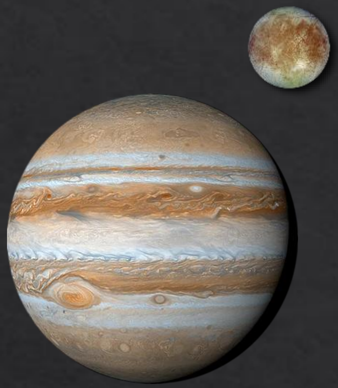
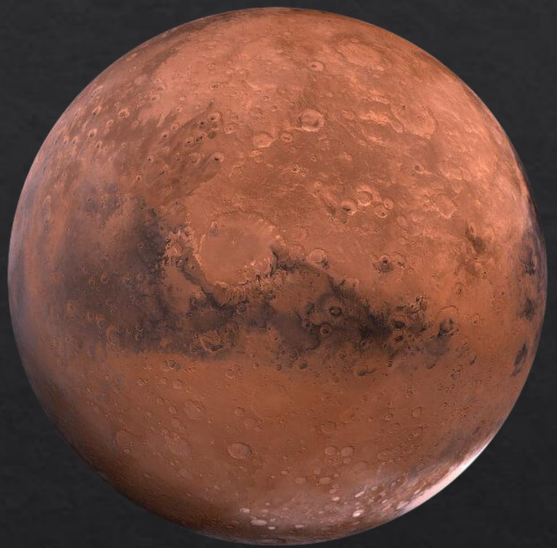


MDOrbit

Interplanetary Mission Optimization



Prepared By:

Elamin, Mayar | Pagan, Sebastian | Weber, Jacob

Iowa State University

Department of Aerospace Engineering

Project Pivot: Ramjet Optimization → Interplanetary Mission Optimization

- Initial Focus: Ramjet optimization constrained by speed, altitude, combustion limits, and geometry.
- Optimization Goal: Intake pressure, fuel input, heat addition, geometry, and thrust ratios.
- Challenges Identified: Project scope exceeded available resources, time, and current expertise.
- New Focus: Optimization of Δv and staging masses in interplanetary mission planning.

Introduction

- Deep space exploration has technical & economic challenges.
- Growing interest in Europa & Mars demands efficient mission planning.
- Study: Earth → Europa using Mars & Jupiter gravity assists to save fuel.
- Focus: Optimize flight path & staging within mission constraints.
- Key factors:
  - Delta-V budgets
  - Planetary alignment windows
  - Gravitational assist strategies
- Goal: A framework for efficient, cost-effective deep space missions.

Literature Review

Historic Missions:

- Pioneer 10 & 11 (1970s) - first close-up data.
- Voyager 1 & 2 - revealed active, young surface.
- Galileo - confirmed likely subsurface salty ocean.

Europa Clipper (2024-present):

- Dozens of flybys, studying habitability & surface composition.
- Avoids direct orbit to limit radiation exposure.

Gravity Assists:

