Revista Mexicana de Astronomía y Astrofísica Serie de Conferencias (RMxAC), **59**, 87–91 (2025)

https://doi.org/10.22201/ia.14052059p.2025.59.17

UNSYNCHRONIZED FIREBALL ANALYSIS AND CHALLENGES IN DIMENSIONLESS ATMOSPHERIC FLIGHT PARAMETRIZATION: THE SPMN230522 SUPERBOLIDE AS A CASE STUDY

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RESUMEN

La triangulación de las trayectorias de bólidos facilita la reconstrucción del vuelo atmosférico y la determinación de la órbita heliocéntrica. La sincronización de fotogramas entre estaciones de observación no es trivial, especialmente con equipos de bajo rendimiento. Para abordar esto, implementamos un enfoque desincronizado compensando con una calibración de cámara robusta. En el contexto del análisis de entrada atmosférica, el método α-β ofrece un modelo adimensional efectivo, aunque sus resultados son sensibles a las técnicas de suavizado de datos. Esto se subraya con el evento del superbólido SPMN230522 que cruzó Cataluña el 23 de mayo de 2022, analizado por la Red de Investigación sobre Bólidos y Meteoritos (SPMN). Además, el diagrama α-β se ha revelado como una herramienta valiosa para la identificación de bólidos con potencial de generar meteoritos, demostrando su eficacia mediante su aplicación a la extensa base de datos de la red FRIPON.

ABSTRACT

Triangulation of fireball trajectories facilitates atmospheric path reconstruction and heliocentric orbit determination. Frame synchronization across networks with varied equipment capabilities presents a challenge. To address this, we implement an unsynchronized approach, underpinned by robust camera calibration. For atmospheric entry analysis, the α-β method offers an effective dimensionless model, though its outcomes are sensitive to the data smoothing techniques employed. This is underscored by the SPMN230522 superbolide event crossing Catalonia on 23 May 2022, analyzed by the Spanish Fireball and Meteorite Network (SPMN). Furthermore, the α-β diagram has proven to be a useful tool for pinpointing meteorite-producing fireballs, with its application to the FRIPON network's comprehensive dataset further validating its utility.

Key Words: Ablation — Atmospheric flight — Fireballs — Meteorites — Meteors — Superbolides

1. INTRODUCTION

Ground-based meteor networks offer in-depth studies of meteoric activity and facilitate campaigns aimed at recovering recently fallen meteorites (Wetherill & Revelle 1981; Brown et al. 2013). These meteorites provide valuable scientific insights into the origin and evolution of our Solar System (Ceplecha et al. 1998; Trigo-Rodríguez et al. 2015; Kyrylenko et al. 2023). Optical devices used for fireball multistation triangulation enable the reconstruction of atmospheric trajectory, luminosity, possible strewn field, and heliocentric orbit (Ceplecha 1987; Gritsevich & Koschny 2011; Dmitriev et al. 2015; Moilanen et al. 2021).

One critical and non-trivial aspect of research in this field involves determining the velocity curve (along with its associated uncertainty) of a meteoroid as it undergoes ablation upon entering Earth's atmosphere (Egal et al. 2017). Extracting spatial-temporal information from recordings captured by different cameras and merging them can be challenging due to occasional unsynchronized stations and data storage errors, which are more prevalent in pro-am collaborations that often involve equipment of varying performance. Consequently, it becomes imperative to employ methods not reliant on

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VII Workshop on Robotic Autonomous Observatories (October 16-20, 2023)
Editors: Maria Gritsevich, Alberto J. Castro-Tirado, Petr Kubánek, Shashi B. Pandey, and David Hiriart - DOI: https://doi.org/10.22201/ia.14052059p.2025.59.17

achieving precise timing synchronization. Thanks to robust lens calibration techniques (Borovicka et al. 1995), we can achieve a high level of spatial accuracy when observing fireballs. This, in conjunction with the plane intersection method, enables us to consistently arrange the captured frames based on meteoroid height, thereby facilitating the collection of point-by-point, combineable velocity measurements.

A neat approach to assess the trajectory without making assumptions about any parameters is through the α-β method (Gritsevich 2007, 2009) with its latest modification applicable to arbitrary atmospheric models or weather conditions (Lyytinen & Gritsevich 2016). It relies on dimensionless equations resulting from scaling laws applied to the single-body flight theory (Stulov 1997), providing the ballistic coefficient α and mass-loss parameter β for any event with a certain level of deceleration, using only height y and velocity v data. Due to observational constraints that yield velocity dispersion and nonlinearity of the formulas, this approach benefits from smoothing the data. However, results may be sensitive to this pretreatment.

