Fragmentation of Meteoroids detectable with 3D Spectrograms of Meteor Head Echoes

14.1.2025
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Abstract: (The graphical abstract can be found at the end of the document.)
Many 3D spectrograms of meteor head echoes show an identical picture: Shortly before the end, the spectrograms have a bulbous shape and a drop in signal intensity, which often drops to zero. In order to investigate this effect more closely, a second meteor receiving system was recently installed. Interesting spectrograms of head echoes were recorded: They show pulsations of various kinds. According to the literature, fragmentation of the meteoroids and the resulting interference can be the cause. In order to investigate the head echoes more closely, 2D and 3D spectrograms are now used in parallel. This article shows the first recordings of the head echoes with the new setup. Three of the images show echoes from fragments that continue their flight after the meteoroid explodes. The stronger the trail, the less material remains for the onward flight - that is a first impression.

1 Introduction

Head echoes are caused by reflections from the plasma that directly surrounds the meteoroid and move at about the same speed as the meteoroid. (Close et al., 2007) The head echoes of the recorded meteors often have a bulbous shape in the 3D representation used shortly before their end and the signals drop to zero. However, head echoes in my previous spectrograms extend far beyond the edge of the plot and are therefore incomplete, see Figure 1, upper image. The reason for this is that more emphasis has been placed on the trail echoes in the evaluation so far. Recently, the meteor echoes have also been recorded with a second system that records the head echoes completely (Sicking, 2025). Bulges and dips can be seen on the head echoes. Pulsating meteor events were observed with the EISCAT UHF radar system (Kero et al., 2008). The authors postulate that reflections on fragments lead to interference and cause pulsations. I received the reference to fragmentation of head echoes from Prof. Asta Pellinen-Wannberg. I asked her whether she knew of any literature on "oscillations" on head echoes.

2 Setup

The setup was described in detail in the previous article (Sicking, 2025). In order to be able to examine the head echoes in detail, one system now records 2D spectrograms, the other system logs the data in the 3D format used previously. The 2D representation has the advantage that the temporal course of the head echo can be seen. This makes it possible to see from the 2D spectrogram whether fragments are flying further in the direction of the meteoroid's flight. However, amplitude changes such as the pulsations and relative sizes of the echoes can only be seen in the 3D representation, so 3D is the best type of representation for me. The direct comparison of 2D and 3D will be used in the future to examine the head echoes.

3 Result and Discussion

The spectrogram in Figure 1 below shows an example from January 2nd at 0:14. In addition to the bulge before the decay, it shows strong pulsations across the entire frequency range. As written above, Kero et al. explain pulsations on the head echo by interference caused by reflections from ionized fragments. In detail: The radar waves reflected by parallel flying ionized particles add up or attenuate each other depending on their phase position. This process is called interference or fading. Causes of the phase shift can be the changing distance between the particles and the Faraday rotation. The fluctuations initially look like oscillations, but they are not such, since the Doppler shift is plotted on the x-axis. I prefer the term fading.

The upper spectrogram is an example from the Geminids 2024. It was recorded close to the radiant passage of 180°. The image shows how head echoes are cut off on the right side. In addition to head echoes with slight pulsations, there are also two jagged echoes. Pulsations and dips are present in all streams and in sporadic meteors.

Figures 2 and 3 show further interesting head echoes. In Figure 2 above, only two particles appear to interfere very harmoniously, while in Figure 2 below, several particles interact. Here, the fragments have already decayed

to such an extent that the actual meteor trail cannot be seen at all. The second head echo in the lower image appears to come from just one particle.
In Figures 1-3, fragments appear to continue flying after the explosion. I recorded a Perseid in August 2023. At its tip, particles can also be seen continuing their flight, see Figure 4. In Figures 1-3, however, it is difficult to see whether particles continue to fly. Therefore, it is necessary to record in 2D as well.

2D and 3D recordings are running in parallel

Both systems are currently configured to record head echoes optimally. One system records in 2D, the other in 3D. The course of the head echo can be clearly seen on the 2D plot. It is also possible to see whether fragments after decay are related to the head echo or whether it is just a GRAVES glitch.
In Figures 5 to 8, the 2D recording was stretched in the Y direction, i.e. in the time axis, using the graphics program IrfanView. The corresponding 3D plot was then inserted in a free area. The time and frequency axes are shown in Figure 5.

Further information can be found in the Figure Captions.

