Dark flight integrator in-action (2015 Easter bolide re-calculated)

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Abstract:

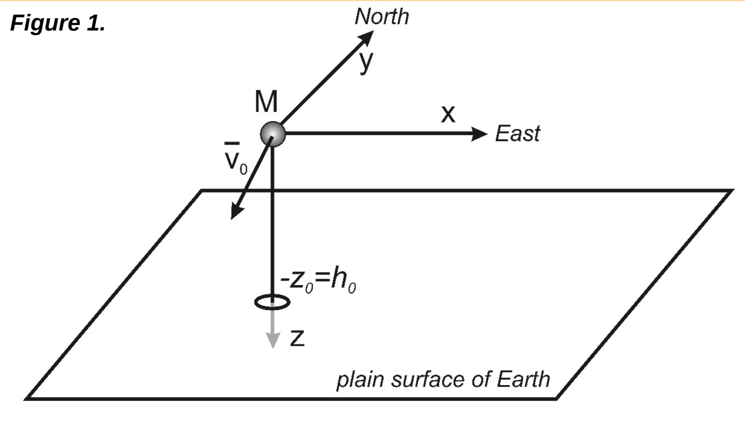
As an extension of our previous meteor atmospheric trajectory calculator code, a new dark flight integrator has been developed by us. Hereby we discuss the accepted atmosphere model, and the relevance of the wide-range behaviour of the drag coefficient. As trivial test, we compare our result with the analytic solution of freefall and step by step go to the more realistic cases. The first real application we made was the re-calculation of the so-called „Easter bolide" flown over Hungary on April 06, 2015, 17:31:01 UTC. The thrown field has been derived for different sized stone pieces, and the probable effect of disintegration is also considered by Monte Carlo simulation of wide range of the characteristic speed of "blow up". There was only one mini-expedition to the site for trying to recover some pieces – without success yet. The work will be continued.

Introduction, motivation

The need of better understanding of the meteor flight in the atmosphere, and the subsequent probable fall-generating blowing bolides over Hungary in the last few years motivated us to build an own integrator code for solving the "dark flight" part of the meteor phenomena. In this poster we present the basics of our model, and show a few of its test results with and without real wind data. In addition, we show the very first real application to the so-called "Easter Bolid of 2015". The field searches has already been started on the resulted thrown fields areas, but no meteorite was found as yet.

For the sake of more a clearer overview (and better understanding) on the kinematics of the meteoroid body in the atmosphere - we choosed first plain Earth model with planparallel atmosphere. The selected Cartesian coordinate system and the initial configuration can be seen on ***Figure 1.***

Figure 1.



The meteoroid body is now described as homogeneous sphere, with a radius of *r* , and density of *r* .

The direction of the initial velocity vector is given by two angles: α is the angle with the *z* axis (zenithal distance), and the azimuth angle (considered by the usual manner, as anywhere in the spherical astronomy). The components of the initial velocity vector are:

$$v_{x,0} = -v_0 \cdot \sin\alpha \cdot \sin Az \;,\quad v_{y,0} = -v_0 \cdot \sin\alpha \cdot \cos Az \;,\quad v_{z,0} = -v_0 \cdot \cos\alpha \;; \qquad (1)$$

while the only components of the initial acceleration are the $a_{z,0}=g(h_0)$. The value of the gravitational acceleration at any given h heights is given with the well-known formula:

$$g(h) = g(0) \cdot \frac{1}{\left(1+\frac{h}{R_F}\right)^2} \qquad (2)$$

where R_F=6371 km , the mean radius of Earth, and $g(0)$=9,80665 m/s^2, the value of gravitational acceleration at the sea level near N 45° geographical altitude.

The atmospheric model and challenges related to the drag law

The meteoroid body is flying through a planparallel atmosphere in our model. Air density is a function of the height. In our approximation the atmosphere is chemically homogeneous. Since the gas exhibits some kind of resistance against the moving bodies, the meteoroid will drag. This will cause a change of the velocity of the moving body, which can be calculated by introducing the related "drag force". Under general conditions, it can be written as:

$$F_d = -\frac{1}{2} \cdot K \cdot A \cdot \rho_a \cdot v_{rel}^2 \qquad (3)$$

This scalar equation is seemingly very simple. As it is well known, the minus sign represents that this force is always reacting opposite direction to the temporary direction of the moving body, while the rel index remembers us that the force is proportional with the "relative speed" of the body, i.e. relative to the surrounding medium. In a real atmosphere we have to have at least a realistic estimations about the wind speeds at different heights. There are some public databases containing some information about this, at a rough time-, and spatial distribution. ra is the density of the air at the given point, $\rho_a=\rho_a(h)$, which is a very important function in our problem. One can take it from real measurements (and interpolating between the known points), or one can use some one-dimensional or two-dimensional approximating calculation. The most generally used formula is the so-called "barometric approximation", which is nevertheless running far from the real in-situ measurements made by using high-altitude balloons:

$$\rho(h) \approx \rho(0) \cdot e^{-\frac{g(h)\cdot M}{R_0 \cdot T_0}\cdot h} \qquad (4)$$

