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Project IMPART

Integrated Modeling and Prediction of Atmospheric Reentry Trajectories

AE 5626 Final Project

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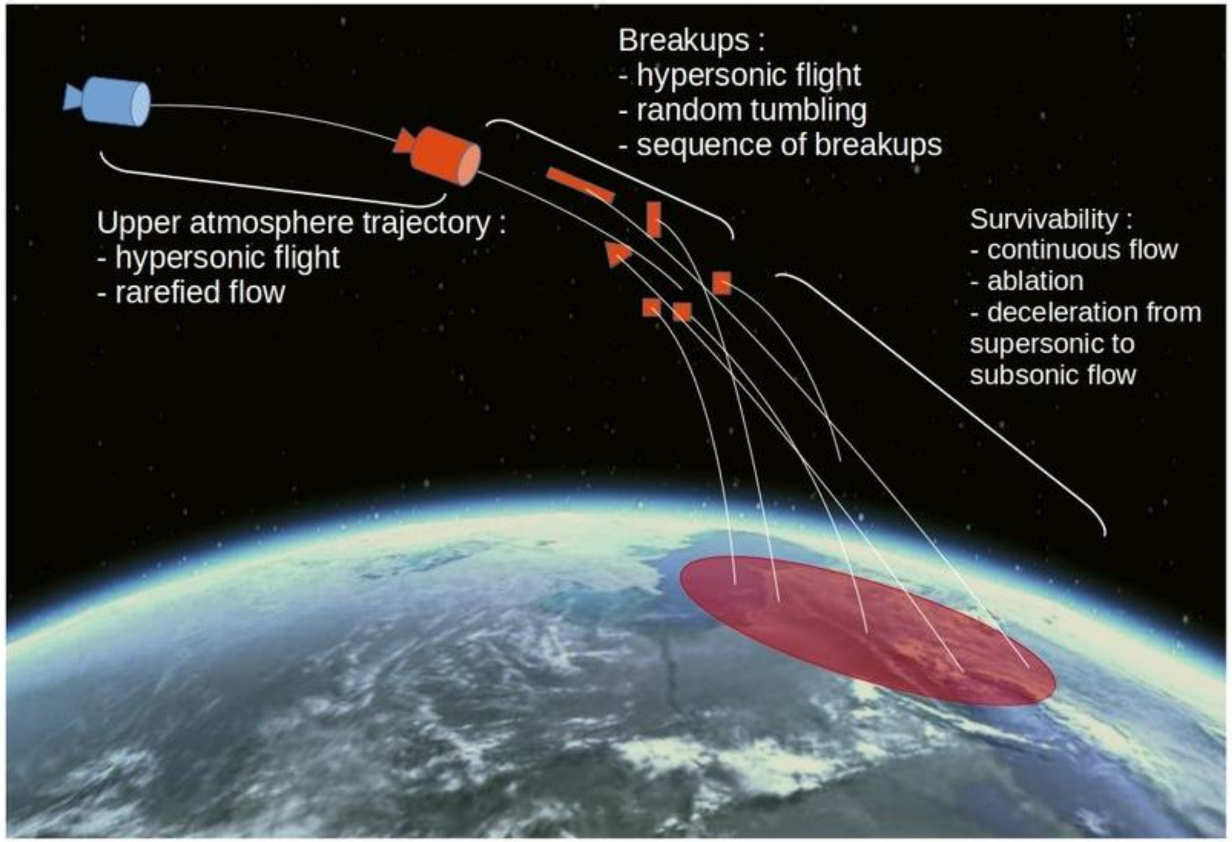
Background & Motivation

Satellite Reentry

- Spans all flight regimes (0 < M < 25+)
- Extremely complex and difficult to predict
- Fragments that explode off the main capsule during reentry can be dangerous
- Trajectory models and impact estimators are crucial for safe reentry
    - High fidelity models do exist, but are generally classified and computationally expensive
    - Many models are not customizable to the users needs



“Uncontrolled reentry of space debris poses a real and growing threat”

Piece of ISS main battery stanchion that hit a house on March 8, 2024

Problem Statement

Seek to address the challenges of predicting satellite reentry trajectories and impact by developing a robust, physics-based simulation framework that integrates:

- Gravitational and atmospheric models
- A model for orbit decay above 100km altitude
- Dynamic equations of motion for reentry, including aerodynamic forces and heating
- Probabilistic and numerical techniques (Monte Carlo, Runge-Kutta, ode113)

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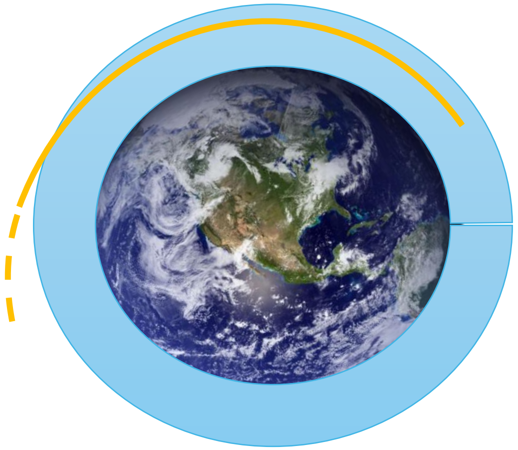
Phases of Reentry

1

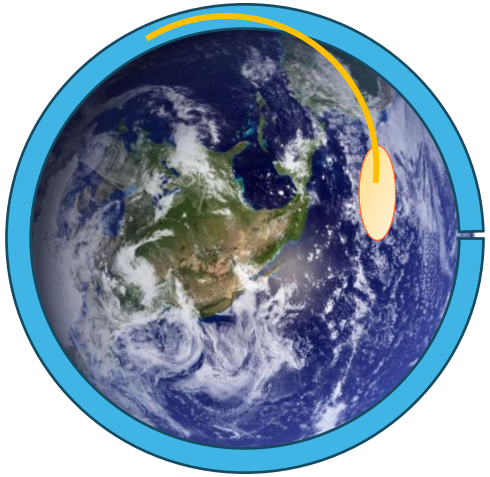
Orbital Decay
(>100 km)

2



Initial Atmospheric Entry
(80 km < alt < 100 km)
Typically where pieces begin breaking apart