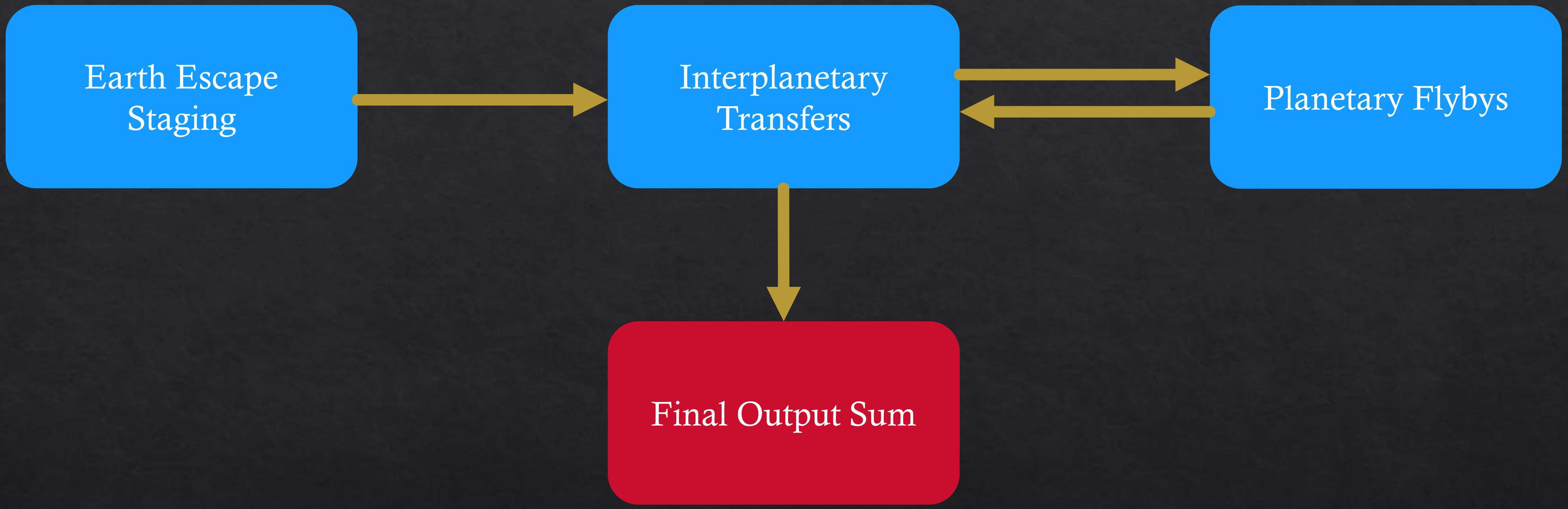
- Used in past missions to save fuel (Galileo, Clipper).

This Study:

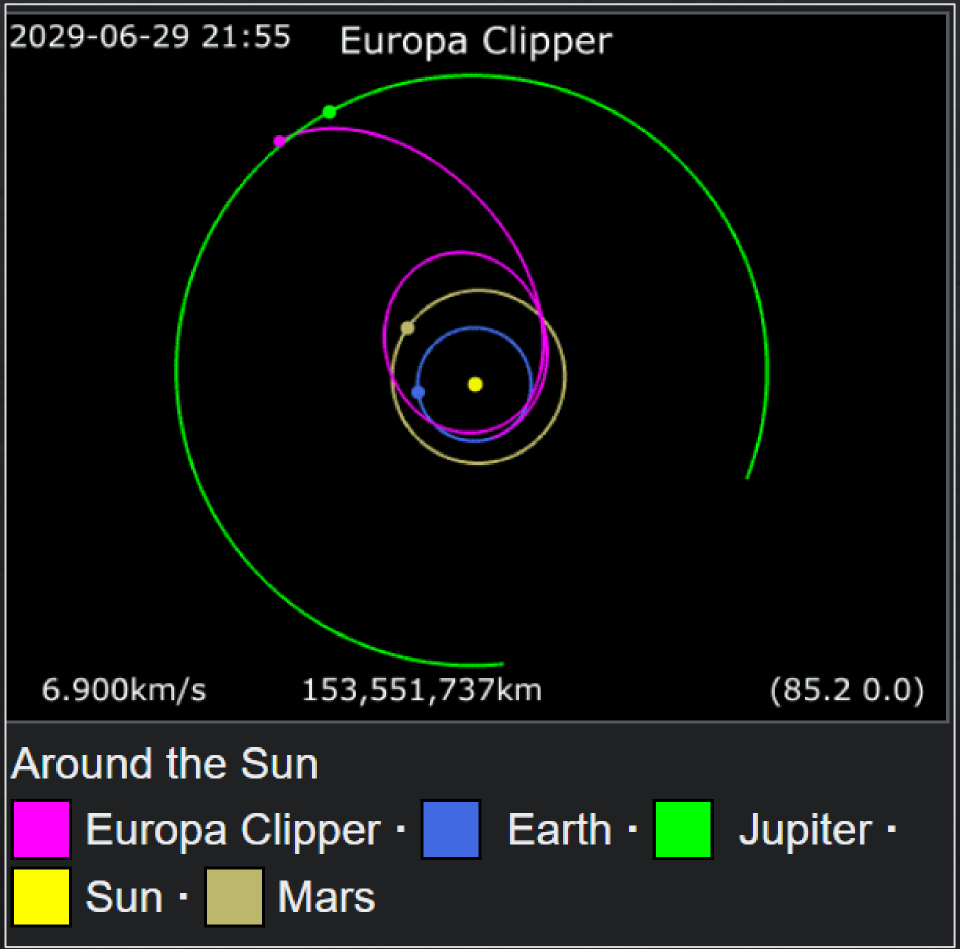
- Builds on proven techniques using Mars & Jupiter flybys.
- Applies MDO for optimal trajectory and staging design.