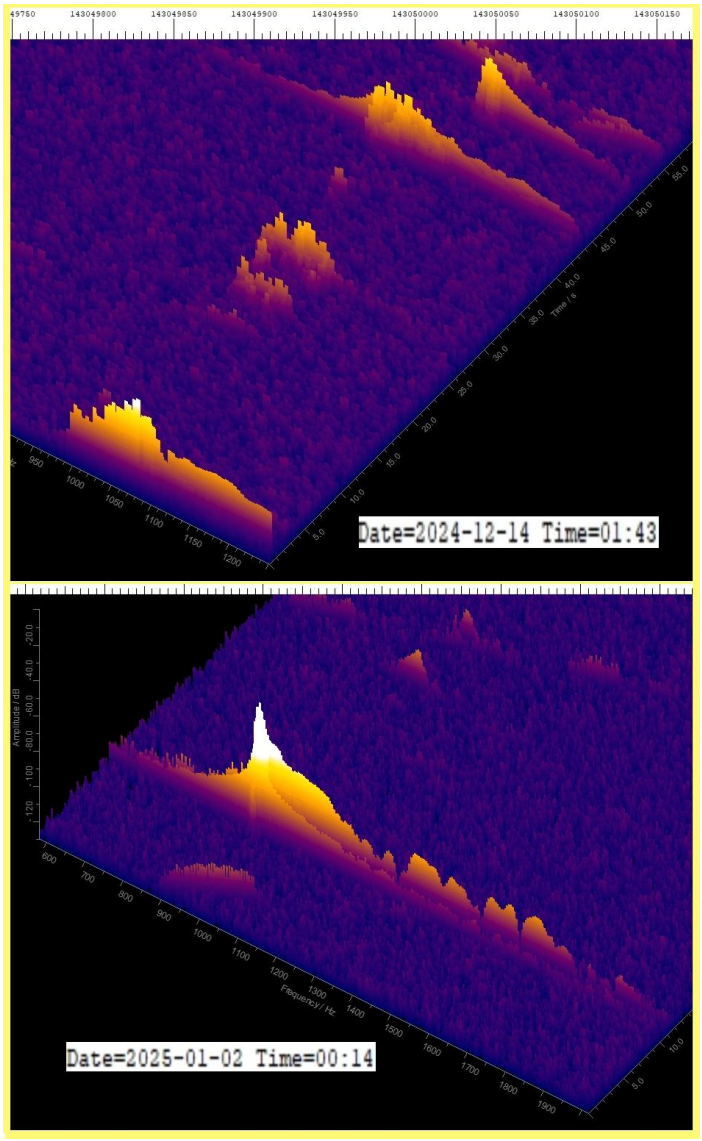

Figure 1 – The spectrogram below from January 2, 2025 0:14 a.m. shows complex pulsations over the entire area in addition to the bulge. The upper spectrogram is from the 2024 Geminids. It shows that head echoes are incomplete in the representation.

