

Mission Trajectory Design to a Nearby Asteroid

A project present to
The Faculty of the Department of Aerospace Engineering
San Jose State University

in partial fulfillment of the requirements for the degree
Master of Science in Aerospace Engineering

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Spring 2015

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Abstract

This paper provides a parametric study of mining the nearby 4 Vesta asteroid. The mission is to launch and rendezvous on the meteoroid for asteroid analysis. To accomplish this mission, five different trajectories were designed to launch a 790kg spacecraft into a low earth parking orbit, and then transferred into the 4 Vesta orbit. Two trajectories were chosen based on the minimum ΔV and minimum time of flight. One mission required a total ΔV of 9.57 km/sec with a total flight time of 1.01 years. The other mission required a total ΔV of 7.99 km/sec with a total flight time of 3.5 years. Also, two round trip missions were designed. The mission is to launch, flyby for asteroid analysis, and safely return to Earth. One mission required a total ΔV of 4.77 km/sec with a total flight time of 4.99 years. The other mission required a total ΔV of 5.14 km/sec with a total flight time of 5.04 years.

Nomenclature

| | |
|-----------------|------------------------------|
| a | = Semi-major Axis |
| e= | Eccentricity |
| $\frac{1}{m}$ | = Specific Mechanical Energy |
| r= | Radius |
| h | = Specific Angular Momentum |
| p | = Semi Latus Rectum |
| $\frac{1}{\mu}$ | = Gravitational Parameter |
| $\frac{1}{E}$ | = Specific Mechanical Energy |
| C3= | Injection C3 |
| ΔV = | Delta-V |
| E | = Earth |
| M | = Mars |
| A= | Asteroid |

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I. Literature Search

The first mission to rendezvous, orbit and land on an asteroid was Near Earth Orbit Rendezvous (NEAR), which was launched in the 1996 and landed on 433 Eros in 2001(Cheng, et al., 1997). After NEAR, the Japanese spacecraft Hayabusa rendezvoused with 25143 Itokawa in 2005 (Kawaguchi, Fujiwara, & Uesugi, 2003). The American spacecraft Dawn is missioned to study Ceres and Vesta. Dawn rendezvoused with 4 Vesta in 2012 and Ceres will be studied in 2015.

The first asteroid observed was in 1801 and its name is Ceres. The second known asteroid is Pallas, the third is Juno, and the fourth is Vesta all discovered up to 1803. These asteroids are in the asteroid belt located between the Mars and Jupiter planets. Half the mass in the asteroid belt is made up of these four bodies. See Figure 1.

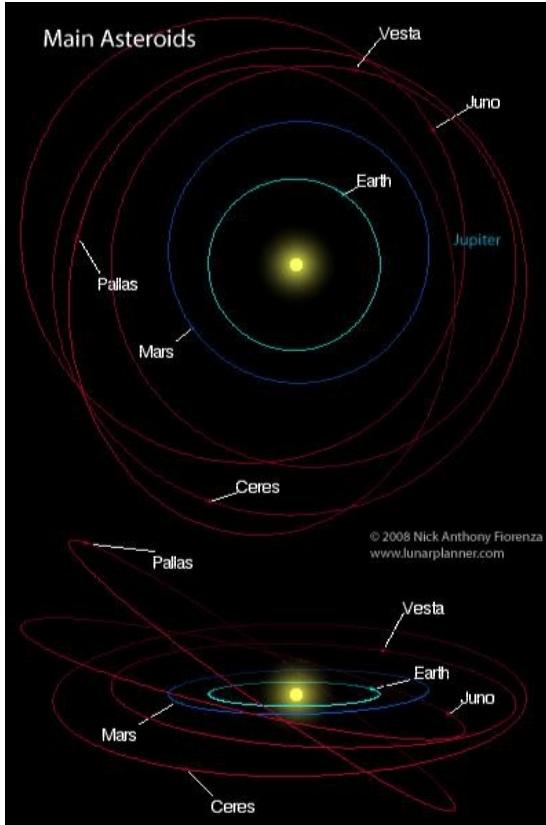


Figure 1: Asteroids, Ceres, Pallas, Juno, and Vesta are shown in between Mars and Jupiter orbits.

