Icarus 294 (2017) 43–57

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

The challenge associated with the robust computation of meteor velocities from video and photographic records

A. Egal[a,*], P.S. Gural[b], J. Vaubaillon[a], F. Colas[a], W. Thuillot[a]

[a] IMCCE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC University. Paris 06, University of Lille, France
[b] Gural Software Development, 351 Samantha Drive, Sterling, VA 20164, USA

ARTICLE INFO

Article history:
Received 18 May 2016
Revised 4 April 2017
Accepted 12 April 2017
Available online 28 April 2017

Keywords:
Meteors
Orbit determination
Data reduction techniques
Image processing

ABSTRACT

The CABERNET project was designed to push the limits for obtaining accurate measurements of meteoroids orbits from photographic and video meteor camera recordings. The discrepancy between the measured and theoretic orbits of these objects heavily depends on the semi-major axis determination, and thus on the reliability of the pre-atmospheric velocity computation. With a spatial resolution of 0.01° per pixel and a temporal resolution of up to 10 ms, CABERNET should be able to provide accurate measurements of velocities and trajectories of meteors. To achieve this, it is necessary to improve the precision of the data reduction processes, and especially the determination of the meteor's velocity. In this work, most of the steps of the velocity computation are thoroughly investigated in order to reduce the uncertainties and error contributions at each stage of the reduction process. The accuracy of the measurement of meteor centroids is established and results in a precision of 0.09 pixels for CABERNET, which corresponds to 3.24″. Several methods to compute the velocity were investigated based on the trajectory determination algorithms described in Ceplecha (1987) and Borovicka (1990), as well as the multi-parameter fitting (MPF) method proposed by Gural (2012). In the case of the MPF, many optimization methods were implemented in order to find the most efficient and robust technique to solve the minimization problem. The entire data reduction process is assessed using simulated meteors, with different geometrical configurations and deceleration behaviors. It is shown that the multi-parameter fitting method proposed by Gural(2012)is the most accurate method to compute the pre-atmospheric velocity in all circumstances. Many techniques that assume constant velocity at the beginning of the path as derived from the trajectory determination using Ceplecha (1987) or Borovicka (1990) can lead to large errors for decelerating meteors. The MPF technique also allows one to reliably compute the velocity for very low convergence angles ($\sim 1°$). Despite the better accuracy of this method, the poor conditioning of the velocity propagation models used in the meteor community and currently employed by the multi-parameter fitting method prevent us from optimally computing the pre-atmospheric velocity. Specifically, the deceleration parameters are particularly difficult to determine. The quality of the data provided by the CABERNET network limits the error induced by this effect to achieve an accuracy of about 1% on the velocity computation. Such a precision would not be achievable with lower resolution camera networks and today's commonly used trajectory reduction algorithms. To improve the performance of the multi-parameter fitting method, a linearly independent deceleration formulation needs to be developed.

1. Introduction

The "CAmera for BEtter Resolution" (CABERNET) is a network of three photographic electronic cameras installed in the south of France since 2013 (Atreya et al., 2012). A field of view of 40°x26° is covered by the cameras with a spatial resolution of 0.01° per pixel. Each camera is used with an electronic shutter mode operating at 100 to 200 Hz which provides a temporal resolution of 5 to 10 ms. The technical performance of this camera network should lead to accurate measurements of meteoroid orbits, under the condition that a robust data reduction process is applied.

Most of the data reduction software implemented to reduce video and photographic measurements like UFOorbit (SonotaCo, 2008) compute multi-station trajectories using the intersecting planes (Ceplecha, 1987) or the least squares method (Borovicka, 1990). These approaches allow one to determine the direction of propagation of the meteors and the position of the radiant. The ve-

* Corresponding author.
E-mail address: auriane.egal@obspm.fr (A. Egal).

http://dx.doi.org/10.1016/j.icarus.2017.04.024

locity is then derived as a second step given the trajectory, by projecting the observations onto the three-dimensional line of the trajectory. However, solving for the trajectory and velocity separately may increase the error on the estimate of the pre-atmospheric velocity V_∞. One has to be very cautious in the computation of this parameter, since its value can substantially influence the characteristics of the orbits of the meteoroids, and especially the semi-major axis determination. As explained in Betlem et al. (1999), a bad estimate of the velocity causes a large discrepancy between the measured and theoretic semi-major axis of the orbits of meteoroids. For example, the difficulty of measuring the deceleration of the Draconids in 2011 led to an important error on the semi-major axis determination (e.g.,Ye et al. 2013; Trigo-Rodríguez et al. 2013; Vaubaillon et al. 2015). The spread of the observed radiant location was extremely large and summed up in Borovička et al. (2014). Another example of the large difference between measured and theoretic orbits concerns the 1999 Leonid storm (e.g.,Trigo-Rodríguez et al. 2002; Brown et al. 2002; Shrbený and Spurný 2009).

