Phase-enhanced trajectory and speed reconstruction of meteoroids using BRAMS data

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In this work, we aim to reconstruct meteoroid trajectories thanks to a forward scatter radio system using a pure continuous wave (CW) transmitted signal with no modulation. To do so, we use the time delays between the meteor echoes recorded at the receivers of the BRAMS (Belgian RAdio Meteor Stations) network. To obtain a better accuracy, the time delays are complemented by information about the signal phase. In this project, we adapt the pre-t_0 phase technique introduced for backscatter radars to forward scatter systems and we illustrate the improved accuracy that it can bring on the meteoroid trajectory and speed reconstruction. To validate our approach, we compare the quality of the radio reconstructions to the trajectories given by the optical CAMS (Cameras for Allsky Meteor Surveillance) network in Benelux.

1 Introduction

The BRAMS (Belgian RAdio Meteor Stations) network is a Belgian project using forward scatter of radio waves to detect and characterize meteoroids. It comprises a dedicated transmitter located in the South-West of Belgium and 46 receiving stations spread all over the Belgian territory and neighbouring countries (see Figure 1 for status in September 2023).

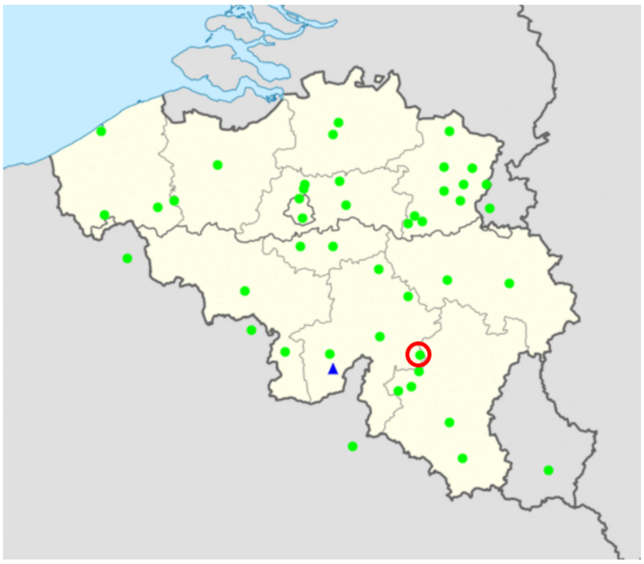

Figure 1 – Map of the BRAMS network in September 2023. The blue triangle is the transmitter located in Dourbes, the red circle is the interferometer located in Humain, and the green dots are the 46 active receiving stations at the time.

The transmitter emits a circularly polarized continuous radio wave with no modulation at a frequency of 49.97 MHz with a power of 130 Watts. All the receiving stations are using a 3-element Yagi antenna set-up vertically and oriented in azimuth towards the transmitter. At the time of writing, approximately a third of the receiving stations are using analog ICOM-R75 receivers, an external sound card to sample the signal coming from the antenna, and are controlled by the freeware program Spectrum Lab running on a PC (Lamy et al., 2015). The other two thirds use digital SDR-RSP2 receivers controlled by a Linux system running on a Raspberry Pi (Anciaux et al., 2020). All stations are equipped with a Garmin GPS that provides timestamps to the BRAMS data and allows a time synchronization between the receiving stations. Additional features of the receiving stations are not described here. Instead, we refer the reader to previous publications in the Proceedings of the IMC (Lamy et al., 2015; Anciaux et al., 2020).

One of the difficulties with forward scatter systems is the determination of individual meteoroid trajectory and speed as the geometry is more complex than in the case of backscatter systems. In the specific case of BRAMS, the absence of modulation in the CW transmitted signal does not allow to estimate the total range traveled by the radio wave between the transmitter (Tx), the reflection point and the receiver (Rx), and therefore makes the problem complex to solve.