Asteroids are important to study because they threaten to collide with Earth. Asteroids that come close to Earth can cause local and even global disasters. They can produce tidal waves that can inundate low lying coastal areas. Although asteroid striking is remote, their trajectories should be studied. Asteroids help understand the origins of the solar system. The prehistoric bodies aid in understanding pre-solar processes as well as provide information on the formation and development of the universe. Asteroids may hold the key to how building blocks of life were delivered to early Earth. Knowing their compositions, structure and size can feed such information. Asteroids can be used for future human exploration. They offer a source of volatiles and rich supply of minerals that can be used for exploration and colonization in our solar system and on Earth. Also, asteroids can be used to generate rocket fuel that will be required to explore and colonize further out in the solar system. By closely investigating the compositions of asteroids, intelligent choices can be made as to which ones offer the richest of supplies of raw materials. Over 11,000 Near-Earth Asteroids are known and approximately 800 of them are greater than 1 kilometer.

Asteroid 4 Vesta is the second largest body in the asteroid belt and Ceres is the first. Ceres was recently categorized as a dwarf planet and not an asteroid, making Vesta the largest known asteroid. Vesta comprises about 10% of the mass of the asteroid belt. Because Vesta is the second largest body, it will provide information of the early solar system formation. Interestingly, Vesta is a dry object with a surface that shows signs of resurfacing. It resembles the rocky bodies of the inner solar system, similar to Earth.

II. Introduction

In this paper, seven mission trajectories for a hypothetical mission that would rendezvous Vesta are designed and studied. Each mission trajectory will have an acronym that represents each mission trajectory. This section will show the mission statement, mission objectives, mission requirements, limitations, constraints, and assumptions that hold for all mission trajectories. The name of the spacecraft used is Earth-Vesta (EV).

A. Mission Statement

The mission statement is to launch and rendezvous to Vesta, and gather scientific data to determine how the solar system is created and how it has evolved.

B. Mission Objective

The main mission objective is to examine the conditions and processes involved in the creation of the solar system.

C. Mission Requirements

The main mission requirements are as follows.

1. The EV spacecraft shall have the first launch no later than 1/1/2033
2. The EV spacecraft shall have the final launch no later than 1/1/2038
3. The EV spacecraft shall determine surface topology.
4. The EV spacecraft shall analyze gravity fields.
5. The EV spacecraft shall investigate the elemental composition.
6. The EV spacecraft shall acquire data.
7. The EV spacecraft shall disseminate data.

D. Mission Limitations

1. Lambert solver determines heliocentric transfer orbits without taking into account gravity due to planetary bodies, solar radiation pressure, and other perturbations.
2. Velocities and ΔV local to a planet are evaluated with two-body dynamics
3. Trajectories are set up to trade mission duration against total ΔV .

E. Mission Constraints

1. The EV spacecraft can launch anywhere between 1/1/2015 to 1/1/2040.
2. The maximum one-way mission duration is of no more than 5 years.
3. The maximum round-trip mission duration is of no more than 10 years.
4. The maximum total ΔV is no greater than 10 km/s for rendezvous.
5. The maximum total ΔV is no greater than 7 km/s for round-trip flyby.

F. Mission Assumptions

1. Trajectory configurations have direct transfers and simple gravity assists
2. Patched two-body approximation:
 - o No account for gravity due to planetary bodies
 - o Neglect solar radiation pressure
 - o Two-body dynamics
 - o Small bodies have zero mass
 - o Coplanar

G. Mission Route Trajectories to Vesta

The following table provides the route of each mission. Earth to Asteroid (EA) indicates the mission trajectory consist of only Earth and Vesta. There are two mission trajectories and each have different characteristics. Earth to Mars to Vesta (EMA) indicates the mission trajectory will travel to Vesta using a Mars gravity assist. There are two mission trajectories and each have different characteristics. Earth-to-Earth to Asteroid (EEA) indicates the mission trajectory will travel to Vesta using an Earth gravity assist. Earth to Asteroid to Earth (EAE) indicates a round-trip

mission trajectory. There are two round trip mission trajectories where each have different characteristics and are compared too. All seven trajectories are studied in a heliocentric frame through NASA Ames Research Center Trajectory Browser and Vesta's orbital parameters are obtained from a NASA Jet Propulsion Laboratory (JPL) asteroid search engine database.

| Route | Acronym |
|----------------------------|---------|
| Earth to Asteroid | EA1 |
| Earth to Asteroid | EA2 |
| Earth to Mars to Asteroid | EMA1 |
| Earth to Mars to Asteroid | EMA2 |
| Earth to Earth to Asteroid | EEA |
| Round Trip Mission Route | |
| Earth to Asteroid to Earth | EAE1 |
| Earth to Asteroid to Earth | EAE2 |

Table 1: Mission Route Trajectories.