3



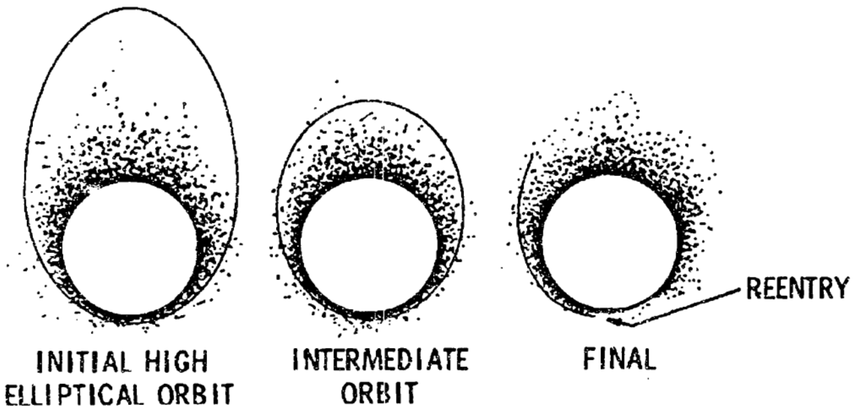
Full Flight Regime to Impact
(<80 km)

Orbital Decay

- Atmospheric drag dissipates satellite's energy
  - decreases semi-major axis
  - changes eccentricity
- Circularizes high eccentricity orbits by
  - Gradually decreasing apogee while maintaining nearly constant perigee over one period
  - Contraction continues until reentry begins

$$\Delta a = -\frac{C_D A}{m} a^2 \int_0^{2\pi} \rho \frac{(1 + e\cos E)^{\frac{3}{2}}}{(1 - e\cos E)^{\frac{1}{2}}} dE$$

$$\Delta e = -\frac{C_D A}{m} a \int_0^{2\pi} \rho \left(\frac{1 + e\cos E}{1 - e\cos E}\right)^{\frac{1}{2}} (\cos E + e) dE$$



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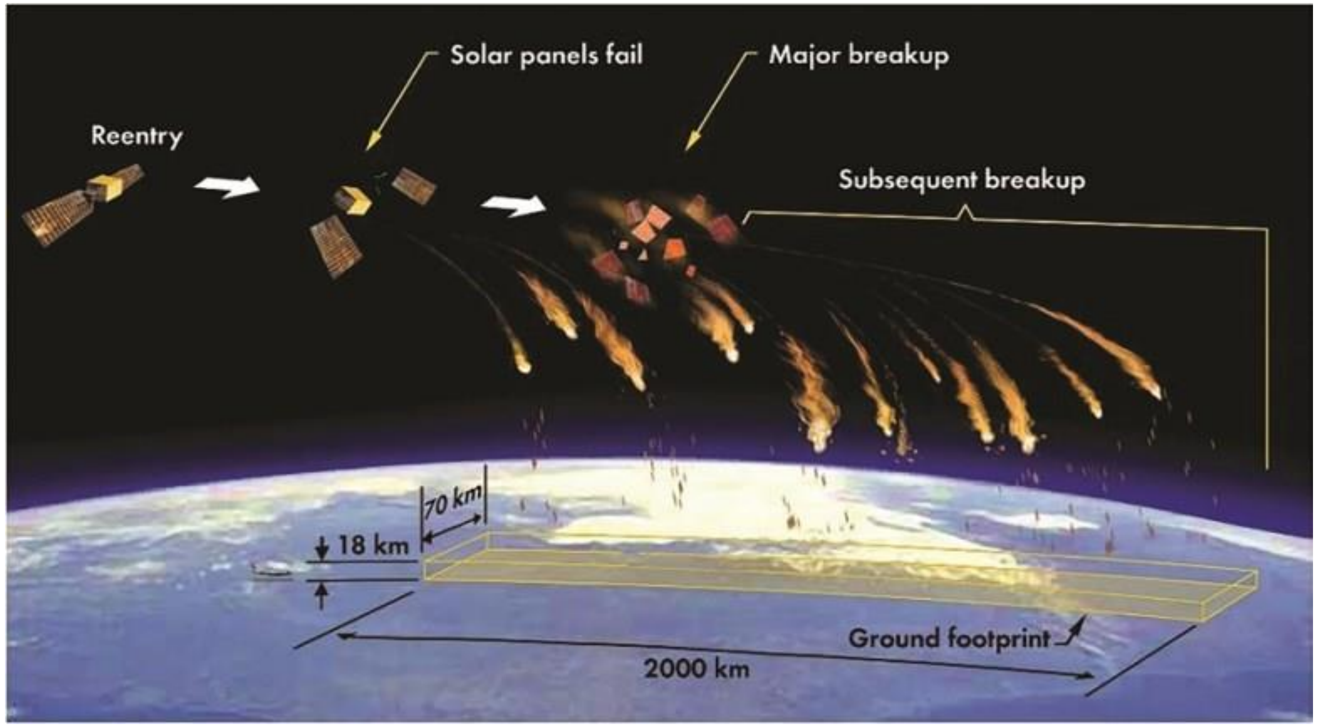
Breakup on Reentry

These 2 contribute the most to complete structural failure (planned or unplanned)

- Aerodynamic forces
- Extreme structural heating
- Very high dynamic pressures
- Sharp variations in atmospheric conditions
- Random tumbling and uncontrolled motion
- Mechanical failure/poor design

Impact



- Generally a large impact footprint expected to maximize awareness
- Only fragments of the original space object have made it this far
- Potential for unexpected pieces of debris (~40% survives the reentry) [1]

Modeling Orbit Decay

Drag Effects, Gravitational Acceleration,
Predicting the Atmosphere

Atmospheric Drag

$$\boldsymbol{a}_{\boldsymbol{drag}} = -\frac{1}{2}\frac{C_D A}{m}\rho V_A^2 \boldsymbol{v}$$

where,

$$B^* = \frac{C_D A}{m}$$

is the ballistic coefficient.

Note: ρ is a function of altitude (not constant)

C_D = satellite drag coefficient

A = aerodynamic effective cross-section area

m = satellite mass

ρ = local neutral density of the atmosphere

$V_A^2 = |\boldsymbol{V} - \boldsymbol{\omega_e} \times \boldsymbol{r}|$ = satellite's relative airspeed

$\boldsymbol{v}$ = unit vector in direction of $(\boldsymbol{V} - \boldsymbol{\omega_e} \times \boldsymbol{r})$

$\boldsymbol{\omega_e} = 2\pi$ rad/day

$\boldsymbol{V}$ = satellite's inertial velocity vector

Total Acceleration

Gravitational Acceleration

Simplistic

$$\mathbf{a}_g = -\frac{\mu \mathbf{r}}{r^3}$$

Advanced empirical

EGM2008 Gravitational Model

$\oplus$ a_{drag} $=$ Total acceleration

Atmospheric Properties

- Several advanced atmospheric density/temp. models exist
  - Mass Spectrometer and Incoherent Backscatter Model (MSIS)
  - Thermosphere/Ionosphere General Circulation Model (TIGCM) - accurate within ± 9% on point-by-point basis [1]
- Models can account for density/temp. dependents such as
  - solar flux
  - geomagnetic index
  - diurnal, monthly, and seasonal variations
- Advanced models are extremely computationally intensive
  - Can take several hours on 8GB RAM/64-bit hardware