We summarize here the approach to reconstruct meteoroid trajectories without interferometry that we discussed in (Balis et al., 2023). Given its inherent sensitivity to the accuracy of the inputs, we then propose an extension to forward scatter systems of the pre-t_0 phase approach discussed for backscatter radars in (Mazur et al., 2020).

2 Trajectory reconstruction without interferometry

The approach is based purely on geometrical considerations and relies on the specular condition of the reflection of the radio wave. The specular reflection point is the point along the meteoroid path for which the total distance traveled by the radio wave is minimum, which means that the total distance $S_i = R_{Ti} + R_{Ri}$ (where R_{Ti} is the distance from the transmitter to the meteor path and R_{Ri} is the distance meteor path-receiver) must be minimum for each receiving station i. Because the geometry Tx-$\mathrm{Rx_i}$ is different for each receiving station $\mathrm{Rx_i}$, the corresponding reflection points will be located at various positions along the meteoroid path. This is illustrated in Figure 2 for a reference station Rx_0 and another station Rx_i. In this example, the specular reflection point P_0 for the reference station is created before the corresponding reflection point P_i. The distance between the two points depends on the speed of the meteoroid which is here assumed constant. As a consequence, the reference station will detect a meteor echo shortly before receiving station i, the time delay between meteor echoes depending on the meteoroid path and speed.

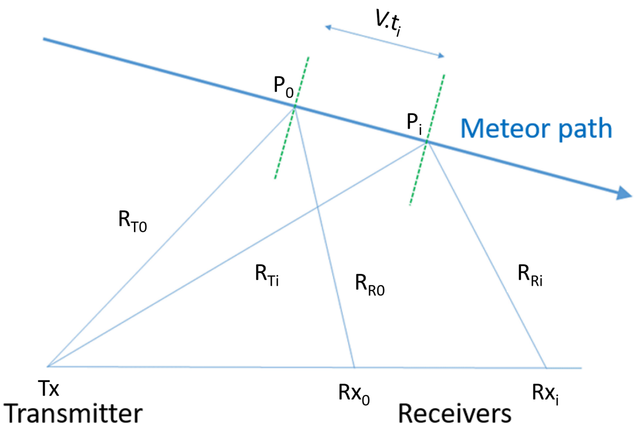

Figure 2 – Specularity and geometry of a forward scatter set-up. The time delay between the creation of the specular point P_0 of the reference station Rx_0 and the specular point P_i of the other station Rx_i is noted t_i. The straight blue arrow indicates the meteor path, travelling at a speed V. The two radio wave paths $Tx - P_0 - Rx_0$ and $Tx - P_i - Rx_i$ are not coplanar.

A meteoroid trajectory can be defined by the 3D Cartesian coordinates of one specular point (the one corresponding to a reference station) and the three components of the velocity which provides the direction (assuming again a constant speed). This gives a total of six unknowns (respectively called X_0, Y_0, Z_0, v_x, v_y and v_z) and therefore the need to have at least six equations to avoid solving an underdetermined system. In Method 1, these equations are provided by the fact that the total derivative, dS_i/dt, must be equal to 0 for at least six stations $i = 1, \ldots, 6$. This leads to a set of ≥ 6 non-linear equations which contains the 6 unknowns and the time delays $\Delta\, t_i$ between meteor echoes recorded at station i and the reference station. A non-linear solver must then be used to solve this set of equations and taking into account additional constraints on the unknowns, such as the height of all reflection points which must lie between e.g. 80 and 120 km altitude, or the speed of the meteoroid which must be larger than $\sim 11\,\mathrm{km/s}$ but smaller than $\sim 72\,\mathrm{km/s}$.

As illustrated in (Balis et al., 2023), this inverse trajectory reconstruction problem is severely ill-conditioned when all the receiving stations lie close to the same plane. This is the case here since the differences in altitude between the receivers are only of a few tens of meters while the trajectories are located at about 100 km in altitude. In this configuration, the output trajectory is highly sensitive to the quality of the input time delays, small errors on the latter leading to large uncertainties on the output trajectory.

