



ORBIT RECONSTRUCTION FOR THE METEOROID OF THE METEORITE- PRODUCING FIREBALL THAT EXPLODED OVER ROMANIA ON JANUARY 7, 2015

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Abstract. In this paper we provide the calculated orbit for the meteoroid of the meteorite-producing fireball that exploded over Romania on 7 January 2015. Based on a large number of records on cameras, a trajectory, speed, and orbital elements are computed. Then, the backward numerical integration of the Solar System’s ordinary differential equations of motion is used to reconstruct the pre-atmospheric meteoroid’s orbit.

Key words: Solar System bodies, meteorites, orbit reconstruction.

1. INTRODUCTION

On 2015 January 7 at 1^h05^m56^s UTC, hundreds of Romanian and even a few Moldavian and Serbian citizens reported seeing or recording on cameras a fireball dropping down from the sky and ending in a violent airburst that lit the night sky like daylight. Up to now, there is no report regarding fallen stone fragments or discovery of surviving meteorites that could turn out to be fragments of this meteoroid.

The meteorite fall occurred three hours after midnight and a large number of cameras was operational and recorded the event. From measurements and fall-angle estimation based on few records that likely caught the fireball, a trajectory and approximate orbit for the fireball and meteorite could be derived [7], [8].

As the Quadrantid meteors flew in the moonlight in early January 2015 this was bearing on the question of a possible relation to our fireball.

2. METHOD OF APPROACH

We shortly review the definitions and approaches to orbital-characteristics analysis applied to photographic or video ground-based observations of meteors. For multi-site registered meteors, it is possible to accurately determine the direction and absolute value for the meteor velocity and thus obtain the topocentric *radiant* (*radiant point* is the point on the sky from which the meteor seems to appear). Based on topocentric radiant one further determines the heliocentric meteor orbit. The additional corrections for the zenith attraction are widely in use and are implemented, for example in [9].

In this paper we use another technique for meteor-orbit determination with higher accuracy. We transform the topocentric radiant in inertial (J2000) coordinate system using the model recommended by IAU [6]. The main difference if compared to previous orbit-determination technique is backward numerical integration of Solar System’s ordinary differential equations of motion instead of adding corrections to speed and radiant location for gravitational pull (including zenith attraction). The gravitational attraction of the central body (the Sun), the perturbations by Earth, Moon and other planets of the Solar System and Pluto, the Earth’s flattening (that play an important role at the initial moment of integration, i.e. at the moment when the meteoroid enters in the Earth’s atmosphere) are included in the equations. By reverse integration of the same equations we can analyze the orbital evolution preceding the meteoroid’s collision with Earth.

We have found the topocentric radiant using the multi-station observations technique [4]. The records on two cameras located in Lugoj and Bucharest were considered in our analyze. First a least squares best fit line is found for the meteor on each camera, using all points on the meteor trajectory. The curvature introduced by gravitational attraction is not significant for meteor accuracy. In the next step, from positional analysis, we have computed the vector normal to the plane containing the meteor as viewed from each site, which is transformed into the unit vector, \mathbf{n} , expressed in a local Earth-based coordinate system. If the unit vectors \mathbf{n}_1 and \mathbf{n}_2 represent normals to the planes containing the meteor as viewed from Lugoj and Bucharest then the cross product $\mathbf{r} = \pm \mathbf{n}_1 \times \mathbf{n}_2$ lie along the trail of the meteor. The apparent radiant of the meteor can thus be determined. The sign of the vector \mathbf{r} , in the direction of the meteor, can easily be obtained in the Earth-based coordinates. Thus, we were able to find the horizon coordinates, the azimuth and the height, of the radiant to be $A = 210.75^\circ$ (measured from the north point) and $h = 59.6^\circ$, respectively.