III. Orbital Mission and Trajectory Planning

This section describes the orbital mechanics of each mission. The orbital parameters of Vesta are calculated and confirmed using NASA Ames Research Center Trajectory Browser and NASA Jet Propulsion Laboratory (JPL) asteroid search engine database. Trajectories will be designed that will fulfill the rendezvous of the mission. Each trajectory presented will be discussed in detail and shown. Also, two round-trip mission trajectories will be defined.

A. Orbital Parameters of the 4 Vesta

Vesta is at 2.36 AU from the center of the Sun. It's orbital parameters are calculated using the following equations. Equation (1) is to determine the specific mechanical energy - ϵ and is first calculated.

$$\epsilon = \frac{V_2}{2} - \frac{\mu}{r} \quad \text{Equation (1)}$$

With this value, the semi-major axis – a can be calculated using Equation 2.

$$a = \frac{-\mu}{2\epsilon} \quad \text{Equation (2)}$$

To determine the eccentricity – e of the orbit, the specific angular momentum – h must be calculated using Equation 3. By equating this expression for specific angular momentum with that given in Equation 4, the eccentricity can be found by solving the system of equations.

$$h = \sqrt{\frac{\mu}{2\epsilon(1-e^2)}} \quad \text{Equation (3)}$$

$$h = \sqrt{\mu r(1+e\cos\theta)} \quad \text{Equation (4)}$$

The inclination can be calculated using the following equation.

$$i = \arccos \left(\frac{h \cdot k}{h} \right) \quad \text{Equation (5)}$$

The orbital parameters of Vesta are calculated and are presented in Table 2.

| Orbital Parameters | |
|--------------------|-------|
| a (AU) | 2.361 |
| e | 0.091 |
| i (degree) | 7.14 |

Table 2: Orbital parameters of Vesta in all missions.

B. Trajectory Solver

Lambert's problem was utilized to compute all trajectories and to find the total ΔV of each trajectory mission. When knowing the time of flight Δt from P_1 to P_2 , then Lambert's problem is to find the trajectory joining P_1 and P_2 . The trajectory is determined once we find v_1 as follows:

$$r = f r_0 + g v_0 \text{ Equation(6)}$$

$$v = f r_0 + g v_0 \text{ Equation (7)}$$

The position and the velocity of any point on the path are determined by r_1 and v_1 . Leaving the previous formulas in function of r_1 and r_2 we get:

$$v_1 = \frac{1}{g} (r_2 - f r_1) \text{ Equation (8)}$$

$$(r_2 - f r_1) = \frac{g'}{g} r_2 - \frac{f' g - f g'}{g} r_1 = \frac{1}{g} (g' r_2 - r_1) \text{ Equation(9)}$$

$$v_2 = f r_1 + \frac{g}{g} \dot{r}$$

Lambert's problem is solved once we determine the Lagrange coefficients f, g and \dot{g} where $z = \infty x^2$.

$$x^2 ()' = \sqrt{\mu} () \quad \frac{1}{\sqrt{\mu}} x^3 ()' = x^2 ()$$

$$f = 1 - r_1 C z \quad f = r_2 r_1 x [z S z - 1] \quad g = \Delta t - \sqrt{\mu} S z \quad g = 1 - r_2 C z \text{ Equations (10-13)}$$

To obtain the values of z and x one could utilize the Gauss problem described in *Fundamental of Astrodynamics* to solve and iterate for these values, and thus solve the Lagrange coefficients.

A Payload Mass

The spacecraft, EV, will carry three instruments to achieve the mission requirements. One instrument is the Framing Camera. The Framing Camera will be to use for navigation, determine surface topology, and analyze gravity fields. The second instrument will be Gamma Ray and Neutron Detector (GRaND). The GRaND will be used to investigate the elemental composition. The third instrument is infrared and visible mapping spectrometer. The total dry mass of EV is 790kg.

D. Launch Vehicle

With spacecraft EV having a dry mass of 790kg, there are many launch vehicles to choose from. The initial payload mass and injection C3 are used to determine the launch vehicle, as shown in Figure 2. They are listed in Table 3 for each mission along with its corresponding launch vehicle.