To alleviate this ill-conditioning, we adapt the pre-t_0 phase technique developed in (Mazur et al., 2020) to the BRAMS network.

3 Pre-t_0 approach

As discussed in (McKinley, 1961), the power by a meteor echo is proportional to $\mathcal{F}_{\sin}^2 + \mathcal{F}_{\cos}^2$ where $\mathcal{F}_{\sin}$ and $\mathcal{F}_{\cos}$ are the Fresnel integrals defined by:

$$\begin{aligned} \mathcal{F}_{\sin} &= \int_{-\infty}^{x(t)} \sin\left(\frac{\pi}{2}x^2\right) dx \\ \mathcal{F}_{\cos} &= \int_{-\infty}^{x(t)} \cos\left(\frac{\pi}{2}x^2\right) dx, \end{aligned} \tag{1}$$

where x is the dimensionless Fresnel parameter along the spiral formed by the parametric plot of the Fresnel integrals:

$$x = s\frac{2\sqrt{2}}{d_f}, \tag{2}$$

where s is the distance along the trail (expressed in km) and d_f is the length of the first Fresnel zone. The exact expression of d_f for forward scatter systems can be found in e.g., (Wislez, 2006).

A plot of $\mathcal{F}_{\sin}$ as a function of $\mathcal{F}_{\cos}$ gives the Cornu spiral, which is useful to describe the amplitude and phase variation of the meteor echo, as illustrated in Figure 3. Indeed, on the top panel, the distance between the starting point (where $\mathcal{F}_{\sin} = \mathcal{F}_{cos} =$ -0.5) and the current location on the Cornu spiral gives the theoretical amplitude of the meteor echo. Similarly, the angle between the horizontal line and the vector joining the starting point and the current location on the Cornu spiral gives the theoretical phase of the meteor echo. The amplitude and phase behaviours as x varies are then plotted on the bottom panel.

The pre-t_0 phase method uses the phase curve of Figure 3 to invert the speed of the meteoroid. After phase extraction from the radio data, each sample is associated

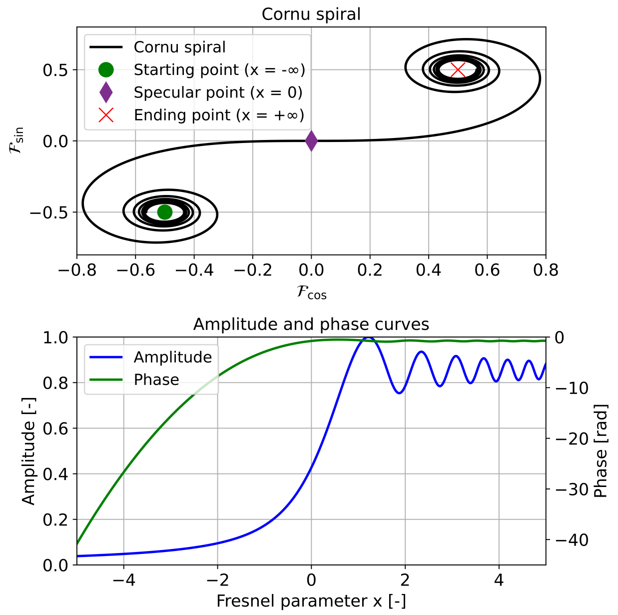

Figure 3 – Cornu spiral and corresponding amplitude and phase curve. Top panel: the spiral and its characteristic points. The green circle indicates the start of the spiral (in $x = -\infty$), the purple diamond is the passage at the specular point ($x = 0$), and the red cross is the end of the spiral (in $x = +\infty$). Bottom panel: Amplitude and phase variation with the Fresnel parameter x.

to a given value of the Fresnel parameter x. Then, this parameter is converted to the distance along the trail s through Equation 2.

