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Simulation of the capabilities of an orbiter for monitoring the entry of interplanetary matter into the terrestrial atmosphere

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ABSTRACT

In comparison with existing ground-based camera networks for meteors monitoring, a space-based optical system would escape dependency on weather and atmospheric conditions and would offer a wide spatial coverage and an unrestricted and extinction-free spectral domain. The potential rates of meteor detections by such systems are evaluated in this paper as a function of observations parameters (optical system capabilities, orbital parameters) and considering a reasonable range of meteoroids properties (e.g., mass, velocity, composition) determining their luminosity. A numerical tool called SWARMS (Simulator for Wide Area Recording of Meteors from Space) has been developed. SWARMS is also intended to be used in an operational phase to facilitate the comparison of observations with up-do-date constraints on the flux and characteristics of the interplanetary matter entering our planet's atmosphere. The laws governing the conversion of a fraction of the meteor kinetic energy into radiation during atmospheric entry have been revisited and evaluated based on an analysis of previously published meteor trajectories. Rates of detection were simulated for two different systems: the SPOSH (Smart Panoramic Optical Sensor Head) camera optimized for the observation of transient luminous events, and the JEM-EUSO (Japanese Experiment Module-Extreme Universe Space Observatory) experiment on the ISS (International Space Station). We conclude that up to 6 events per hour in the case of SPOSH, and up to 0.67 events in the case of JEM-EUSO may be detected. The optimal orbit for achieving such rates of detections depends on the mass index of the meteoroid populations. The determination of this parameter appears therefore critical before an optimal orbiting system might be designed for meteors monitoring.

1. Introduction

The most widely used method of observation of meteors is through ground-based camera networks (Halliday et al., 1978; Oberst et al., 1998; Trigo-Rodríguez et al., 2004; Jenniskens et al., 2011; Bland et al., 2012). These observations are complemented by multi-instruments aircraft campaigns for meteor shower events (Vaubaillon et al., 2013). A dedicated orbital device would hold considerable advantage over ground-based observations. It would provide wide coverage: for instance, one wide-angle camera with field of view of 120 °, at a height of 1200 km would monitor a projected area on the Earth's surface of about 4 millions of km^2. For example, the 60 cameras of the Meteorite Observation and Recovery Project (hereafter "Canadian Network") were distributed over an area of 1.26 millions of km^2 (Halliday et al., 1996). Another advantage is the independence from weather conditions. New scientific perspectives would be also offered such as spectroscopy in a wider spectral domain, including UV, which is not possible

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from the ground due to the atmospheric absorption. Observations using non-dedicated systems, e.g., from military satellites (Brown et al., 2002), have already demonstrated the feasibility and value of orbital observations. Such systems are also envisioned in the context of interplanetary missions (Christou et al., 2012; Mimoun et al., 2012; Oberst et al., 2012; Koschny and McAuliffe, 2009).

We examine here the performance and scientific return of an Earth-orbiting optical system dedicated to the monitoring of meteors. The detection rate is the primary performance parameter of interest and is evaluated as a function of the characteristics of the monitoring device. A simulator, called SWARMS (Simulator for Wide Area Recording of Meteors from Space) has been developed for this purpose. The detection rate is determined as a function of observation conditions and of the characteristics of populations of meteoroids defined by mass, composition, and entry velocity distributions. Distributions of meteoroids' physical properties are inferred from previous studies. An empirical law relating physical properties to meteor luminosity is derived from an analysis of a set of 259 meteors for which detailed observations (light curve, meteoroid mass, velocity as a function of time) are available. A script, called SAT (Script for Analysis of meteor Trajectories) was developed for this purpose and will be made available upon request to the corresponding author.

The architecture of the software is described in Section 2. Section 3 describes SAT and how empirical laws implemented in SWARMS are derived from a set of meteor observations. Populations of meteoroids are described by their mass index. This parameter is varied in the simulations to study its impact on the system performance. The application of SWARMS to two different optical systems, the SPOSH camera and the JEM-EUSO experiment onboard the ISS, are presented in Section 4. For the SPOSH camera, the performance of the system is evaluated for different orbits, whereas the ISS orbit is considered for evaluating the performance of the JEM-EUSO experiment. The impact of the assumptions on the population of meteoroids (mass index) is also examined. Section 5 is dedicated to conclusions.