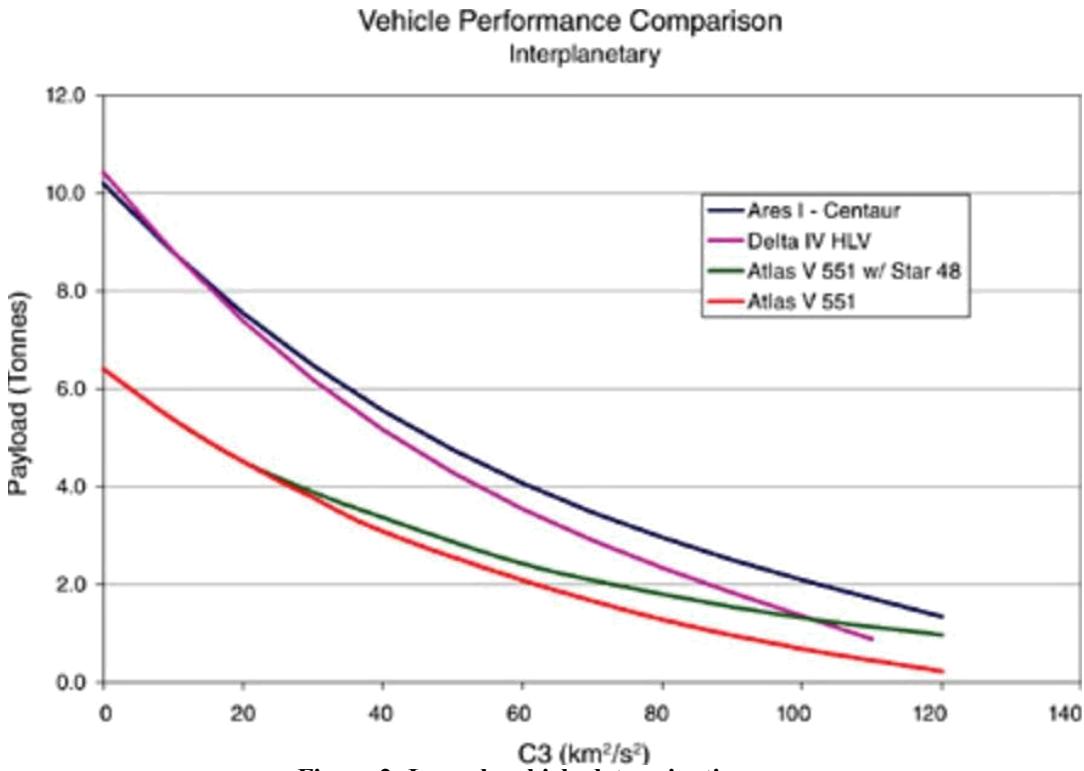


Figure 2: Launch vehicle determination.

| Route | C3 (km ² /s ²) | Wet Payload Mass (kg) | Cost -\$ (10e ₆) | Launch Vehicle |
|-------|---------------------------------------|-----------------------|------------------------------|----------------|
| EA1 | 42.7 | 3719.97 | 350 | Delta IV HLV |
| EA2 | 40.1 | 2721.30 | 138 | Atlas V |
| EMA1 | 33.3 | 2457.57 | 138 | Atlas V |
| EMA2 | 26.3 | 4848.90 | 350 | Delta IV HLV |
| EEA | 25.5 | 2873.34 | 138 | Atlas V |
| EAE1 | 36.3 | 791.07 | 138 | Atlas V |
| EAE2 | 41.5 | 836.97 | 138 | Atlas V |

Table 3: Launch vehicle associated with each mission trajectory.

E. Mission Trajectories to Vesta

Mission 1: Earth to Asteroid (EA1)

The amount of energy it takes to escape Earth's sphere of influence is at an injection C3 of 42.7 km²/s². EV will rendezvous with Vesta using a direct shot trajectory. This trajectory gives the optimal trajectory to Vesta in regards to its short travel duration. The spacecraft will be scheduled to depart Earth July 17, 2037 with a ΔV maneuver of 5.02 km/sec and travel for approximately one year. The spacecraft, EV, will perform its final ΔV maneuver of 4.56 km/sec and arrive the asteroid on July 20, 2038. The total ΔV is 9.57 km/sec with total mission duration of 1.01 years. See Figure 3. The blue orbit represents Earth's orbit, the green orbit represents the transfer orbit, and the grey orbit represents the asteroid orbit. The colors remain the same in the latter figures too.

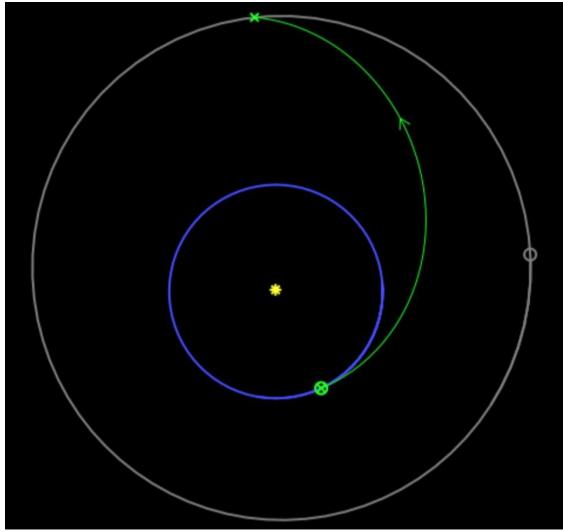


Figure 3: Direct shot to Vesta.

