Johnson Space Center Engineering Directorate

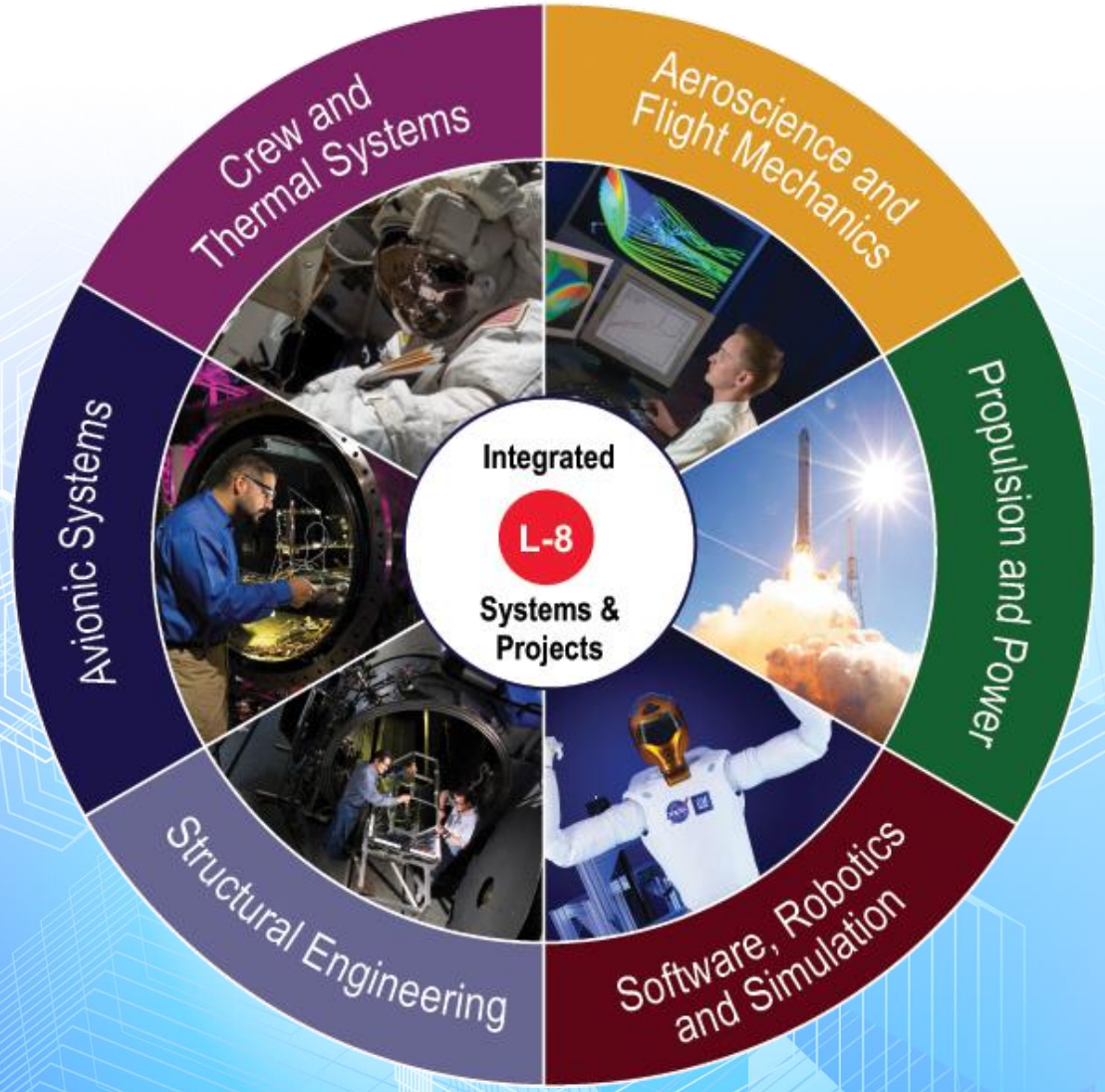
# L-8: Autonomy & Optimization

**Public Release Notice**
This document has been reviewed for technical accuracy, business/management sensitivity, and export control compliance. It is suitable for public release without restrictions per NF1676 #_____ .

Gerald Condon

November 2016

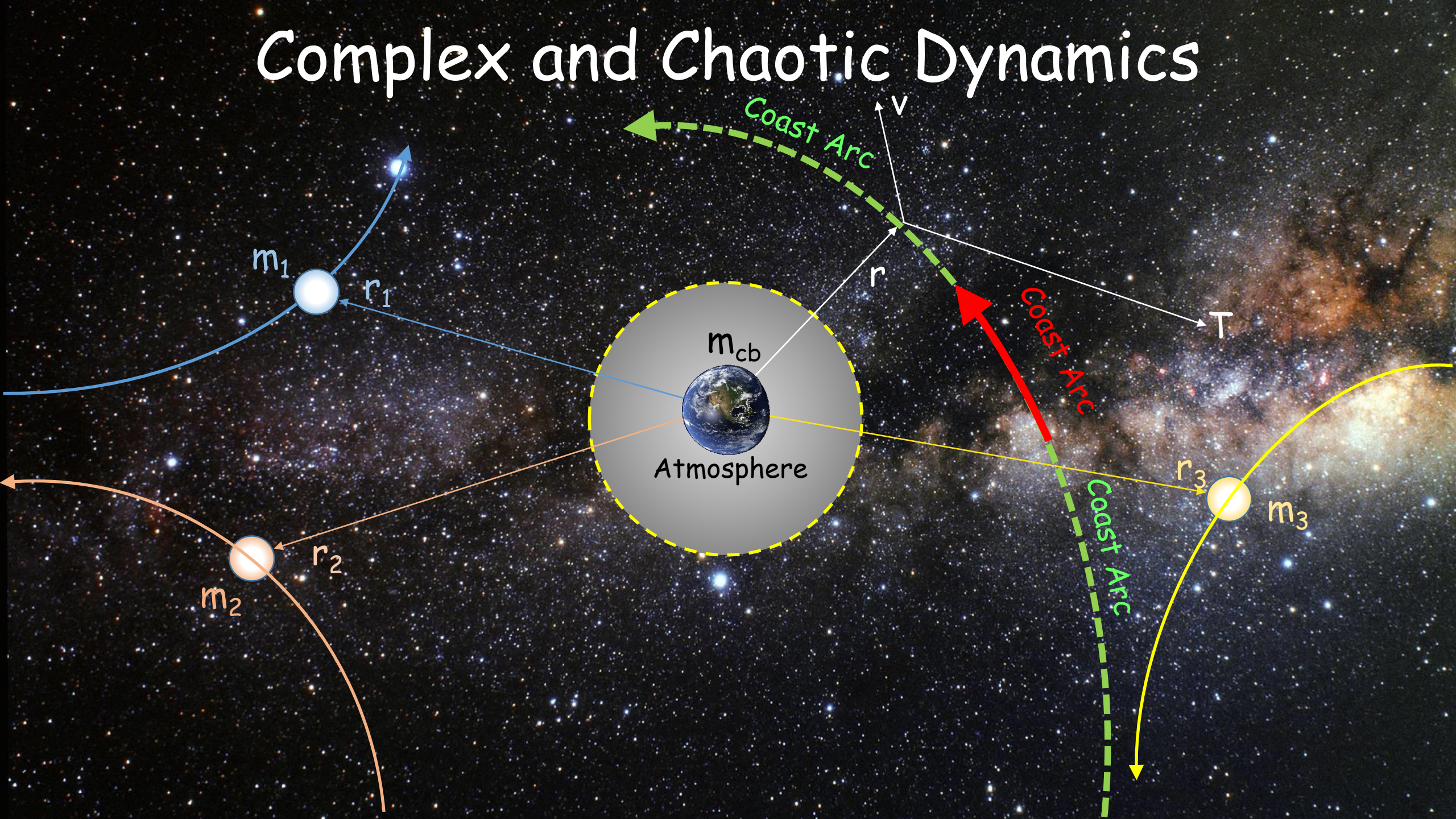
# JSC Engineering: HSF Exploration Systems Development




- We are sharpening our focus on Human Space Flight (HSF) Exploration Beyond Low Earth Orbit
- We want to ensure that HSF technologies are ready to take Humans to Mars in the 2030s.
  - Various Roadmaps define the needed technologies
  - We are attempting to define our activities and dependencies
- Our Goal: Get within 8 years of launching humans to Mars (L-8) by 2025
  - Develop and Mature the technologies and systems needed
  - Develop and Mature the personnel needed
- We need collaborators to make it happen, and we think they can benefit by working with us.

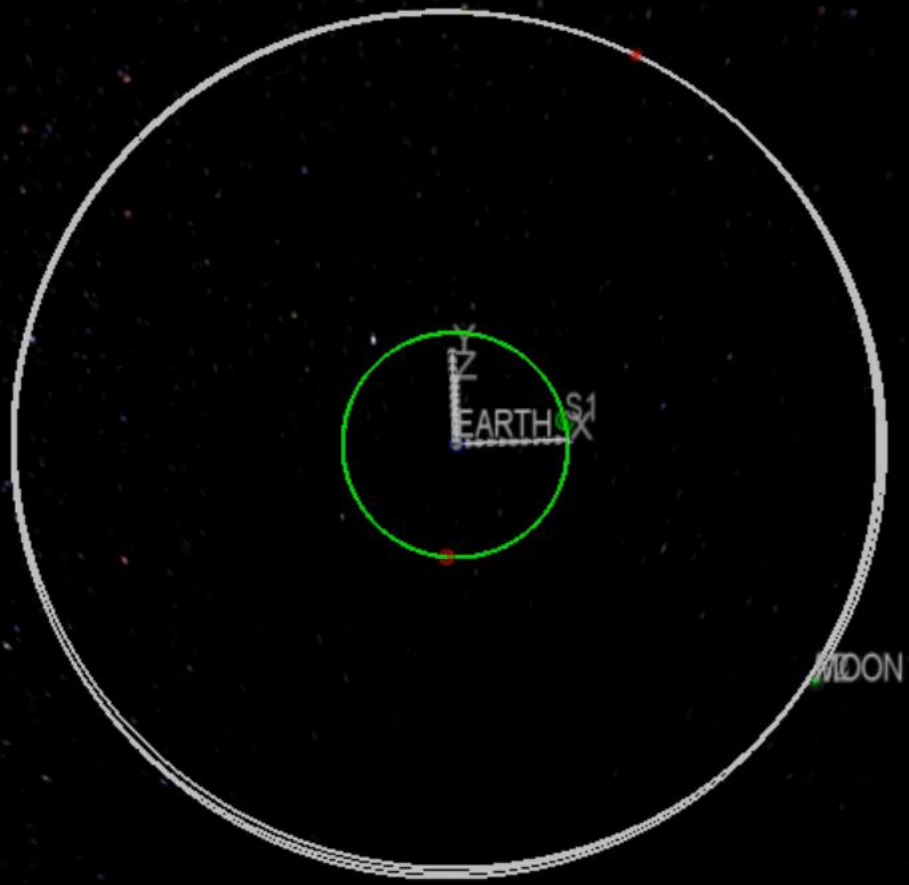
Boilerplate

# Complex and Chaotic Dynamics



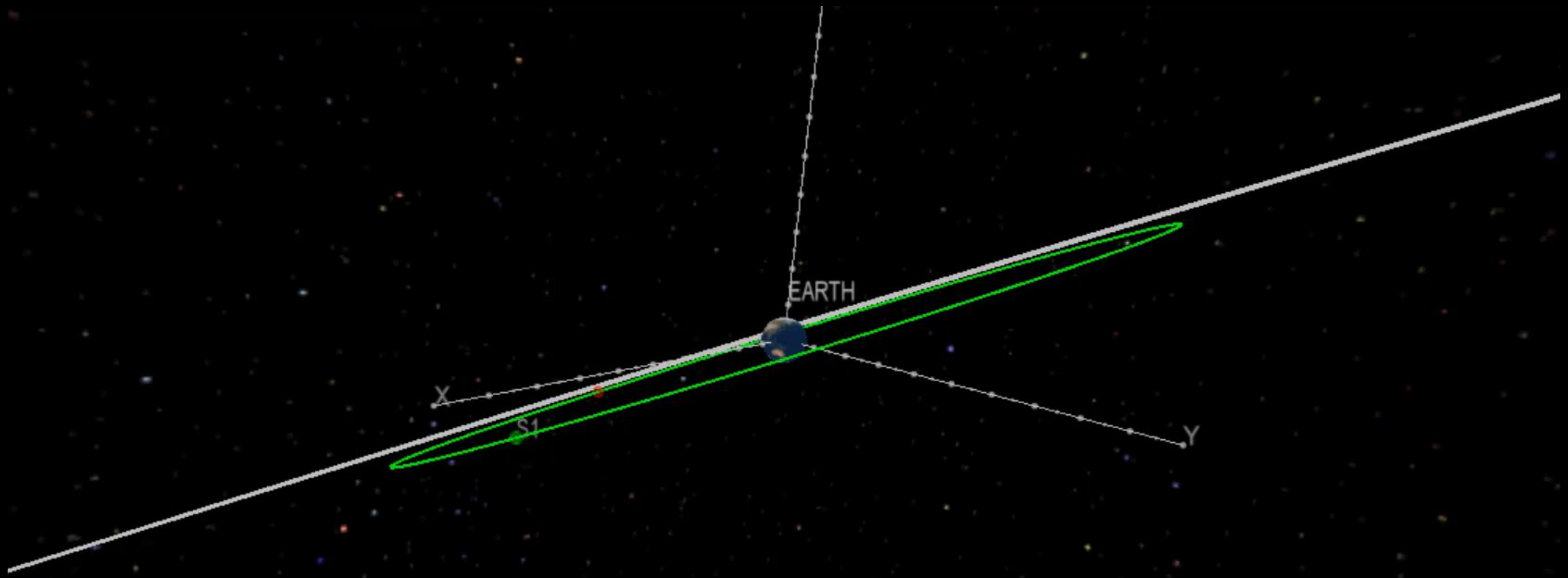
# Example 1: Chaotic Motion in the Earth-Moon System