2. THE SPMN230522 SUPERBOLIDE

We demonstrate and discuss the application of this methodology to the recent meteorite-dropping event recorded by the Spanish Fireball and Meteorite Network (SPMN; Trigo-Rodríguez et al. 2004). The superbolide occurred on May 23, 2022, at 00:42:50 UTC and reached an absolute magnitude of -17. This spectacular event was recorded from 17 SPMN fireball stations, being cataloged as SPMN230522. It was produced by an asteroidal rock experiencing ablation during a luminous path over 100 km to finally suffer an ending explosion near Barcelona at an altitude of 25.4 km (Fig. 1). We analyzed the event with our *3D-FireTOC* software (Peña-Asensio et al. 2021a,b, 2023b).

It has been suggested to employ a three-point moving average technique for data smoothing, which can be applied iteratively and include initial velocity as a free parameter (Sansom et al. 2019, 2021). Figure 2 illustrates the α-β fit for three distinct smoothing scenarios concerning the SPMN230522 event. Despite their apparent similarities, these scenarios yield varying estimates of the meteoroid's mass: ranging from an initial preatmospheric mass exceeding 200 kg with a final mass of $\sim$6 g to an initial mass of $\sim$7 kg with a final mass of $\sim$1.4 kg. The solution with the largest initial mass yields the lowest ending mass as it features a greater mass loss parameter and smaller ballistic coefficient. In contrast, the

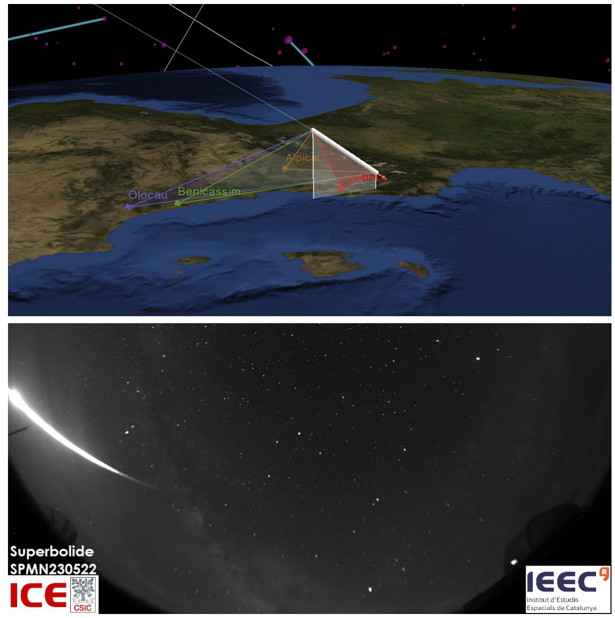

Fig. 1. A fraction of the all-sky camera image showing the SPMN230522 superbolide (bottom) and its 3D reconstruction (top). The device in placed at the Observatori Astronòmic del Montsec (OdM).

solution with the smallest initial mass showcases a lower mass loss parameter and greater ballistic coefficient, resulting in the largest terminal mass.

These variations occur due to the application of different smoothing techniques to raw (y, v) data, yielding distinct datasets (y_i, v_i) that are then used as input in the α-β model. Note that an increase in α is counteracted by a decrease in β in the solution. This is because the contribution of α in the $y = y(v)$ equation is additive, which effectively shifts the curve's position higher in the plot. The β value dictates the curvature of the fit. Consequently, any modifications in the initial data, with a notable emphasis on the initial velocity (as it is employed for the normalization of all velocity measurements), lead to subsequent alteration in the fitted curve. It is worth noting that much of the previously published data, such as MORP by Halliday et al. (1996), primarily consists of pre-smoothed values, for which α-β provides nearly flawless fits (Gritsevich 2009).

3. α-β DIAGRAM IN FRIPON DATABASE

On the other hand, it has been shown that α-β diagram serves as a straightforward yet potent tool for visualizing which fireball events are probable candidates for possessing tangible terminal masses and subsequently can be used to identify the meteorite-producing fireballs (Gritsevich et al. 2012, 2013; Turchak & Gritsevich 2014). This is especially useful

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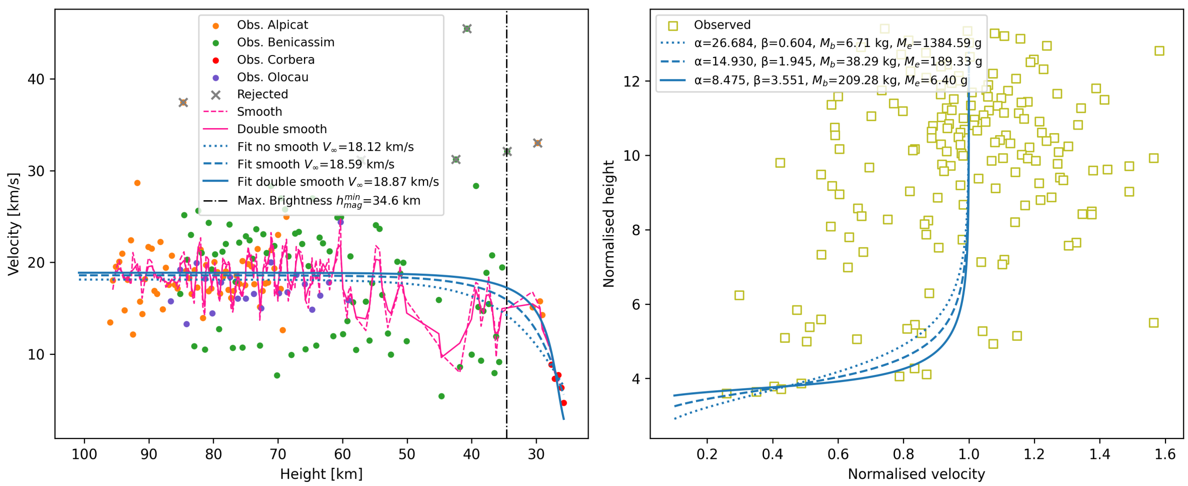

