Tracking Meteor Characteristics Using an Ablation Model

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Introduction

- A ***meteoroid*** is a particle that reaches Earth's atmosphere.
  - The meteoroid generates light and plasma as it travels which is considered a ***meteor***.
  - A ***meteorite*** is the solid particle that reaches Earth's surface at the end of the meteoroid's flight.
- Meteor data is observed through the use of a meteor's ***head echo***– as meteoroids fall they form a plasma that is detected by radars.
- Most meteoroids that enter Earth's atmosphere dissolve before reaching the ground. However, these particles release dust and metals that have a considerable impact on the upper atmosphere. Meteors also form sporadic E ranges, areas in the E layer that interfere with radio signals.
  - Mass loss occurs through two mechanisms–***sputtering*** (meteoroid particles ejected due to collision with air molecules) and ***ablation*** (evaporation of meteoroid particles due to temperature change).

The ***ablation model*** used in this research is written as:

$$\frac{dv}{dt} = \frac{-\gamma A \rho_{air} v^2}{m^{1/3}\rho_m^{2/3}}$$

$$\frac{dm}{dt} = \frac{-4Am^{2/3}C_1}{\rho_m^{2/3}T^{1/2}}\exp\left(-\frac{C_2}{T}\right) - \frac{\Lambda_s A m^{2/3}\rho_{air}v^3}{2Q\rho_m^{2/3}}$$

$$\frac{cm^{1/3}\rho_m^{1/3}}{A}\frac{dT}{dt} = \tfrac{1}{2}\Lambda\rho_{air}v^3 - 4\sigma(T^4 - T_a^4) + \frac{L}{A}\left(\frac{\rho_m}{m}\right)^{2/3}\frac{dm}{dt}$$

$$\frac{dh}{dt} = -v$$

Meteoroid/Air Constants: $A, \gamma, Q, c, \Lambda, L, p_m, T_a, \Lambda_s$

General Constants: C_1, C_2, σ

v is meteoroid speed, m is meteoroid mass, T is meteoroid temp, h is the meteoroid's height, ρ_{air} is the atmospheric air density

Methods

- In this research, we wrote Python code to simulate the trajectory and properties of a meteoroid's path through Earth's atmosphere.
- To demonstrate the techniques used to analyze meteors, general kinematics equations were used to simulate the trajectory of an object falling on Earth's surface **prior to meteor analysis**.
  - The kinematics equations used in figures 1 and 2 are written as:

$$\frac{dx}{dt} = v_x \qquad \frac{dv_x}{dt} = 0 \qquad v_x(t{=}0) = v_0\cos\theta$$

$$\frac{dy}{dt} = v_y \qquad \frac{dv_y}{dt} = -g \qquad v_y(t{=}0) = v_0\sin\theta$$