MATLAB:

① Simplistic analytical density model (Isothermal)

$$\rho = \rho_0 e^{-\frac{z}{H}}$$

② NRLMSISE-00

Naval Research Laboratory MSIS model that is integrated into MATLAB

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NRLMSISE-00

Inputs:

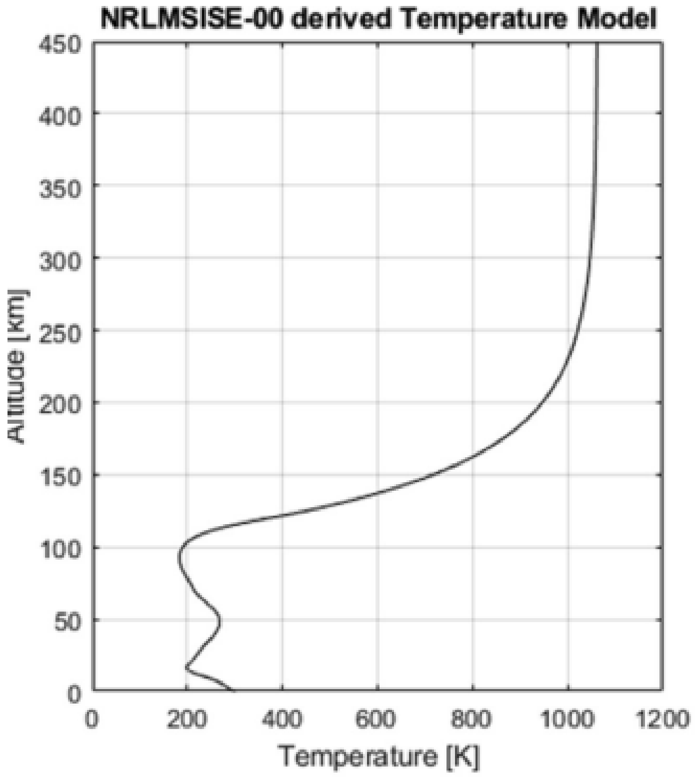
Altitude, latitude, longitude, year, day of year, UT

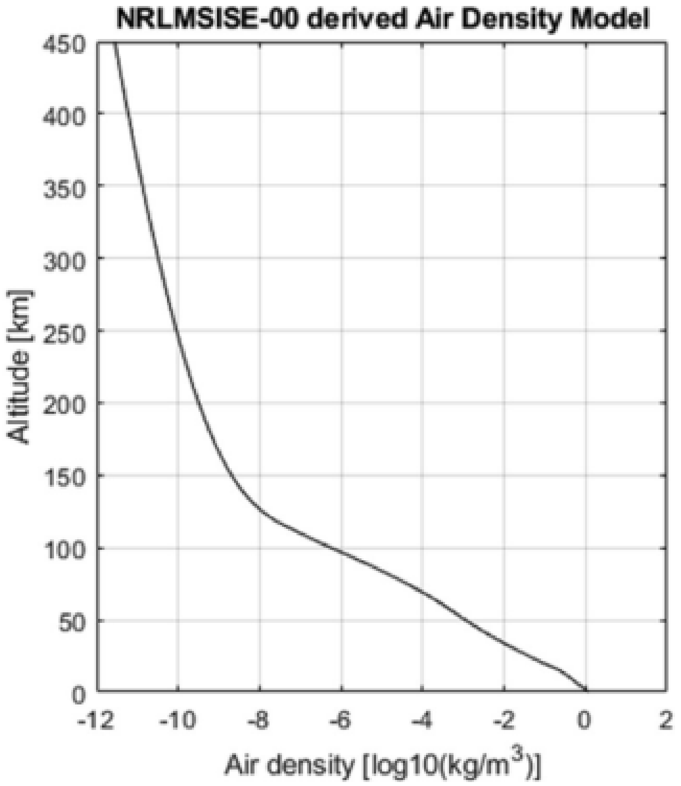
Outputs:

Temperature model

Density model

Up to 1000km





Modeling Reentry

Gravity, Drag, Density, Aerodynamic Coefficients, Mass, and Area

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Aerodynamic & Gravitational Forces

F_{aero} decomposed into 3 main components:

- Drag (D)
  - Acts opposite the direction of the velocity vector
- Lift (L)
  - Perpendicular to the velocity vector
- Side force (Y)
  - Acts in the horizontal plane

$$D = \frac{1}{2}\rho(h)V^2SC_D(\alpha, \beta, M)$$

$$L = \frac{1}{2}\rho(h)V^2SC_L(\alpha, \beta, M)$$

$$Y = \frac{1}{2}\rho(h)V^2SC_Y(\alpha, \beta, M)$$

Ignore variations in coefficients

$F_{gravity}$ decomposed into 2 main components:

- Radial (g_r)
  - Directed opposite the position vector
- Lateral (g_ϕ)
  - Acts perpendicular to the position vector
- Depends on J2

$$g_r = \frac{\mu}{r^2}\left[1 - \frac{3}{2}J_2\left(\frac{R_\oplus}{r}\right)^2(3\sin^2\phi - 1)\right]$$

$$g_\phi = \frac{3\mu J_2}{r^2}\left(\frac{R_\oplus}{r}\right)^2\cos\phi\sin\phi$$

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Equations of Motion

$$\frac{dV}{dt} = -\frac{D}{m} - g_r \sin(\gamma) + g_\phi \cos(\gamma) + r\omega_e^2 \cos(\phi)(\cos(\phi)\sin(\gamma) - \sin(\phi)\sin(\psi)\cos(\gamma))$$