A new method of trajectory computation that simultaneously solves a coupled solution to the radiant position, velocity and deceleration was proposed by Gural (2012), and is currently applied to the data produced by the CAMS network (Jenniskens et al., 2011). This technique yields a more robust solution for the trajectory as all the spatial and temporal measurement information are processed simultaneously. It is a particularly interesting way to solve the straight line trajectory of a meteor since it provides accurate results on the radiant determination even for convergence angles below 20°. In this work, improvements on the velocity computation when using this method are more deeply explored. In order to find a reliable way to determine the radiant coordinates and the pre-atmospheric velocity of the meteors recorded by CABERNET, an analysis of different computation methods based on Ceplecha (1987), Borovicka (1990) and Gural (2012) is performed. The accuracy and limitations of these different techniques are highlighted by the use of simulated trajectories of meteors ('fakeors', cf. Barentsen 2009). Some of them are built following the propagation models assumed by Gural (2012), and other ones are created by numerical integrations using the Borovička et al. (2007) model. To simulate realistic meteors equivalent to the ones recorded by the CABERNET cameras, an analysis of the measurement errors on the location of the centroids in the images provided by the network is also conducted. The structure of the article is the following:

- Section 2: presentation of the propagation models and the cost functions used to solve the multi-parameter fitting of Gural (2012)
- Section 3: estimate of the uncertainty on the location of the centroids in the images provided by CABERNET
- Section 4: creation of the fakeors used to test the accuracy of different methods of trajectory computation
- Section 5: comparison of local and global optimization methods able to minimize the cost functions of Section 2
- Section 6: analysis of the accuracy of the pre-atmospheric velocities computed using Ceplecha (1987), Borovicka (1990) and Gural (2012) for the fakeors defined in Section 4
- Section 7: influence of the convergence angle on the angular error on the radiant direction and on the velocity computation
- Section 8: limitations of the deceleration models

2. Propagation models

We quickly summarize here the propagation models used to solve the multi-parameter fitting (Gural, 2012). In an Earth-centered inertial frame, each station s is located at a position $\vec{r_s}$ relative to the center of the Earth. The station s record $Nmeas(s)$ positions of a meteor starting with a state vector $(t_{beg}, \overrightarrow{X_{beg}}, \overrightarrow{V_{beg}})$ and following a straight trajectory. All the line-of-sight measurements recorded by the station at time t_{js} (cf. Fig. 1) have a relative time to the begin point of $t'_{js} = t_{js} - t_{beg} + \Delta t_s$. The timing offset parameter Δt_s takes into account clock errors and the non-synchronization of the cameras of each station. The relative time measurements t'_{js} are used to build the motion models of (1). The meteor starts at a position $\overrightarrow{X_{beg}}$ and moves according to one of the following velocity models: a constant velocity along the track, a linearly decreasing velocity in time or an exponential deceleration.

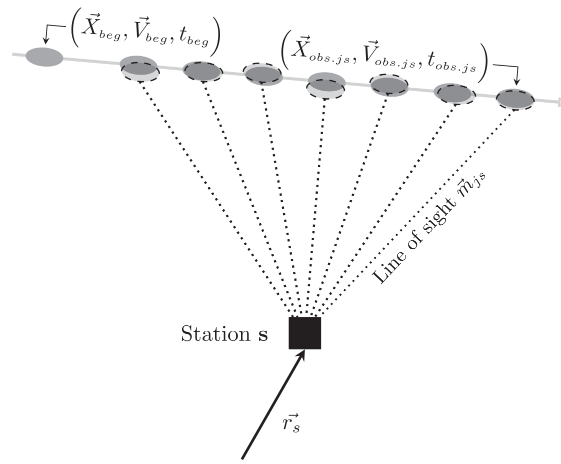

Fig. 1. Motion model of a meteor recorded by the station s. The measurement errors on the direction of the line-of-sights $\vec{m_{js}}$ causes a discrepancy between the real (filled ellipse) and observed (dashed ellipse) position of the meteor.

$$\begin{cases} \overrightarrow{X_s(t'_{js})} = \overrightarrow{X_{beg}} + X(t'_{js}) * \dfrac{\overrightarrow{V_{beg}}}{\|\overrightarrow{V_{beg}}\|} \\ X(t'_{js}) = \|\overrightarrow{V_{beg}}\| t'_{js} \\ X(t'_{js}) = \|\overrightarrow{V_{beg}}\| t'_{js} - |a_1| {t'_{js}}^2 \\ X(t'_{js}) = \|\overrightarrow{V_{beg}}\| t'_{js} - |a_1| e^{|a_2| t'_{js}} \end{cases} \tag{1}$$

with $s = \{1, \ldots, N_{stations}\}$ and $j = \{1, \ldots, N_{meas(s)}\}$

To determine the unknown parameters $\overrightarrow{X_{beg}}$, $\overrightarrow{V_{beg}}$, a_1, a_2 and Δt_s, a cost function with respect to real measurements needs to be minimized. In Gural (2012), the sum of the angles between the modeled and measured line-of-sights $\overrightarrow{m_{js}}$ is used (cf. Eq. (2)).

$$min \sum_{s=1}^{N_s} \sum_{j=1}^{N_{meas(s)}} arcos(\overrightarrow{m_{js}}.[\overrightarrow{X}_s(t'_{js}) - \vec{r_s}]) \tag{2}$$

In this work, we minimize the sum of the squared residuals of the standard coordinates of the meteor, which is a classical least squares problem. We start by converting the ECI (Earth-Centered Inertial) rectangular coordinates into celestial coordinates with (3).

$$\begin{cases} \overrightarrow{X_s}(t'_{js}) = \overrightarrow{[x, y, z]} \\ \alpha_{js} = atan\left(\dfrac{y}{x}\right) \\ \delta_{js} = asin\left(\dfrac{z}{\sqrt{x^2 + y^2 + z^2}}\right) \end{cases} \tag{3}$$

To obtain the standard coordinates (ξ, η), we perform a gnomonic projection of the celestial coordinates by (4). The tangential point (α_0, δ_0) of the transformation is an average right as-