# Example 1: Chaotic Motion in the Earth-Moon System



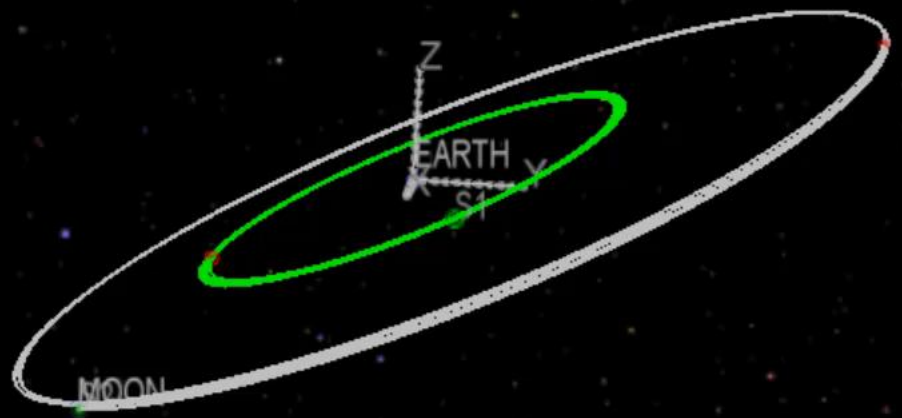

caotic-motion-ex01-01.mp4

# Example 1: Chaotic Motion in the Earth-Moon System




caotic-motion-ex01-02.mp4

# Example 1: Chaotic Motion in the Earth-Moon System

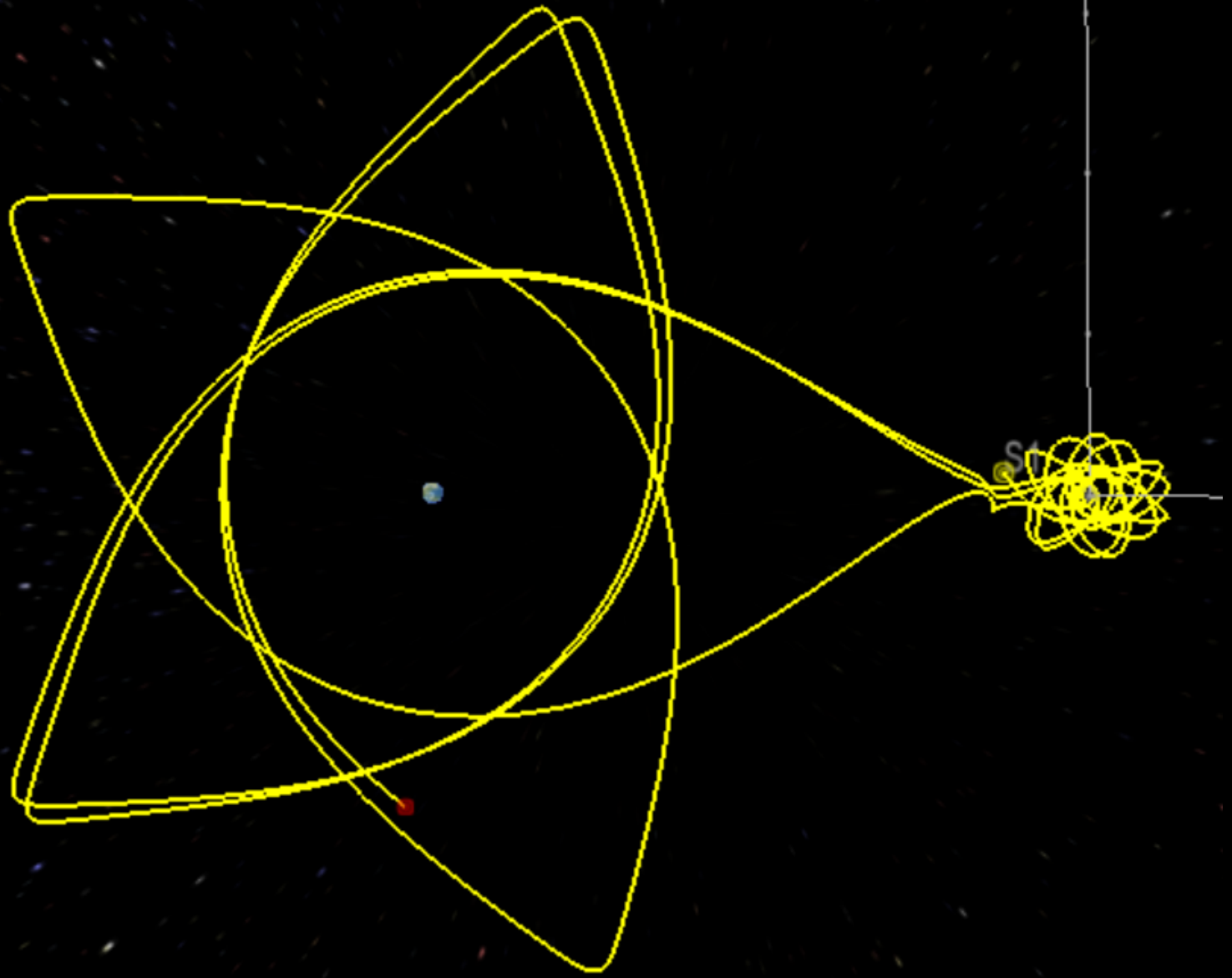



caotic-motion-ex01-03.mp4

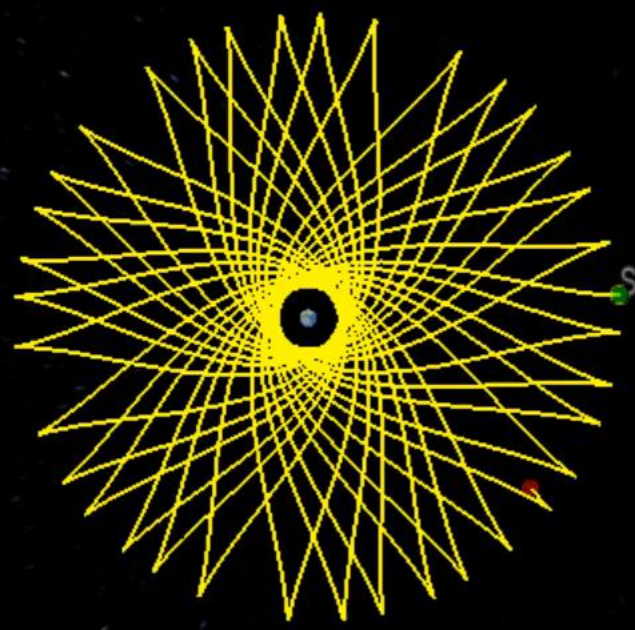
# Example 1: Chaotic Motion in the Earth-Moon System

caotic-motion-ex01-04.mp4

# Example 2: Chaotic Motion in the Earth-Moon System

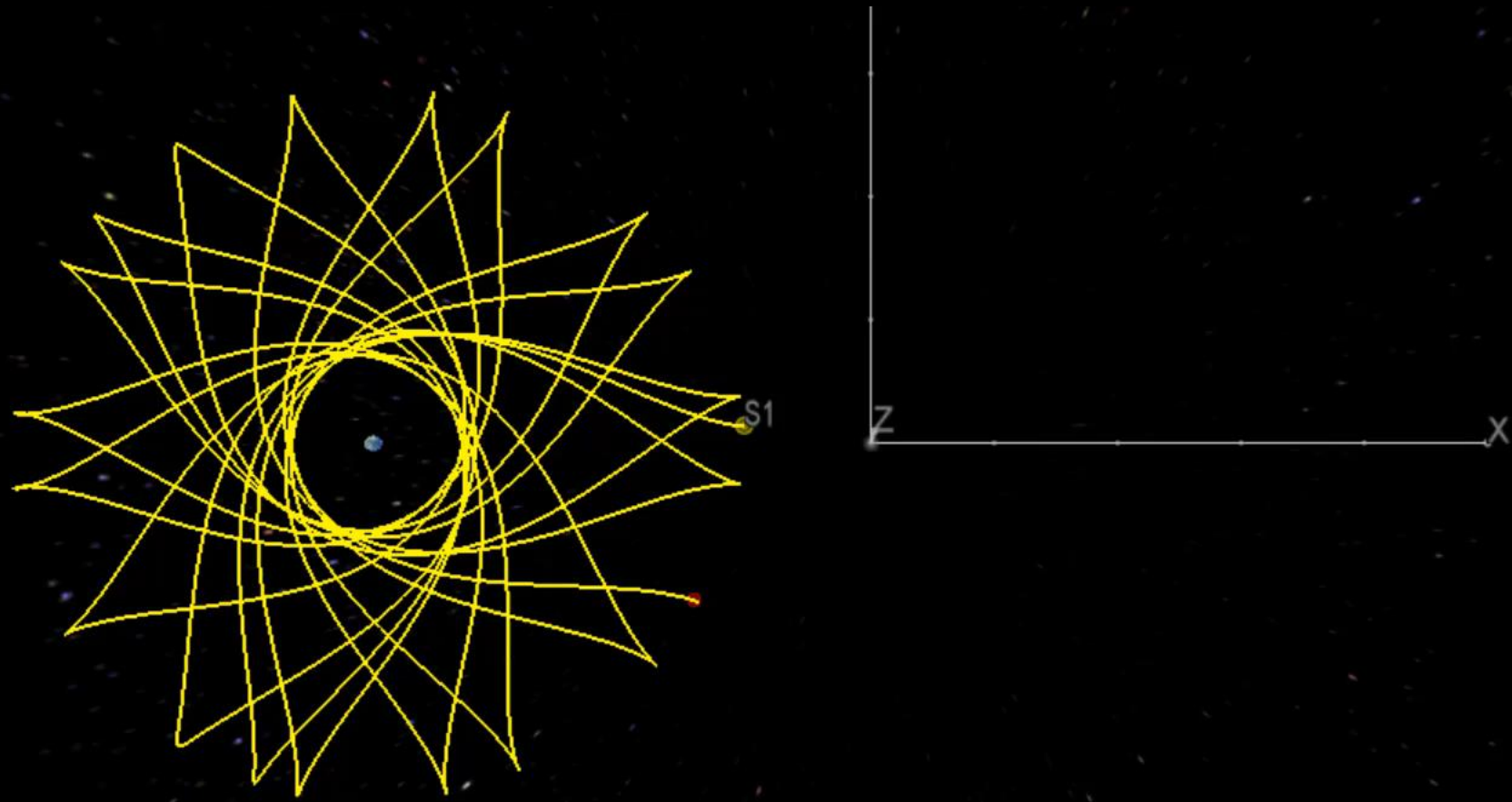


# Example 2: Chaotic Motion in the Earth-Moon System

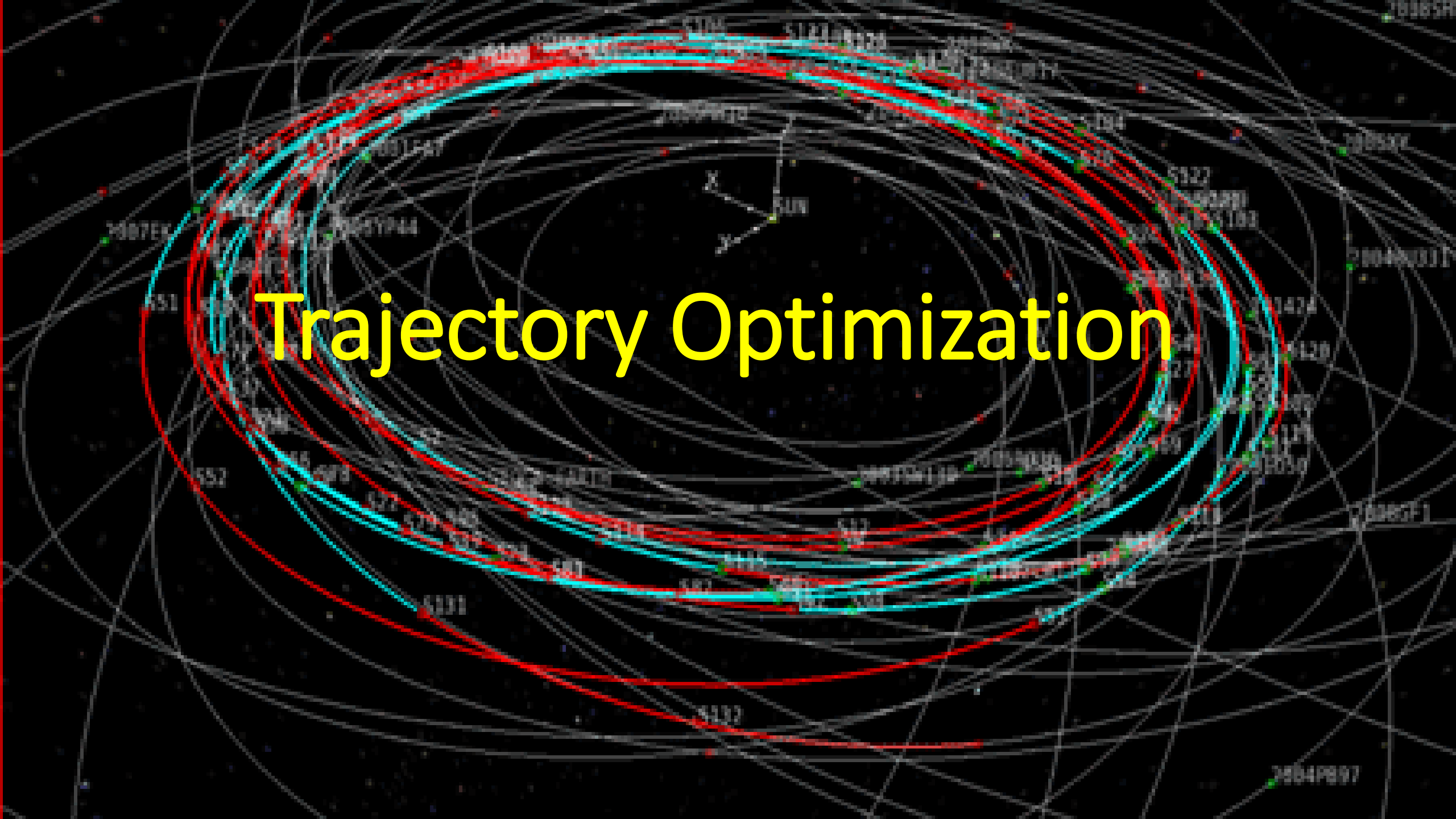


caotic-motion-ex02-01.mp4

# Example 2: Chaotic Motion in the Earth-Moon System




caotic-motion-ex02-02.mp4


Trajectory Optimization

# Basic Problem of Trajectory Optimization

Find the optimal value of a set of optimization variables, $X_p$

Initial conditions, times of maneuvers, directions of delta-v's, or steering direction of finite thrust vector, etc.

... subject to equality constraints, $C_{eq}(X_p) = 0$

Final position and velocity must match target, segments must be connected to be continuous, etc.