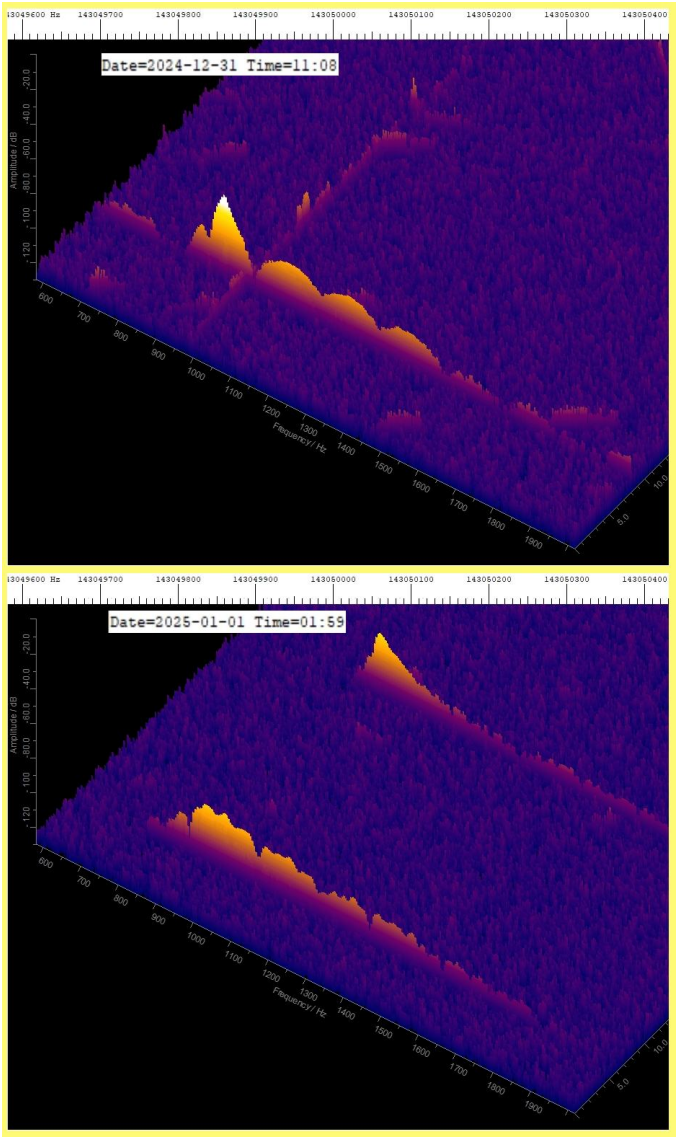

Figure 2 – Lower image: Two head echoes from January 1, 2025 1:59 a.m. are shown. The echo in the foreground shows complex pulsations. The spectrogram in the upper image from December 31, 2024 11:08 a.m. shows very harmonious pulsations. The head echoes show that particles may be flying further. In order to be able to assess this, 2D spectrograms are used below, which were not available here before.

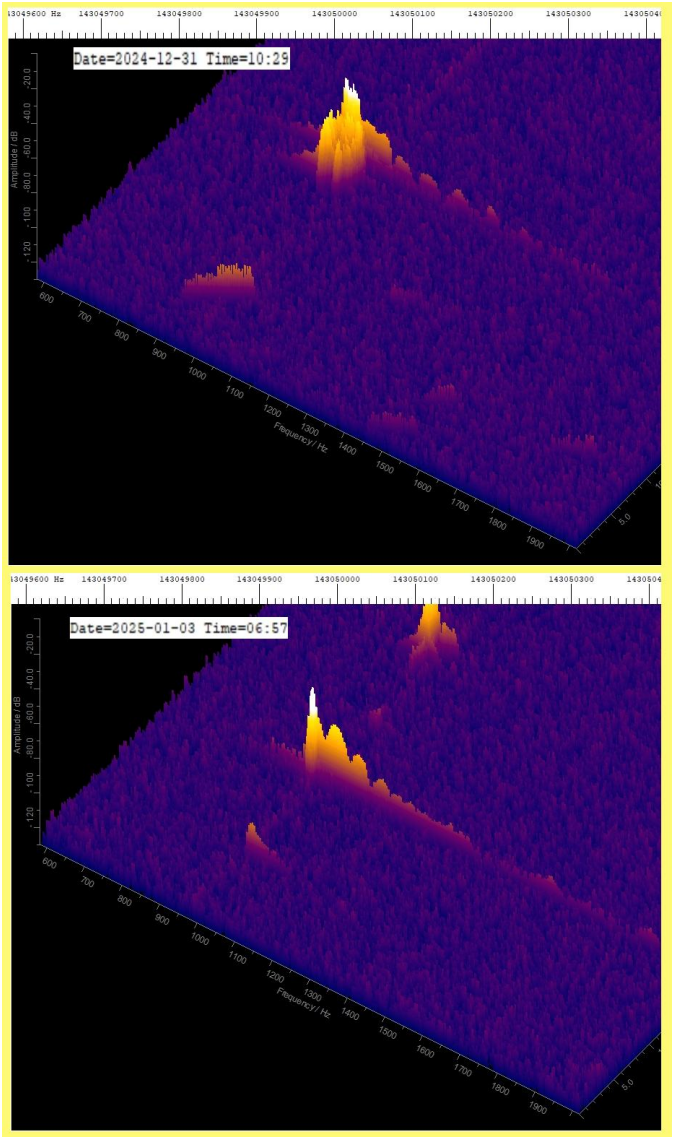

Figure 3 – Two head echoes with higher frequency pulsations from January 3, 2025 at 6:57 a.m. and from December 31, 10:29 a.m. In both cases, particles that have not burned up appear to continue flying.