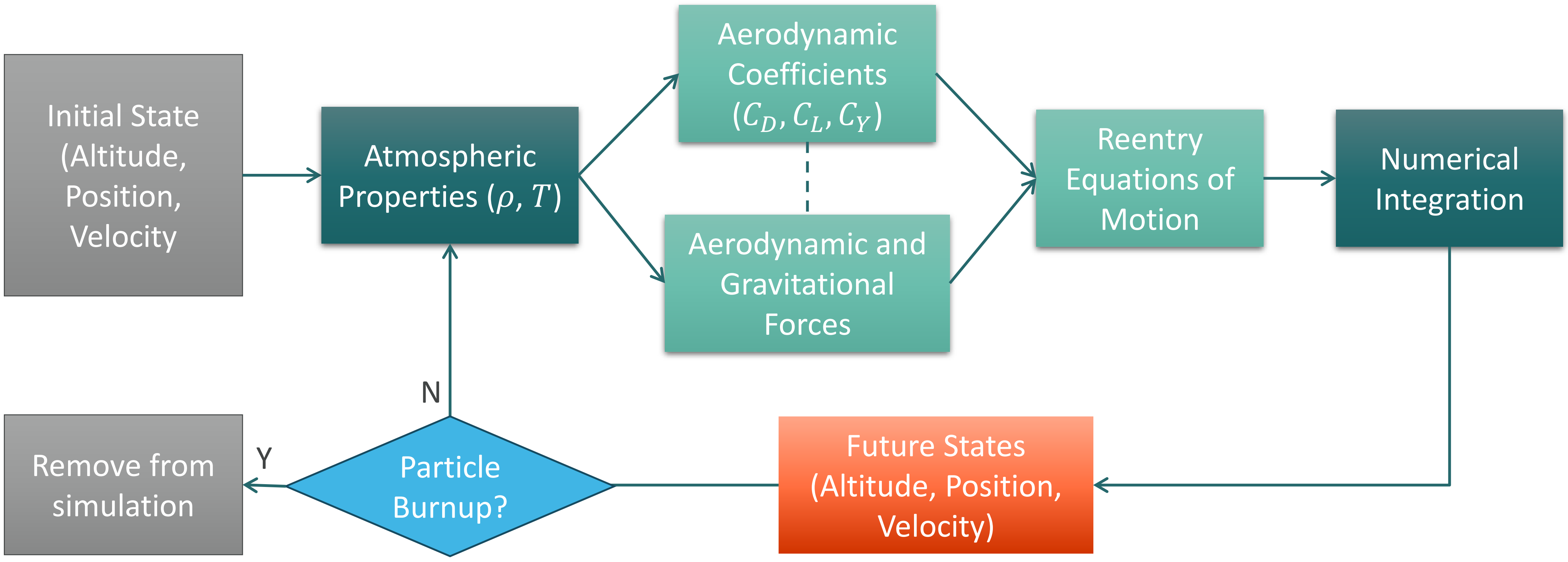
$$\frac{d\gamma}{dt} = \frac{L}{mV} - \frac{g_r}{V}\cos(\gamma) + \frac{g_\phi}{V}\sin(\gamma)\sin(\psi) + \frac{V}{r}\cos(\gamma) + 2\frac{\omega_e}{V}\cos(\phi)\cos(\psi) + rr\omega_e^2(\cos(\phi)\cos(\gamma) - \sin(\phi)\sin(\psi)\sin(\gamma))$$

$$\frac{d\psi}{dt} = \frac{Y}{m\cos(\gamma)V} - \frac{V}{r\cos(\gamma)}\tan(\phi) + \frac{g_\phi}{V}\frac{\cos(\psi)}{\cos(\gamma)} + 2\frac{\omega_e}{V}(\sin(\psi)\cos(\phi)\tan(\gamma) - \sin(\phi))$$

$$\frac{dr}{dt} = V\sin(\gamma) \qquad \frac{d\phi}{dt} = \frac{V\cos(\gamma)\sin(\psi)}{r} \qquad \frac{d\theta}{dt} = \frac{V\cos(\gamma)\cos(\psi)}{r\cos(\phi)}$$

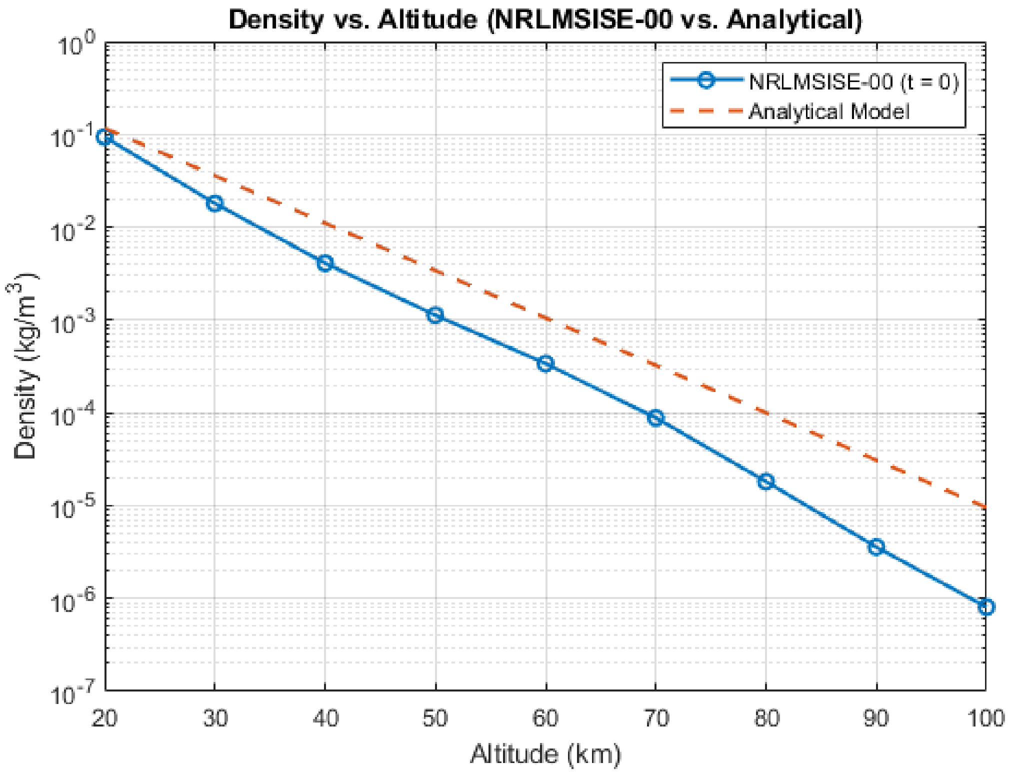
EOM primarily functions of: (velocity, FPA, heading angle, altitude, latitude, longitude, mass)