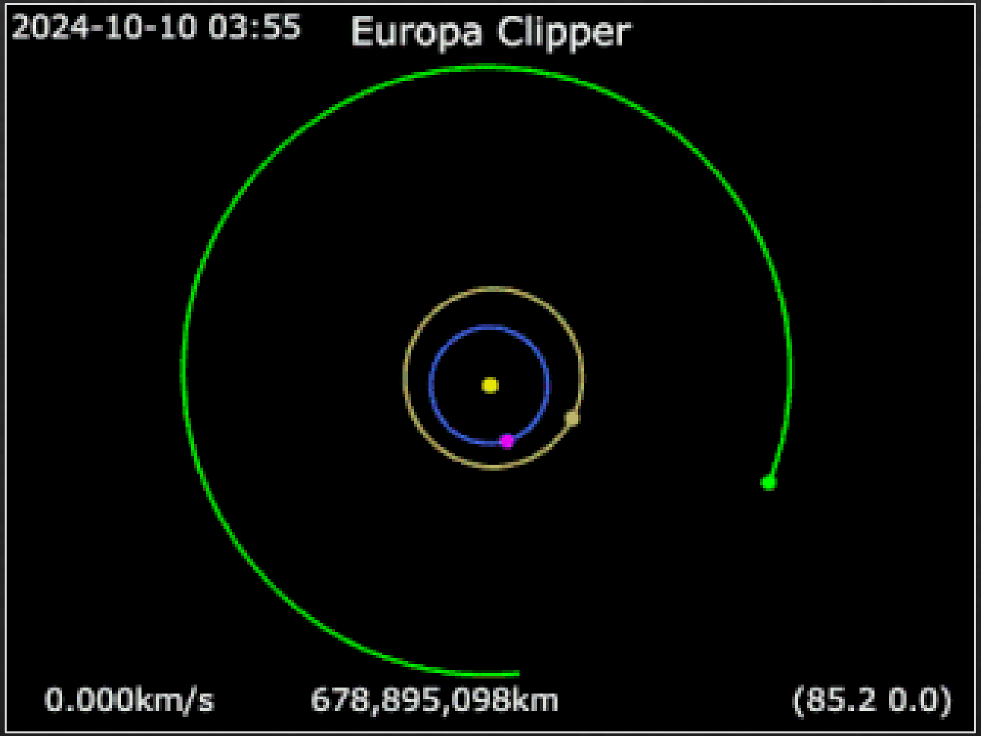
Europa Clipper launched on October 14, 2025

Technical Approach



Our Journey





Video Depicting Europa Clipper Mission's Trajectory

Technical Approach – Rocket Staging Optimization

Purpose:

- Optimize multi-stage rocket design to minimize total launch mass while meeting a delta-V requirement.