Fig. 2. α-β of SPMN230522 with initial (M_b) and terminal (M_e) masses for different smoothing cases.

when large fireball databases are available. Such analysis has proven valuable when applied to MORP, PN, DFN, MOROI, SPMN, FFN, and EN fireball network data (Gritsevich et al. 2012; Moreno-Ibáñez et al. 2020; Boaca et al. 2022; Peña-Asensio et al. 2023a, 2024b), where meteorite falls including Pribram, Lost City, Innisfree, Neuschwanstein (ABC 2003), Benesov (Gritsevich 2007), Park Forest (Meier et al. 2017), Annama (Trigo-Rodríguez et al. 2015), Bunburra Rockhole (Sansom et al. 2015), Kosice (Gritsevich et al. 2017), Dingle Dell (Devillepoix et al. 2018), Murrili (Sansom et al. 2020), Cavezzo (Gardiol et al. 2021), Arpu Kuilpu (Shober et al. 2022), Madura Cave (Devillepoix et al. 2022), and Traspena (Andrade et al. 2023). Nevertheless, its application to non-decelerating meteor could be further optimized (Peña-Asensio et al. 2024a).

Values of α and β can be used to infer the degree of deepening of meteors in the atmosphere and determine terminal heights of their luminous flight (Gritsevich & Popelenskaya 2008; Moreno-Ibáñez et al. 2015, 2017). In Figure 3, we present an α-β distribution based on the observed terminal height of the luminous phase and the atmospheric trajectory slope using a large data sample from the FRIPON database, which consists of 646 events recorded from June 2018 to December 2021. The FRIPON project, initiated in 2016 by IMCCE at Observatoire de Paris, boasts an impressive network comprising more than 150 cameras and 25 European radio receivers (Colas et al. 2020). Our representation of the acquired data in Fig. 3 provides a clear depiction of the likelihood of meteorite recovery.

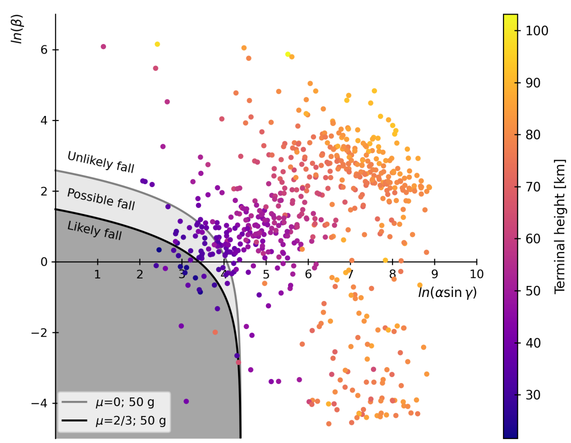

Fig. 3. α-β distribution for FRIPON data, post removal of trajectory slope dependence, plotted against terminal height. It includes meteorite fall regions and meteoroid spin limits. 50 g terminal mass is used as a threshold for meteorite production. μ represents meteoroid rotation, with 0 for no spin and 2/3 for uniform ablation across the surface.

4. CONCLUSIONS

Ground-based meteor networks play a vital role in our understanding of meteoric phenomena and the recovery of fresh meteorites. Our methodology addresses the challenges posed by unsynchronized multistation data. We implement the α-β method, which provides a versatile means of assessing meteoroid atmospheric trajectories. However, the sensitivity to data smoothing techniques is evident, as demonstrated in our analysis of SPMN230522 superbolide. The choice of smoothing technique alters estimates of meteoroid mass. Additionally, the α-β

diagram, exemplified using FRIPON database data, offers a powerful visual tool to assess the likelihood of fresh meteorite recovery, which would benefit from advances in the method.

Acknowledgments: The SPMN-CSIC network initiative has been funded by several CSIC and MICIN grants (PGC2018-097374-B-I00, PGC2018-097374-B-I00, AYA2015-67175-P, and AYA2011-26522). This study was supported by the European Research Council (ERC grant agreement No. 865657) and the Academy of Finland project No. 325806. We also thank Observatori del Montsec IEEC personnel for all-sky camera maintenance.

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