A new approach to meteor orbit determination

Vasily Dmitriev[1], **Valery Lupovka**[1] **and Maria Gritsevich**[1,2,3]

[1] **Moscow State University of Geodesy and Cartography (MIIGAiK), Extraterrestrial Laboratory, Moscow, Russian Federation**
vm.dmitriev90@gmail.com
vlupovka@miigaik.ru
maria.gritsevich@fgi.fi

[2] **Finnish Geodetic Institute, Department of Geodesy and Geodynamics & Finnish Fireball Network, Helsinki, Finland**

[3] **Russian Academy of Science, Dorodnitsyn Computing Center, Department of Computational Physics. Moscow, Russian Federation**

It is known that orbits of meteoroids colliding with the Earth are exposed to significant perturbations prior to the impact, primarily under the influence of gravity and atmospheric drag at the end of the trajectory. Standard methods of pre-impact meteor orbit computation (Ceplecha, 1987) are traditionally based on a set of static corrections applied to the observed velocity vector, see e.g. (Andreev, 1991). In particular, the popular concept of so-called "zenith attraction" is used to correct the direction of the meteoroid trajectory and its apparent velocity in the Earth's gravity field. In this work, we carry out explicit trajectory integrations of the meteoroids with the aim to investigate the magnitude of errors involved by choosing the mentioned simplifications.

1 Theory of the proposed method

We use strict transformations of coordinate and velocity vectors according to the IAU International Earth Rotation and Reference Systems Service (IERS) (IERS Conventions, 2010) and backward numerical integration (Plakhov et al., 1989) of equations of motion. A similar approach was applied in (Zuluaga et al., 2013) for the Chelyabinsk asteroid orbit reconstruction using the "mercury6" software (Chambers, 1999). In (Clark and Wiegert, 2011) the authors have compared the meteoroid orbit determination method of Ceplecha with the results of numerical integration, which showed good agreement for both approaches.

Specifically, the following transformations are in use. Transformation of the velocity vector from topocentric to geocentric coordinate system:

$$\begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix} = \mathbf{M}^T \begin{pmatrix} V_n \\ V_e \\ V_u \end{pmatrix}, \qquad (1)$$

$$M = Q_1 R_2(90-\varphi) R_3(\lambda), \qquad (2)$$

where $(Vn, Ve, Vu)^T$ and $(Vx, Vy, Vz)^T$ are the topocentric and geocentric velocity vectors; R_2, R_3 and Q_1 are appropriate rotation and mirror matrices, accordingly; B and L – geodetic latitude and longitude of the beginning point of the atmospheric trajectory.

Diurnal aberration is taken into account as:

$$\begin{pmatrix} \Delta V_x \\ \Delta V_y \\ \Delta V_z \end{pmatrix} = -a_e \omega_{\oplus} \begin{pmatrix} \cos B \sin L \\ \cos B \cos L \\ 0 \end{pmatrix}, \qquad (3)$$

where ω is the Earth rotation velocity, a_e- the equatorial Earth radius. 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 (IERS Conventions, 2010):

$$\begin{pmatrix} X_{in} \\ Y_{in} \\ Z_{in} \end{pmatrix} = \mathbf{R}^T \begin{pmatrix} X_{geo} \\ Y_{geo} \\ Z_{geo} \end{pmatrix}, \qquad (4)$$

$$\begin{pmatrix} Vx_{in} \\ Vy_{in} \\ Vz_{in} \end{pmatrix} = \mathbf{R}^T \begin{pmatrix} Vx_{geo} \\ Vy_{geo} \\ Vz_{geo} \end{pmatrix}, \qquad (5)$$

$$\boldsymbol{R} = P\, N\, \Pi\, S, \qquad (6)$$

where P is the precession matrix, N – the nutation matrix, Π – the polar motion matrix, and S – the apparent Greenwich Sidereal Time matrix.