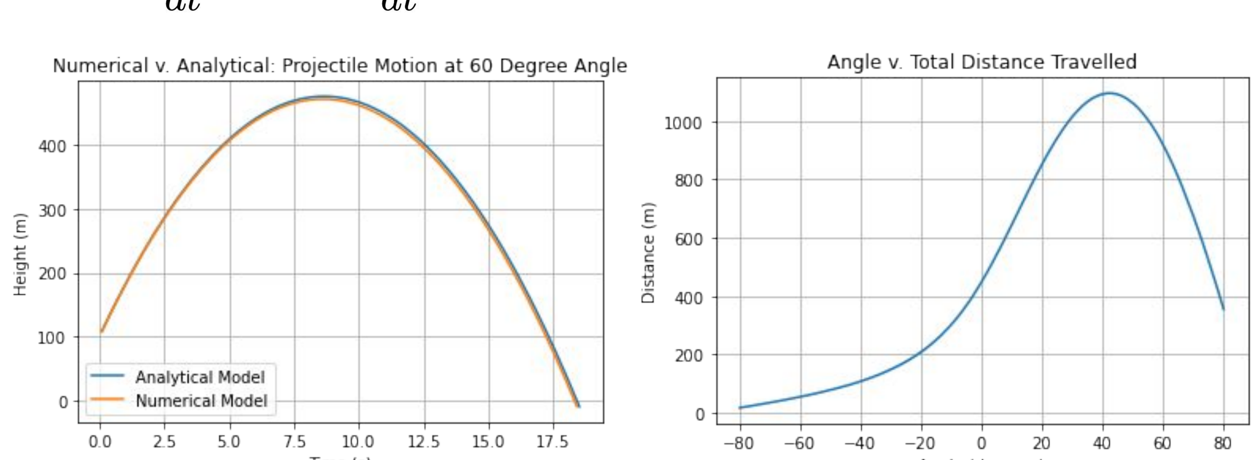

Figure 1: (Pictured to the left) Height v. Time, analytical (represented by the blue line) and numerical (represented by the orange line) models were used to identify the trajectory of a projectile that is launched at a speed of 100 m/s from a height of 100 meters and an angle of 60 degrees. (Pictured to the right) Distance v. Angle, the impact of the initial angle on the projectile's total x-distance travelled.

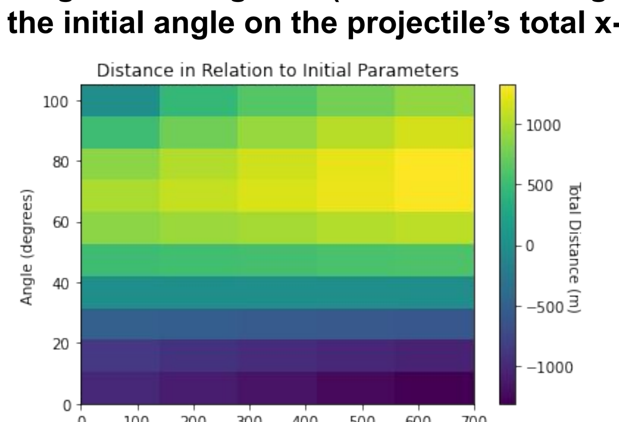

Figure 2: Use of imshow color-mapping to model the correlation of a projectile's initial height and angle to the total distance it travels when launched at 100 m/s.

- These methods were then applied to an ***ablation model***– a system of ordinary differential equations that model a meteoroid's change of mass, temperature, and velocity throughout its flight. Our simulations used the forward Euler time-step Method.
  - The ablation model was broken down to understand the impact of key variables and constants on a meteoroid's properties.

Results

- The analytical and mathematical simulations using the ablation model confirm the findings in the dissertation (Fucetola, 2012). We also compared the use of different variables and constants to determine the most important factors in developing an accurate model of meteoroid trajectory.