Mission 2: Earth to Asteroid (EA2)

The amount of energy it takes to escape Earth's sphere of influence is at an injection C3 of $40.1 \text{ km}^2/\text{s}^2$. EV will rendezvous with Vesta using a 3.68-year transfer orbit. The spacecraft will be scheduled to depart Earth July 2, 2020 with a ΔV maneuver of 4.92 km/sec . EV will perform its final ΔV maneuver of 3.64 km/sec and arrive the asteroid on March 7, 2024. The total ΔV is 8.56 km/sec with a total mission duration of 3.68 years. See Figure 4.

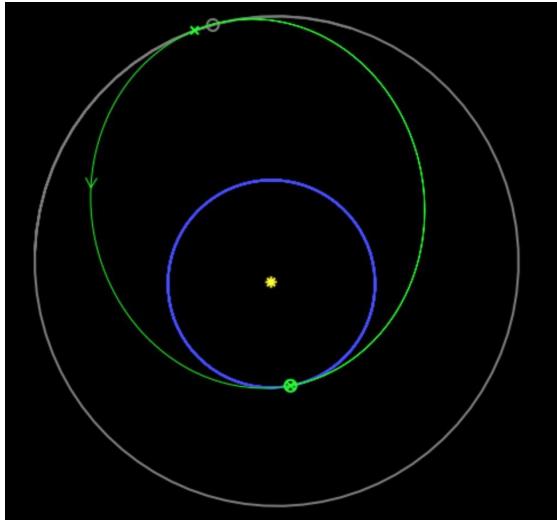


Figure 4: Rendezvous mission to Vesta.

Mission 3: Earth to Mars to Asteroid (EMA1)

The amount of energy it takes to escape Earth's sphere of influence is at an injection C3 of $33.3 \text{ km}^2/\text{s}^2$. EV will rendezvous with Vesta using a Mars gravity assist. This trajectory gives the optimal trajectory to Vesta in regards to its total ΔV . The spacecraft will be scheduled to depart Earth June 18, 2038 with a ΔV maneuver of 4.65 km/sec and will have a 1.88-year transfer trajectory. A Mars flyby will occur on May 6, 2040 with a 10.16-km/sec relative speed at a 0.71 radii altitude. The ΔV maneuver is 188 m/sec followed by a 1.62 year transfer trajectory. EV will perform

its final ΔV maneuver of 3.16 km/sec and arrive the asteroid on December 19, 2041. The total ΔV is 7.99 km/sec with a total mission duration of 3.5 years. See Figure 5. The red orbit represents Mars orbit.

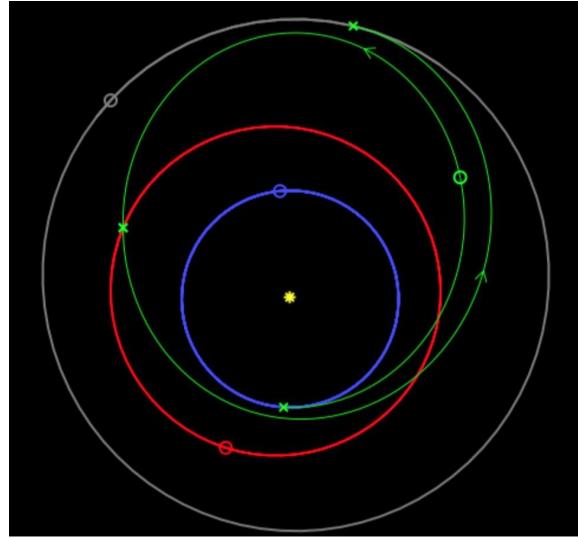


Figure 5: Rendezvous mission to Vesta using Mars gravity assist.

Mission 4: Earth to Mars to Asteroid (EMA2)

The amount of energy it takes to escape Earth's sphere of influence is at an injection C3 of $26.3 \text{ km}^2/\text{s}^2$. EV will rendezvous with Vesta using a Mars gravity assist. The spacecraft will be scheduled to depart Earth February 1, 2023 with a ΔV maneuver of 4.36 km/sec and will have a 1.4-year transfer trajectory. A Mars flyby will occur on June 27, 2024 with a 10.75 m/sec relative speed at a 0.43 radii altitude. The ΔV maneuver is 109 m/sec followed by a 1.14 year transfer trajectory. EV will perform its final ΔV maneuver of 5.23 km/sec and arrive the asteroid on August 17, 2025. The total ΔV is 9.7 km/sec with a total mission duration of 2.54 years. See Figure 6.