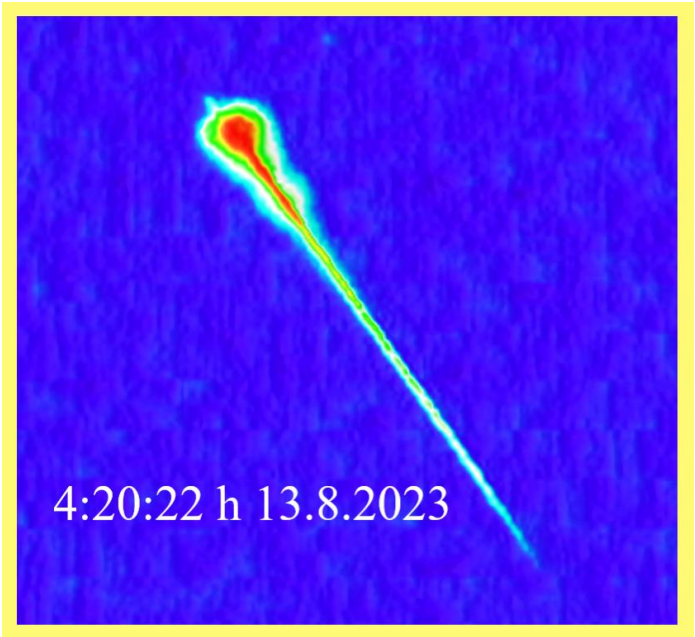

Figure 4 - Image of a Perseid from August 13, 2023. It is nice to see that there are several explosions and the particles continue to fly unevaporated. The image was taken with a USB camera and a Python script by the author and edited with IrfanView and ImageJ.