***All plotted meteors have an initial height of 120 km**

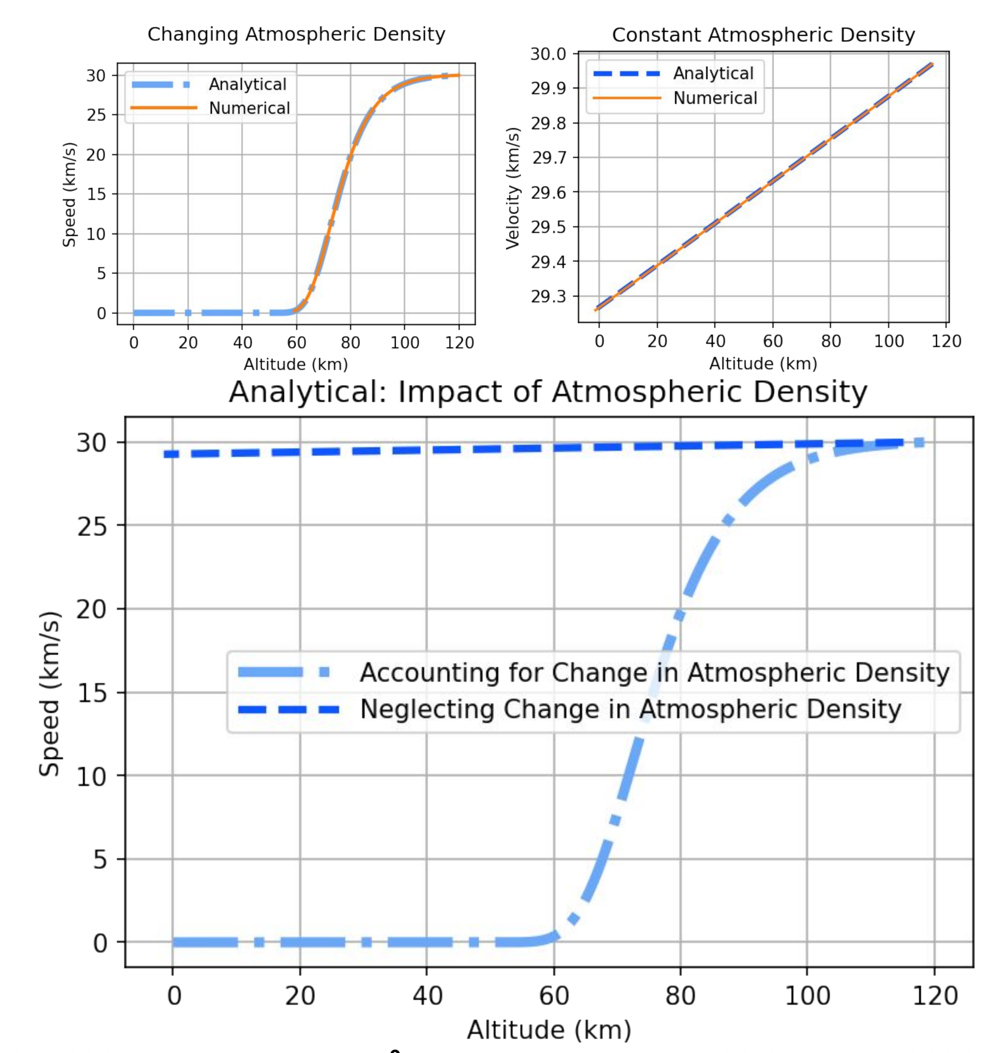

Figure 3: Speed v. Altitude plots for a 10^{-9} kg meteoroid at an initial speed of 30 km/s. (The upper left plot) Compares the analytical and numerical solutions accounting for changing atmospheric density. (The upper right plot) Compares the solutions with a constant atmospheric density. (The bottom center plot) The analytical model of the acceleration equation for changing atmospheric density is portrayed by the dash-dot light blue line, the model for constant air density is represented by the dashed dark blue line. By holding the atmospheric air density constant the deceleration of a meteoroid is drastically slower.
***Note that the y-axis scales on the upper plots are different.**

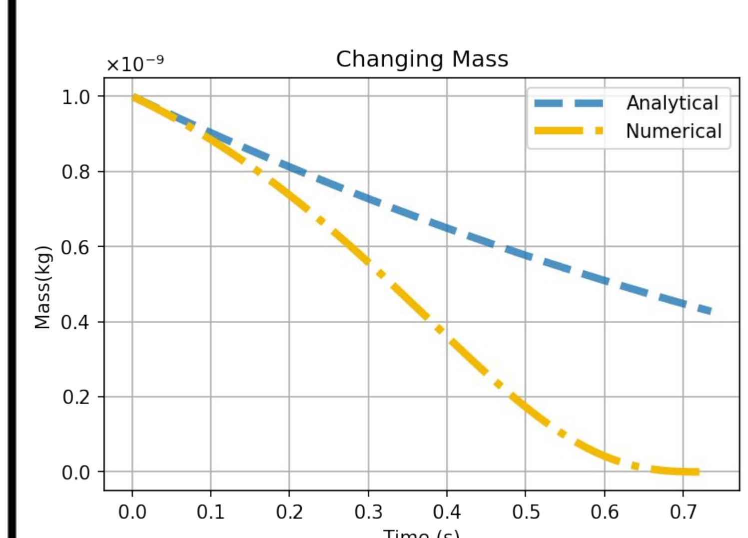

Figure 4: Mass v. Time plot for a 10^{-9} kg meteoroid at an initial speed of 30 km/s. The dashed blue line uses the the analytical model of the acceleration and mass loss equations. While the dash-dot yellow line uses the numerical model. The analytical model is only accurate for values that keep velocity and atmospheric air density nearly constant.

