Fresnel holography for radio characterization of meteoroid fragmentation

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Meteoroid fragmentation is essential for interpreting radio and optical data as it is probable that meteoroids of all sizes fragment. Characterizing this phenomenon should give useful insights about the distribution and evolution of dust particles in the Solar System, and eventually allow a better determination of meteoroid fluxes, which is crucial for meteoroid environment models to estimate impact risks to spacecraft. The Fresnel Transform (FT) is a powerful tool which shows potential to characterize the meteor trail ionization through radar measurements. However, in the past, it has mainly been employed for the purpose of computing meteoroid velocity. In this work, we present details of a new Python software package which allows the computation of the FT applied to meteor echoes. With this software, we apply the FT to meteor echoes detected at the 3 frequencies of the Canadian Meteor Orbit Radar (CMOR) and compare the results with the high-resolution imagery furnished by the Canadian Automated Meteor Observatory (CAMO) as validation. We show that the scattering amplitudes are frequency-dependent and we suggest directions for further analysis.

1 Introduction

It has been argued within the scientific community that meteoroids of all sizes fragment. Observations with the high-resolution optical network CAMO (Canadian Automated Meteor Observatory) have shown that 90% of all observed meteoroids fragments (Subasinghe et al., 2016). The remaining 10% may fragment as well, as it was shown that meteors with a very short wake cannot be fitted with a single body model (Campbell-Brown, 2017).

Incorporating fragmentation in ablation models is essential for a proper characterization of the structure and composition of meteoroids. The latter determine the dynamics of meteoroids in space, their ablation behavior when they enter the atmosphere and the potential damage that they cause to spacecraft. Ignoring fragmentation leads notably to an overestimation of ablation coefficients, an underestimation of meteoroid densities (Moorhead et al., 2017) and limit the accuracy in the determination of meteoroid orbits (Vida et al., 2018).

Although high-resolution observations of meteor trails through optical means at mm-sizes have been done in the recent years (Campbell-Brown, 2017; Vida et al., 2021), there are few works examining fragmentation for small meteoroids detected by radar. The Fresnel Transform (FT), an approach that utilizes both the phase and amplitude associated to the radio echo of a meteor was developed by Elford (2001). This technique was suggested as a novel means to study the structure of the ionized trail immediately behind the head of the meteor. Although it is potentially highly effective for computing the variation of the electron line density along the trail and therefore characterizing fragmentation, to date the FT has been mainly used for the computation of meteoroid velocity (Baggaley & Grant, 2005; Campbell & Elford, 2006; Holdsworth et al., 2007; Roy et al., 2007).

In (Elford, 2004), it was claimed that the FT was able to provide evidence of fragmentation. The deviation of the scattering amplitude from the usual exponential fall off behind the meteoroid head would then be the evidence of the creation of secondary trails. More specifically, local peaks in the scattering pattern would correspond to a local increase in trail ionization and hence be a proof of fragmentation.

The goal of the present work is to critically examine the claim that FT uniquely identifies fragmentation in ionization trails and to develop a Python package which will allow the computation of the FT applied to backscatter meteor echoes, with a specific aim of examining the process of fragmentation at small meteoroid sizes. We apply the FT to simulated meteor echoes and show its sensitivity to aliasing. Then, we apply our tool to meteor echoes detected at the 3 frequencies of the Canadian Meteor Orbit Radar (CMOR) and compare the results with the high-resolution imagery given by CAMO. This comparative analysis shows the frequency dependence of the FT outputs and the numerous parameters interfering with the interpretation of the FT.

2 Software development

We develop software taking as an input the time series of a radar meteor echo, meteoroid speed and range. The resulting output is the corresponding Fresnel Transform. To start, we look at the results obtained with a modelled echo following the Cornu Spiral (McKinley, 1961). We simulate echoes at a low speed of 12 km/s and at a high speed of 50 km/s, assuming a pulse repetition frequency (PRF) of 532 Hz, the same PRF as for CMOR. The results are shown in Figure 1. For clarity, we do not display the phases but only the amplitudes of the time series and of the FT.

It appears quite clearly that the FT of the low-speed meteoroid is as expected: a sharp ionization rise around the meteoroid head, then an exponential decay further back in the trail. However, when the speed is increased, the FT output becomes impossible to interpret due to aliasing. This phenomenon occurs when the sampling rate of a signal is insufficient to capture the true frequency content of that signal, leading to distortion of the observed data (Smith, 2013). As a consequence, we focus our study to low-speed meteoroids in the framework of this project.