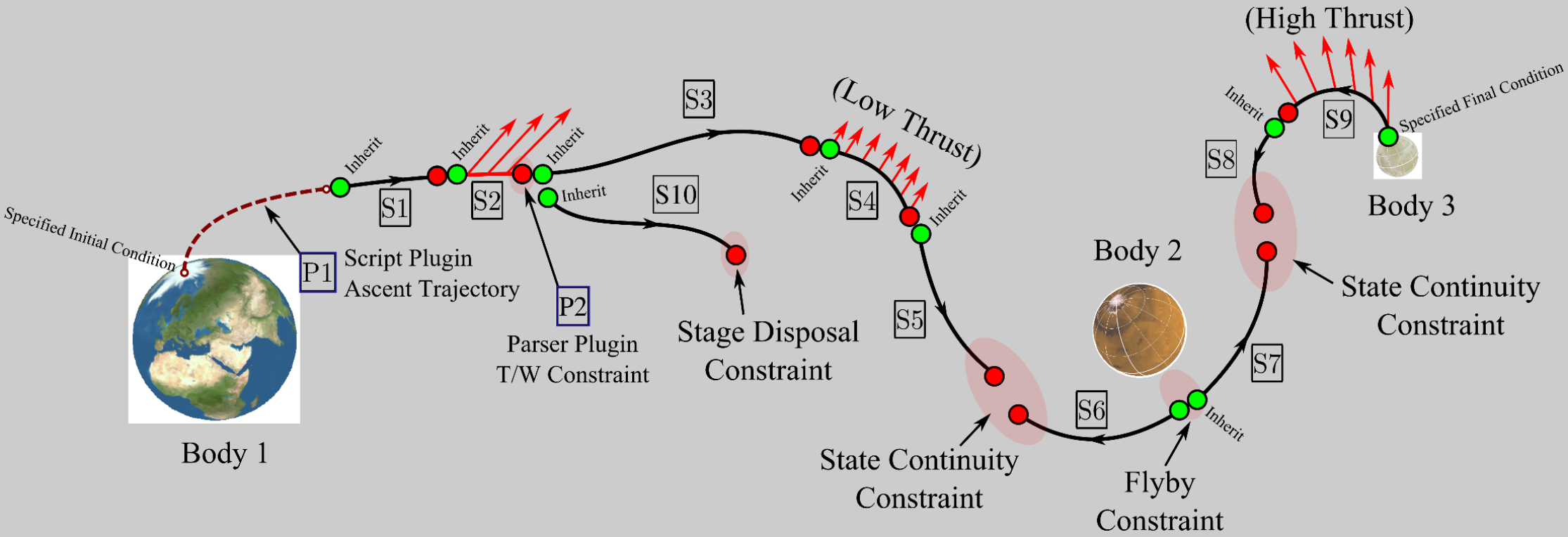
... and inequality constraints, $C_{ineq}(X_p) <= 0$

Minimum flyby radii, maximum allowable propellant, etc.

... while minimizing or maximizing and objective function, $F(X_p)$

Such as min delta-v, min-time, max impact velocity, etc.

# Complex Trajectory with Complex Gravity Fields



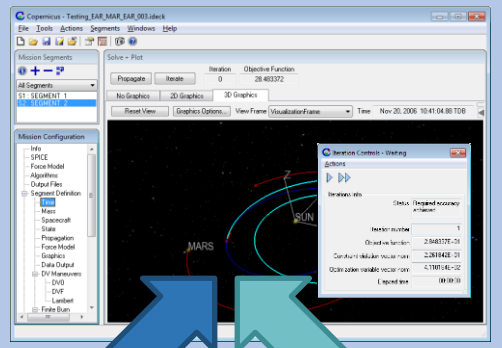

- Multiple spacecraft and propulsion systems.
- Segment to segment information inheritance.
- Plugins allow user-defined capabilities.
- Optimization variables and constraints.
- Forward and backward propagation.

The simple segment construction method can be used to create anything from a simple trajectory to an extremely complex set of interdependent trajectories .

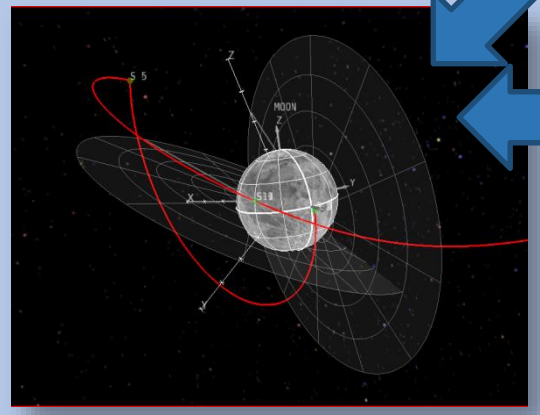
# Ground Based Function

Copernicus marries a powerful computation engine with a friendly GUI and an interactive OpenGL graphics visualization capability.

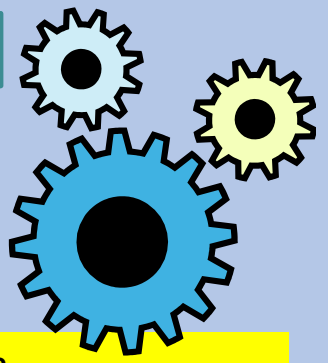
## Main Program



**GUI**
- User Inputs
- Mission Design
- Design Modifications
- Numerical Feedback



**Visualization**
- Aid in Problem Set-Up
- Trajectory Solution Feedback
- "Real" Trajectory Insights



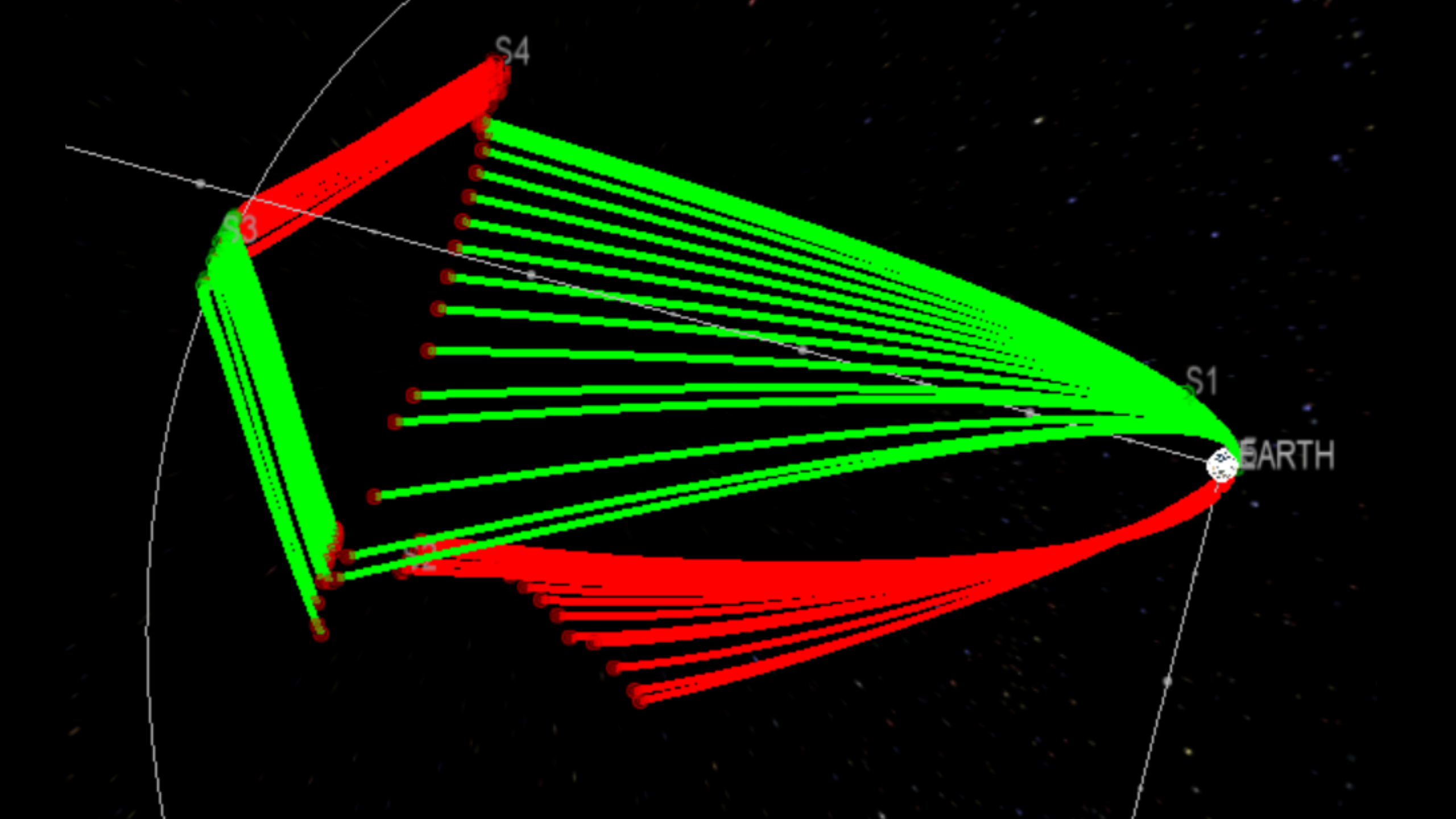
**Engine**
- Trajectory Segments
- Optimization
- Integration
- Control Algorithms
- Engine Models

## Copernicus Libraries

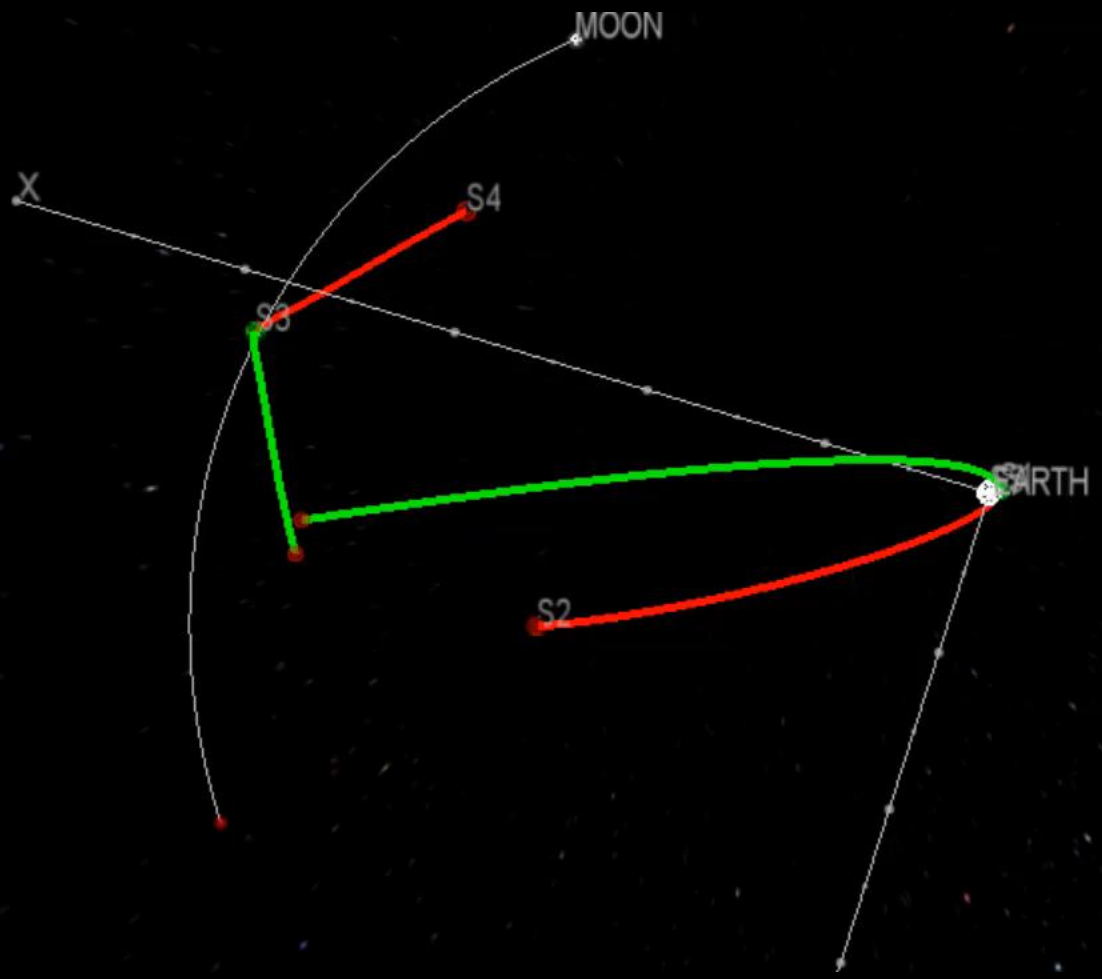
**Toolkit Library**
- Celestial Mechanics Routines
- SPICE Interface
- Math Utilities
- Coordinate Transformations
- Binary File I/O
- Gravity Models

**Batch Library**
- Distributed Processing
- Automated Copernicus Runs
- Production Data Output

The holy grail of trajectory optimization is finding the initial guess for the unknown set of optimization variables that converges to a solution, for any problem

