Improved meteoroid trajectory and speed reconstruction with BRAMS: pre-t_0 phase technique and uncertainty analysis

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We present an enhanced method for reconstructing meteoroid trajectories and speeds using the Belgian RAdio Meteor Stations (BRAMS) forward scatter network. A novel extension of the pre-t_0 phase technique, which was originally developed for backscatter radar, is adapted to continuous-wave forward scatter systems. By analyzing the phase evolution before the meteoroid reaches the specular reflection point, we derive precise speed estimates. These pre-t_0 speeds are integrated with time-of-flight measurements in an optimization solver, enabling trajectory determination without interferometry. A Markov Chain Monte Carlo framework propagates these measurement uncertainties, yielding robust confidence intervals on meteoroid trajectory and speed. Validation against optical data from the CAMS-BeNeLux network shows systematic improvements with mean speed errors $<5\%$ and inclination errors of 2–4°.

1 Introduction

Accurate meteoroid trajectory and speed determination are necessary inputs to study the origin, flux, and atmospheric impact of small bodies. While optical systems provide high trajectory precision, radio techniques such as the BRAMS forward scatter network operate continuously and detect much smaller particles. Traditional single-station radar speed methods, such as pre-t_0 amplitude (Baggaley & Grant, 2005), post-t_0 amplitude (Ellyett & Davies, 1948), Fresnel Transform (Elford, 2004), and pre-t_0 phase (Cervera et al., 1997), differ mainly in their use of amplitude or phase information. Among these, the pre-t_0 phase method has shown better robustness at low signal-to-noise ratios and minimal sensitivity to fragmentation.

We build on earlier trajectory trajectory work using the times of flight measured at several BRAMS receivers (Balis et al., 2023). Here, we extend the pre-t_0 phase analysis from backscatter to continuous-wave forward scatter systems. This paper summarizes the algorithm, its implementation, and its validation against CAMS-BeNeLux optical data. It is based on a peer-reviewed paper recently published in Radio Science (Balis et al., 2025).

2 Methodology

2.1 Pre-t_0 phase

The pre-t_0 phase technique relies on the Cornu spiral representation of Fresnel diffraction (McKinley, 1961). The Cornu spiral associates a phase value to each location along the meteoroid trajectory. After phase extraction from the radio data, each sample is linked to a given value of the dimensionless Fresnel parameter x thanks to the Cornu spiral model. Using baskcatter range information, the Fresnel parameter curve $x(t)$ is then converted to the distance along the trail $s(t)$. The slope of this curve gives an estimate of the meteoroid speed v.

More formally, the dimensionless Fresnel parameter x can be related to the distance s along the trail as:

$$s = \frac{\sqrt{2}d_f}{2}x, \tag{1}$$

where d_f is the length of the first Fresnel zone depending on the transmitter–meteor–receiver geometry.

In the forward scatter case, we have (Wislez, 2006):

$$d_f = 2\sqrt{\frac{\lambda R_\mathrm{T} R_\mathrm{R}}{(R_\mathrm{T} + R_\mathrm{R})\left(1 - \sin^2\phi\cos^2\beta\right)}}, \qquad (2)$$

where λ is the wavelength, R_T is the distance from the transmitter to the meteor specular point and R_R is the distance from the specular point to the receiver. ϕ is the half forward scatter angle and β is the angle between the meteoroid trajectory and the propagation plane.

The BRAMS processing pipeline isolates a few seconds of data around each echo, applies band-pass filtering, constructs the analytic signal via Hilbert transform, extracts and unwraps the phase, and identifies the t_0 point, as illustrated in Figure 1.

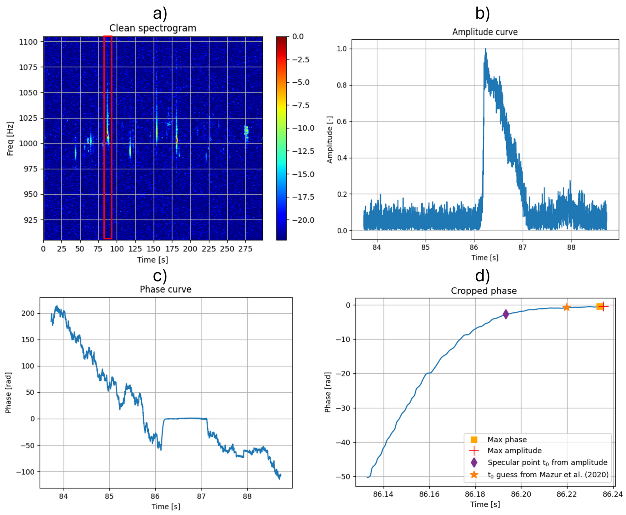

Figure 1: Phase information extraction from BRAMS data. a) Spectrogram after beacon subtraction. The power is color-coded in dB FS (Decibels relative to Full Scale). The red rectangle highlights the meteor of interest. b) Amplitude of the meteor echo obtained after bandpass filtering. c) Phase of the meteor echo obtained after bandpass filtering and wind drift subtraction. The green rectangle is the part of the phase curve used for pre-t_0 speed computation. d) Zoom on the green rectangle of panel c).