3 Frequency dependency

In order to validate our interpretation of the FT, we look at events simultaneously detected by the 3 frequencies of CMOR (17, 29 and 38 MHz) and by CAMO (Vida et al., 2021; Weryk et al., 2013). To make sure that we analyze common events between radar and optical records, we look for meteors which have sufficiently close speeds, ranges and timings, as computed from CMOR and CAMO. We also ensure that the radar specularity condition is met by checking that the angle between the trajectory and the line of sight from the radar to the detected meteor is close to 90°.

As an example, we take a meteor whose optical velocity is 24.7 km/s. As the radar receives most of the power in the first Fresnel zone, which is a few kilometers in length centered around the specular point, we constrain our FT analysis on this region. As shown in the top and middle panels of Figure 2, the initial homogeneous meteor trail split in two distinct fragments. Nonetheless, in the bottom panel, the FT curves computed at the 3 CMOR frequencies do not show clear similarities.

On the one hand, it is not surprising that different radar frequencies lead to different ionization patterns.

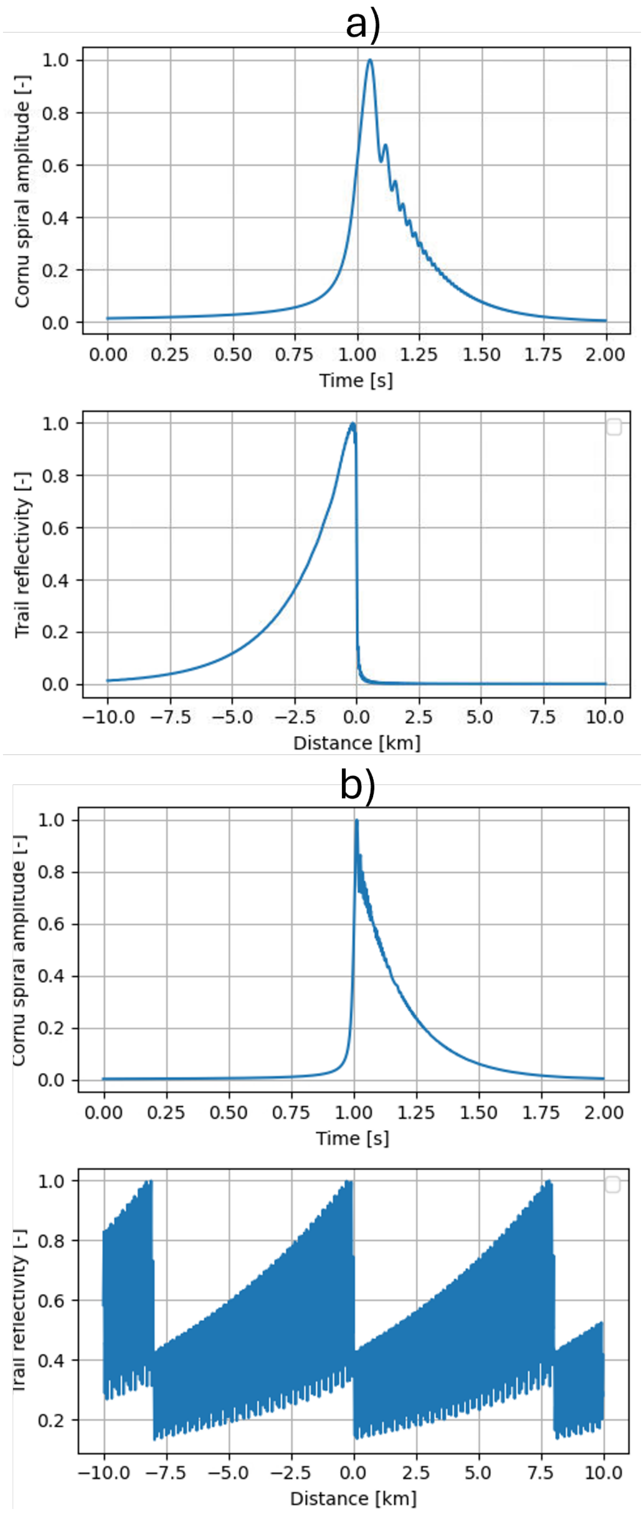

Figure 1 – Panel a) shows the amplitude of the simulated time series and its corresponding FT amplitude for a meteoroid travelling at a speed of 12 km/s. Panel b) shows the same curves for a speed of 50 km/s. Both meteoroids are simulated with a PRF = 532 Hz. The distances shown are measured from the position of the meteoroid at the specular point.