3-DOF Simulation Flowchart

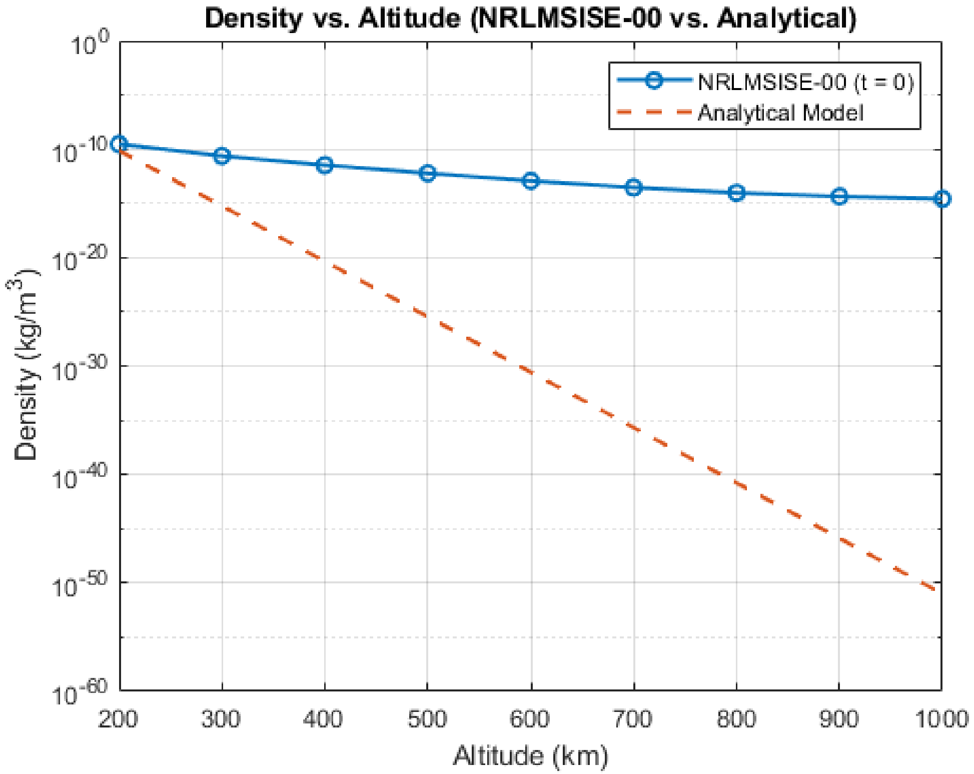


Results

Accuracy of Density Model (MSIS)



Low altitudes



High altitudes

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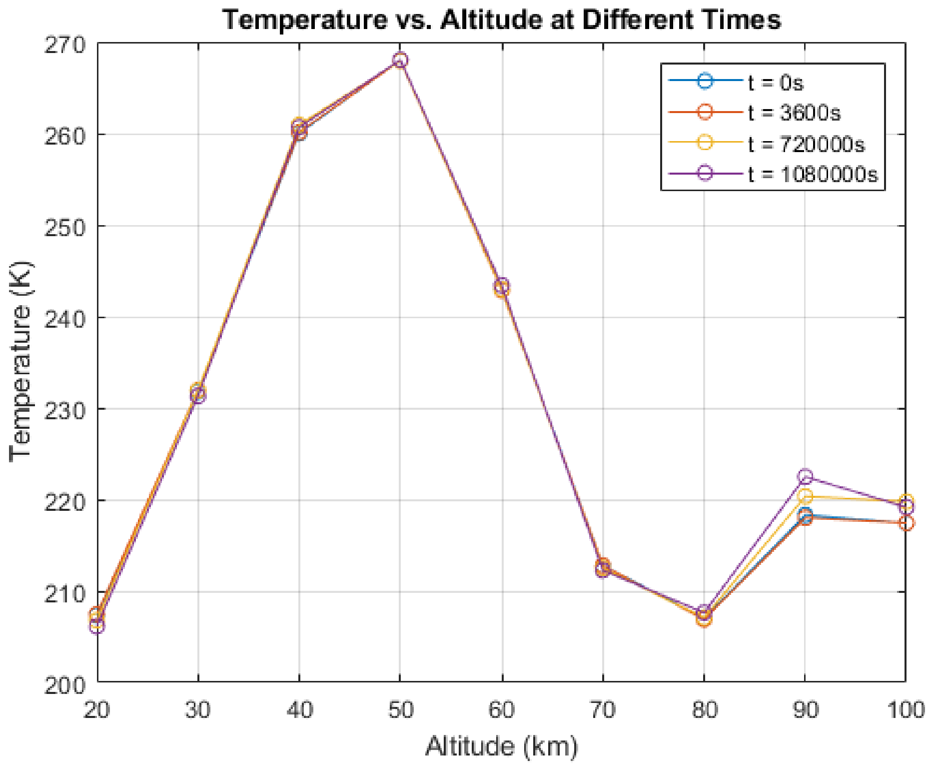
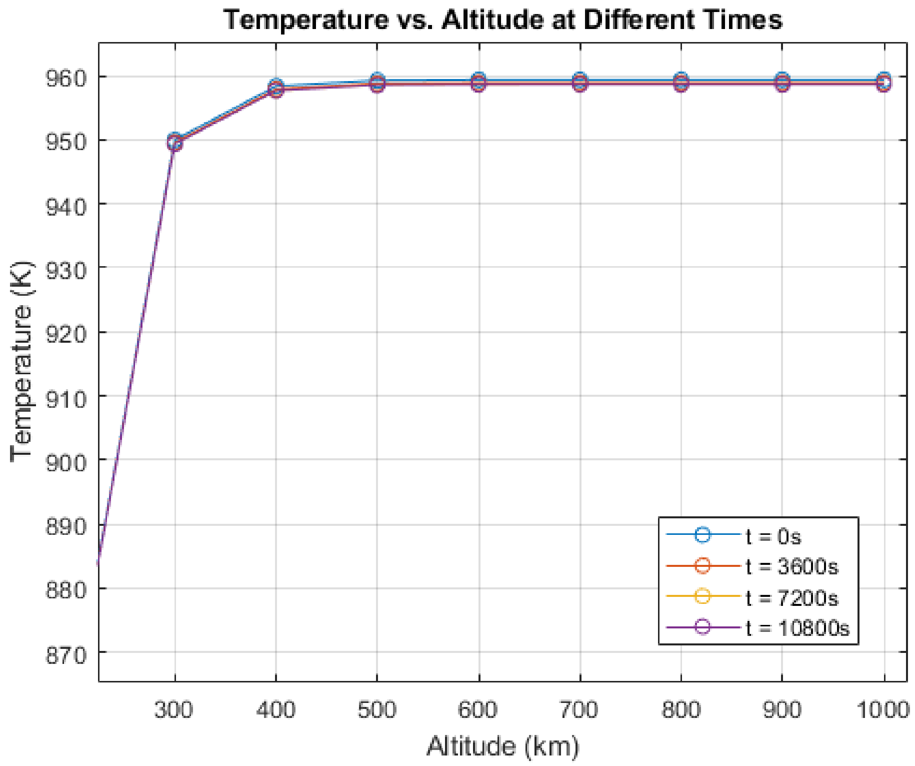
Temperature Model Variation (MSIS)