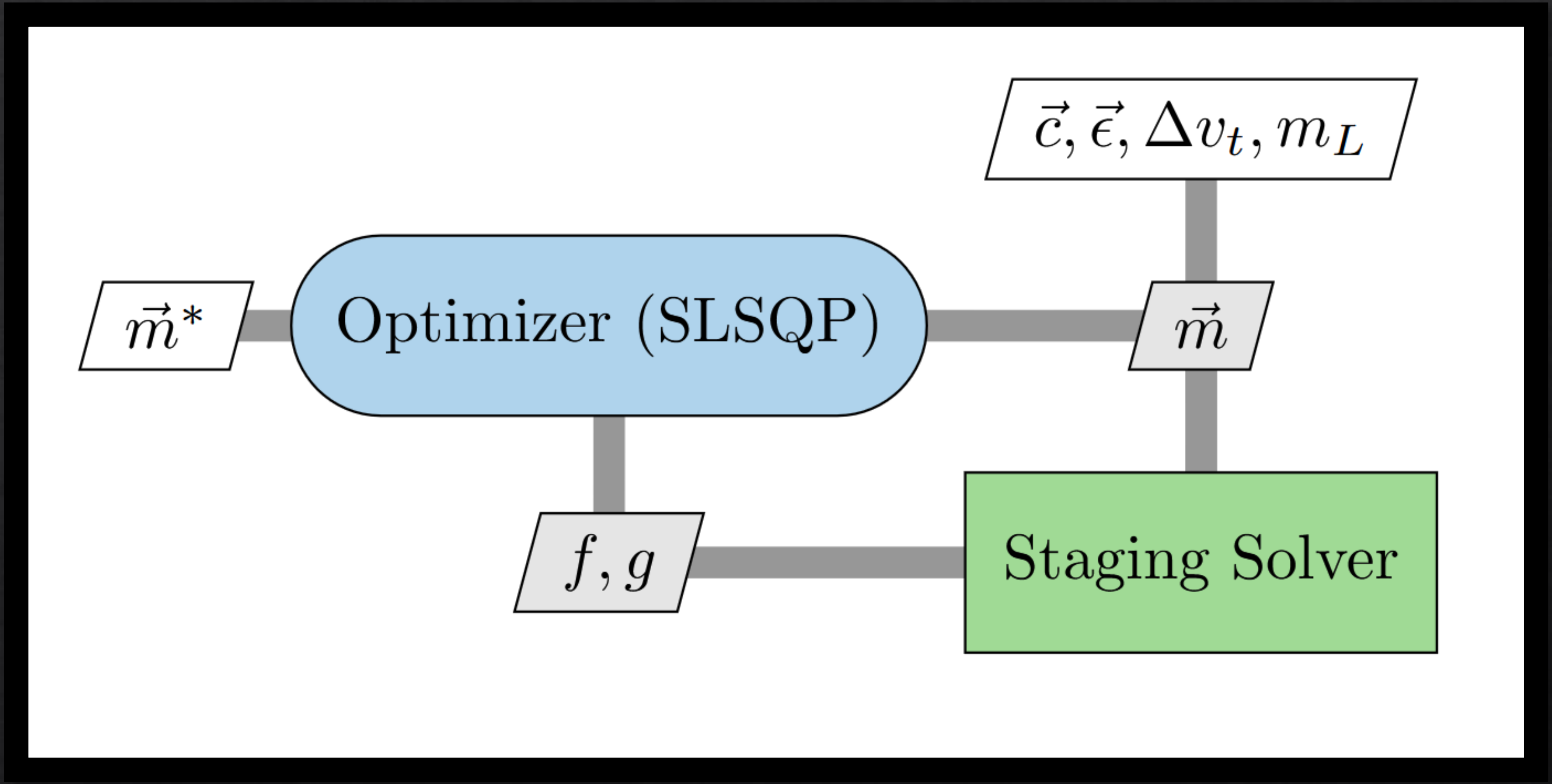
Approach:

- Uses the Optimal Staging Rocket Equation to calculate achievable delta-V for a staged system.

$$\sum_{i=1}^{n} c_i \, ln \frac{m_i + m_{i+1} + \cdots + m_n}{\varepsilon_i m_i + m_{i+1} + \cdots + m_n} - \Delta V_T$$

- Applies constraint-based optimization to balance fuel mass, structural mass, and payload capacity.