While the different models and interpolated real measurements exhibit minor discrepancy from each others at low or very high altitudes, but at medium heights (between 20-80 km, which interval is the most important for meteor flight) they exhibit large differences. As it can be seen on ***Figure 2***, only the International Standard Atmosphere (1975) is representing well enough the real measurements. The plots referred as ECMWF and WMO showing real data valid at the date of Easter Bolide 2015, while "Stratolab-8" data were delivered by our own balloon experiment over Hungary in 2017. The preliminary result shown in this poster were carried by using a one-dimensional power-formula atmospheric model (since the starting height of all studied cases remained below 33 km, thus the mentioned formula was an acceptable simplification).

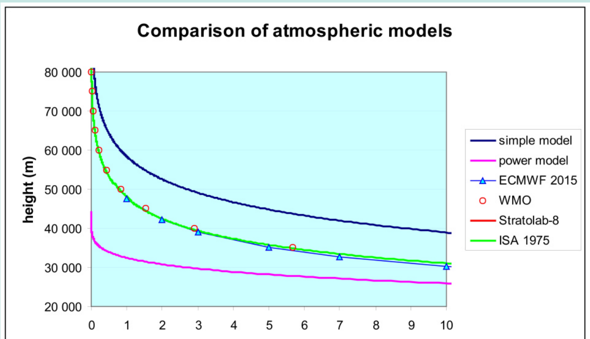


Figure 2.

The problem of the *K* factor (the so-called "drag coefficient") in formula (3) introduces much larger uncertainty. Although one can find some efforts for theoretical derivation of its value, but most generally its tabulated values are based on laboratory experiments. In many previous dark flight calculations one can find the very simple substitution for *K* as a constant value around 0,4-0,5 (considering spherical or conical meteoroid body, since *K* is depending on the form of the moving body, why it is often cited as "form factor"). However, it is well-known nowadays, that *K* has a strong dependence on the relative speed and on the Reynolds number (which is characterizing the motion in the given medium). Some authors apply a simple dependency only on the Mach number (and what is also a problem: on rather narrow interval) <u>or</u> on the Reynolds-number. In the reality: *K* depends on both factors. During the dark flight, meteoroid motion can exhibit big changes in the Mach- and Reynolds numbers (see a concrete example of the 2015 Easter Bolid on ***Figures 3a, b, c***, below). *K* formulae are from Vinnikov et al. 2016.

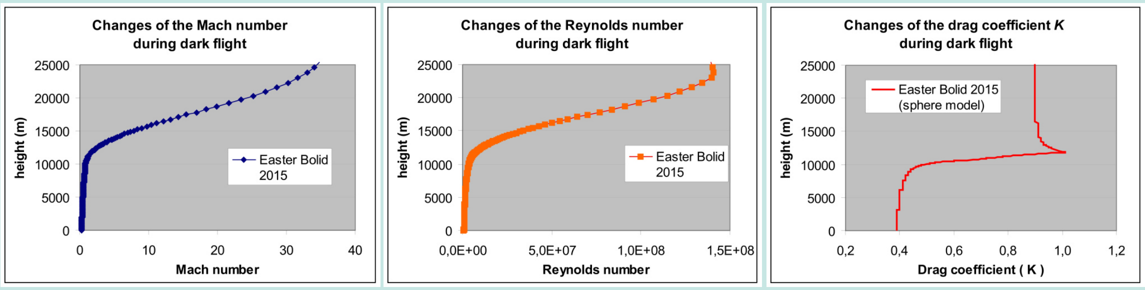


Figure 3 a. ***Figure 3 b.*** ***Figure 3 c.***

The integration and test runs

The integration goes by the well-known and simple way: in each *i*-th step we take the (i-1)-th vector of the velocity, calculate the components of drag force by the drag law as by formula (3). After this, we can calculate the components of acceleration. In our approximation the temporary change of the meteoroid mass (and thus, the change of the cross section area of its body) is not yet taken into account, as well as the possible fragmentation on the course of time. We consider the body as a constant mass and radius object.

$$a_x = -\frac{3}{8}\cdot K \cdot \frac{1}{r}\cdot\frac{\rho_a}{\rho_m}\cdot v_{rel}\cdot v_{rel,x} \;,\quad a_y = -\frac{3}{8}\cdot K \cdot \frac{1}{r}\cdot\frac{\rho_a}{\rho_m}\cdot v_{rel}\cdot v_{rel,y} \;,\quad a_z = g-\frac{3}{8}\cdot K \cdot \frac{1}{r}\cdot\frac{\rho_a}{\rho_m}\cdot v_{rel}\cdot v_{rel,z} \qquad (5)$$

g is the gravitational acceleration at the actual height, ρ_m is the density of the meteoroid (for stone meteoroids we accepted 3,4 g/cm^3). With these values, we can determine the velocity-, and spatial movement change of the body during the applied Δt step. The ρ_a density of the air is recalculated at each integration steps, while the temperature (which is needed for calculating the kinematic viscosity and the Reynolds number) is taken from world meteorological databases for the given date. The calculation is automatically stopped when the *z* coordinate achieve *0*. We are especially interested about the final (x,y) coordinates, since they directly give us the most probable falling site.The total time spent until the fall is also an interesting data. Later we added an automatical change of the initial size of the meteoroid body, and simulating the possible blow up, the code can add occasional side speed components to the initial velocity vector. Thus, we can study the most probable thrown fields, and thus, support the field searches in real cases.

