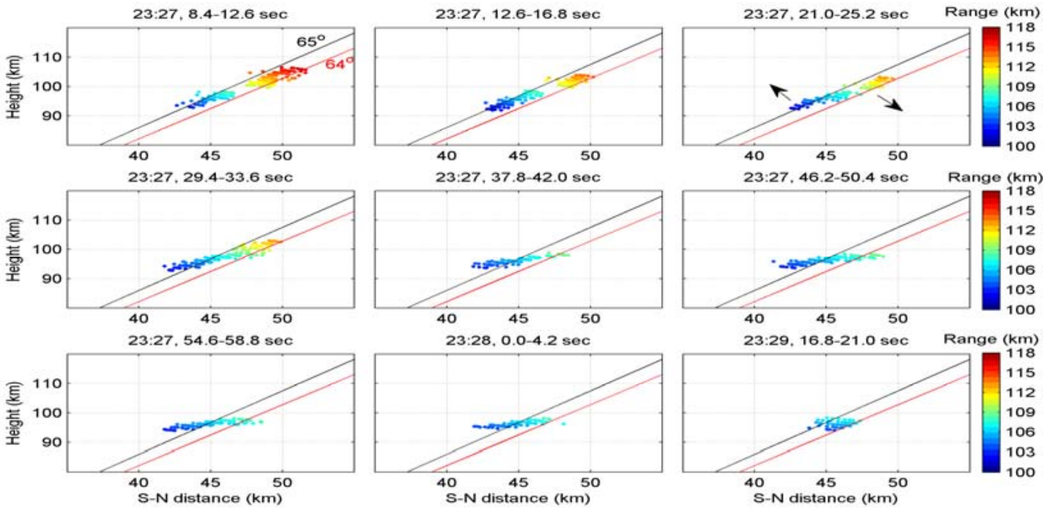

Figure 2. Echo patterns projected on the vertical-meridional plane for the long duration trail during different time intervals. The superposed arrows in the top panel show the motion of the echoing region.

4. Discussion and summary

From the observations of meteor trail echoes detected by the Sanya VHF radar presented in the previous section, we can summarize the main results as follows: (1) There are many meteor trail events observed during one hour interval. However, the trail irregularity echoes, only in one case sustained for a long time of about 4 min. (2) The irregularity structure associated with the long duration trail changed its shape from the initially formed strip-type to layer-type in the vertical-meridional plane as time proceeds. (3) For the long duration RSTE event, only those echoes around the altitude 97 km sustained for a long time.

It has been suggested that the duration of RSTEs depends on several factors, including the background ionospheric density, background electric field and/or wind, and the meteoroid parameters, for example meteor mass and velocity [6]. Besides the above factors, the radio science aspect sensitivity also plays a definite role on the RSTE duration of actual radar observations [8-9]. Returning to Figure 1, it is noted that another meteor trail event (labeled as 'C') initiated at 23:25:10 UT with a duration of about 15 s. This brings a question that why the meteor trail 'C' lasted only 15 s but the trail 'A2' continued to exist for 4 min, whereas both of them came from the region perpendicular to **B**. Further, we may note that the difference between the onset time of the two trail events is only 2 min. This relatively short time interval allowed us to assume the same background conditions. From earlier model simulation results [6] we know that under the same ionospheric and atmospheric conditions, the duration of meteor trail depends upon the characteristics of the meteoroid. Larger meteors with a mass more than 1 mg potentially produce long duration trails while microgram meteors produce short duration trails. The long duration RSTEs observed in the present study, therefore, could be interpreted in terms of the mass of the meteor, which could be apparently larger than those of meteors associated with the short duration RSTEs. On the other hand, it is known that the durations of meteor trail at different altitudes are dictated primarily by the external electric field/wind, diffusion rate and the polarization of meter trail as a function of altitude [6]. In particular, on the basis of the Doppler spectral bifurcation or Doppler velocity shear characteristics associated with long duration RSTEs, the neutral wind shear has been suggested to be a possible candidate to account for the observed long duration RSTEs at a specific altitude [7, 10]. By taking a similar way as *Li et al.* [5], the drifts of trail irregularity associated with the long duration RSTEs were obtained. It was found that the drifts of trail irregularity have an obvious shear from 50 ms^{-1} to -50 ms^{-1}. The shear structure of the winds observed in this study reminds us of suggestions made by *Bourdillon et al*. [7] that the structured wind shear drives parts of the trail plasma in a way similar to the process responsible for the formation of sporadic E layer, and sustains the trail for a long time. In this context, the cause responsible for the structural evolution of trail irregularity from the initially formed strip-type to layer-type could be linked with the neutral wind effect.

5. References

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