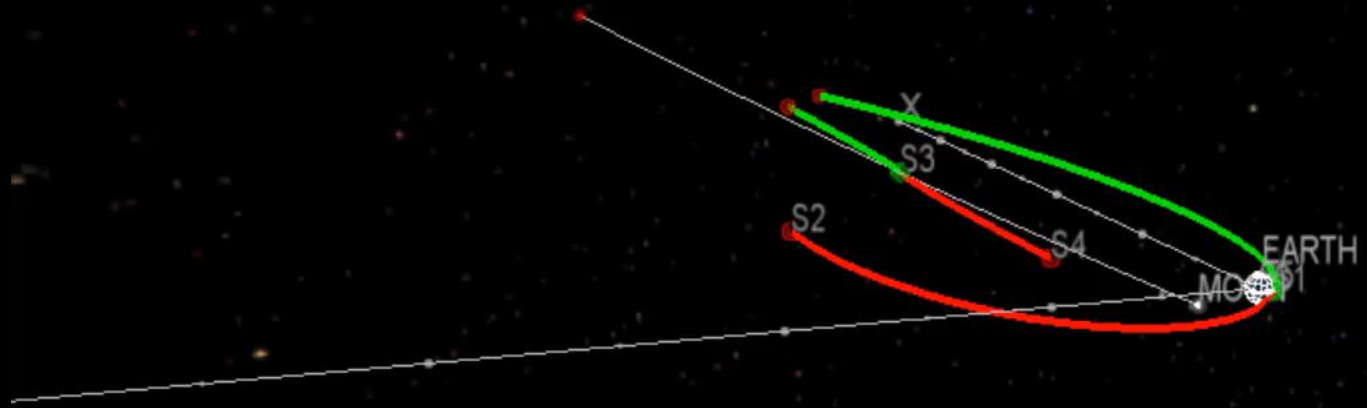

S4
S3
S1
EARTH

# Example 3: Construction of a Lunar Free Return



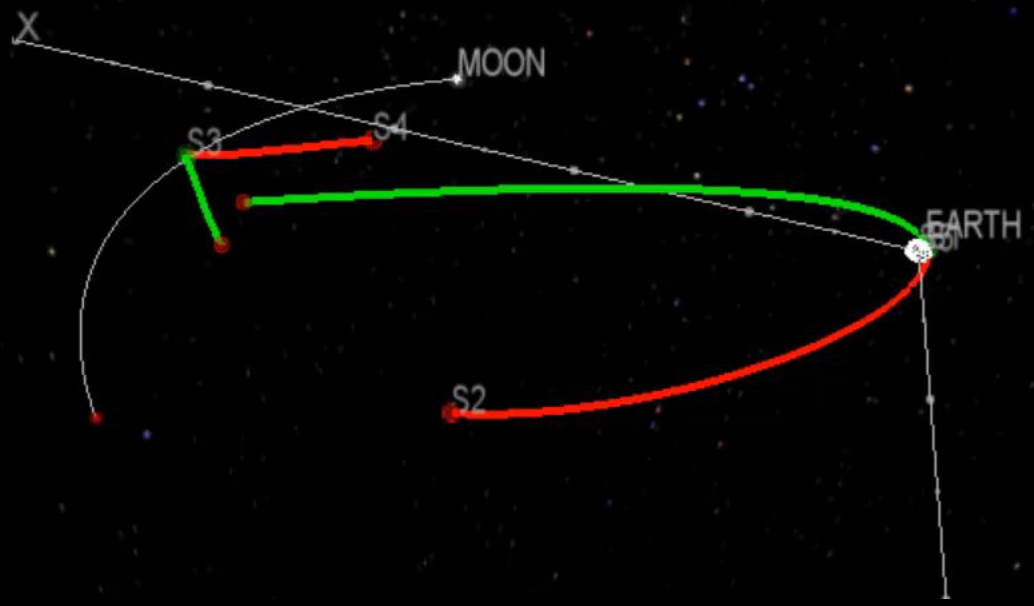

lfr-example-01.mp4

# Example 3: Construction of a Lunar Free Return



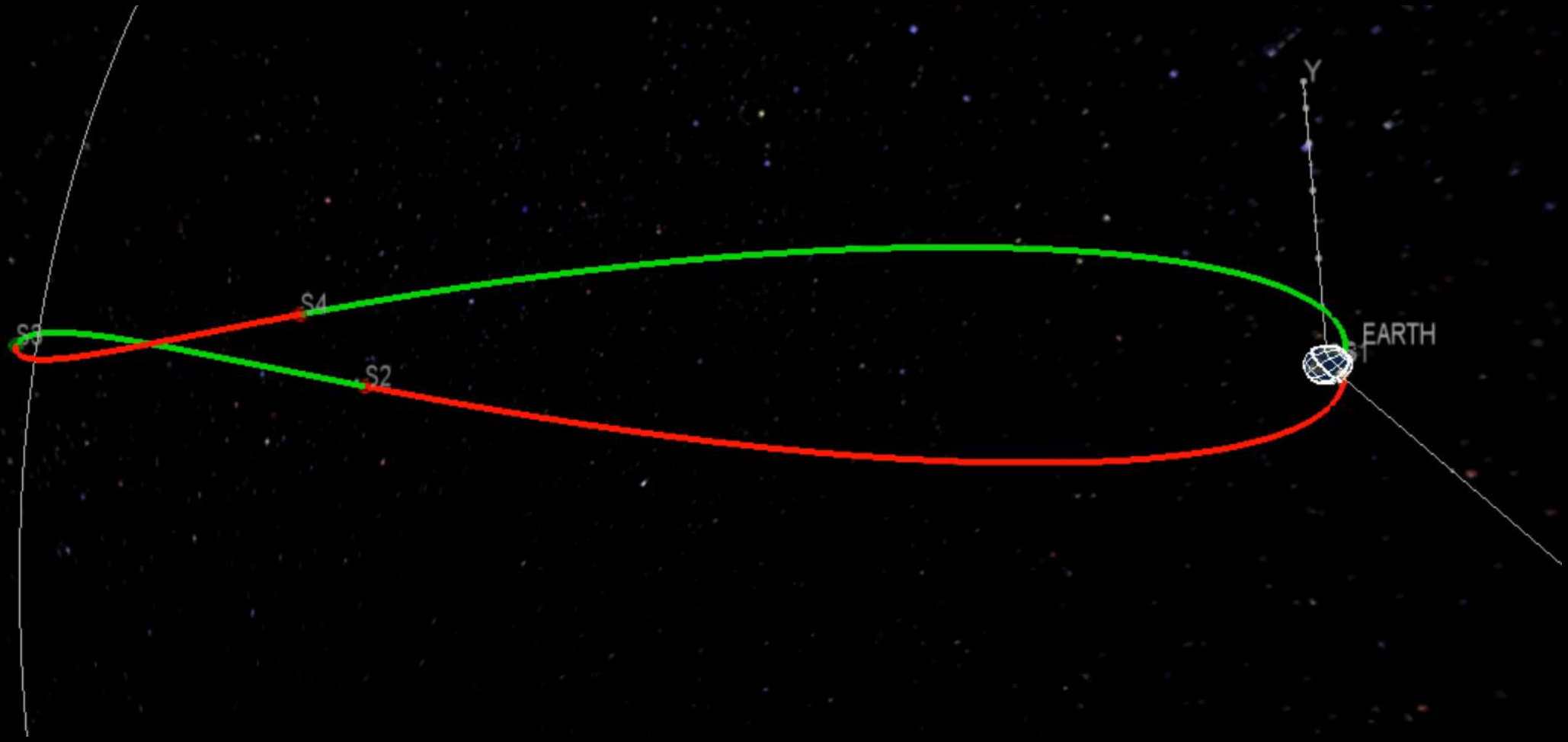

lfr-example-01.mp4

# Example 3: Construction of a Lunar Free Return



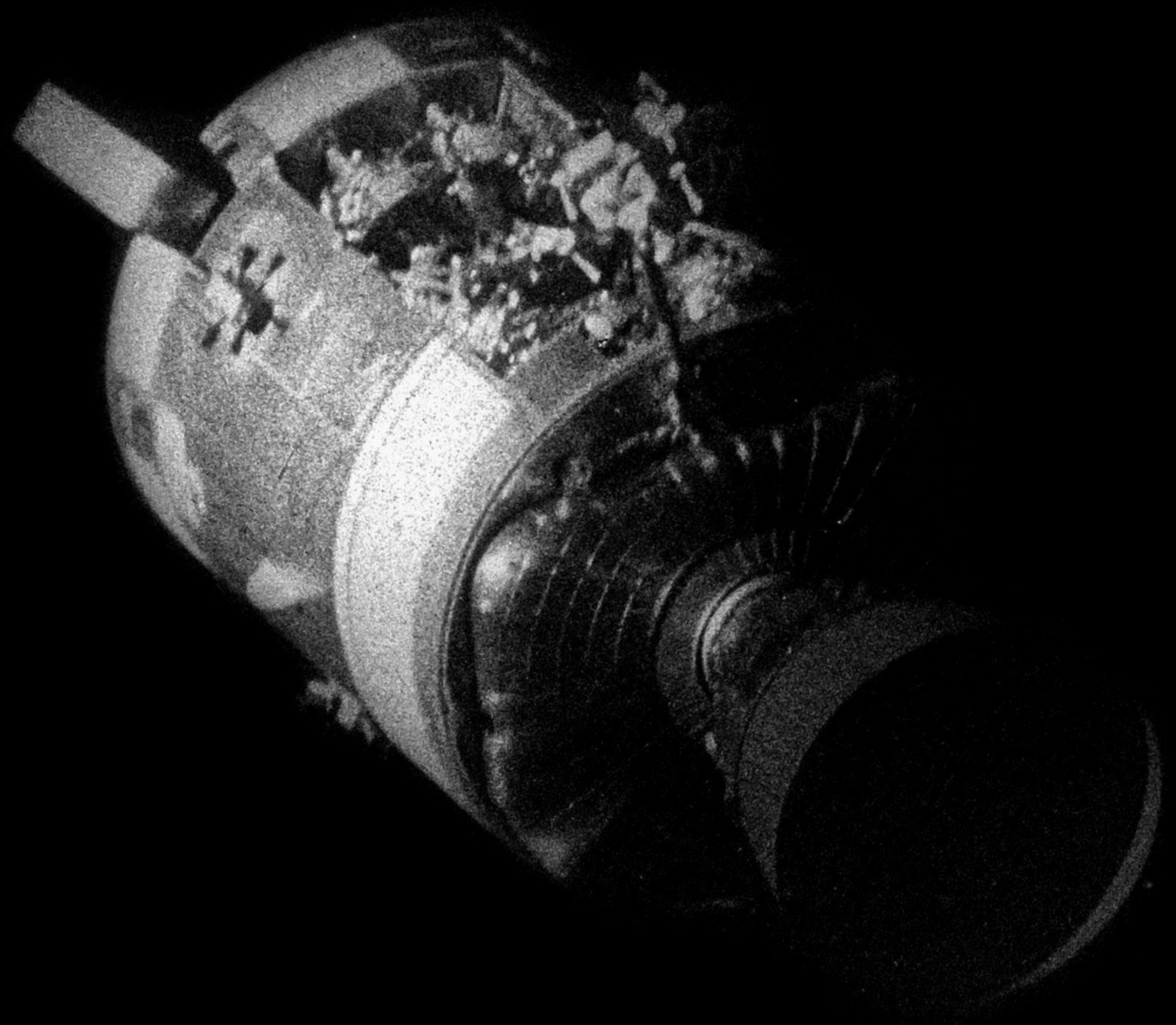

lfr-example-01.mp4

# Example 3: Construction of a Lunar Free Return

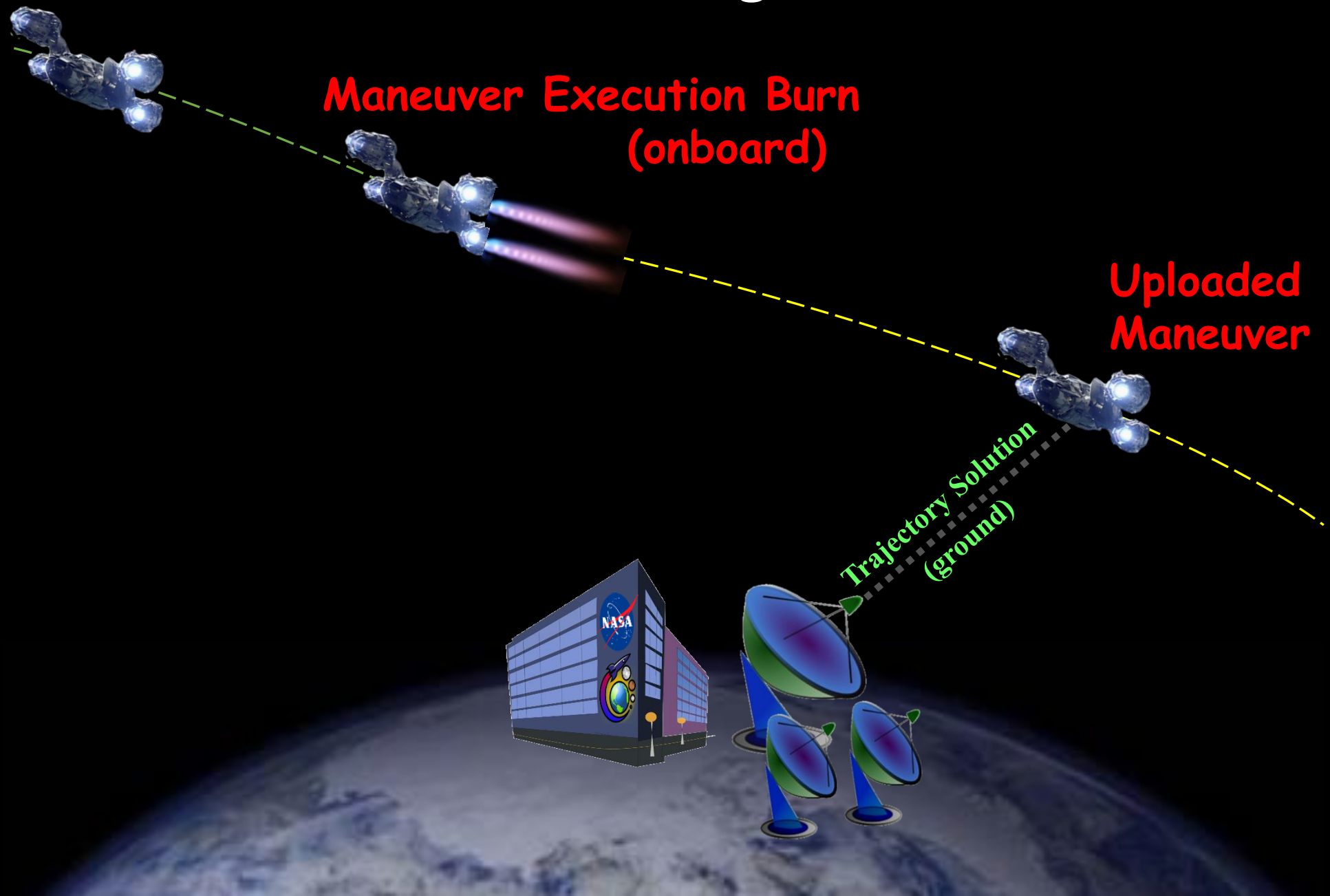



lfr-example-01.mp4

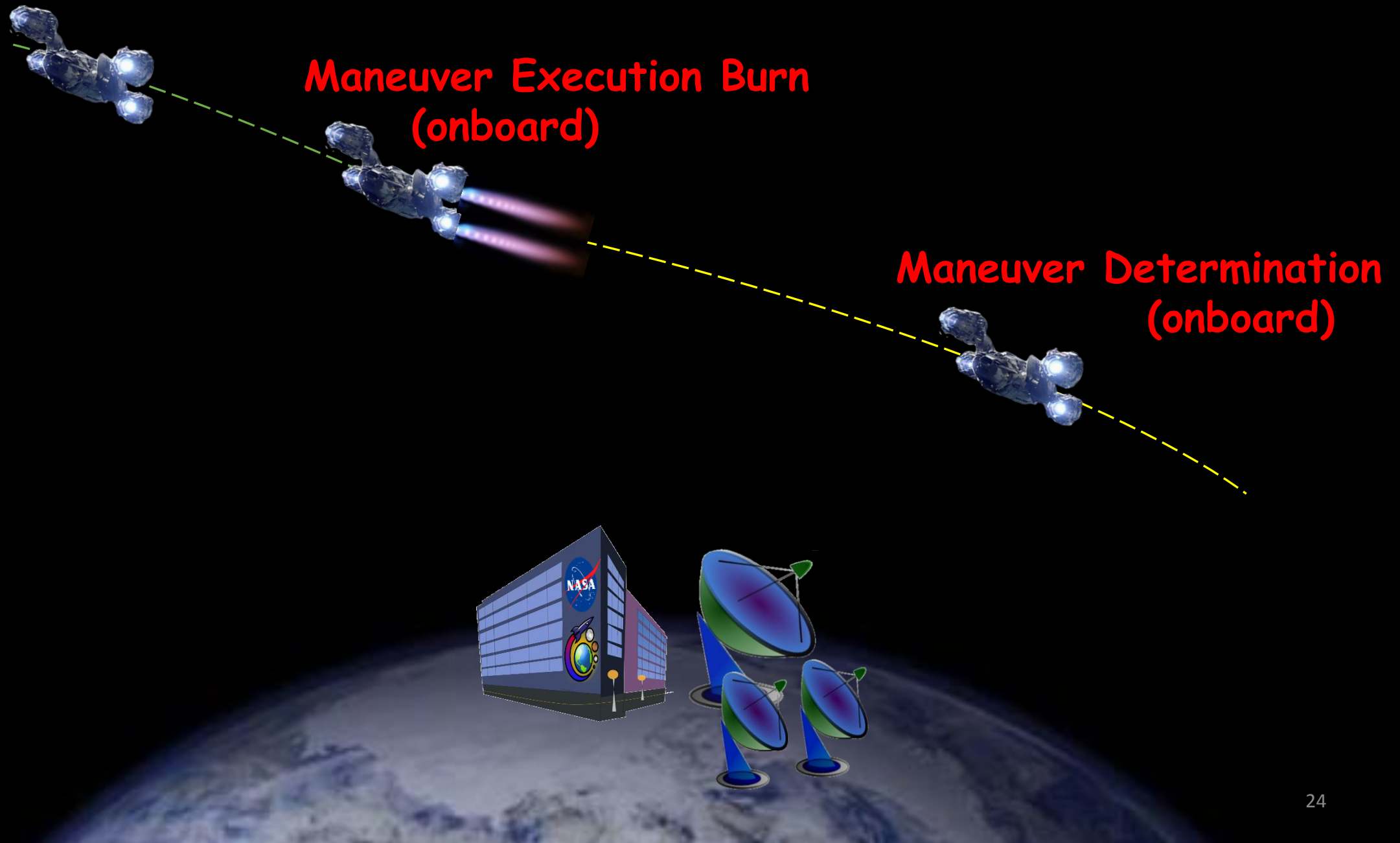
- Apollo 13 had a catastrophic failure
- Fortunately, and with the grounds intense intervention, the crew was able to return back to earth, safely
- If, on Apollo 13, the communications link had been also lost, most likely, the crew would not have returned home, safely
- The Apollo 13 incident most likely would not have been survivable but for the ground's assistance.