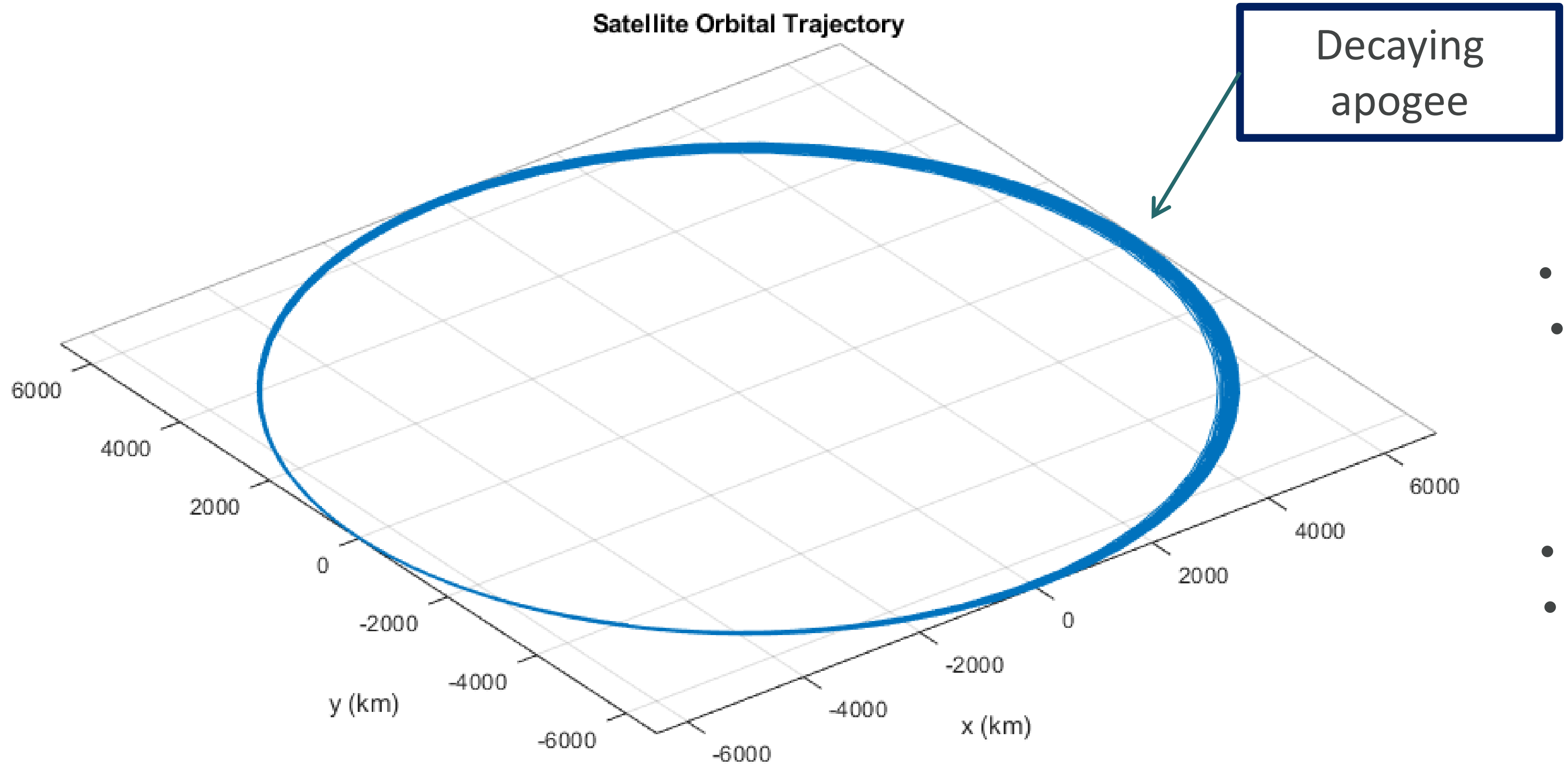


Low altitudes



High altitudes

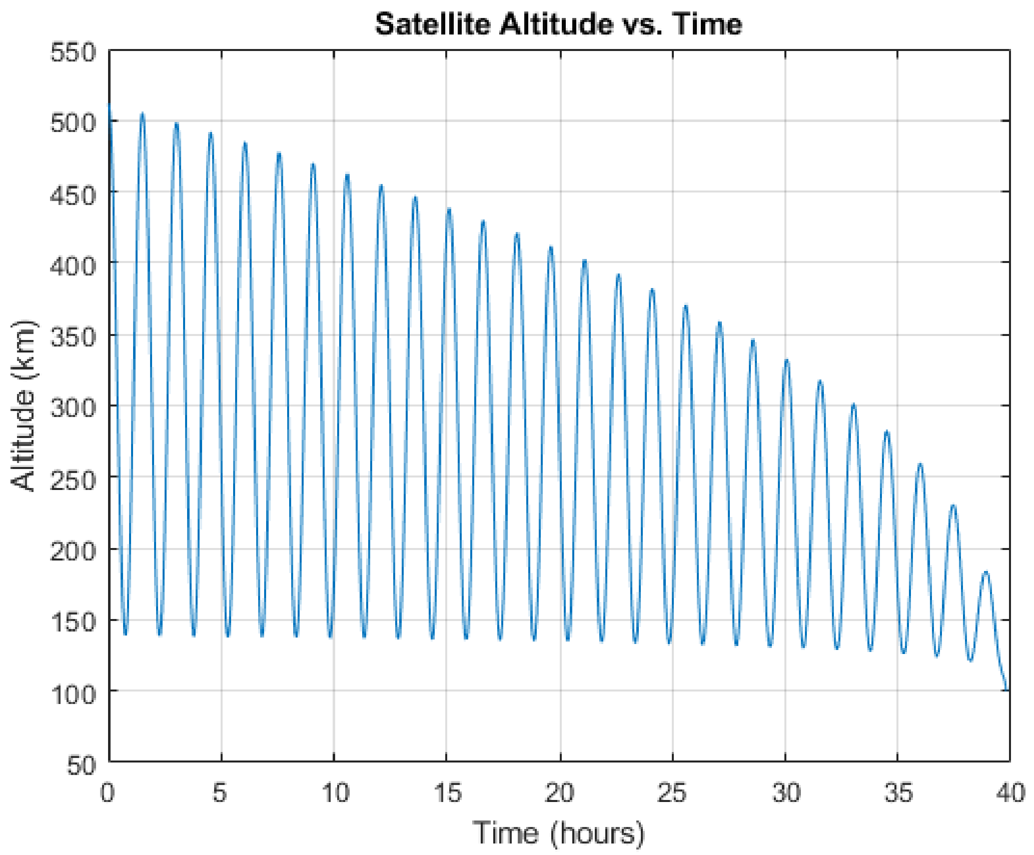
Orbital Decay Model (High Mass)



