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Determination of meteoroid orbits from ground-based meteor observations using numerical integration of equations of motion

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Abstract

The paper describes a technique for determining orbits of meteoroids from ground based meteor observations based on the integration of differential equations of motion. We conduct an analysis of the perturbations of the motion of the meteoroids immediately preceding their Earth encounters. We performed comparisons of the proposed technique with classical methods.

1. Introduction

It is known, that orbits of meteoroids colliding with the Earth are exposed to significant perturbations before encounter, primarily under the influence of gravity and atmospheric drag at the end of trajectory. Standard method of preatmospheric meteoroid orbit computation [1], traditionally based on a set of corrections applied to the observed velocity vector (e.g. see [2, 3, 4]). In particular, the popular concept of «zenith attraction" is used to correct the direction of the meteor trajectory and its apparent velocity in the Earth's gravity field. In our work, we review other more explicit approaches to orbit determination.

2. The Method

In our work, we review the definitions and approaches to orbit determination of meteoroids applied to photographic and/or video ground-based observations of meteors. In this technique, we used strict transformations of coordinate and velocity vectors recommended by IAU International Earth Rotation and Reference Systems Service (IERS) [5] and backward numerical integration [6] of equations of motion. It should be noted that a similar approach was applied by [7] for the Chelyabinsk meteorite orbit reconstruction using the “mercury6” software [8].

2.1. Coordinate transformation

Specifically, the following transformations are used. A velocity vector is transformed from the topocentric to the geocentric coordinate system. Diurnal aberration is calculated. Transformation of the beginning point coordinates and velocity vectors from the Earth-fixed geocentric coordinate system ITRF2000 to Geocentric Celestial Reference System (GCRS) realization ICRF2 (J2000) is conducted accordingly to IERS Conventions [5]. Contributions of polar motion and high order nutation are negligible in comparison to observation errors, so these effects can be skipped in this case. The JPL ephemeris DE421 [9] is used for transformation of meteoroid position and velocity vectors from the geocentric to the heliocentric coordinate system. As result, required initial conditions for numerical integration - meteoroid position and velocity vectors are obtained in the celestial geocentric coordinate system ICRF2 (J2000).

2.2. Orbital integration

Backward integration of equations of perturbed meteoroid motion:

$$\ddot{\vec{r}} = \frac{GM_{Sun}}{r^3}\vec{r} + \ddot{\vec{r}}_{Earth}\left(C_{nm}, S_{nm}, \vec{r}, t\right) + \\ + \ddot{\vec{r}}_{Moon}\left(r, t\right) + \sum \ddot{\vec{r}}_{planets}\left(\vec{r}, t\right) + \ddot{\vec{r}}_{atm}\left(\vec{r}, t\right)$$

was performed by an implicit single-sequence numerical method [6]. The equations of perturbed meteoroid motion include central body (Sun) attraction, perturbations from Earth gravity field, Moon, other planets, and atmospheric drag. For obtaining undistorted heliocentric orbit backward integration was performed until the meteoroid intersected with the Hill sphere (i.e. about 4 days backwards in this case).

3. The Tools

A software tool for determination of orbit of meteoroids was development. This software has a graphics user-friendly interface and uses SPICE [10] routines and kernels for coordinate transformation and computing ephemeris. In addition, it has a module for visualization of computation results.

4. The Results

4.1. Comparison with results of other authors

Orbits of several meteorites were calculated and compared with results obtained by other authors who have used the "classical" approach (Table 1 and Table 2). For the comparison, we used the published meteor state vectors at the beginning of the luminous meteor trails as starting points for the integrations.

Table 1. Calculation ot the orbit of the Košice meteorite.

	Borovička et al.,2013	*This research*
a, (AU)	2.71±0.24	2.72±0.21
e	0.647±0.032	0.649±0.022
i°	2.0±0.8	2.06±0.49
Ω°	340.072±0.004	340.146±0.013
ω°	204.2±1.2	204.07±0.14
M°	---	355.112±0.007
Epoch, (UTC)		2010-02-24 22:24:47.0

Table 2. Calculation of the orbit of the Chelyabinsk meteorite.

	Popova et al., 2013	*This research*
a, (AU)	1.76 ± 0.16	1.761±0.07
e	0.581 ± 0.018	0.581±0.025
i°	4.93 ± 0.48	4.992±0.04
Ω°	326.4422 ± 0.0028	326.454±0.0016
ω°	108.3 ± 3.8	108.81±1.21
M°	---	17.419±0.12
Epoch (UTC)	2013-02-15.139	2013-02-11 03:20:30.0

The technique of backwards integration allows us to analyze the meteoroid orbital evolution preceding the collision with Earth and to obtain the precise meteoroid orbit before the encounter.

4.2. Perturbation of meteoroid motion

The estimations of the influence of Earth and Moon gravity fields perturbations at the meteoroid orbit are presented in Table 3.

Table 3. Influence of different perturbations on the resulting orbit. (Integration was done on 4 days backward).

Perturbations	***Δa, km***	***Δe***	***Δi°***
Earth gravity	3779	0.00021	0.00114
Moon gravity	4086	-0.00016	0.00112
Perturbations	***ΔΩ°***	***Δω°***	***ΔM°***
Earth gravity	-0.000441	-0.01109	0.00675
Moon gravity	-0.000009	-0.00794	-0.00215

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