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Validation of the open-source software Meteor Toolkit

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Abstract

This study focuses on validation of the Meteor Toolkit – an open-source software for determining the meteoroid orbit based on meteor observations using the integration of differential equations of motion. In our recent work [2, 3], we have performed comparisons of the proposed technique with traditional methods and with the available results of meteoroid orbits calculated by the other authors. Here we validate Meteor Toolkit using the trajectory data of HAYABUSA space vehicle re-entry.

1. Introduction

It is known that the orbits of meteoroids that collide with Earth are exposed to significant perturbations prior to the encounter, these are primarily from the influence of gravity and atmospheric drag at the end of its trajectory. A standard method of meteoroid orbit computation [1] is traditionally based on a set of corrections applied to the observed velocity vector. In particular, the popular concept of 'zenith attraction' is used to correct the direction of the meteor's trajectory and its apparent velocity in the Earth's gravity field.

Progress beyond the state of the art: In the recent work we proposed other, more explicit approaches to orbit determination and to error propagation analysis [2, 3]. Our approach to meteor orbit determination is based on strict transformations of the coordinate and velocity vectors according to the IAU International Earth Rotation and Reference Systems Service (IERS) [4] and the backward numerical integration of differential equations of motion [5,6]. We have implemented this technique for the determination and analysis of meteoroid orbits into an open-source software entitled "Meteor Toolkit" [7].

2. The software

Free distributable open-source software Meteor Toolkit for determination and analysis of orbit of meteoroids was developed. This software is based on strict transformations of coordinate and velocity vectors according to the IAU International Earth Rotation and Reference Systems Service (IERS) [3] and backward numerical integration of differential equations of motion [4, 5]. The software has a graphics user interface and uses freely distributed routines and kernels from the SPICE system [8] for coordinate transformation and computing the ephemeris. The JPL ephemeris, DE421 [9], is used for transformation of the meteoroid's position and velocity vectors from a geocentric to a heliocentric coordinate system. The backward integration of equations of perturbed meteoroid motion:

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

is performed by implicit single-sequence numerical methods [5-6]. The equations of perturbed meteoroid motion include central body (Sun) attraction, perturbations from Earth gravity field, Moon, other planets, and from atmospheric drag. To obtain an undistorted heliocentric orbit a backward integration is performed until the meteoroid intersects with the Hill sphere. The JPL Horizons On-Line Ephemeris System [10] database of comets and asteroids is then searched for the meteoroid's potential parent body. In addition, the software has a module for visualizing the computational results. In summary, "Meteor Toolkit" enables robust analysis of the orbital motions of meteoroids through time prior to Earth's capture, enables search for their potential parent bodies, as well as to obtain characteristic physical meteoroid parameters and calculate the location of meteorite's impact with the ground [11-14].

3. Observations and Control Data

HAYABUSA mission re-entry trajectory data is useful for validation of a software for orbit determination because from one side the event was well recorded by the fireball network cameras and from the other side the orbit of the HAYABUSA space vehicle before Earth's gravitational influence was determined with the help of radio technical trajectory measurements. Therefore it is possible to compare results of orbit determination based on different types of observation and obtained by different methods. In this research the position, height and velocity of the space vehicle and capsule at the corresponding time estimated by TV and photographic observations were taken from papers [15] and [16]. Azimuth and elevation of the velocity vector (radiant) were obtain by straight lines between points of HAYABUSA re-entry trajectories. Initial state vector of the HAYABUSA space vehicle obtained by JAXA in the Earth-Centered Inertial Equatorial Coordinate System J2000.0 [17] was transformed into heliocentric orbital elements relative to the ecliptic.

4. Results

The results of the HAYABUSA orbit determination, obtained with the help of the Meteor Toolkit from the photographic observations of the space vehicle and the capsule from the fireball networks, are presented in Tables 1 and 2, respectively. For comparison, the same tables give orbital elements computed from the HAYABUSA state vector after the final orbit correction. For both, the spacecraft and the capsule, the orbital elements obtained differ from the control ones within the influence of observation errors.

Table 1. Calculation of the orbit of the HAYABUSA space vehicle at 2010-06-09 UTC 06:04:00.0.

	Telemetry	*This study*
a, (AU)	1.32378	1.32335±0.0027
e	0.25730	0.25692±0.0015
i°	1.68396	1.68346±0.0162
Ω°	82.46602	82.46656±0.0017
ω°	147.47394	147.54737±0.3710
M°	16.07552	16.045887±0.3508

Table 2. Calculation of the orbit of the HAYABUSA capsule at 2010-06-09 UTC 06:04:00.0.

	Telemetry	*This study*
a, (AU)	1.32378	1.32312±0.0027
e	0.25730	0.25730±0.0015
i°	1.68396	1.64934±0.0162
Ω°	82.46602	82.46570±0.0017
ω°	147.47394	147.22083±0.3710
M°	16.07552	16.22785±0.3508

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