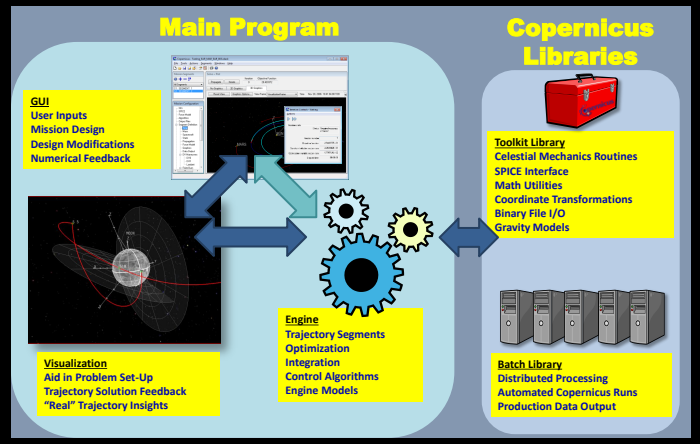
# Ground Based Mission Planning / Maneuver Execution



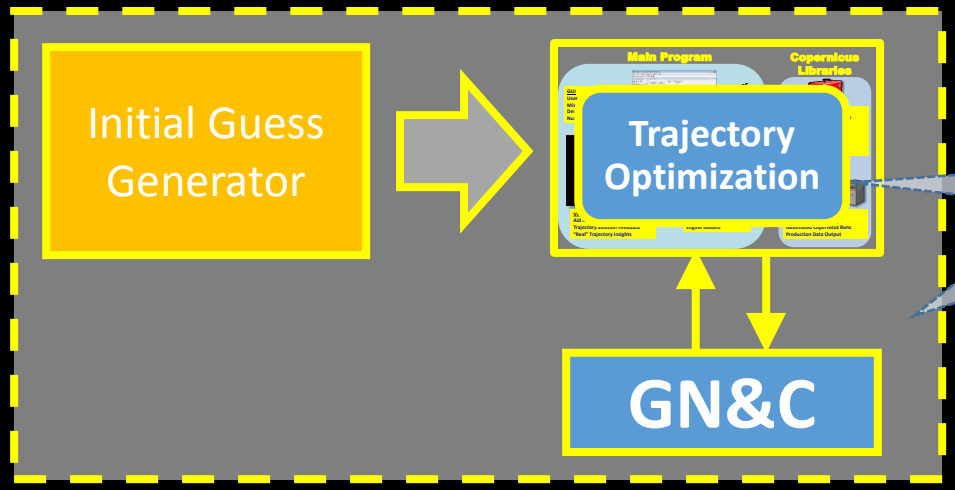
# On-Board Based Mission Planning / Maneuver Execution

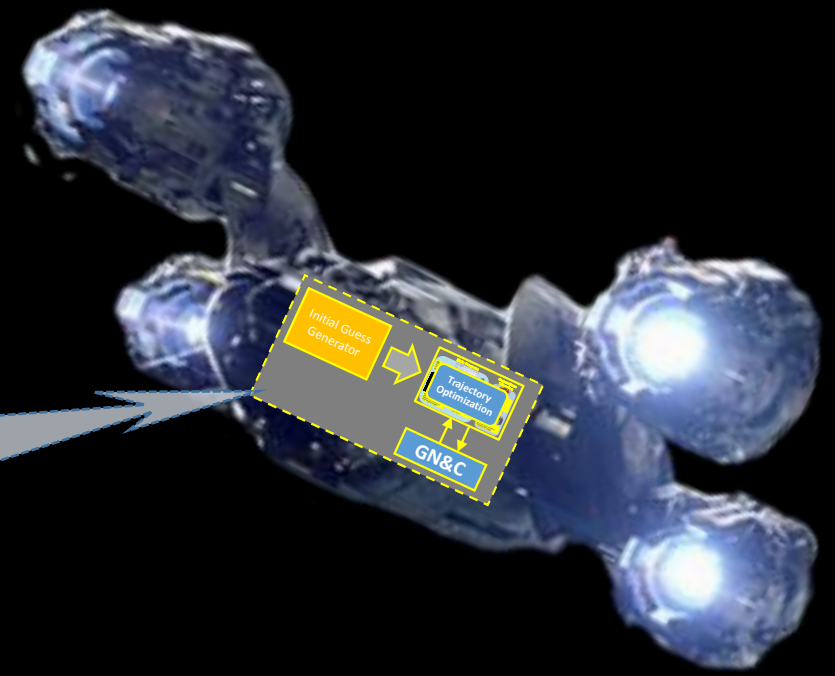


# Moving Mission Planning (Algorithm Optimization) Onboard




Dedicated Onboard Trajectory Design and Optimization



# Notional Onboard Scheme

**Onboard**

***Onboard Flight Software***

**Maneuver Cmd. Data**

**Nav State Data**
**Epoch, Environment Data**

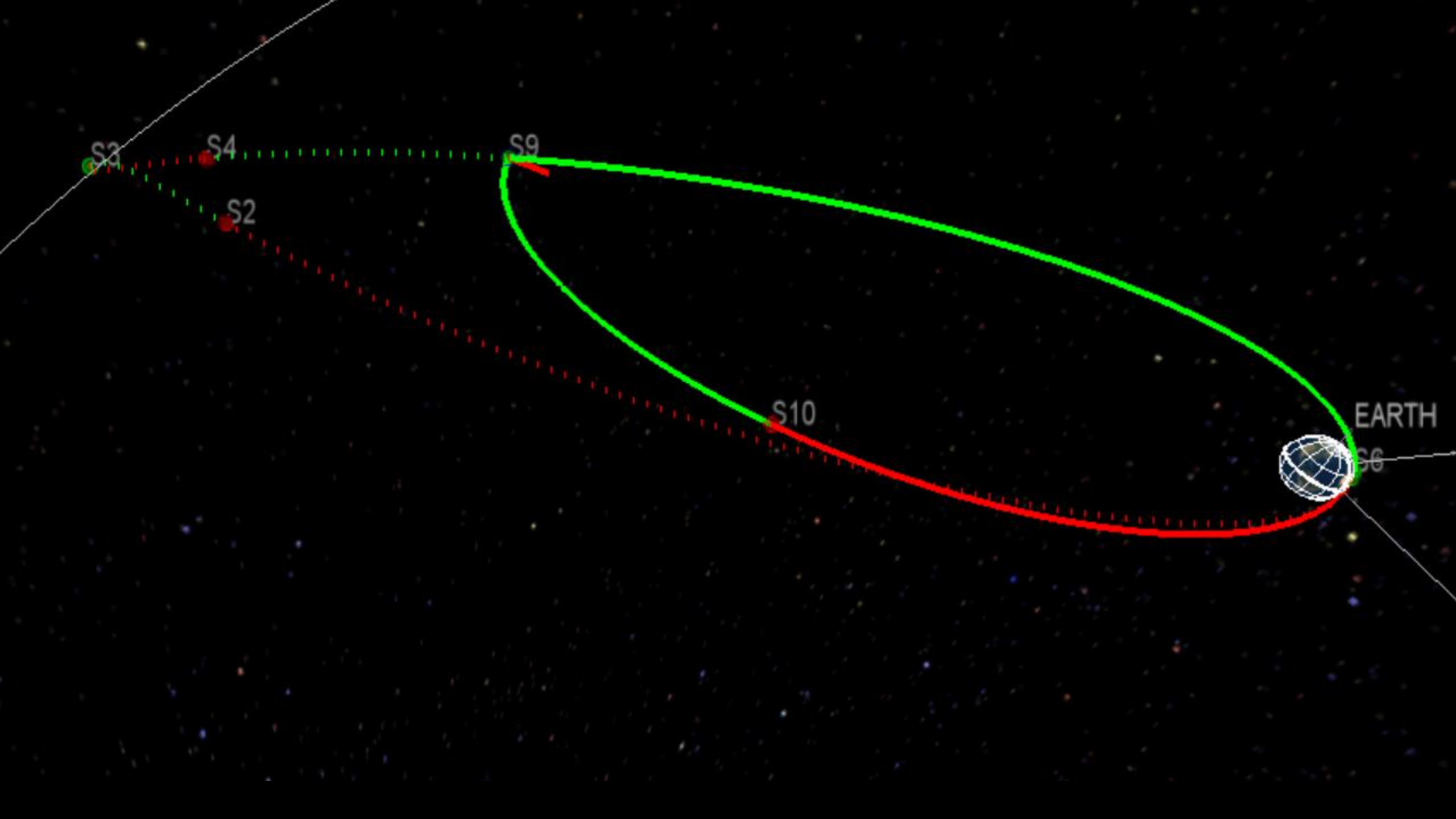
**Current time**
**Current state**
**Current prop**
**Current mass**
**Engine Data**
**Mass**
**SRP Coef.**
**…**

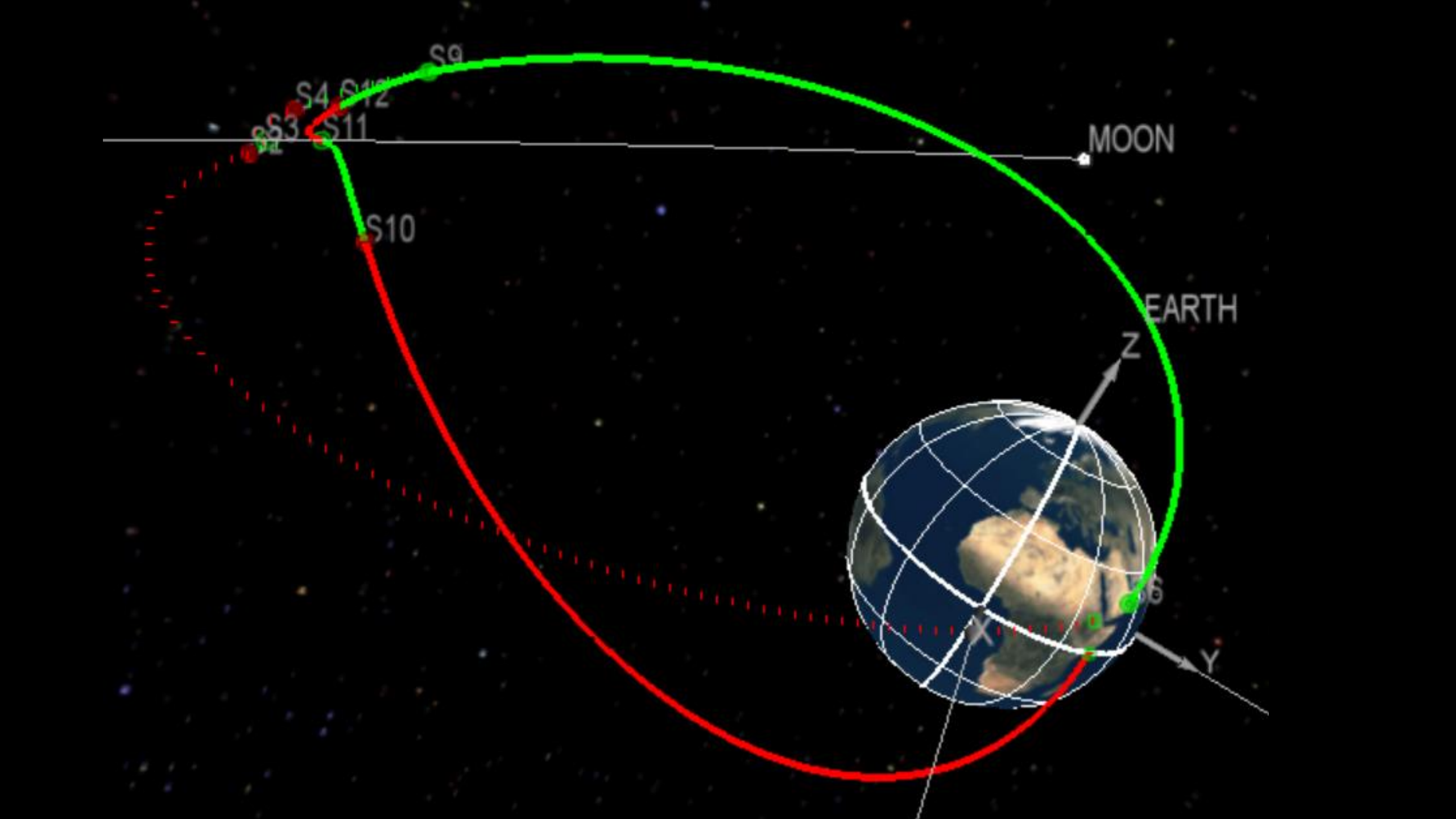
***Copernicus***
**Interface Module**
***(Python Executive)***

**Current State**
**Propagated State**
**Maneuver times**
**Maneuver DVs**
**Maneuver duration**
**Other Future event details**
**…**