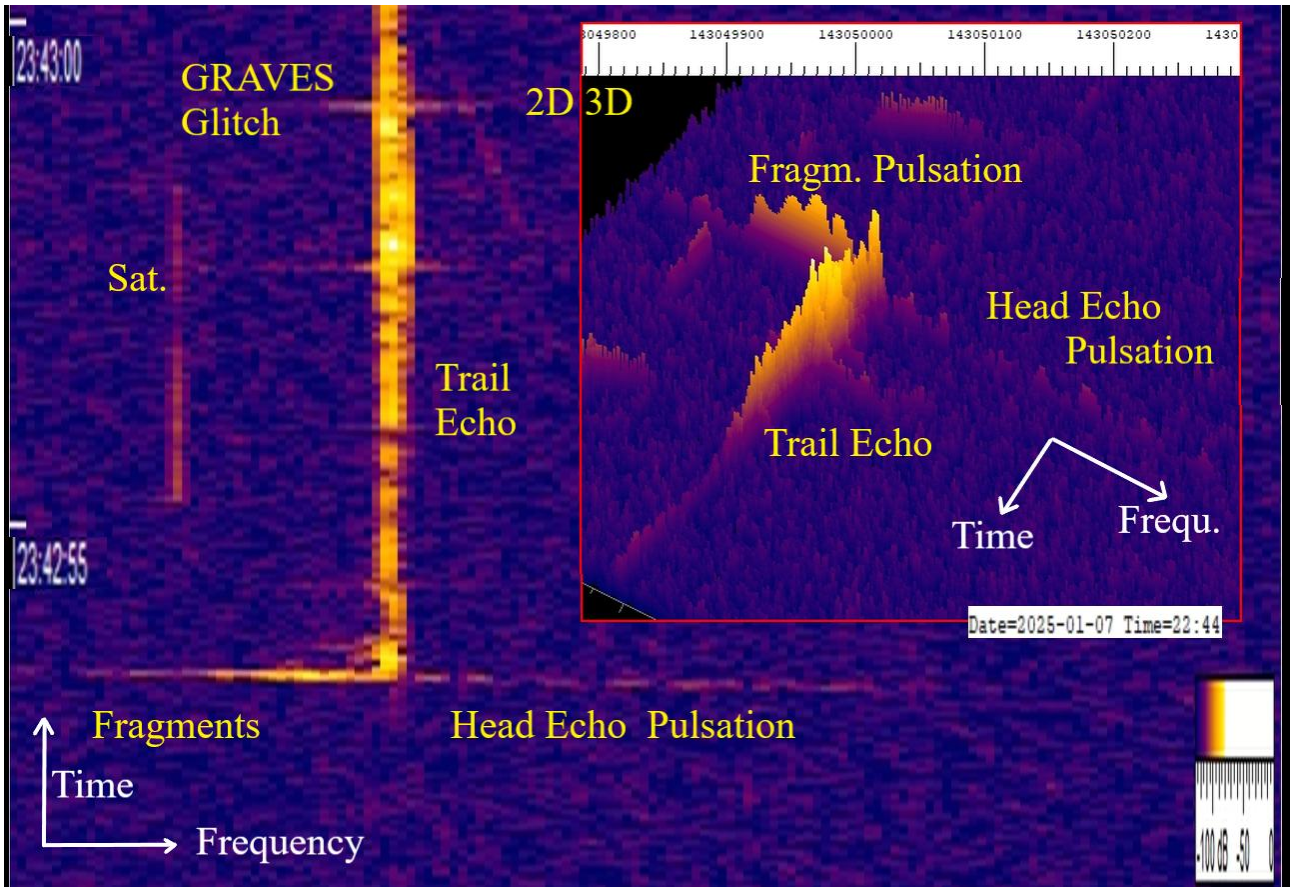

Figure 5 – The image shows a 2D and a 3D representation of one and the same meteor echo. A weak head echo with pulsations can be seen. After the explosion, a lot of material continues to fly and causes clear and very beautiful pulsations in the 3D spectrogram. Axes for time and frequency are drawn in this image. The image was taken on January 7, 2025 at 22:44 UT. The local time is shown on the left edge of the image. The two recording PCs have the same time setting. Nevertheless, Spektrum Lab shows a difference of one minute. The cause is not yet known.

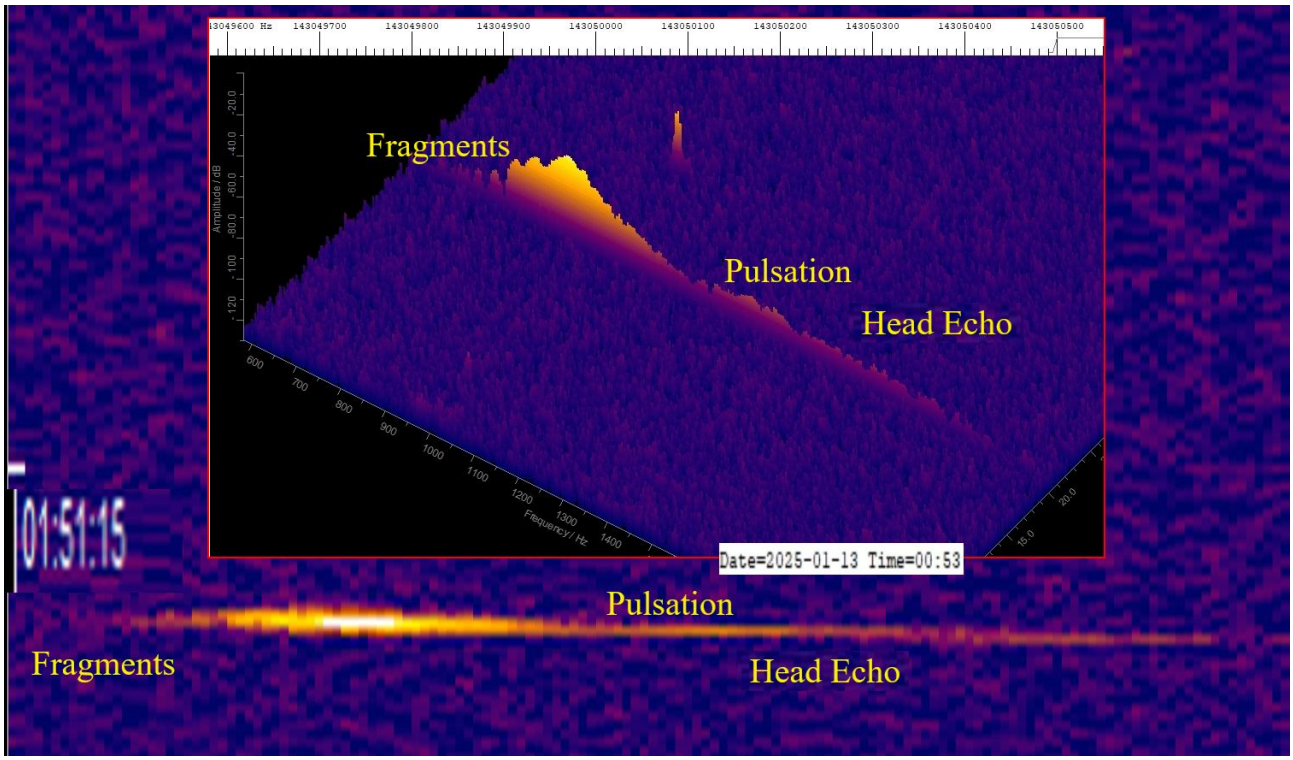

Figure 6 – A beautiful meteor echo with head echo and fragments. There was not enough material left for a trail.