Adapting a recent pre-t_0 phase method for backscatter radar (Mazur et al., 2020) to the forward scatter case, a linear fit of the Fresnel parameter vs. time before the t_0 point provides the pseudo-speed $\frac{dx}{dt}$. With the knowledge of geometry information, d_f can be computed and the pre-t_0 speed can then be determined using:

$$v = \frac{\sqrt{2} d_f}{2}\frac{dx}{dt}. \qquad (3)$$

2.2 Trajectory solver and uncertainty

Our novel trajectory reconstruction solver combines time-of-flight (Δt_i) and pre-t_0 speed ($v_{j,\mathrm{pt0}}$) measurements in a weighted least-squares cost function:

$$L = \sum_{i=1}^{n}\left(\frac{\Delta t_{i,obs} - \Delta t_{i,mod}}{\sigma_{\Delta t_{i,obs}}}\right)^2 + \sum_{j=1}^{m}\left(\frac{v_{j,pt0} - v_{j,mod}}{\sigma_{v_{j,pt0}}}\right)^2, \qquad (4)$$

where $\Delta t_{i,obs}$ is the experimental time of flight measured between a station i and a reference station, while $\Delta t_{i,mod}$ is a time of flight coming from the forward trajectory reconstruction problem. $v_{j,pt0}$ is the experimental pre-t_0 speed measured at a receiver j while $v_{j,mod}$ is the meteoroid speed. $\sigma_{\Delta t_{i,obs}}$ and $\sigma_{v_{j,pt0}}$ are the uncertainties respectively on the time of flight at station i and on the pre-t_0 speed at station j. Their determination are discussed in our recent paper (Balis et al., 2023). In Equation 4, one station can provide both a time of flight and a pre-t_0 phase.

This quantity is minimized via an optimization algorithm. To obtain confidence intervals on the trajectory solution, we employ a Markov Chain Monte Carlo (MCMC) sampler following the Single Component Adaptive Metropolis (SCAM) algorithm (Kastinen & Kero, 2022). The MCMC posterior distributions of position and velocity components yield confidence intervals on speed, altitude, and inclination.

3 Results

3.1 Validation with optical data

We validated our method on ten meteors simultaneously observed by both BRAMS and the CAMS-BeNeLux network. Table 1 summarizes the comparison between the BRAMS maximum a posteriori (MAP) solutions and CAMS trajectories.

Parameter	Mean Error	Max Error
Speed	3.1%	10%
Altitude	4.4 km	10 km
Inclination	2.8°	4°

Table 1: Comparison between BRAMS reconstructions (including pre-t_0) and CAMS trajectories.

The inclusion of pre-t_0 information significantly alleviates the ill-conditioning in the forward scatter trajectory reconstruction problem. Even with a single pre-t_0 speed measurement, the inclination error can drop from tens of degrees to less than 4°.

An example MCMC plot for one trajectory is shown in Figure 2. The width of the histograms in the diagonal plots gives us an indication of the uncertainty in the six parameters of the solution [X_0, Y_0, Z_0, V_x, V_y, V_z]. The off-diagonal plots illustrate the correlations between each pair of parameters. In this case, it appears that the position parameters X_0, Y_0 and Z_0 are quite decorrelated, as their scatter plots are almost circular.

However, there is a strong linear correlation between the different velocity components V_x, V_y and V_z, which is another proof of the ill-conditioning of the trajectory reconstruction problem without interferometry. There is also some moderate correlation between the velocity components and the position parameters.

4 Conclusion

The pre-t_0 phase method, when integrated with time-of-flight observations, strongly enhances trajectory reconstruction in forward scatter radio networks. The approach improves speed and inclination accuracy without requiring interferometry, making it applicable to many meteor events. Future work will include (i) incorporating deceleration models to improve the accuracy of the pre-atmospheric speed determination (Vida et al., 2018), and (ii) coupling with Fresnel Transform speed determination (Holdsworth et al., 2007) to further constrain the trajectory solution. These developments will enable more accurate orbit determinations and improved assessment of meteoroid atmospheric dynamics, ultimately contributing to a deeper understanding of meteoroid origins and their link to parent bodies in the Solar System.