The contributions of the polar motion and high order nutation are negligible in comparison to the observation errors, so these effects can be skipped in this case. The JPL ephemeris DE421 (Folkner et al., 2009) is used for the transformation of the meteoroid position and velocity vectors from the geocentric to the heliocentric coordinate system.

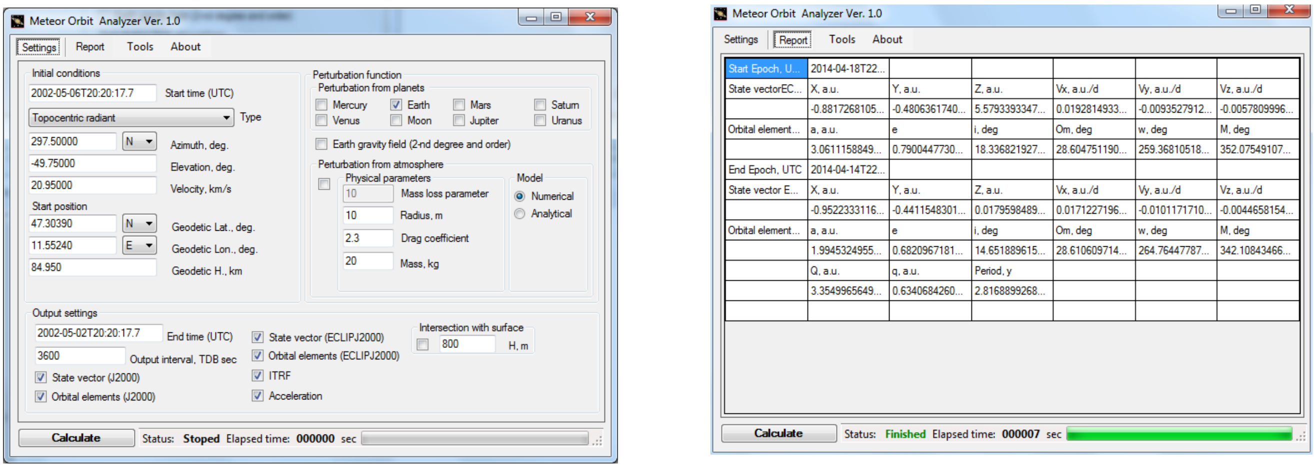

Figure 1 – The interface of the main window of Meteor toolkit.

As a result, the required initial conditions for numerical integration – the meteoroid position and velocity vectors are obtained in the celestial geocentric coordinate system ICRF2 (J2000). Backward integration of the equations of the perturbed meteoroid motion:

$$\ddot{\vec{r}} = -\frac{GM_{Sun}}{r^3}\vec{r} + \ddot{\vec{r}}_{Earth}(C_{nm}S_{nm}, \vec{r}, t) + \ddot{\vec{r}}_{Moon}(\vec{r}, t) + , \\ + \sum \ddot{\vec{r}}_{planets}(\vec{r}, t) + \ddot{\vec{r}}_{atm}(\vec{r}, t) \quad (7)$$

is performed by an implicit single-sequence numerical method (6). The equations of the perturbed meteoroid motion include the central body (Sun) attraction, perturbations by the gravity field of the Earth, Moon, and other planets, as well as the atmospheric drag. Backward integration was performed until the meteoroid intersected with the Hill sphere (i.e. about 4 days before the actual event of a meteor) to obtain an undistorted heliocentric orbit. An example of values of the components in the right part of equation (7) is presented in the *Figure 2*. The values on the right correspond to the time of entry into the dense layers of the atmosphere.

2 Tools

We have developed a software tool called "Meteor Toolkit" for the determination of the orbit of a meteoroid. This software has a graphics user-friendly interface and uses SPICE routines and kernels for coordinate transformation and computing ephemeris. In addition, it has a module for visualization of computation results. Screenshots of this software are presented on *Figure 1*. Meteor Toolkit makes it possible to perform an analysis of the orbital motion of the meteoroid before the collision with the Earth. Also, we can determine the location of a potential meteorite fall by continuing integration of the equations of motion to the intersection with the surface of the Earth. This could be of great help to find possible meteorite fragments. Often there is the problem of determining the characteristics of an alleged clash Near-Earth asteroid. With the initial conditions of the asteroid orbital elements, using the Meteor Toolkit it is possible to calculate the estimated collision coordinates and other characteristics such as speed relative to the ground, the angle of entry into the atmosphere, etc. This software can be run on Windows OS, or on a virtual machine emulating Windows. In addition, one would need .Net framework 3.5 or a later version.