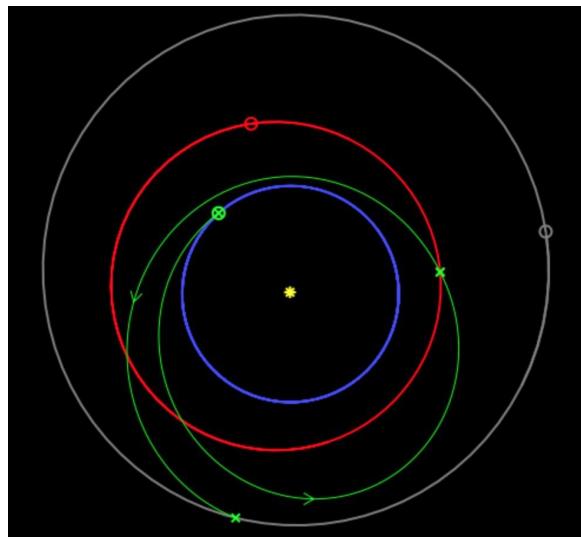


Figure 6: Rendezvous mission to Vesta using Mars gravity assist.

Mission 5: Earth-to-Earth to Asteroid (EEA)

The amount of energy it takes to escape Earth's sphere of influence is at an injection C3 of $25.5 \text{ km}^2/\text{s}^2$. EV will rendezvous with Vesta using a deep space maneuver and an Earth gravity assist. The spacecraft will be scheduled to depart Earth July 29, 2024 with a ΔV maneuver of 4.33 km/sec . Then, EV will perform a deep space maneuver on August 1, 2025 with a ΔV maneuver of 172 m/sec . An Earth flyby will occur on July 3, 2026 with a 10.35 m/sec relative speed at a 0.94 radii altitude. The ΔV maneuver is 8 m/sec followed by a 1.31 year transfer trajectory. EV will perform its final ΔV maneuver of 3.62 km/sec and arrive the asteroid on October 26, 2027. The total ΔV is 8.13 km/sec with a total mission duration of 3.24 years. See Figure 7.

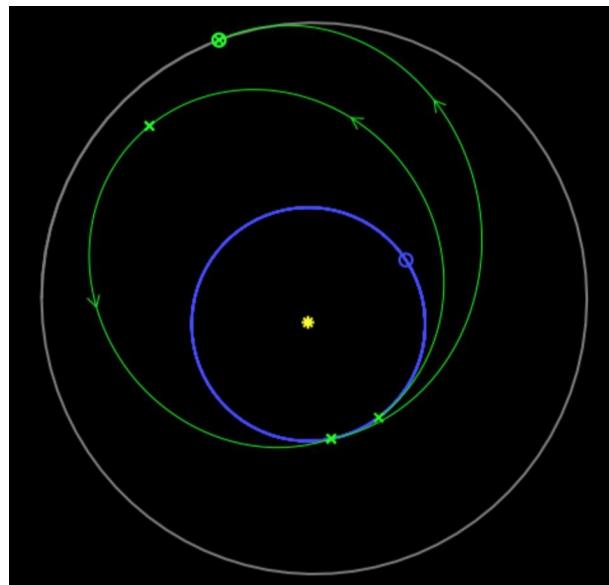


Figure 7: Rendezvous mission to Vesta using Earth gravity assist.

Mission 6: Earth to Asteroid to Earth (EAE1)

This mission is a round-trip flyby to Vesta. The amount of energy it takes to escape Earth's sphere of influence is at an injection C3 of $36.3 \text{ km}^2/\text{s}^2$. The spacecraft will be scheduled to depart Earth February 22, 2019 with a ΔV maneuver of 4.77 km/sec . EV will travel on a three year transfer trajectory. Then, EV will perform the Vesta flyby that will occur on April 3, 2022 with a 8.65 km/sec relative speed at a 1.31 radii altitude. The ΔV maneuver is 4 m/sec followed by a 1.88 year transfer trajectory to Earth. EV will perform an Earth reentry at 12.55 km/sec on February 20, 2024. The total ΔV is 4.77 km/sec with a total mission duration of 4.99 years. See Figure 8.