File I/O
- Input decks
- Data files
- System calls

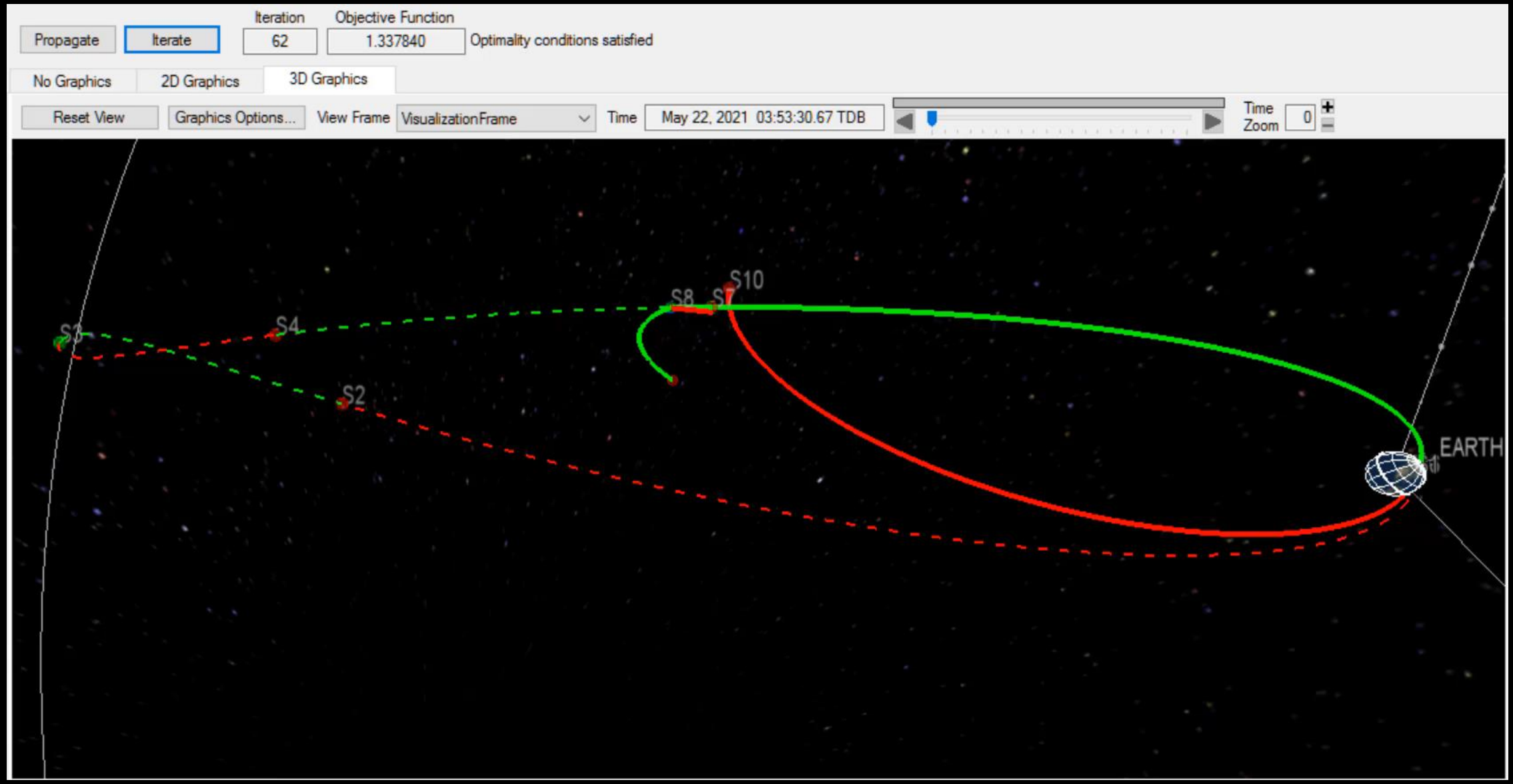
**Initial Guess Generator (IGG)**


S3
S4
S9
S2
S10
EARTH
S6


S9
S4
S12
S3
S11
S10
MOON
EARTH
Z
Y
X
6

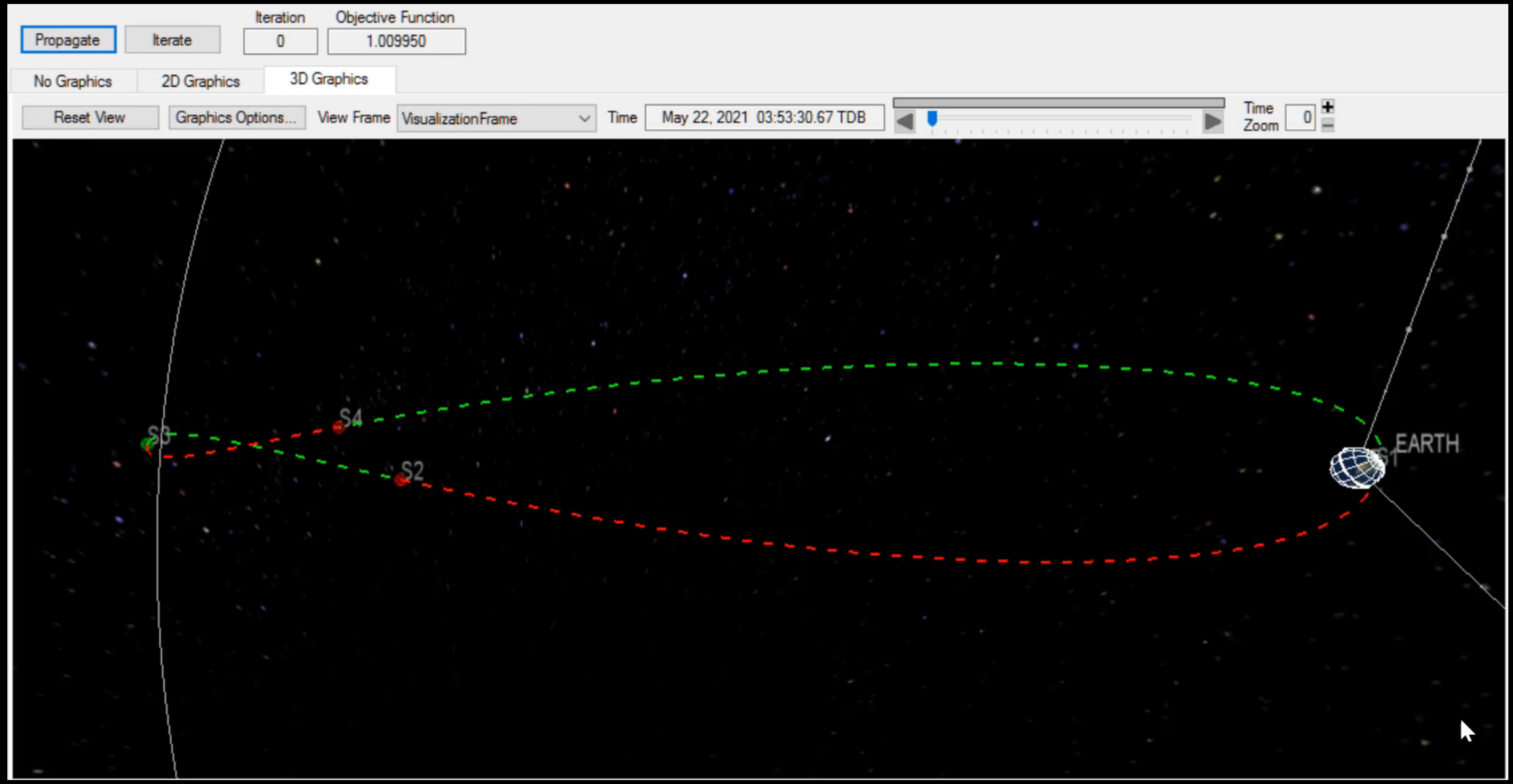
labort-ex01-01.mp4

# Example 4: Abort to Direct Return



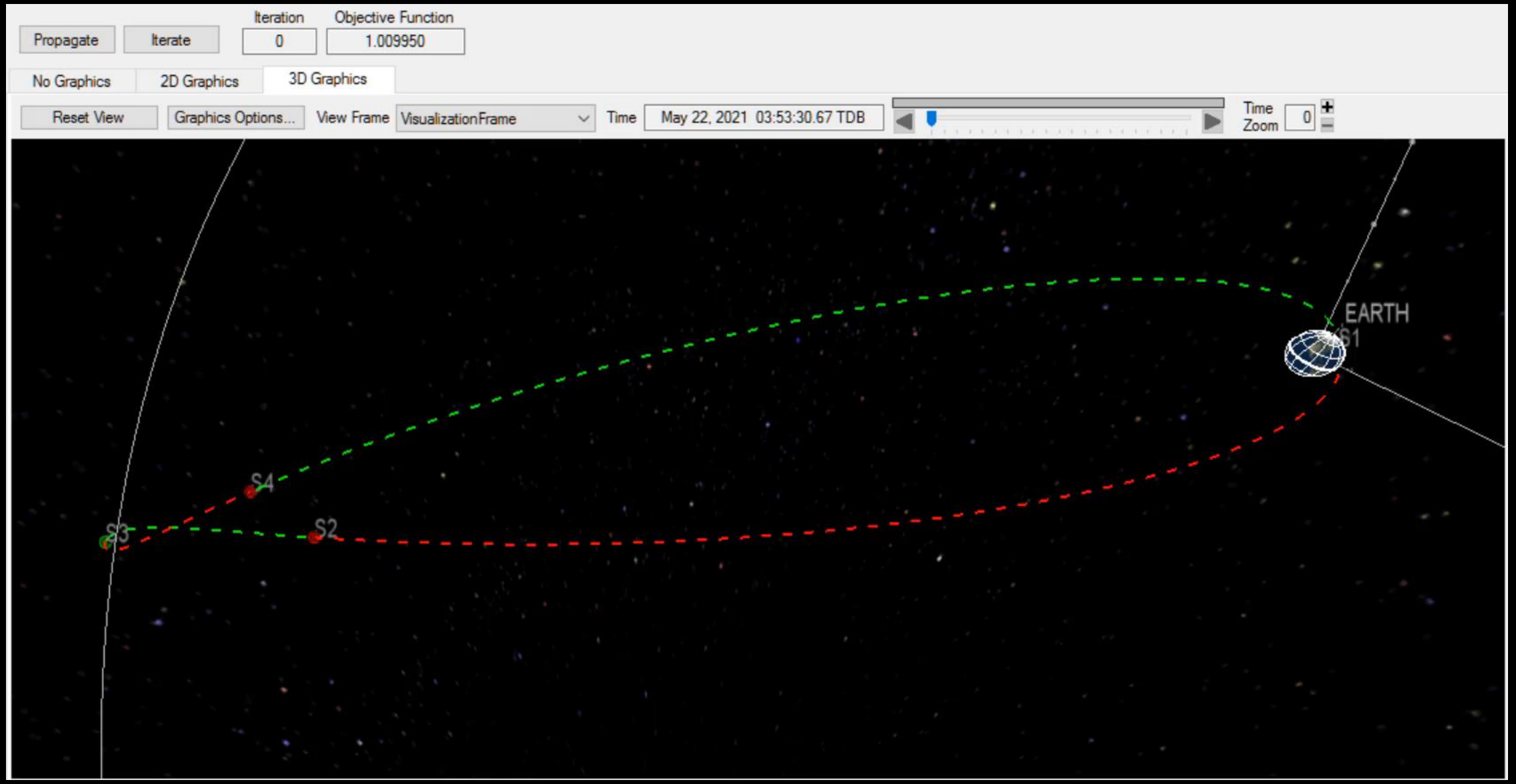
labort-ex01-02.mp4

# Example 4: Abort to Direct Return



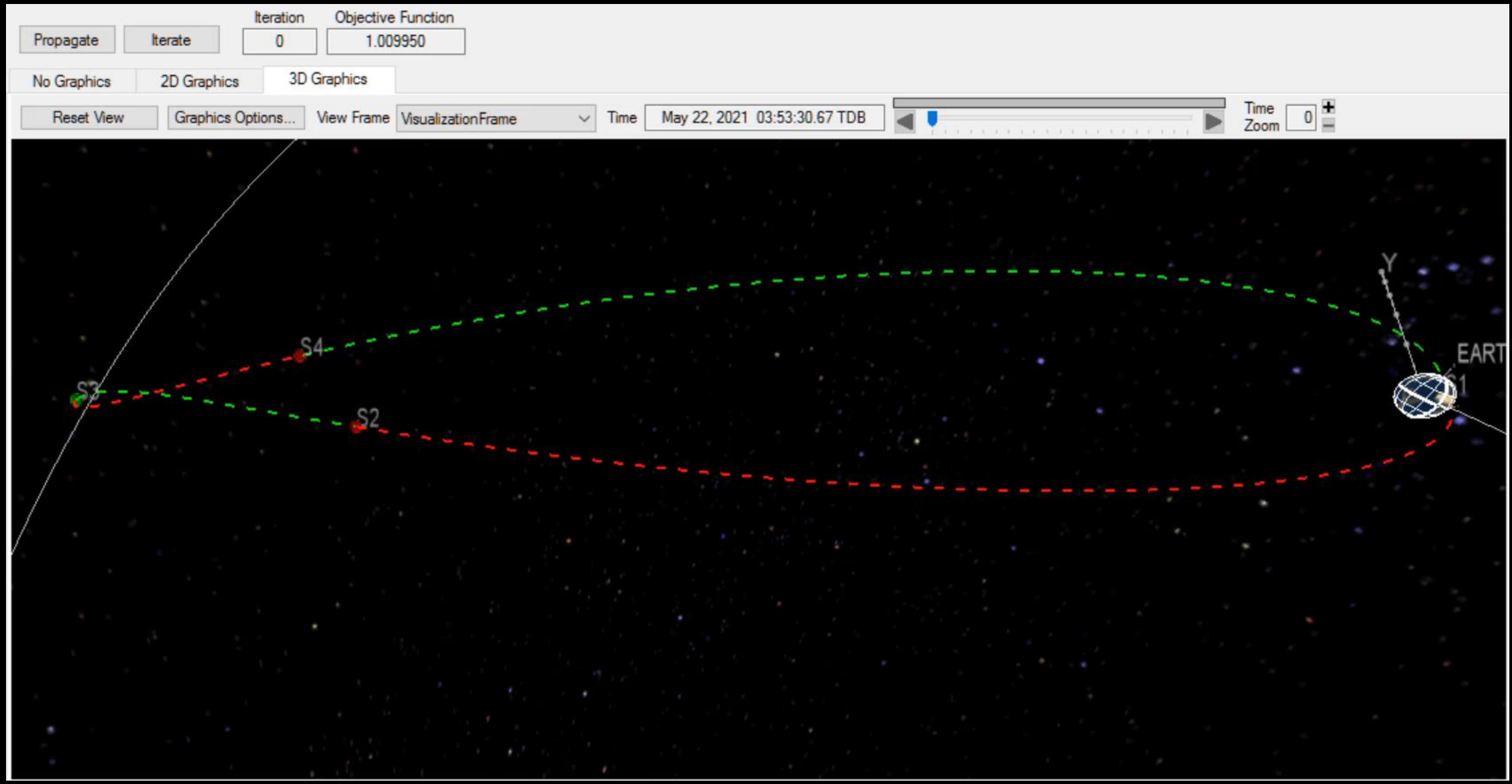
labort-ex01-03.mp4

# Example 4: Abort to Direct Return



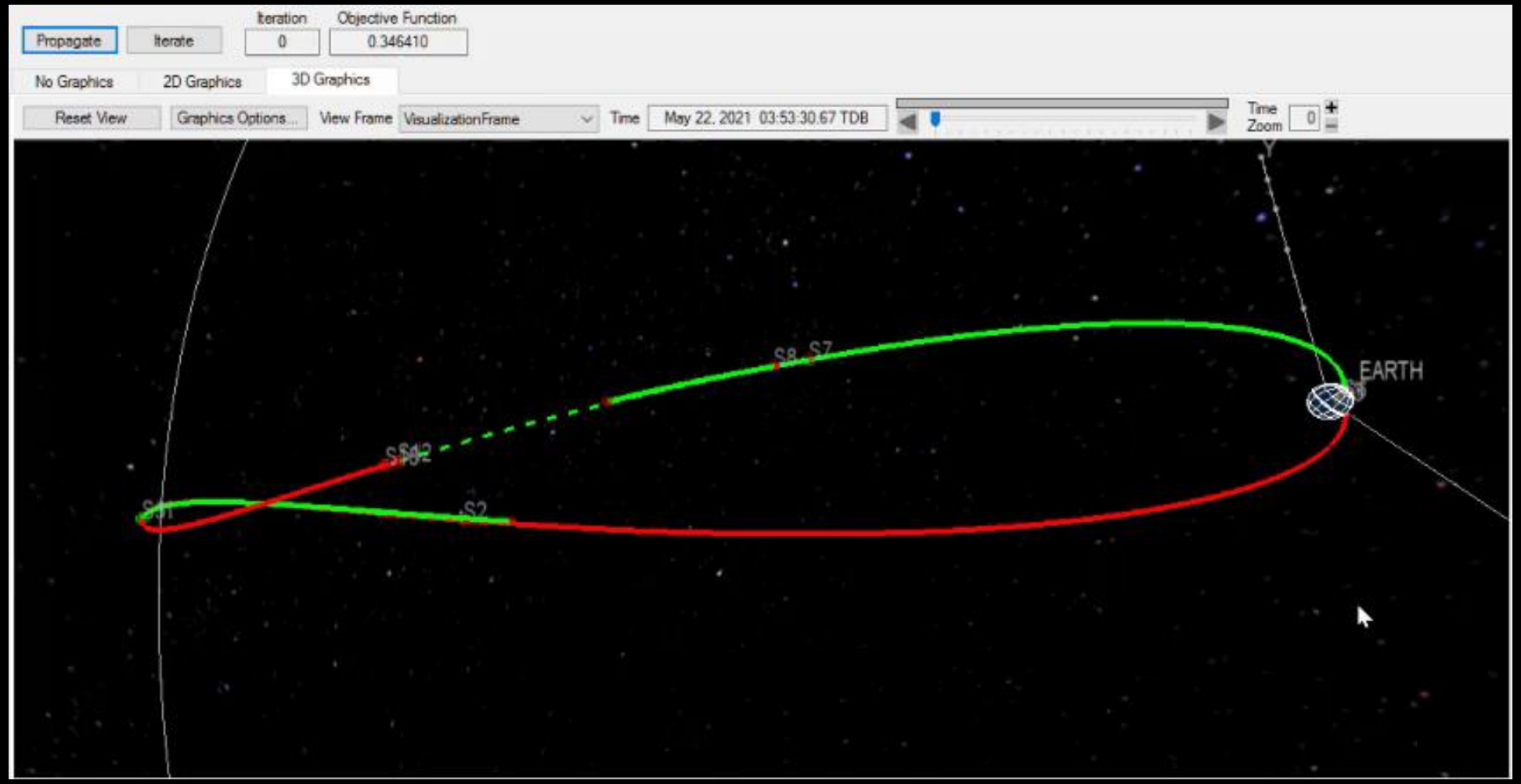
labort-ex01-04.mp4