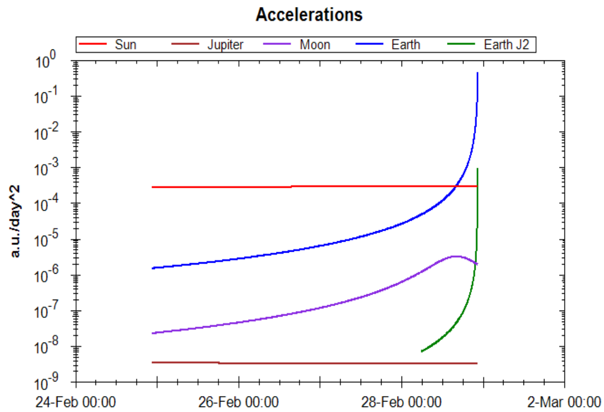

Figure 2 – Absolute values of the components of the right part of the equation (7) calculated for the meteoroid Košice.

3 Summary and discussion

The accuracy of the proposed method does not propagate the observational uncertainties, while obtained results are in good agreement with the traditional orbit-determination method.

Unlike the traditional method, the described approach allows to take into account the effects of meteoroid attraction by the Moon and planets, Earth's gravity field, as well as atmospheric drag.

An increase in pre-atmospheric velocity and/or the lowering of the beginning height of a meteor result in bigger differences between the proposed and traditional approaches.

The proposed technique enables analysis of the meteoroid orbital motion before its collision with the Earth. This only requires further integration (back in time) of the same equations of motion.

Portable software with GUI to determine a heliocentric orbit of a meteoroid and analyze it in time before the impact has been developed in accordance with the here described technique.

Acknowledgements

This work was carried out in MIIGAiK and supported by the Russian Science Foundation, project No. 14-22-00197.

References

Ceplecha Z. (1987).“Geometric, dynamic, orbital and photometric data on meteoroids from photographic fireball networks”. *Bull. Astron. Inst. Czechosl.*, **38**, 222–234.

Andreev G. (1991). “The Influence of the Meteor Position on the Zenith Attraction”. In Heinlein D.; and Koschny D., editors, *Proceedings of the International Meteor Conference*, Violau, Germany, September 6-9, 1990, IMO, pages 25–27.

IERS Conventions (2010). Petit G., and Luzum B., editors, IERS Technical Note No. 36, 2010, 179 pp.

Plakhov Y. V., Mytsenko A. V., Shelpov V. A. (1989) “Method for the numerical integration of equations of perturbed satellite motion in problems of space geodesy”. *Geodeziia i Aerofotos'emka*, No. 4, 61–67. In Russian.

Zuluaga J., Ferrin I., Geens S. (2013) “The orbit of the Chelyabinsk event impactor as reconstructed from amateur and public footage”. Eprint arXiv:1303.1796. Submitted to *Earth and Planetary Science Letters* (EPSL), 10 pp.

Chambers J. E. (1999). “A hybrid symplectic integrator that permits close encounters between massive bodies”. *Monthly Notices of the Royal Astronomical Society*, **304**, 793–799.

Clark D. L., Wiegert P. A. (2011). “A numerical comparison with the Ceplecha analytical meteoroid orbit determination method”. *Meteoritics & Planetary Science*, **46**, 1217–1225.

Folkner W. M., Williams J. G., Boggs D. H. (2009) “The Planetary and Lunar Ephemeris DE 421”. *The Interplanetary Network Progress Report*, **42-178**, 1–34.