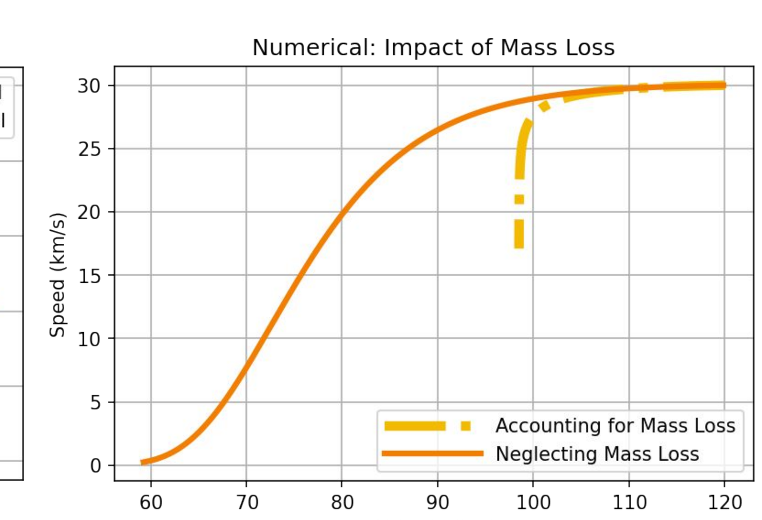

Figure 5: Speed v. Altitude plot for a 10^{-9} kg meteoroid at an initial speed of 30 km/s. The dash-dot yellow line uses the the acceleration and mass loss equations. While the solid orange line uses the acceleration equation, neglecting mass loss. The decay in mass causes the speed of the meteoroid to decrease at a faster rate.

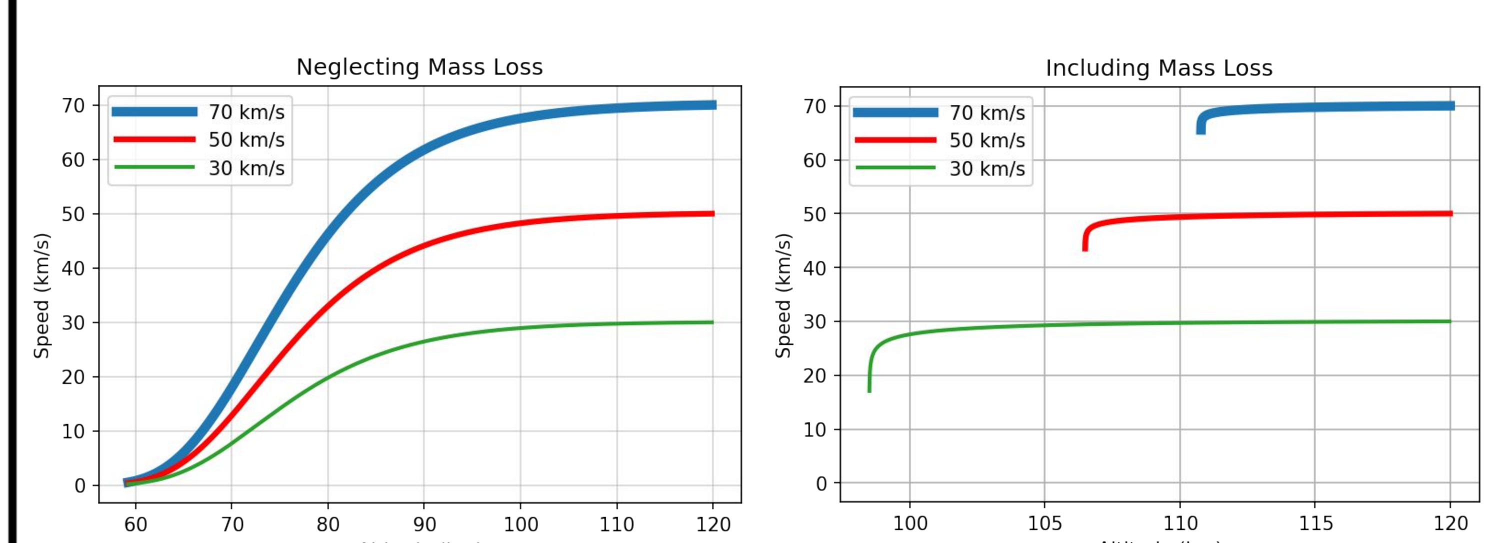

Figure 6: Speed v. Altitude plots for a 10^{-9} kg meteoroid. (The plot on the left) Uses a numerical model of the acceleration equation (neglecting mass loss). (The plot on the right) Uses a numerical model including the mass loss and acceleration equations. The blue lines represent an initial velocity of 70 km/s, the red lines represent a velocity of 50 km/s, and the green lines represent a velocity of 30 km/s. Meteoroid decelerate at a slower rate when accounting for mass loss.