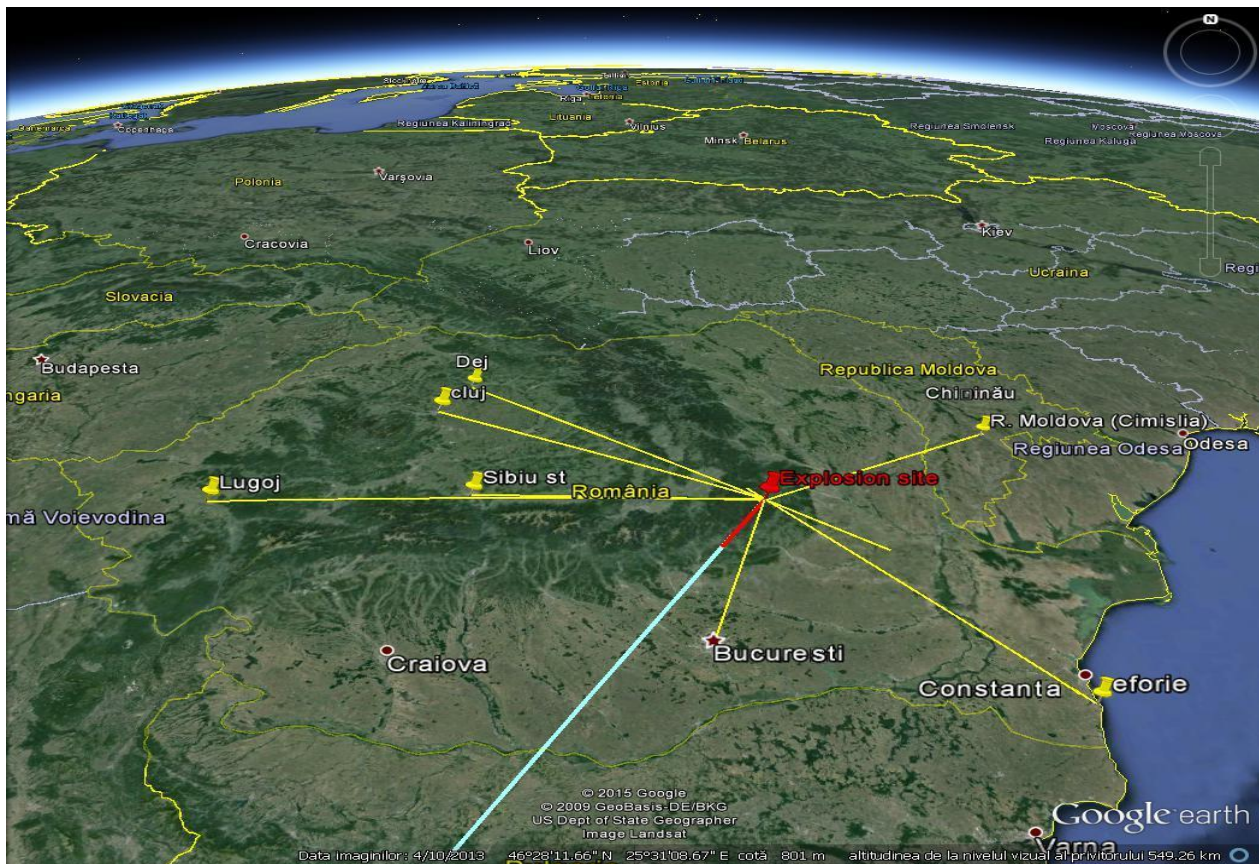


Fig. 1 – The explosion site and the projection on the ground (red line) of the atmospheric trajectory of the falling fireball as it results from detailed analysis of the records of few cameras that caught the fireball.

The explosion site (Fig. 1) were found by a combined detailed positional analysis of many cameras that recorded the falling fireball and its explosion with the facilities provided by the Google Earth software tool. Its geodetic coordinates, longitude and latitude, are 26.63° E and 45.75° N, respectively. Also, the vertical height of explosion is found to be ~ 42 km. This value is in agreement with that found by applying a technique that uses the sound speed in an Earth's atmosphere model. While the analysis is done in Cartesian coordinates fixed on the Lugoj camera, a small correction were applied for the curvature of the Earth in determining the vertical height of explosion. Taking into account the height, h , of the radiant point, we have immediately found that the pre-atmospheric meteoroid entered in the Earth's atmosphere (and become

visible as a fireball) at a vertical height of ~ 119.41 km. The geodetical coordinates, longitude and latitude, of the beginning point of its atmospheric trajectory are 26.33° E and 45.4° N, respectively.

The time information provided by the video frame rate can be used to determine velocities. The average trajectory length and the average of duration suggest a speed of 40.8 km/s. Using that speed in calculations, the aphelion is not located in the asteroid belt but beyond the orbit of Jupiter. If we take into account some amount of deceleration, then the best estimate for the initial speed is in the range $40.8 \text{ km/s} < V_\infty < 44 \text{ km/s}$. An initial speed of ~ 42.4 km/s, corresponding to a geocentric speed of ~ 41.01 km/s has been chosen as the favoured solution. As we have noted before, once the precise time and corrected geocentric velocity vector have been determined, one can readily calculate the orbital parameters ($a, e, i, \Omega, \omega, M$) [1].

For the total impact energy, we adopted the value of 0.4 kt (kilotons) reported by NASA (see <http://neo.jpl.nasa.gov/fireball>). We have then estimated (see <http://www.purdue.edu/impactearth>) the diameter and the mean density of the pre-atmospheric meteoroid to be 87 cm and 5.45 g/cm^3 , respectively. Also, the energy of the airburst is estimated to be 0.086 kt.

3. THE METEOROID ORBIT

Having the location (geodetic longitude and latitude) of the beginning point of atmospheric trajectory and the topocentric velocity vector in that point we use transformation of coordinate and velocity vector according to the IAU International Earth Rotation and Reference Systems Service (IERS) [5] from topocentric to geocentric coordinate system (data equinox J2000). Detailed matrix transformations can be found, for example, in [2]. Then, the JPL ephemeris DE431 [3] is used for the transformation of the meteoroid position and velocity vectors from the geocentric to the heliocentric coordinate system.