2. A simulator for wide area recording of meteors from space (SWARMS)

2.1. Basic principles of meteor science

All equation parameters with units and definitions are summarized in Table 1. Upon entry into the atmosphere, the kinetic energy E_{kin} of a meteoroid is converted into luminous energy according to the following empirical law relating the instantaneous luminous intensity I (in W) and the rate of kinetic energy loss (Nemtchinov et al., 1994):

$$I = -\tau(t, \rho, \ldots)\frac{dE_{kin}}{dt}, \quad (1)$$

where τ is the instantaneous luminous efficiency. The instantaneous luminous efficiency may vary with meteor properties and with time. It is then convenient to introduce a global luminous efficiency ($\overline{\tau}$), defined as the ratio between total radiated energy and lost kinetic energy (which in most cases is equivalent to the total initial kinetic energy as the meteoroid rarely reaches the ground). Our simulations use values of global luminous efficiencies and do not consider the details of the meteoroid trajectories. Optical detectors operate in a finite spectral domain, whereas τ and $\overline{\tau}$ are defined as panchromatic quantities. The spectrum of meteor emissions could vary from one event to another and should affect the estimations of τ or $\overline{\tau}$ from optical observations. As the overwhelming majority of meteor spectra available have been limited to the panchromatic visible domain, no definitive conclusion regarding the spectral energy distribution can be drawn. This represents an important source of uncertainty in any simulations using the concept of luminous efficiency.

2.2. SWARMS specificiations

The three major specifications of the simulator are listed below.

1. A number of assumptions currently made in meteor science may be modified in the future, affecting the calculation of the number and size-distribution of meteoroids, or the estimation of the luminous efficiency from a given meteoroid physical property. New hypotheses or new constraints should be easily implemented.
2. The detector characteristics must be also tunable in order to facilitate the evaluation of the performance of different optical systems.
3. The orbital parameters of the mission must be also tunable. It is indeed expected that trade-off between coverage and distance to phenomena (higher orbit increases coverage but meteors will be farther on average and thus appear fainter) should be routinely done for the purpose of optimization.

2.3. Architecture of the simulator

The general architecture of the simulator is shown in Fig. 1. The algorithm is based on the succession of physical processes leading to meteor detection. We used the Python language to develop SWARMS. The step-by-step calculation of a detection rate for a given situation is given in this section.

2.3.1. Step 1: Generation of the survey area

We describe here how the algorithm determines the field of view of the detector, the corresponding area projected on the terrestrial atmosphere, and how this area is meshed.

Generation of mesh: A mesh representing one hemisphere of the Earth is generated. Each mesh element has the same surface area. The range of latitudes is divided into 200 regular intervals. The range of longitudes is also divided into regular intervals, the number of segments being dependent on the latitude ϕ. The equator ($\phi=0$) is divided into $n=1000$ segments. For other latitudes the number of intervals is equal to $ncos\phi$ (rounded down). With these parameters, a total number of $N=127{,}924$ mesh elements are generated. The coordinates of each mesh element are then converted into a cartesian frame with the origin at the center of the sphere using the average terrestrial radius + 100 km (as meteors usually occur around this altitude).

Discrimination of points in the field of view: The field of view of the detector (Fig. 2) is determined by its orientation (α) with respect to nadir-pointing and aperture (ω). A mesh including only the N_m elements monitored by the detector is extracted from the global mesh. The distance between each point P_i at the center of each mesh element and the detector (O) is then calculated. The surface of the monitored area is given by

$$S_{monitored} = \frac{N_m(\alpha, \omega)}{N}S, \quad (2)$$

where S is half the surface of the Earth.

2.3.2. Step 2: Generation of physical properties of meteoroids

SA population of meteoroids entering the Earth's atmosphere within the field of view of the detector and during a given time of observation is generated at this step. The mass, velocity and density of these meteoroids are randomly assigned from statistical distributions illustrated in Fig. 3.