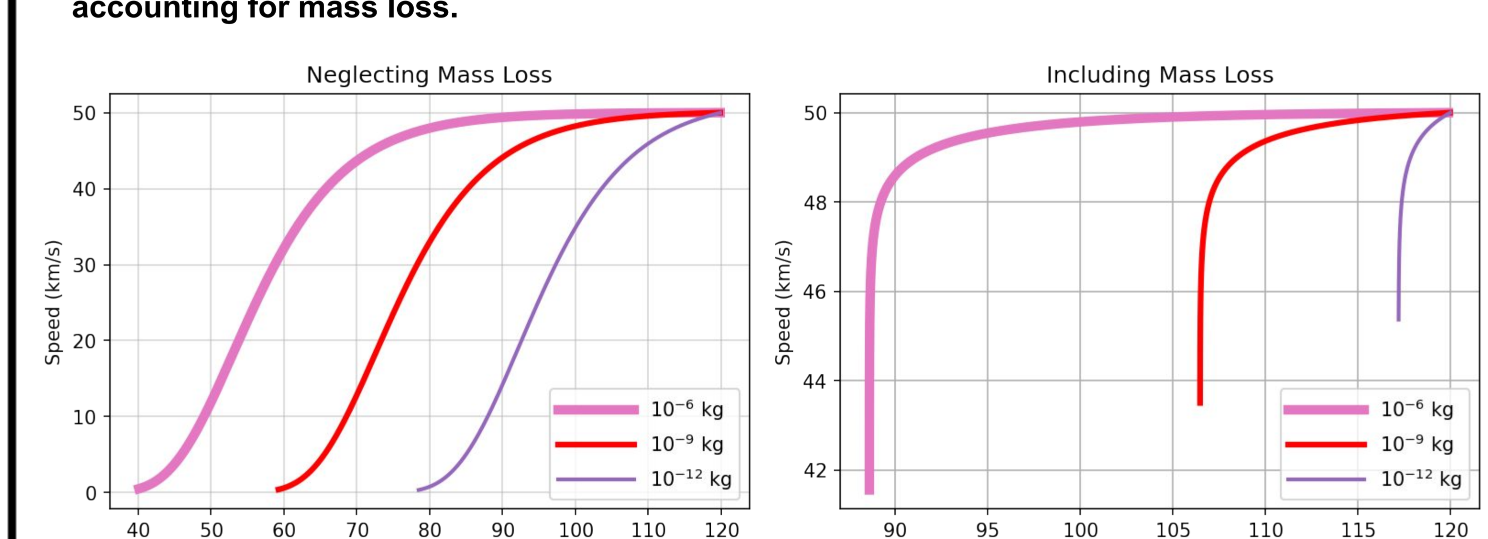

Figure 7: Speed v. Altitude for a meteoroid traveling at 50 km/s. The left plot uses a numerical model of the acceleration equation (neglecting mass loss). The right plot uses a numerical model of the mass loss and acceleration equations. The pink line represents an initial mass of 10^{-6} kg, the red line represents a mass of 10^{-9} kg, and the purple line represents a mass of 10^{-12} kg. The more massive a meteoroid is the slower it will decelerate.
***Note that the y-axis scales between the plots are not the same.**

Conclusions

- The change in atmospheric density is a key part of measuring a meteoroid's deceleration over time.
  - The analytical model with a constant atmospheric density is only accurate for the higher altitudes, but once the air density begins to change the models deviate from each other.
- The constant mass plot is only accurate for the higher altitudes, at a certain point the meteoroid will completely dissolve.
  - The use of an analytical model while taking mass loss into account only produces accurate results when velocity and atmospheric air density are constant.
- The atmospheric density is considerably greater at lower altitudes. As shown in Figure 6, faster particles will be observed higher in the atmosphere, while slower particles will be detected at lower altitudes.
  - More massive particles will be observed lower in the atmosphere while less massive particles will only be detected at high altitudes.
- To establish a fully accurate simulation of a meteoroid's trajectory, all variables must be taken into account (atmospheric air density, mass loss, and change in temperature).

Future Work

These simple simulators may enable working backwards from radar data to determine a meteoroid's original properties and predict its evolution over time.

NASA is working to develop this technology to avoid damage to spacecraft and aerometers that research what exactly is entering the atmosphere.

References

1) N. Fucetola, E. Determining Meteoroid Properties Using Head Echo Observations from the Jicamarca Radio Observatory. 2012.

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