Finally, the GPS timestamps can be used to obtain a curve of the distance along the trail as a function of time $s(t)$. Taking the slope of this curve gives us a measurement of the meteoroid velocity $v(t)$. The great advantage of this approach with a forward scatter set-up such as BRAMS is that it allows to sample the meteoroid velocity at several specular points on the trajectory. This feature is potentially interesting for the use of a deceleration model. However, since we use a constant speed model in this study, only the pre-t_0 information at the reference station is employed. This reference station is defined as the first receiver on the trajectory which has a signal-to-noise ratio (SNR) of at least 20 dB.

4 Results

To validate the trajectory reconstruction solver and the novel pre-t_0 method, we compare our results with optical data from the CAMS BeNeLux network (Jenniskens et al., 2011; Roggemans et al., 2016). Data were provided for 2 clear consecutive nights from 29 to 31 July 2020, in a period without any strong activity from meteor showers. From this data, we selected 8 trajectories spanning a wide range of radiants and velocities, and which yielded reliable pre-t_0 information.

Out of the 8 cases, 6 BRAMS reconstructions with pre-t_0 are in a very good agreement with CAMS, i.e. the discrepancy in terms of velocity is less than 5% compared to the CAMS data while the inclination difference is less than 2°, as illustrated in Figure 4. The improvement brought by the use of the pre-t_0 information is particularly striking for trajectories 477 and 532.

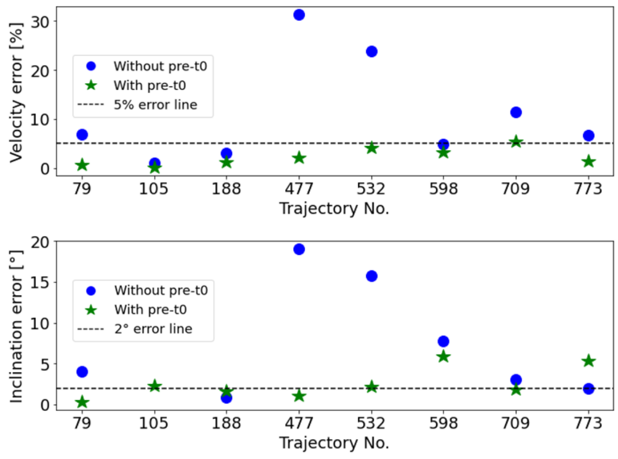

Figure 4 – Comparison of the reconstruction results without interferometry obtained without and with pre-t_0 phase information. The trajectory numbers correspond to the 8 selected CAMS trajectories.

It appeared that the trajectories which are the most difficult to reconstruct are trajectories 598 and 773, i.e. the trajectories with the highest speeds. This phenomenon can be explained because, as the meteoroid enters the atmosphere faster, it spends less time in the observable region of BRAMS. Thus, the time delays between the exploitable specular points tend to be smaller. As a result, errors on the identification of the specular point location at each receiver lead to larger relative errors on the measured time delays. The pre-t_0 phase method alleviates this phenomenon, but the quality of the reconstruction remains dependent on an accurate determination of the specular point timings.

5 Discussions and perspectives

The pre-t_0 phase method brings significant improvements on the trajectory reconstructions without interferometric data. It is important to highlight that the approach combining information coming from the time delays and the phase can be applied to all archived BRAMS past data, contrary to the method with interferometry which can only be used for meteors detected at our interferometer in Humain.

To further enhance the quality of the reconstructions, we are currently developing and testing deceleration models, applying the pre-t_0 phase method at all stations with a sufficiently good SNR. In parallel, we are also implementing an algorithm exploiting the Doppler information obtained from head echoes, inspired by the approach proposed in (C. Steyaert, 2010). This will give us another way to estimate meteoroid velocities.

All of these tools combined will then be applied together to reconstruct a large sample of trajectories and compare the results with optical data from CAMS-BeNeLux and GMN (Vida et al., 2021).

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