XDSM Diagram - Staging



Technical Approach – Rocket Staging Optimization

- Design Variables:

Rocket Stage Masses ($\vec{m}$): Represents the combined structural and fuel masses of each rocket stage arranged in a vectorial form for ease of computation.

- Objective: Minimize stage mass components m_i
- Constraints: $m_1, m_2 > m_L$,

Initial Values
Full Stage 1 Mass = 433,180.7 kg
Full Stage 2 Mass = 111,583.7 kg
Total Mass = 544,764.4 kg

Technical Approach – Interplanetary Transfers

Purpose:

- Optimize Δv cost of a transfer orbit injection for both transfers.

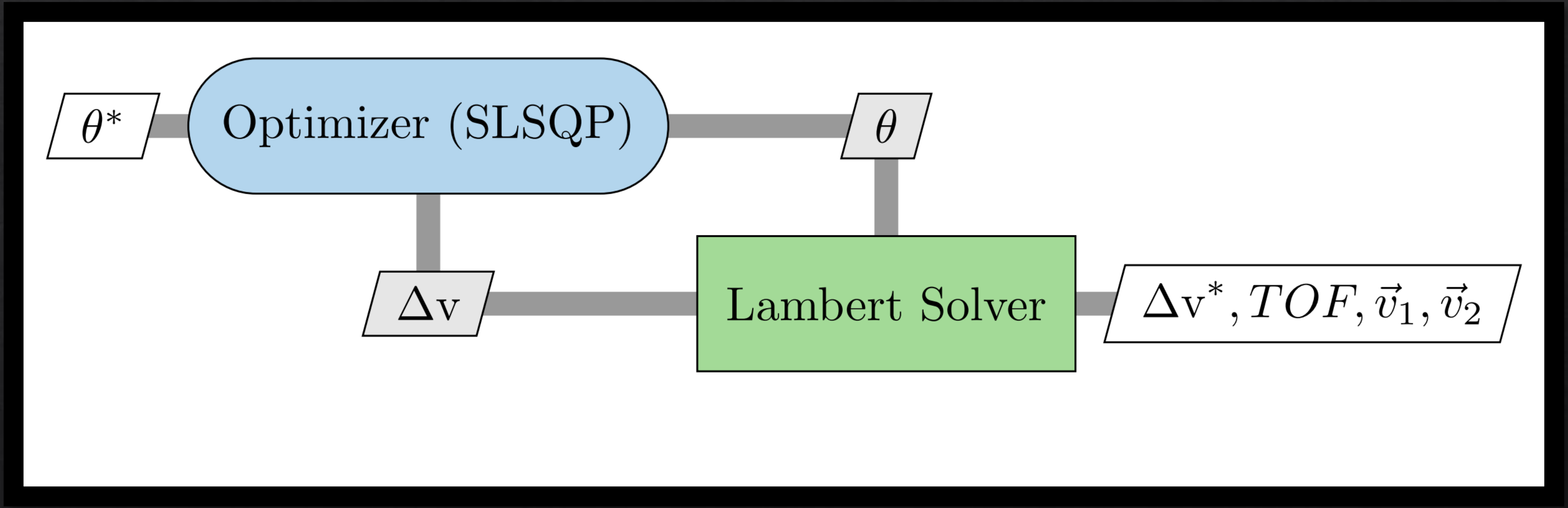
Approach:

- Uses a specialized formulation of Lambert's problem to optimize the minimum energy transfer orbit.

$$\sqrt{\mu} t_m = \left[\frac{s^3}{8}\right]^{1/2} (\pi - \beta_m + \sin(\beta_m))$$

$$\Delta v_1 = |v_1 - v_p|, \Delta v_2 = |v_0 - v_2|$$

XDSM Diagram - Interplanetary Transfers



Technical Approach – Interplanetary Transfers

- Design Variables:

Transfer Angle (θ): Represents the total angle spanned by the transfer between Earth-Mars and Earth-Jupiter in heliocentric frame.