# Example 4: Abort to Direct Return



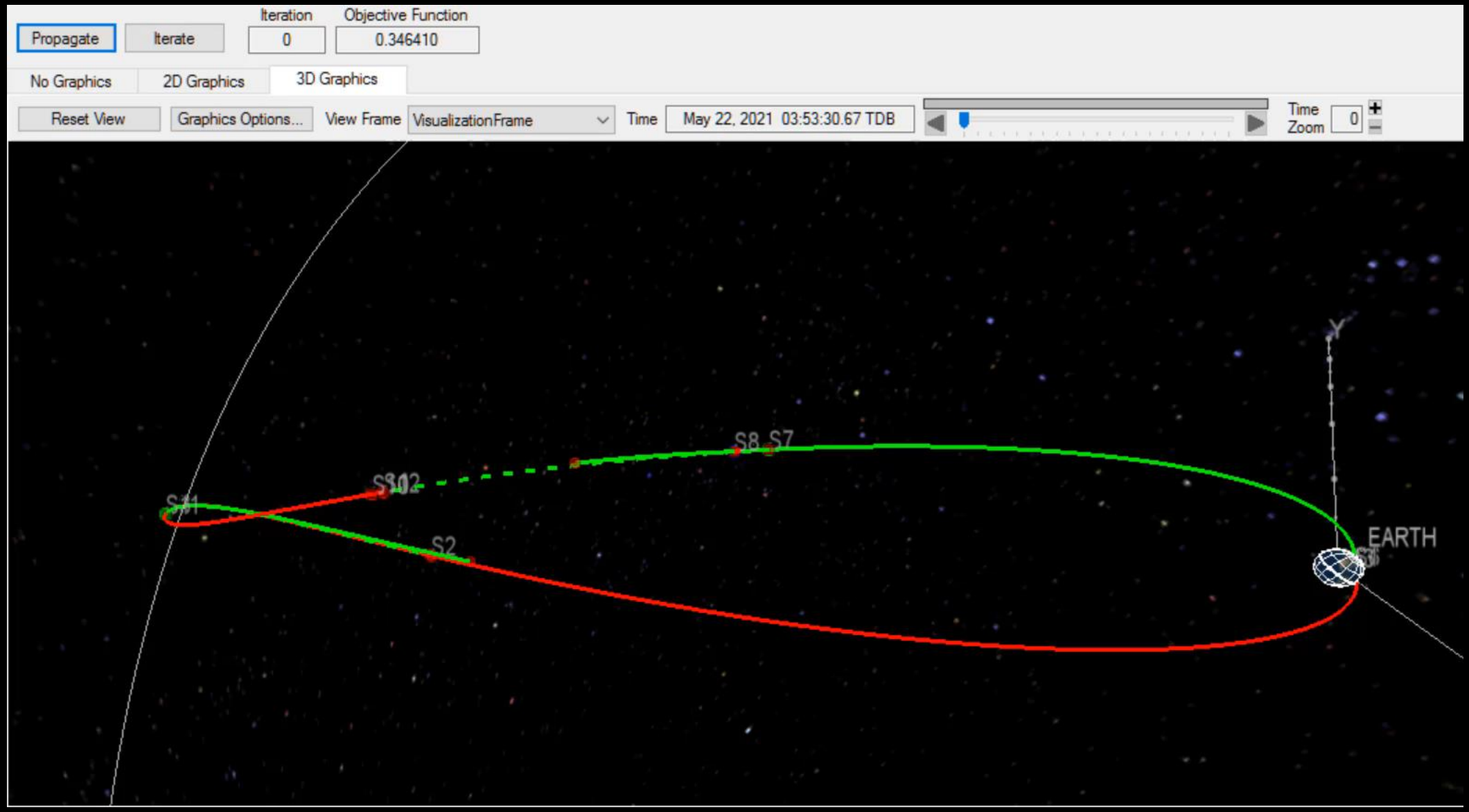
labort-ex02-01.mp4

# Example 5: Abort to Moon Shorten Return Time



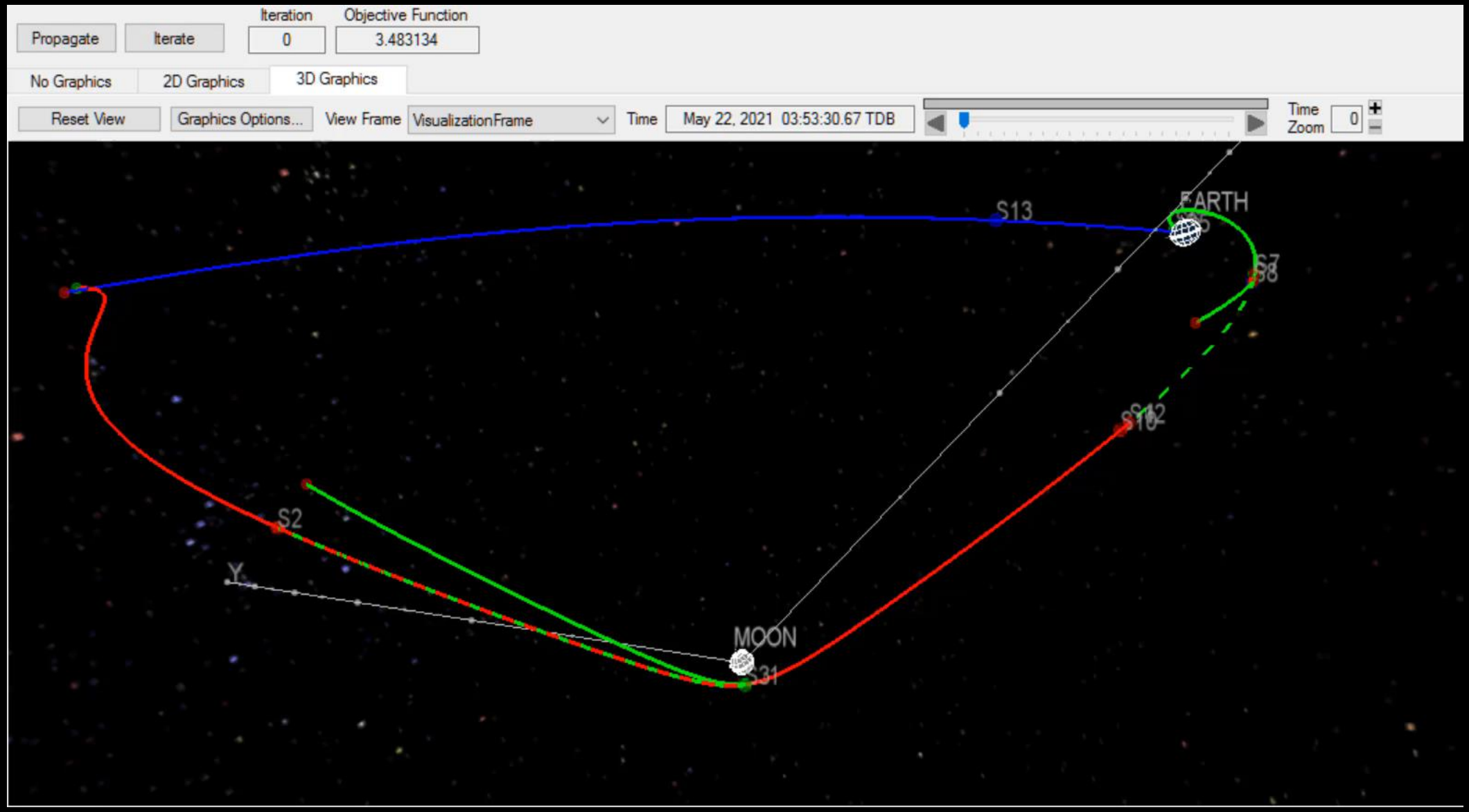
labort-ex02-02.mp4

# Example 5: Abort to Moon Shorten Return Time



labort-ex02-03.mp4

# Example 5: Abort to Moon Shorten Return Time

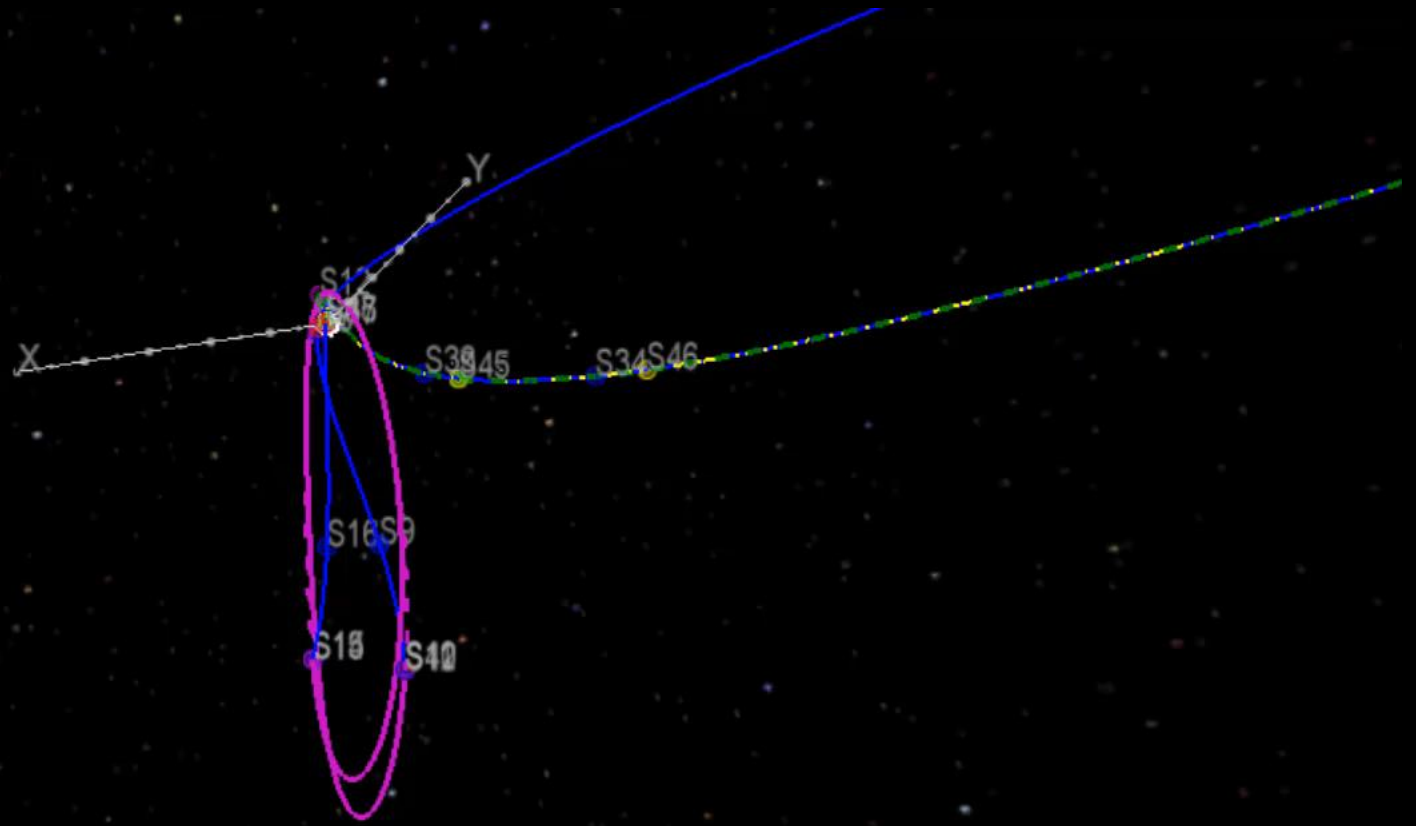


# Other things that can be shown

- The EM-1 Trajectory
- The EM-2 Trajectory (the real one from Ricky)
- The EM-3 Trajectory (the nice NRO transfer)
- The ARM Trajectory