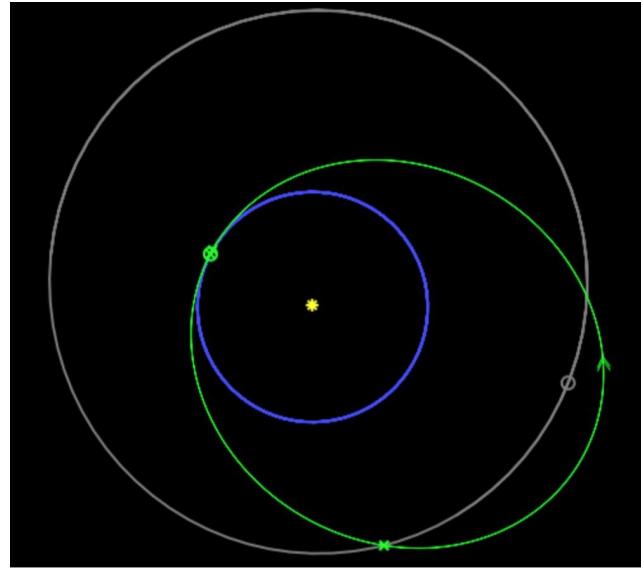


Figure 8: Round-trip flyby to Vesta.

Mission 7: Earth to Asteroid to Earth (EAE2)

This mission is a round-trip flyby to Vesta. The amount of energy it takes to escape Earth's sphere of influence is at an injection C3 of $41.5 \text{ km}^2/\text{s}^2$. The spacecraft will be scheduled to depart Earth August 2, 2031 with a ΔV maneuver of 4.97 km/sec . EV will travel on a 3.5 year transfer trajectory. Then, EV will perform the Vesta flyby that will occur on January 1, 2035 with a 6.38 km/sec relative speed at a 10.53 radii altitude. The ΔV maneuver is 170 m/sec followed by a 1.62 year transfer trajectory to Earth. EV will perform an Earth reentry at 13.26 km/sec on August 15, 2036. The total ΔV is 5.14 km/sec with a total mission duration of 5.04 years. See Figure 9.

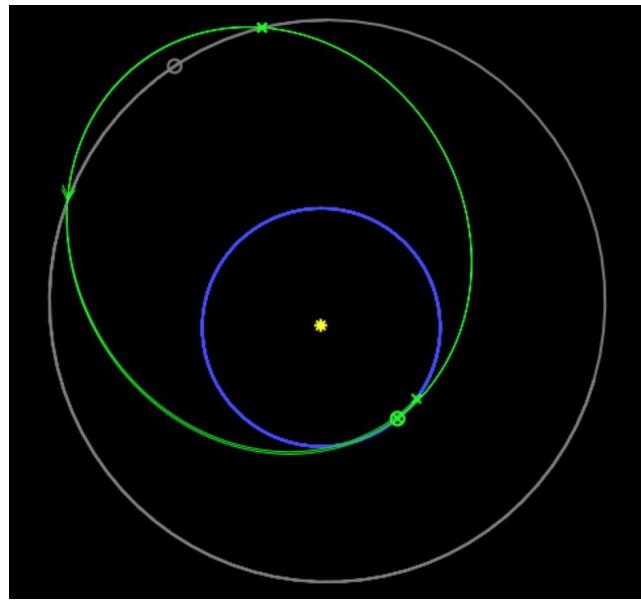


Figure 9: Round-trip flyby to Vesta.

A Fuel Consumption

The rocket and the EV spacecraft will each carry their own fuel. Table 4 below shows the total fuel that is consumed by EV alone to achieve the post-injection ΔV maneuvers for each mission trajectory. The total fuel consumption for the 790kg spacecraft (dry) was calculated using Equation (43). The Isp is 300 seconds and gravity is 9.81m/s².

$$m_p = m_i \left[1 - \exp \left[- \frac{V}{I_{sp} g} \right] \right] \quad \text{Equation (14)}$$

| Route | EV Spacecraft Wet Mass (kg) | EV Spacecraft Fuel Mass (kg) |
|-------|-----------------------------|------------------------------|
| EA1 | 3719.97 | 2929.97 |
| EA2 | 2721.30 | 1931.30 |
| EMA1 | 2457.57 | 1667.57 |
| EMA2 | 4848.90 | 4058.90 |
| EEA | 2873.34 | 2083.34 |
| EAE1 | 791.07 | 1.07 |
| EAE2 | 836.97 | 46.97 |

Table 4: Fuel consumption for all mission trajectories.