Indeed, two frequencies are sensitive to two different length scales. For instance, we expect that a lower frequency would lead to a slower exponential decay than a higher frequency. This is what we observe on the bottom panel of Figure 2.

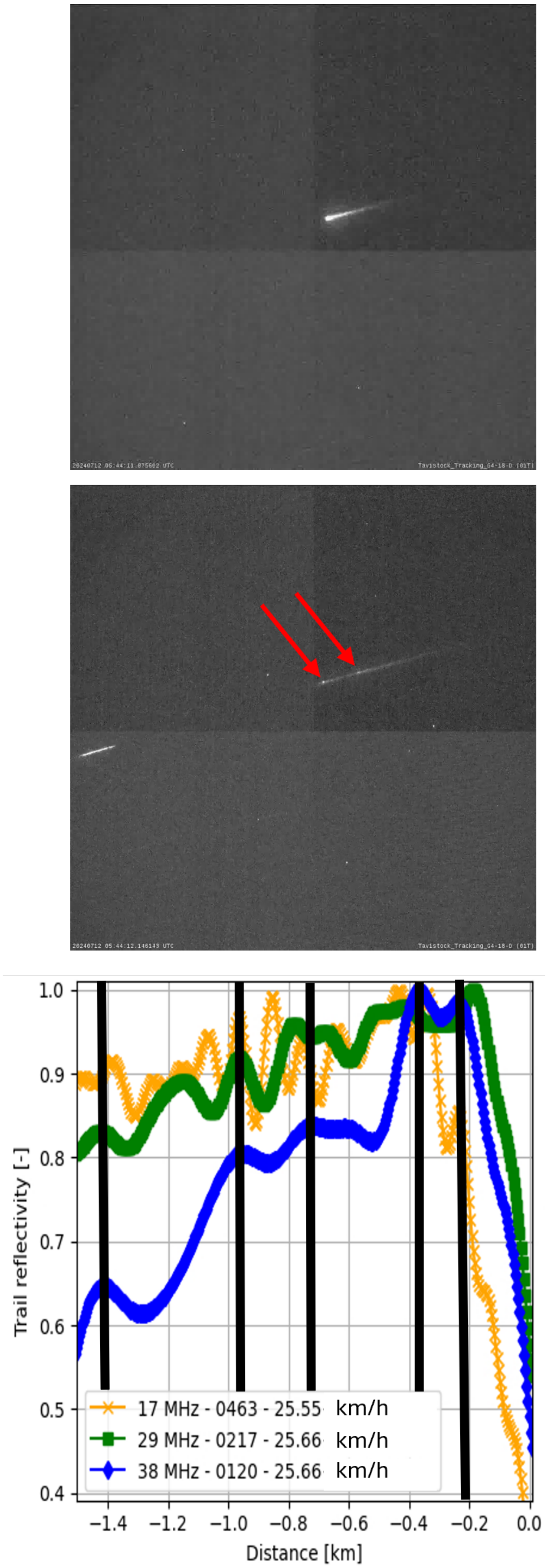

Figure 2 – Top panel: Initial CAMO image of the event. Middle panel: Subsequent CAMO image of the event, 271 ms later. Here, the field of view is approximately 1.5° and the pixel resolution is roughly 3 m at the range of the meteor. The red arrows show the distinct coaxial fragments. Bottom panel: FT results at the 3 CMOR frequencies. The vertical black lines indicate the positions of the local peaks in the FT amplitude computed at 38 MHz.

On the other hand, if the FT gives us insight into fragmentation, the peaks in the FT amplitudes should appear at the same locations at the 3 frequencies. Indeed, the creation of fragments should come with an increase in the ionization, leading to a local maximum in the FT amplitudes. However, when we look at the bottom panel of Figure 2, we see that the local peaks obtained at 38 MHz do not necessarily match the local peaks at the other frequencies. This shows that there exist frequency-dependent effects interfering with our use of the FT as a tool to characterize fragmentation.