- Objective: Minimize Δv required to inject the transfer orbit
- Constraints: $0 \leq \theta \leq 2\pi$, $TOF \leq 365\ days$

Initial Values
$\theta = 75°$
TOF $= 182\ days$
$\Delta v = 17.4\ km/s$

Technical Approach – Mars Flyby Into Ellipse

Purpose:

◈ Optimize Δv for flyby and establish heliocentric ellipse

Approach:

◈ Perform optimal gravity-assist at Mars that leads into an ellipse to meet back up with Earth.

$$v_0^2 = v_{Earth}^2 + v_{\infty_{Earth}}^2 - 2 v_{Earth} v_{\infty_{Earth}} \cos(\pi - \delta)$$

$$\beta = \sin^{-1}\left(\frac{v_{\infty_{Earth}}}{v_0}\right)$$

$$v = \sqrt{\mu\left(\frac{2}{r} - \frac{1}{a}\right)}, T = 2\pi\sqrt{\frac{a^3}{\mu}}$$

Technical Approach – Mars Flyby Into Ellipse

- Design Variables:

Semimajor Axis (a): Find semimajor axis to create a feasible ellipse post-Martian flyby

- Objective: Δv post-flyby
- Constraints: $2/\pi \leq \delta \leq \pi$, $Altitude > r_{Earth}$, $r_{peri_{ellipse}} < 1$, $0 < e < 1$

Initial Values
$a = 1.2$ AU
$e = 0.5$
TOF $= 422\ days$
$r_p = 1$ AU
alt = 4,000 km
$\Delta v = 75.44\ km/s$

Technical Approach – Orbit Raise to Europa

Purpose:

- Optimize Δv for an orbit raise from established rotation around Jupiter into Europa's orbital radius

Approach:

- By optimizing trajectory of the orbit with respect to transfer time, the magnitude of Δv will decrease given a large TOF considering a 2D plane coordination system

Results and Discussion

Staging			
Parameter	**Initial Value**	**Optimized Value**	**% improved**
Stage 1 Mass (kg)	433,180.7	96,618.0	70
Stage 2 Mass (kg)	111,583.7	58,117.2	
Total Mass (kg)	544,764.4	154,735.27	
Earth to Mars Transfer			
θ (deg)	75°	180°	83
TOF (days)	182	260	
Δv (km/s)	17.4	2.91	
Mars to Jupiter Transfer			
θ (deg)	190°	79°	92
TOF (days)	1000	861	
Δv (km/s)	75.44	6.24	

Mars FlyBy Into Ellipse			
Parameter	**Initial Value**	**Optimized Value**	**% improved**
a	1.2 AU	1.1 AU	92
e	0.5	0.14	
TOF	1,000 days	372.3 days	
r_p	1 AU	0.96 AU	
alt	4,000 km	47,158 km	
Δv	75.44 km/s	6.24 km/s	
Jupiter to Europa Orbit Raise			
Parameter	**Initial Value**	**Optimized Value**	**% improved**
TOF (min)	1250.0	1933.49	33
Total Orbit Raise (km)	320900	370900	
Δv (km/s)	18.8	12.52	

References

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[3] NASA. "Galileo - NASA Science." *Science.nasa.gov*, 2024, science.nasa.gov/mission/galileo/.

[4] NASA. "About | Mission – NASA's Europa Clipper." *NASA's Europa Clipper*, Oct. 2019, europa.nasa.gov/mission/about/.

[5] Prussing, John E Prussing, and Bruce A Conway. *Orbital Mechanics*. New York, Oxford University Press, 2013.

Team Tasks

- Jacob Weber:
  - Reviewed Orbital Mechanics textbook and other astrodynamics literature for equations used in coding.
  - Contributed in staging optimization and transfer optimization scripts.
- Mayar Elamin:
  - Worked on developing XDSM diagrams.
  - Contributed in staging optimization script.
  - Commented staging optimization script in detail.
- Sebastian Pagan:
  - Worked on developing XDSM diagrams.
  - Contributed in staging optimization script.
  - Worked on flyby scripts.