IV. Results

The EA1 trajectory requires a high post-injection ΔV of 4.56 km/s with a total fuel consumption of 3719.97kg and a mission duration of approximately one year. In comparison, EA2 trajectory requires a lower post-injection ΔV of 3.64 km/s with a total fuel consumption of 1931.30kg and a mission duration of 3.68 years. As a result, EA1 mission trajectory is optimal. The EMA1 trajectory requires a low post-injection ΔV of 3.34 km/s with a total fuel consumption of 3719.97kg and a mission duration of 3.5 years. EMA2 trajectory requires a higher post-injection ΔV of 4.36 km/s with a total fuel consumption of 4058.90kg with a mission duration of 2.54 years. As a result, EMA1 mission trajectory is optimal. EEA trajectory is requires a higher post-injection ΔV than EMA1. Table 5 shows each mission trajectory in detail.

| Route | Post ΔV (km/sec) | Injectio n ΔV (km/sec) | ΔV_{tot} (km/sec) | TOF (years) | Fuel (kg) | C3 (km ² /s ₂) | Earth Departure | Destination Arrival | Abs. DLA (degrees) |
|-------|--------------------------|--------------------------------|---------------------------|-------------|-----------|---------------------------------------|-----------------|---------------------|--------------------|
| EA1 | 4.56 | 5.02 | 9.57 | 1.01 | 2929.97 | 42.7 | 7/17/2037 | 7/20/2038 | 24 |
| EA2 | 3.64 | 4.92 | 8.56 | 3.68 | 1931.30 | 40.1 | 7/2/2020 | 3/7/2024 | 27 |
| EMA1 | 3.34 | 4.65 | 7.99 | 3.5 | 1667.57 | 33.3 | 6/18/2038 | 12/19/2041 | 24 |
| EMA2 | 4.36 | 4.36 | 9.7 | 2.54 | 4058.90 | 26.3 | 2/1/2023 | 8/17/2025 | 21 |
| EEA | 4.33 | 4.33 | 8.13 | 3.24 | 2083.34 | 25.5 | 7/29/2024 | 10/26/2027 | 2 |

Table 5: Characteristics of one-way rendezvous mission trajectories to Vesta.

Table 6 shows the details of two round-trip mission trajectories. EAE1 is the optimal flyby mission trajectory due to the post-injection ΔV , mission duration, fuel consumption, and injection C3.

| Route | Post ΔV (m/s) | Inject. ΔV (km/s) | ΔV_{tot} (km/s) | TOF (yrs) | Fuel (kg) | C3 (km ² /s ₂) | Earth Depart. | Flyby Date | Dest. Arrival | Abs. DLA (deg) | Flyby speed (km/s) | Reentry speed (km/s) |
|-------|-----------------------|---------------------------|-------------------------|-----------|-----------|---------------------------------------|---------------|------------|---------------|----------------|--------------------|----------------------|
| EAE1 | 4 | 4.77 | 4.77 | 4.99 | 1.07 | 36.3 | 2/22/2019 | 4/3/2022 | 2/20/2024 | 11 | 8.65 | 12.55 |

| | | | | | | | | | | | | |
|------|-----|------|------|------|-------|------|-----------|----------|-----------|---|------|-------|
| EAE2 | .17 | 4.97 | 5.14 | 5.04 | 46.97 | 41.5 | 8/ 2/2031 | 1/1/2035 | 8/15/2036 | 8 | 6.38 | 13.26 |
|------|-----|------|------|------|-------|------|-----------|----------|-----------|---|------|-------|

Table 6: Characteristics of round-trip flyby mission trajectories to Vesta.

V. Conclusion

The Lambert Theorem was used to design and analyze trajectories to and from the 4 Vesta asteroid. The highlight of the EA1 mission trajectory is that although 78% of the spacecraft is fuel, the mission duration is only 368 days. EA1 is the optimal mission trajectory. The EMA1 trajectory requires the lowest post-injection ΔV of 3.34 km/s with a total fuel consumption of 1667.57kg. The highlight of this mission trajectory is that the spacecraft carries the least amount of fuel and performs the least amount of ΔV , but however, EMA1 mission trajectory has the maximum mission duration of 3.5 years. EMA1 is an optimal mission trajectory too. As for the round-trip fly by mission trajectory, EAE1 is the optimal. The spacecraft's ΔV may be reduced with a more efficient propulsion system such as a solar sail or electric conducting a low-thrust performance. Not only will efficient propulsion be more effective, it will be far less expensive as well. The trajectories maybe optimize for future work in considering gravitational pulls from other bodies, solar pressurization, and other perturbations. Nonetheless, the above analysis serves as a parametric study in mission trajectory design.

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