Backward integration of equations of the perturbed meteoroid motion:

$$\ddot{\vec{r}} = -\frac{GM_{Sun}}{r^3} \vec{r} + \ddot{\vec{r}}_{Earth}(C_{nm} S_{nm}, \vec{r}, \dot{\vec{r}}, t) + \ddot{\vec{r}}_{Moon}(\vec{r}, \dot{\vec{r}}, t) + \sum \ddot{\vec{r}}_{planets}(\vec{r}, \dot{\vec{r}}, t), \quad (1)$$

is performed using the Everhart's RADAU 15^{th} order integrator with 10^{-15} accuracy. In addition to Newtonian gravitational attraction, the relativistic effects as well as the perturbation due to Earth's oblateness are taken into account. Backward integration was performed until the meteoroid intersected with the Hill sphere (i.e. about 15 hours and 30 minutes before the actual event of a meteor) to obtain an undistorted heliocentric orbit (Fig. 2). The corresponding orbital elements are listed in Table 1 together with those obtained with the meteoroid orbit determination method of Ceplacha and numerical integration at the beginning point of the atmospheric trajectory. The results show good agreement for both approaches.

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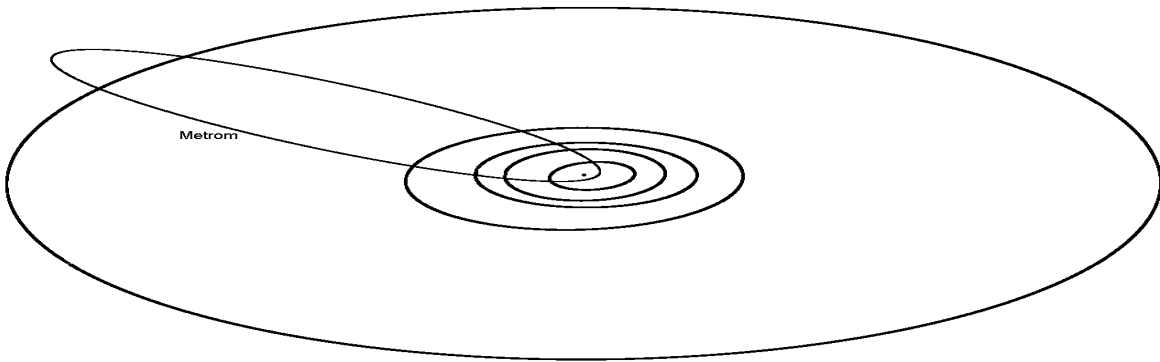


Fig. 2 – The heliocentric undistorted orbit of the pre-atmospheric meteoroid (denoted Metrom), together with the orbits of the first five planets.

Table 1
Orbital elements of the Metrom meteoroid

	a [AU]	q [AU]	e	i [deg]	Ω [deg]	ω [deg]	M [deg]
Metrom ¹	3.00	0.114	0.962	2.24	106.194	143.35	353.69
Metrom ²	4.12	0.103	0.975	0.63	106.185	144.45	356.24
Metrom ³	4.15	0.103	0.975	0.63	106.215	144.36	356.29

¹ The orbital elements of the undistorted heliocentric orbit.

² The orbital elements determined with Ceplecha's method.

³ The orbital elements after numerical integration.

4. SUMMARY AND DISCUSSION

On 2015 January 7, at 1^h05^m56^s UTC, a fireball has dropped down from the sky and exploded over Romania. Fortunately, the meteor's trajectory was recorded by few cameras and this gave us the opportunity to determine its topocentric radiant point and velocity vector. We estimate that the errors that come from observations are less than 5%.

The orbit of the pre-atmospheric meteoroid that provided meteorite-producing fireball was then reconstructed by backward numerical integration of the Solar System's ordinary differential equations of motions together with the equation of the perturbed meteoroid motion (1). This enables analysis of the meteoroid orbital motion before its collision with the Earth.

The computed orbit of the meteoroid is a very eccentric ($e = 0.962$) elliptic prograde one with low inclination on the ecliptic plane ($i = 2.24^\circ$). Also, it is Jupiter-crossing and Sun-grazing ($q = 0.114$ AU). The revolution period of the meteoroid on its orbit around the Sun is about 8 years. These characteristics suggest us that this meteoroid comes from an Earth-crossing debris stream originating in a Jupiter-family comet or an M-type asteroid on a cometary orbit. This excludes any link with the Quadrantids meteor shower whose parent body is known to be the Near Earth Asteroid (NEA) 2003 EH1.

Finally, we note that, the meteoroid had a close-approach with the Moon about 3 hours and 30 minutes before the meteor event, when it passed at only 42201.09 km from the Moon's surface. As in that night the Moon was at two days after full moon, it was very bright on the night sky. This made to be practically impossible for the meteoroid to be observed with small telescopes, coming from the moonlight.

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Received February 12, 2015