4 Optical comparison

To further interpreting the FT, we compare our FT amplitudes with two different optical outputs. First, the light curve manually reduced from the wide-field and narrow-field cameras of the CAMO system. Secondly, we compare the FT amplitude with the instantaneous brightness of the wake, in a region approximately a hundred meters long behind the meteor head. The latter is obtained by looking at the optical frame which is the closest to the radar specular point. There, the pixel intensities are summed on each cross-section of the meteor, giving us a profile representing the brightness evolution as a function of the longitudinal position within the trail.

The results obtained for a meteor travelling at 28.6 km/s are given in Figure 3. To compare the different curves, the results have been normalized. As expected, the length scales of the optical outputs differ significantly. Indeed, the trail brightness is very local and is concentrated on a few tens of meters around the meteoroid head. On the other hand, the light curve, which represents the cumulative past "history" of the meteor ablation along the trail, spans over about 20 km.

Between these extremes, the FT curve can be theoretically computed on any chosen interval. In practice however, looking at the FT amplitudes after a couple of km does not make much sense as most of the radar power comes from the first Fresnel zone. As a result, there is no evident correlation between the FT and optical results such as the light curves or the local trail brightness, as each of these outputs gives a picture of the trail at different length scales. In addition to the one example shown here, we explored in detail the light curve and local wake distribution in relation to the FT amplitude for other events, finding essentially the same behaviour.

5 Conclusion

The scattering behaviour output by the FT appears to be frequency-dependent. This indicates that other phenomena interfere with a possible interpretation that the FT amplitude bumps would be evidence for fragmentation. A comparison of FT amplitudes with optical detections showed no clear match with the light curve. A probable explanation is that the length scales studied by each method are different. Simulations should

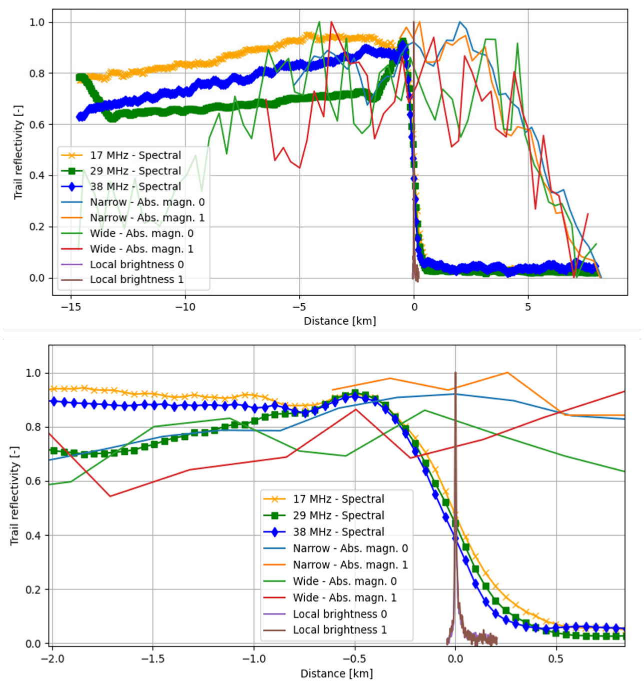

Figure 3 – Top panel: Comparison between FT amplitudes at 3 CMOR frequencies, light curves from both wide-field and narrow-field CAMO cameras, as well as local trail brightnesses from both narrow-field CAMO cameras. Bottom panel: Zoomed comparison.

be run to better understand the parameters influencing the FT outputs.

However, it is important to note that the results presented in this paper were obtained using a PRF of 532 Hz. To validate these findings, additional tests with a higher PRF are necessary. Increasing the PRF by a factor of 4 can mitigate aliasing, allowing the analysis of meteors traveling at twice the speed. In any case, the Fresnel Transform remains a crucial tool for accurately determining meteoroid velocities, calculating mesosphere-lower thermosphere temperatures, and measuring wind speeds. As such, it should continue to be leveraged for these key applications.

6 Acknowledgement

Joachim Balis is funded by the Solar-Terrestrial Center of Excellence (STCE). This work was supported in part by funding from NASA cooperative agreement 80NSSC24M0060. Additional financial support for this project was provided by Mitacs, the University of Liège, and the Wallonia-Brussels Federation.

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