The very first tests contained the verification with the analytically solvable "free-fall" case, in a homogeneous atmosphere. Moreover, an existing similar software was also available for comparison with our detailed results (Csizmadia, 2016). A few comparison results can be found on ***Figures 4a, b***. Our code runs were carried with two different *K* calculations.

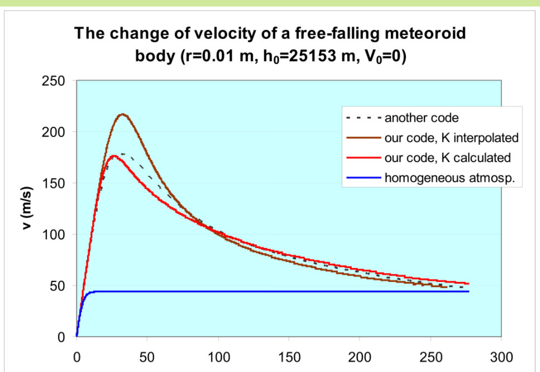


Figure 4 a.

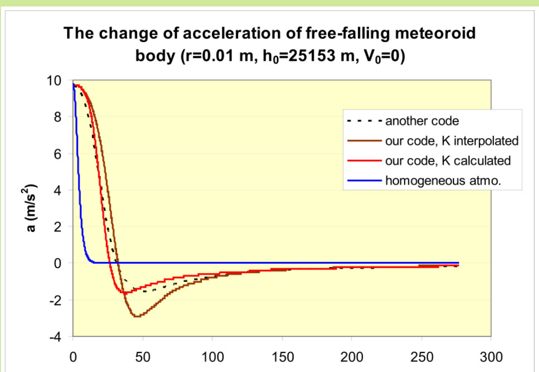


Figure 4 b.

After the successful tests, the first real case of the application of our new code were the so-called Easter Bolide of 2015, observed over Hungary on 2015/04/06, 17:31 UTC. The final step for achieving a more realistic situation were the consideration of the horizontal wind speeds (they modify the *x* and *y* components of the vrel). There are a few sources containing such data, with a given time- and spatial resolution. We used the archival ECMWF profiles, for supplying which we

Effects of winds and some initial parameters

It is and interesting question, what is the effect of some initial parameters, and the real winds on the final place of the touchdown? For this, we show one of our results: the dark flight path in x-z plane, for wide interval of initial velocity, including the real v_0 (see ***Figure 5.***). All other data are referring to the Easter Bolid, as it were hypothetically a 10 cm sized spherical body. What is very interesting: let us compared the two brown-colored lines! The left S-shaped one shows the path of the slowest piece, with winds, while the other, parabolic one is the same initial speed, but without winds. The effect of the atmospheric winds caused about 800 m difference in the *x* coordinate of the falling site.

The effect of the different masses on the falling site is shown on the ***Figure 6***, below. In this case we present the final results in x-y plane, converted to geographical coordinates.

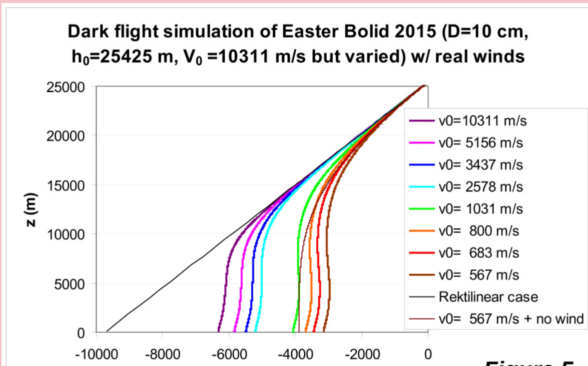


Figure 5.

Figure 7:
Search at the site, 2017

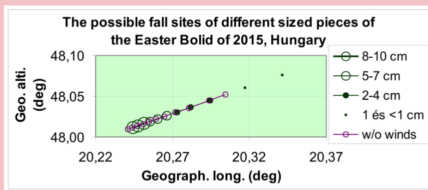


Figure 6.

References:

Csizmadia, 2016, private communication
Vinnikov, V. V., Gritsevich, M. I. and Turchak, L. I., 2016, AIP Conference Proceedings <u>**1773**</u>, 110016