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Numerical Simulation for Dark Flight Stage of Meteoroid Fragments

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Abstract

This paper is concerned with numerical simulation of meteoroid dynamics. The simulations of bolide ballistics are carried out via hard sphere approximation. System of differential equations for movement and heat transfer is solved in Lagrange variables via Runge-Kutta methods. The drag force of atmospheric air is computed via Henderson formula, valid for wide ranges of Reynolds and Mach numbers. The parameters of surrounding gas are obtained from standard atmosphere model. Meteoroid fragmentation is modeled as sequential division of parent body into two parts using random weighting coefficient for parent mass. Computational results show that maximum splinter masses are in good agreement with corresponding observations and measurements.

1. Introduction

Meteoroid passage through the Earth atmosphere usually exhibits two consequent stages, namely: atmospheric entry as a bolide, and dark terminal part of the trajectory. Only exceptions are the massive dense bodies like metalic meteorites having completely bright path down to the planetary surface, and micrometeorites and space dust, losing velocity in upper atmosphere. Generally, the initial bright part of the trajectory is considered linear [1], however, more dense atmospheric layers promote the aerodynamic drag as a main contributing factor to meteoroid deceleration below speed of sound. The accurate estimation of dark flight trajectory is essential at determining the search area of meteorite fragments. Therefore, the numerical simulation becomes the most reliable mean to obtain dark flight trajectories.

2. Mathematical model

To efficently estimate the dark flight trajectory we consider following assumptions. First, we assume that the simulated meteoroid is subjected to fragmentation and can become an ansemble of fragments at the end of bolide stage of the trajetory. Second, due to large number of simulated fragments reaching orders of 10^3–10^4, we consider a simplified ballistic model, which represent the fragments as homogeneous balls with specified density. The dynamics for each fragment is governed by a system of differential equations accounting for drag and gravity. To increase accuracy of the simulation, the drag coefficient is computed via Henderson formula [2]. The atmospheric properties are calculated via 1976 US Standard Atmosphere model [3], which is sufficient for endoatmospheric simulations. The temperature correction for air viscosity is carried out via Sutherland formula [4]. The gravity acceleration and the shape of Earth are modelled according to WGS84 model [5]. For better representation of fragments scatter area we consider Earth landscape via global satellite digital elevation map GTOPO30 wth precision of 30 arcseconds. The fragmentation processes are described via expression [6] for stagnation pressure threshold

$$p^*_{imp} = \sigma_0 m_0^\alpha m_P^\alpha, \quad (1)$$

where m_0 is the initial mass of meteoroid, $\alpha = 0.25$ is a scaling factor, σ_0 is the mean static strength of the meteoroid material. The sizes of the resulting pair of fragments are computed with stochastic model [6]:

$$\xi \sim R\left[0;1\right], r_{P,1} = \xi r_P, r_{P,2} = \left(1-\xi^3\right)^{1/3} r_P. \quad (2)$$

The presented model was implemented in the form of computational algorithm. The numerical simulations were carried out with initial parameters, corresponding to Chelyabinsk meteorite (see tables 1-2)

Table 1: Initial conditions [7] for numerical simulation.

Parameter	Value
Altitude, km	32.47
Longitude, deg.	62.06
Lattitude, deg.	54.92
Velocity, km/s	13.43
Descent angle, deg.	-16.33
Azimuth angle, deg.	271.60

Table 2: Meteoroid properties [8, 9].

Parameter	Value
Initial diameter, m	18.0
Initial mass, t.	11000
Density, g/cm^3.	3.6
Strength, MPa	10.0

During the computational experiments we corrected initial material strength to 0.6 MPa, as estimated in [6] for Benesov bolide.

3. Summary and Conclusions

Computational results show that terminal velocities and maximum splinter masses are in good agreement with corresponding observations and measurements. For example, the computed mass for the largest Chelyabinsk meteorite fragment is 692 kg and the piece recovered from Chebarkul Lake has mass of 654 kg. The following research will be aimed for implementation of more detailed atmospheric models, including simple modifications for cold and hot climates, wind charts and jet streams, and more complex multiparametric models such as NRLMSISE-00, as well as accounting for lift force of irregular shaped fragments. More accurate models would give better estimations for dark flight trajectory, would help to define robust location of fallen fragments and significantly speed up their recovery.

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