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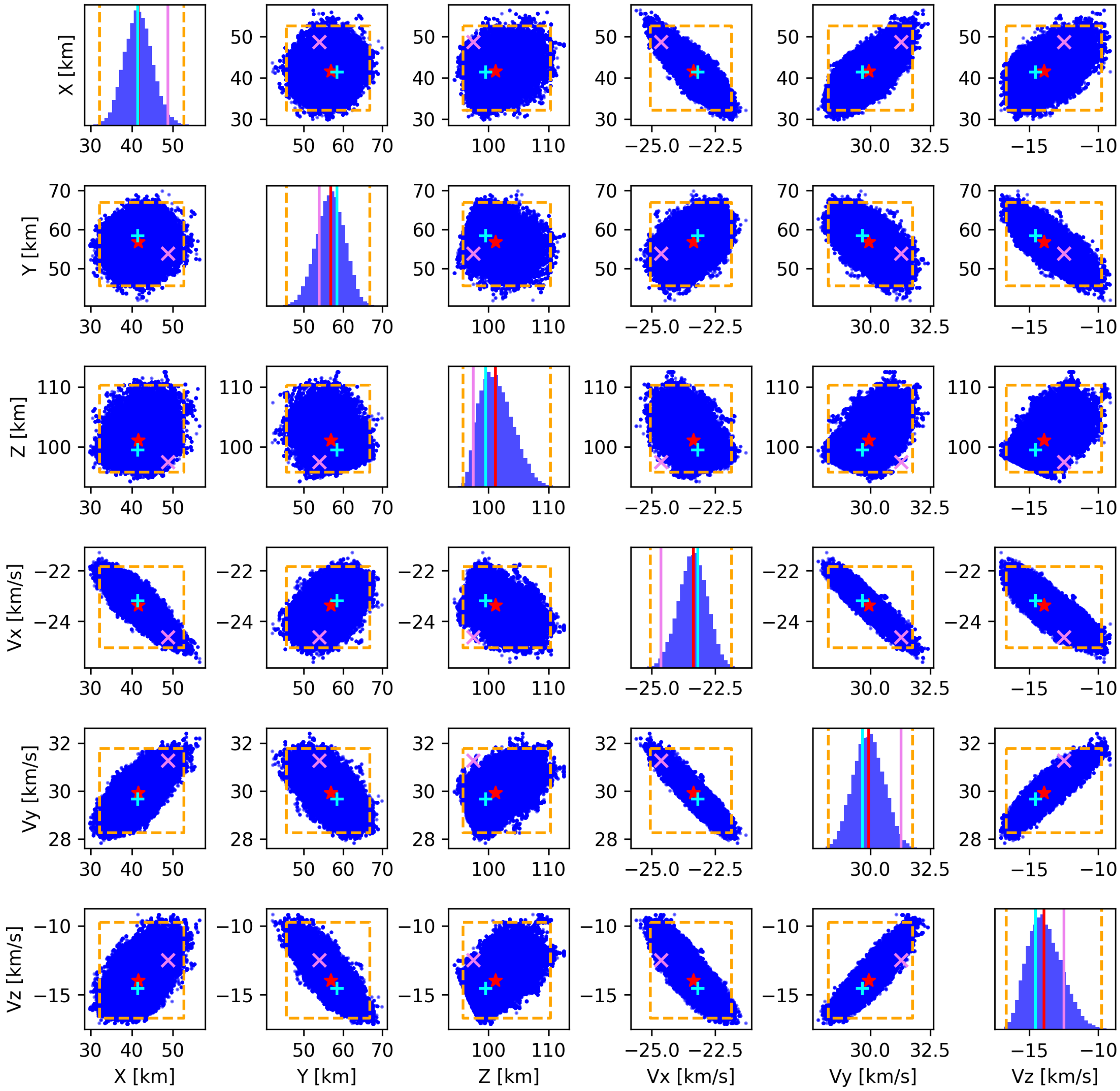

Figure 2: Scatter matrix for the parameters of one trajectory obtained with 300000 samples (in blue) of the SCAM algorithm. The cyan plus/line is the solution returned by the solver. The red star/line is the median of the posterior distribution. The violet cross/line is the CAMS solution. The dashed orange lines show the 3σ confidence intervals.