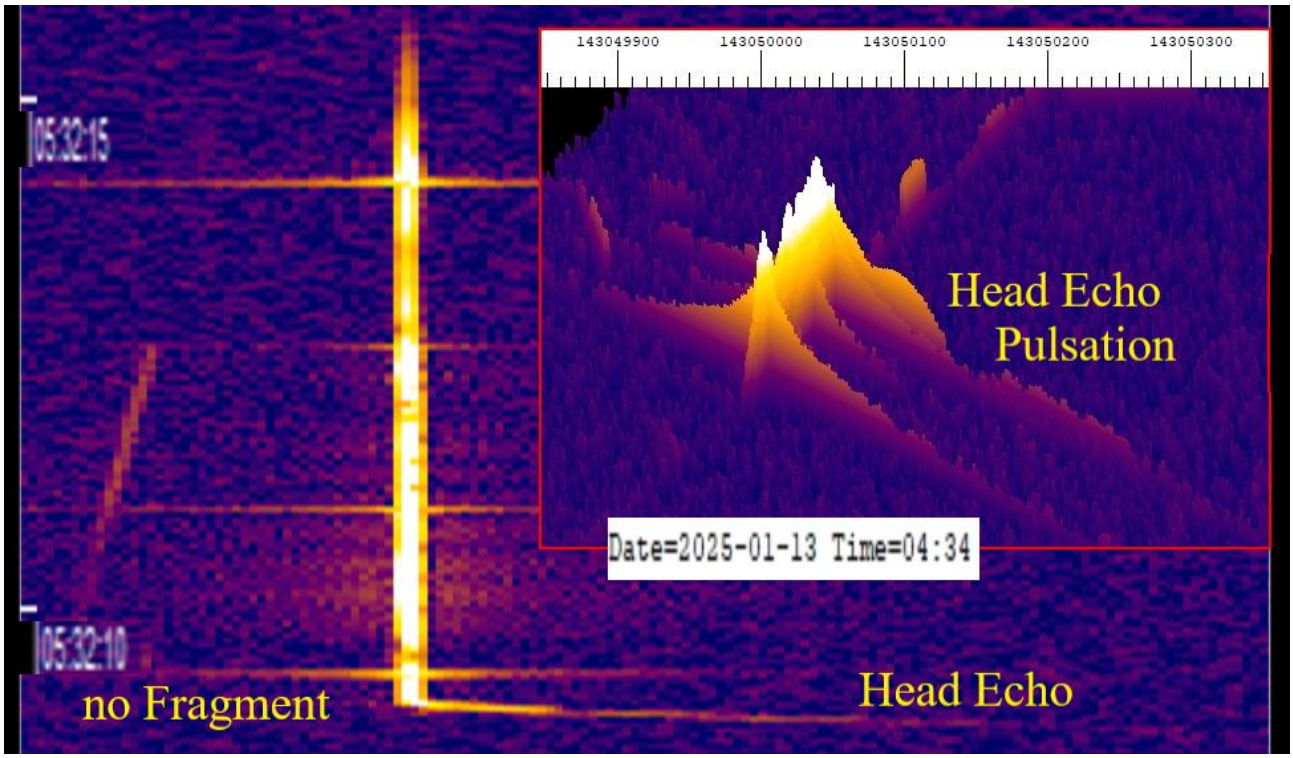

Figure 7 – Here all the matter has been vaporized and ends up as a trail. There are no further flying fragments. The head echo shows the bulge, as has been shown many times before. The GRAVES glitches serve excellently as markers.