Figures of each of these will suffice

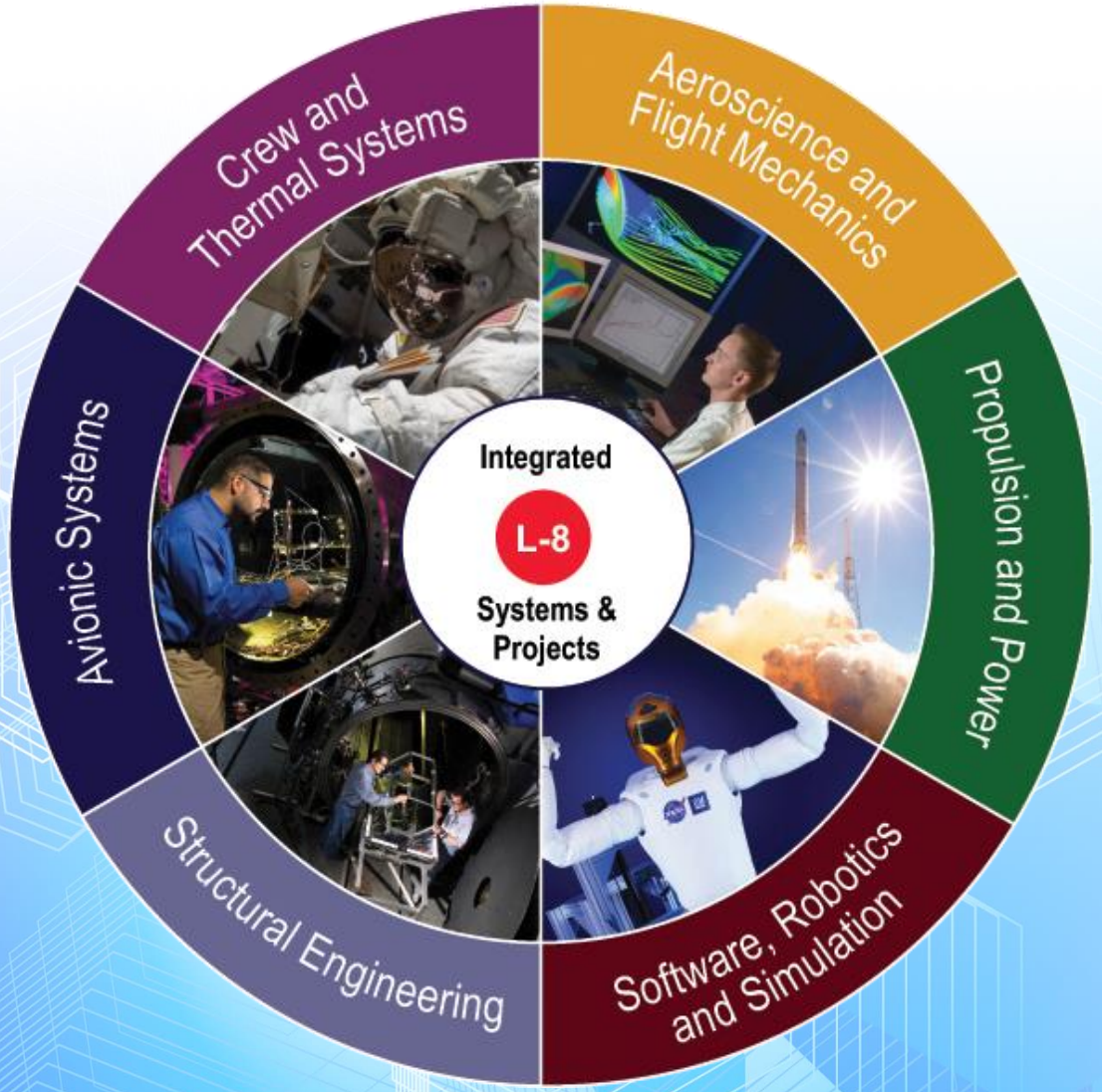
nro-mission-example.mp4



# The key problems to solve for the future

- Pre-Flight
  - Open loop trajectory design and optimization---the ‘initial guess’ problem
    - Tools like the one you just saw (Copernicus) allows users to construct the initial guess by hand
    - It is possible, and we have done it, to construct Initial Guess Generators for any type of problem
- In-flight
  - Automatic replaning, or computing multiple abort options on the fly
    - Some will pose the problem of getting home the fastest with the given amount of prop remaining
    - Others will pose the problem of setting the return time, and minimizing the prop required to do so, so as to save fuel in case other problems come up

# JSC Engineering: HSF Exploration Systems Development

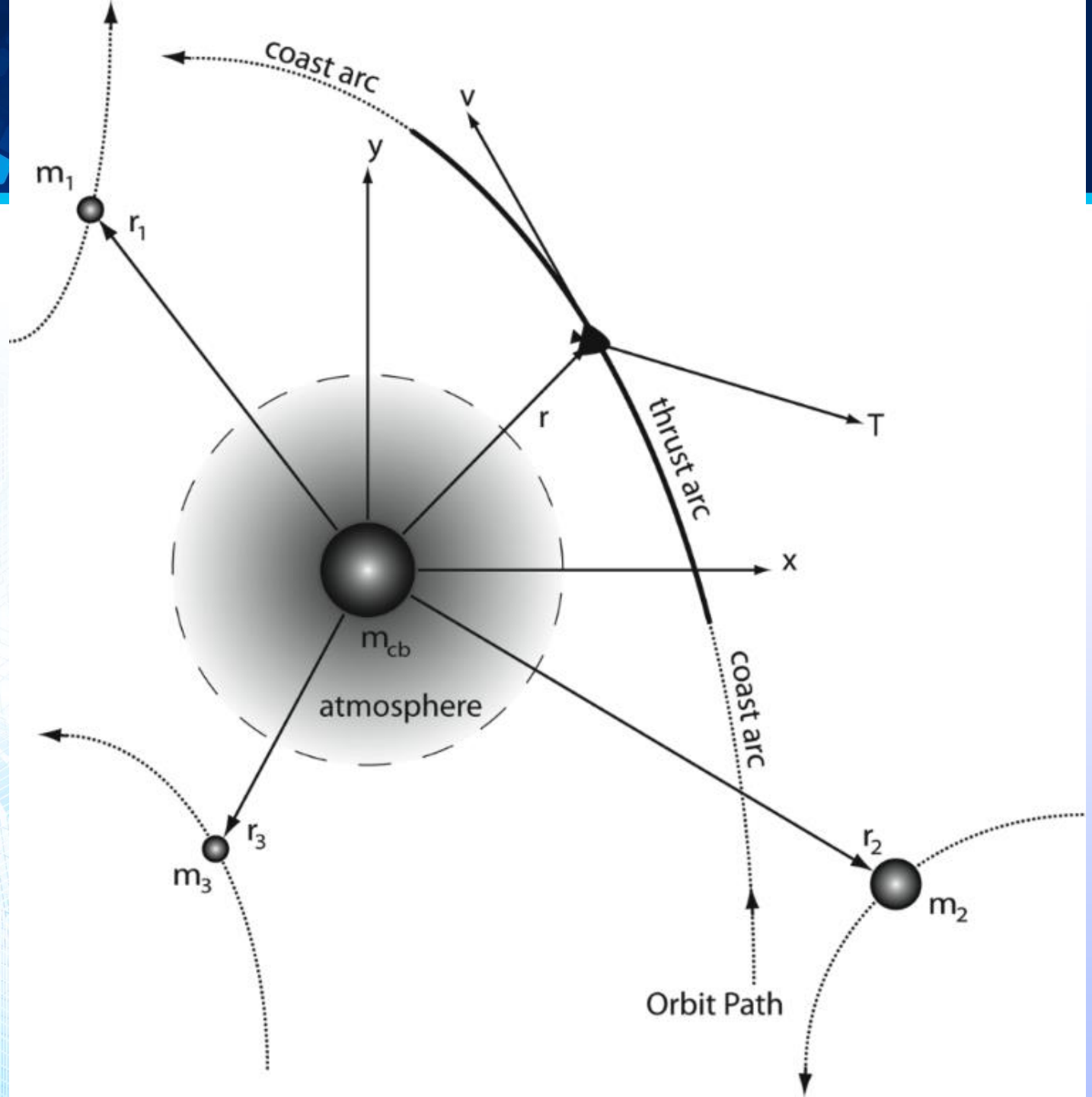



- We want to ensure that HSF technologies are ready to take Humans to Mars in the 2030s.
- Our Goal: Get within 8 years of launching humans to Mars (L-8) by 2025

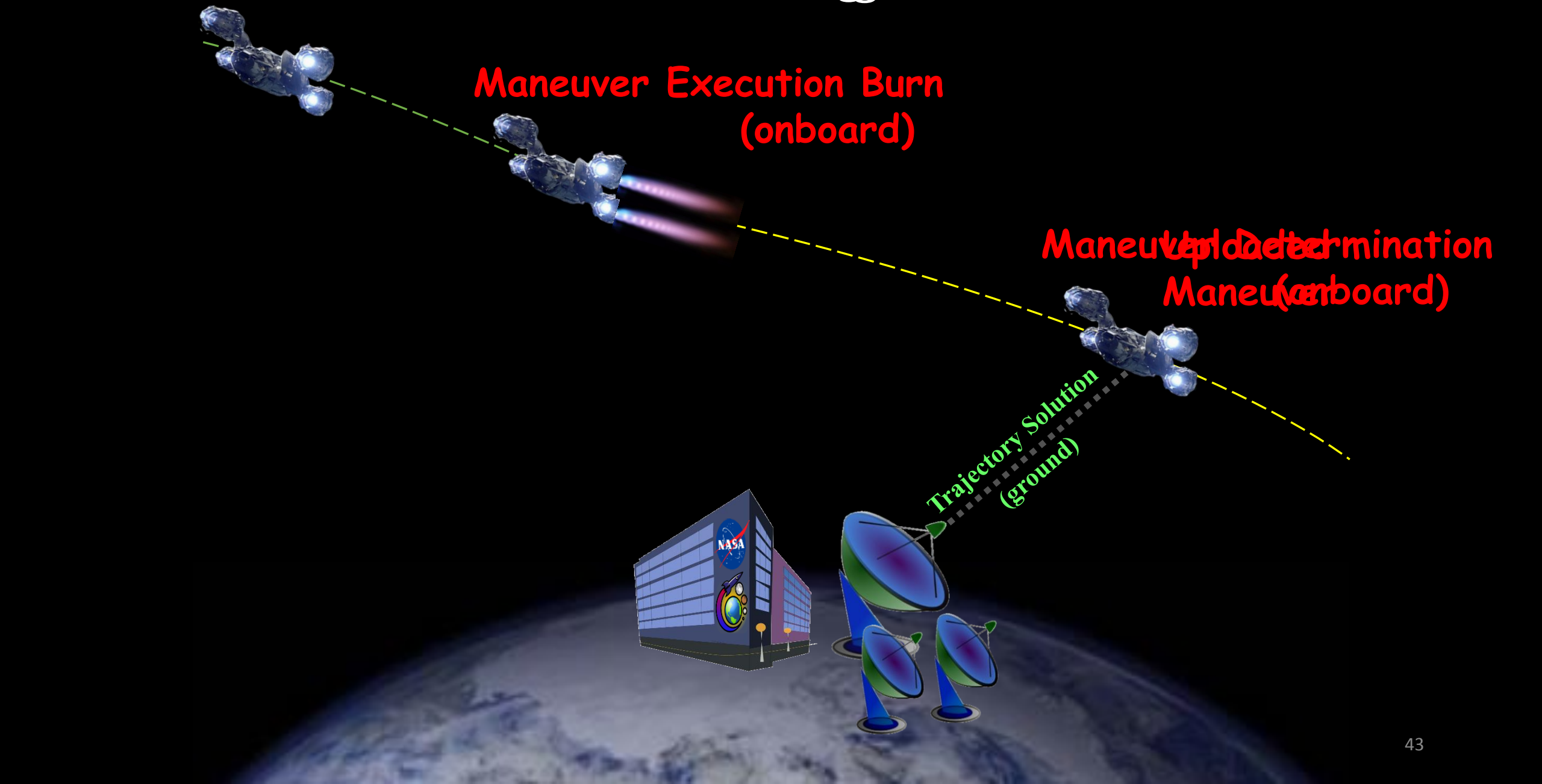
- We need collaborators to make it happen, and we think they can benefit by working with us.
  - Pointer to Co-Dev Announcements
  - Pointer to intake site

**Boilerplate**

# Backup


coast arc
v
y
$m_1$
$r_1$
r
thrust arc
T
x
$m_{cb}$
atmosphere
coast arc
$r_3$
$m_3$
$r_2$
$m_2$
Orbit Path

# Presentation Script

- Discuss the complex dynamics associated with spaceflight in complex force fields
  - Show Three examples of particle motion in the Earth-Moon, Sun-perturbed system
- Discuss the basic problem of trajectory optimization
  - Modeling the dynamics (as shown in the previous bullet of complex motion)
  - Simultaneous Targeting and Optimization of any quantity (typically min DV, or min time)
  - This main bullet should show a diagram that already exists….the cartoon diagram of several disconnected segments and how we need to connect them and optimize at the same time
- Discuss the importance of the initial guess and the importance of having a state of the art tool like Copernicus
  - Use the construction of the lunar free return as an example of this  (show ideck movie of this)
  - Show several Copernicus idecks/videos that illustrate the iteration process graphically
  - Show an earth-mars-earth free return (how it is constructed, the final animated flight).
- Crew autonomy…not dependent on the ground segment…to deal with any event, especially those unforeseen, enroute.
  - An enroute abort calculations as examples.

# On-Board Based Mission Planning/Maneuver Execution