Study Parameters:

- Initial altitude of ~ 500 km
- 2 days of simulation time
- $C_d = 2.2$ = const.
- $A = 10\ m^2$
- Mass is 1000 kg
- ode113 used as integrator
- Decay simulator cut-off at 100km to switch to reentry simulator

Orbital Decay Model (High Mass)



Study Parameters:

- Initial altitude of ~ 500 km
- 2 days of simulation time
- $C_d = 2.2$ = const.
- $A = 10\ m^2$
- Mass is 1000 kg
- ode113 used as integrator
- Decay simulator cut-off at 100km to switch to reentry simulator

Conclusions:

- Satellite reduced altitude to 100km in less than 40 hours
- Apogee consistently decreased
- Rapid decent after ~ 37 hours

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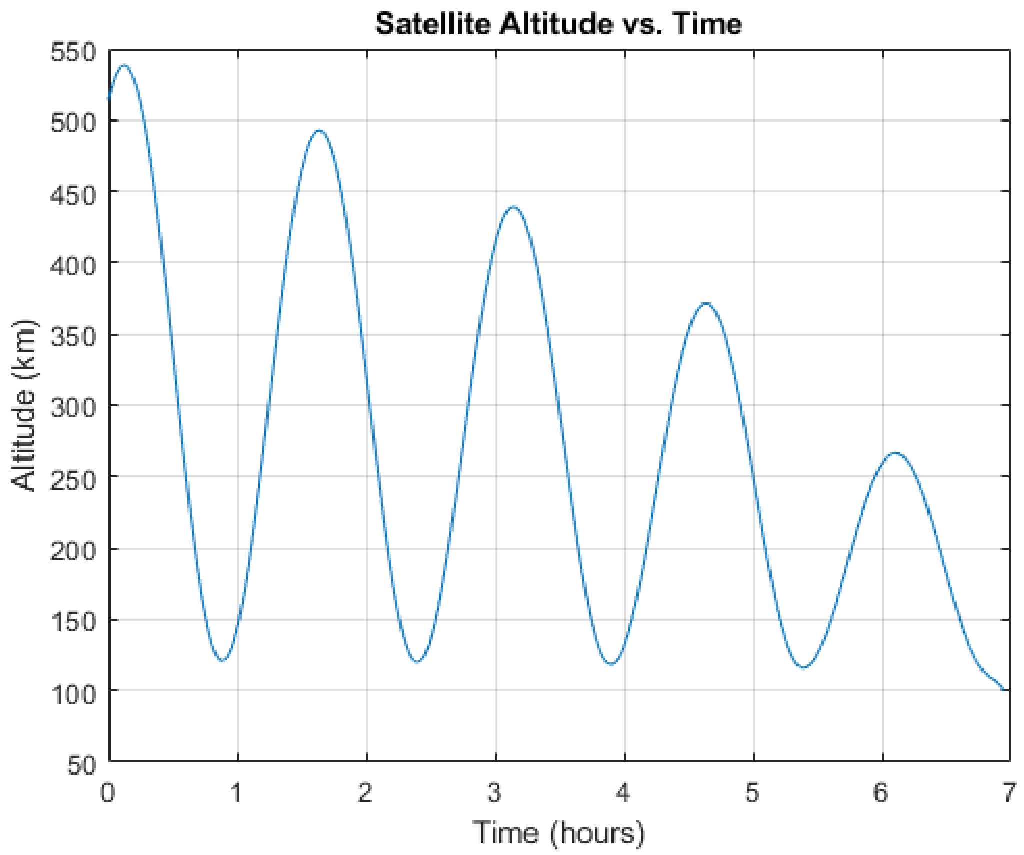
Orbital Decay Model (Lower Mass)



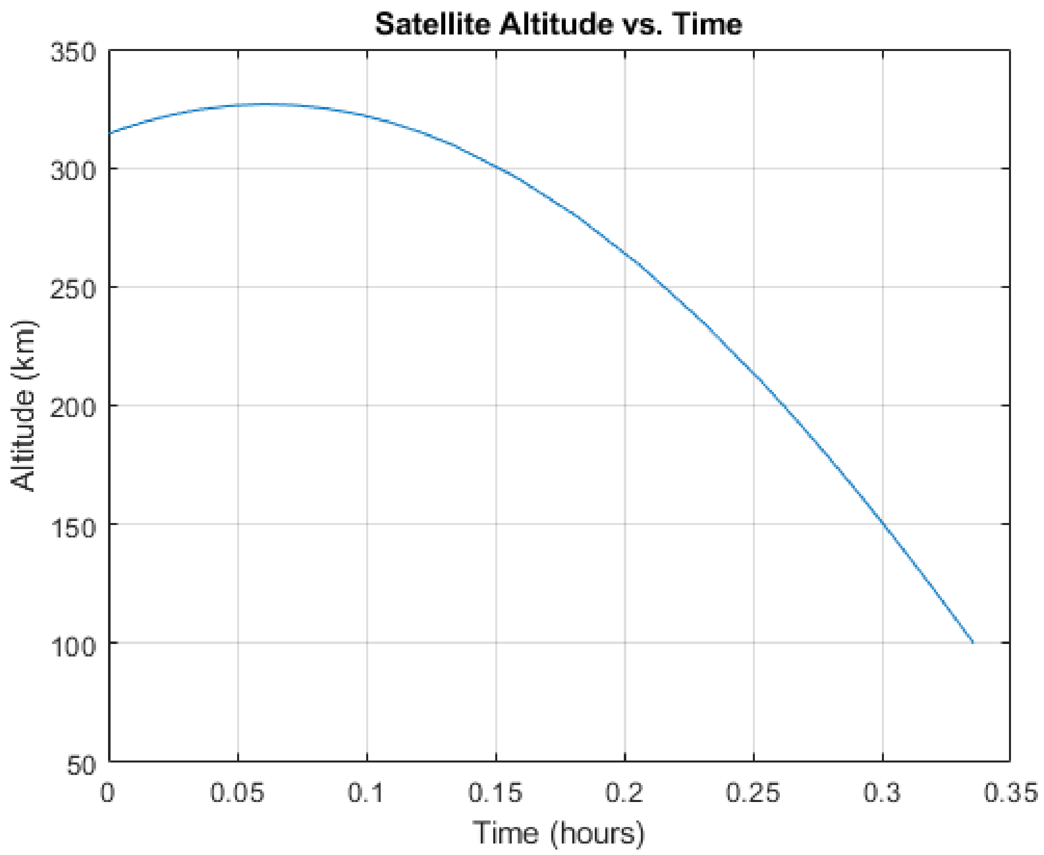
Study Parameters:

- Initial altitude of ~ 500 km
- 2 days of simulation time
- $C_d = 2.2$ = const.
- $A = 10\ m^2$
- <u>Mass is 500 kg</u>
- ode113 used as integrator
- Decay simulator cut-off at 100km to switch to reentry simulator

Conclusions:

- Reducing mass caused a quicker decent due to larger deceleration due to drag

Orbital Decay Model (Low Altitude)



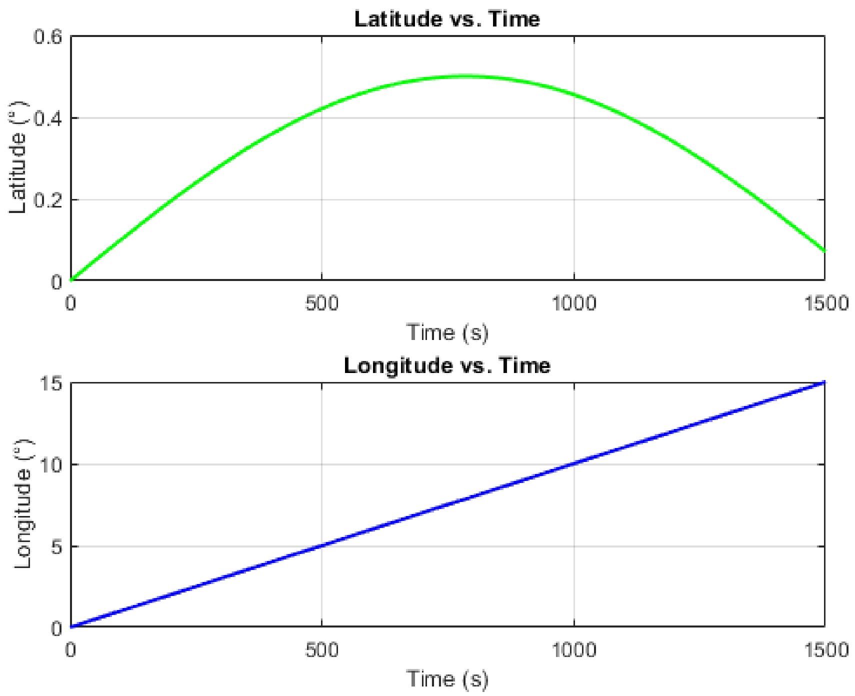
Study Parameters:

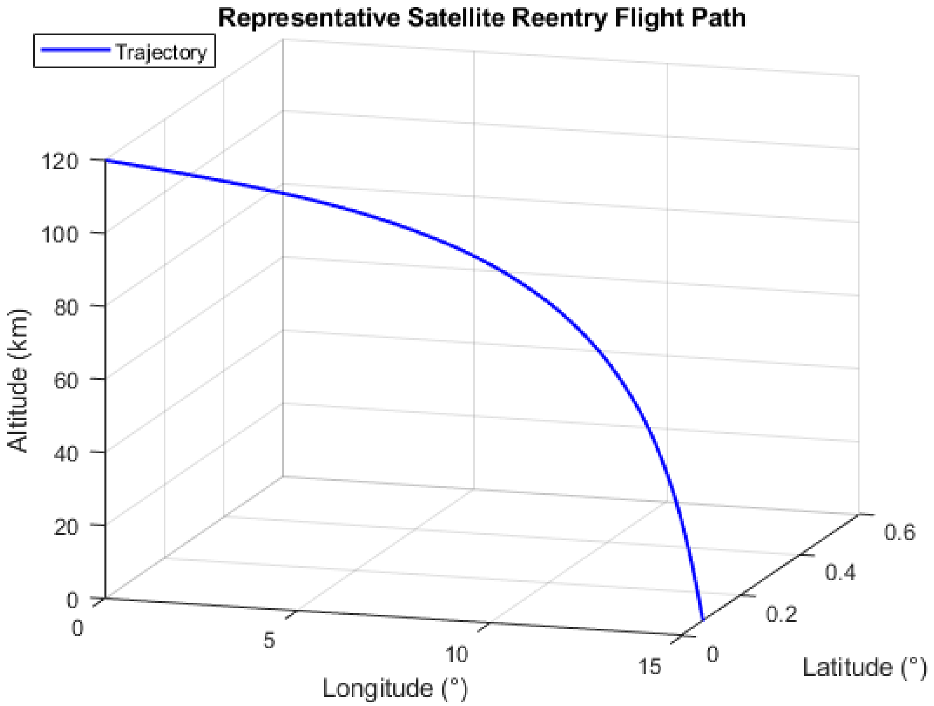
- Initial altitude of ~ 350 km
- 2 days of simulation time
- $C_d = 2.2$ = const.
- $A = 10\ m^2$
- Mass is 1000 kg
- ode113 used as integrator
- Decay simulator cut-off at 100km to switch to reentry simulator

Conclusions:

- Starting at a lower altitude brings rapid decent due to drag
- < 1 hour to object breakup phase (100 km)

Reentry Model





Conclusions:

- Plots are not converging on correct results
- Still troubleshooting to see what the errors are

Future Work

1

Fix the reentry model

Troubleshoot the current errors with the state estimator for the reentry simulator

2

Create functions for C_D, C_L, C_Y

Significantly improve upon aerodynamic force estimation by assuming changing coefficients

3

Impact analysis and heat model

Develop full impact analysis using advanced heating models throughout the < 80 km altitude phase. Need more time to develop heating model that is functional for this case

References

[1] Neuenfeldt, Brian D., et al. *A Survey of Uncontrolled Satellite Reentry and Impact Prediction*. Sept. 1993. Accessed 5 Dec. 2024.

[2] European Space Agency. “Orbital Decay.” *Www.esa.int*, 30 Sept. 2014, www.esa.int/ESA_Multimedia/Videos/2014/09/Orbital_Decay. Accessed 5 Dec. 2024.

[3] “Simulating reentries for safer satellites,” *Www.esa.int*, 2016. https://www.esa.int/Space_Safety/Clean_Space/Simulating_reentries_for_safer_satellites. Accessed 5 Dec. 2024.

[4] ResearchGate, On-ground risk estimation of reentering human-made space objects. Accessed: Dec. 04, 2024. [PNG]. Available: https://www.researchgate.net/figure/Simplified-representation-of-an-upper-stage-reentry_fig3_341569089

[5] L. David, “Uncontrolled reentry of space debris poses a real and growing threat,” *SpaceNews*, Jun. 05, 2024. https://spacenews.com/uncontrolled-reentry-of-space-debris-poses-a-real-and-growing-threat/