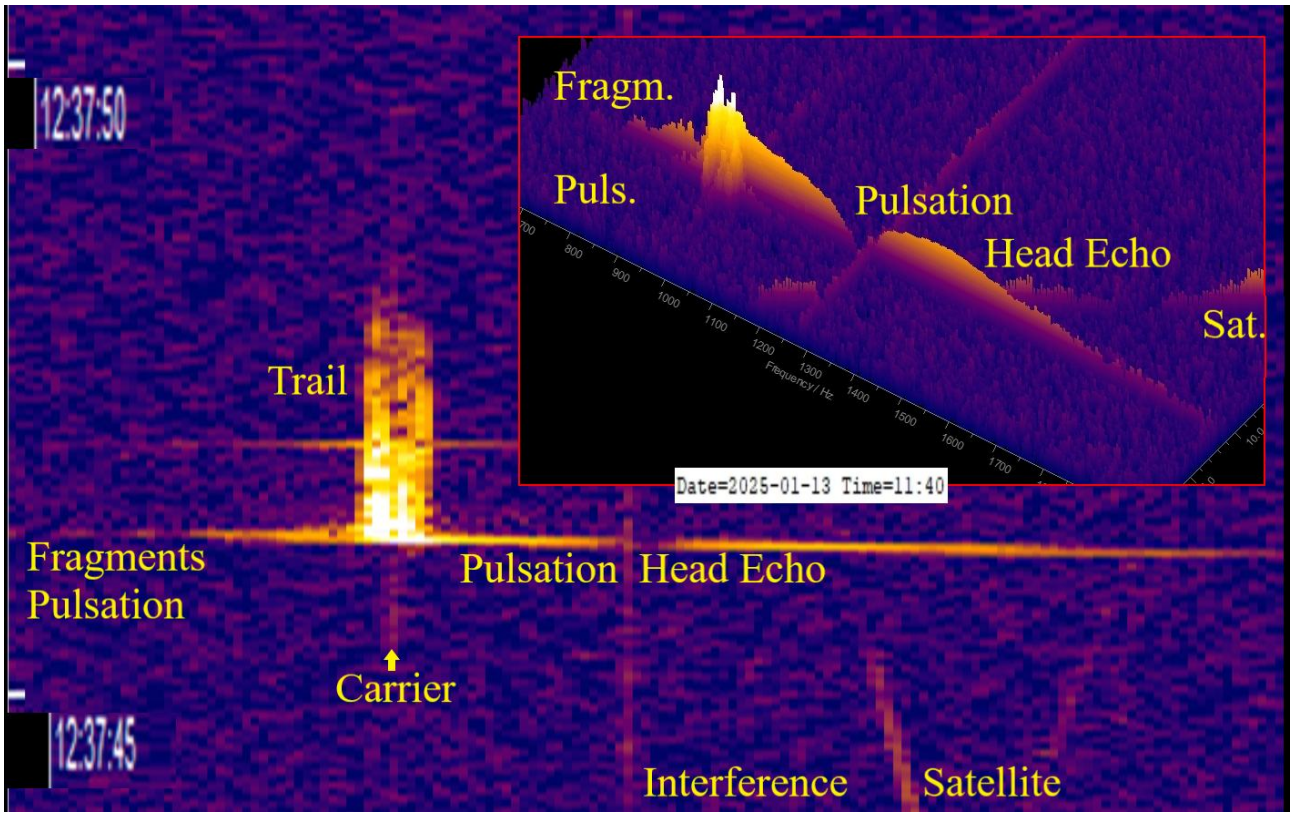

Figure 8 – Here the trail is weaker than in Figure 7, but more material remains for the onward flight. The head echo shows a pronounced pulsation. Occasionally there is a disturbance that can be seen in the middle of the 2D image. Satellite echoes are always present. The GRAVES carrier is marked with *Carrier*.

4 Conclusion

The 3D representation of the spectrograms, which were generated using the powerful GRAVES radar, allows interesting insights into the plasma of the head echo. Fading or pulsation in the spectrogram of the head echo shows when a meteoroid is travelling in fragments. It is also possible to see whether particles continue their flight after the explosion. My previous work had already shown that the 3D spectrogram can be used to determine when meteoroids and radar beams are running parallel. It will be very exciting to explore further streams.

Acknowledgements

Literature

Close S., Brown P., Campbell-Brown M., Oppenheim M., Colestocka P. (2007). "Meteor head echo radar data: Mass–velocity selection effects". *Icarus*, **186**, 547–556.

Kero, J., Szasz, C., Pellinen-Wannberg, A., Wannberg, G., Westman, A., and Meisel, D. D. (2008). "Three-dimensional radar observation of a submillimeter meteoroid fragmentation". *Geophysical Research Letters*, **35**, L04101.

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Graphical Abstract