PYROS: PlanetarY Research and Observation Satellite

Srivastava Archit[1], Nagda Bindi[2], Kumar Darpan[3], Kumlungmak Moodang Kittiwin[4], and Fatakdawala Murtaza[5]
Florida Institute of Technology

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Focused to design a trajectory to place a 500 kg spacecraft, launched from Earth, into a 200-1000 km orbit around Ganymede (Jupiter's largest moon), the paper takes inspiration from various successful missions to and beyond Jupiter, and constructs a trajectory of Earth-Mars-Jupiter-Callisto-Ganymede with gravity assist flybys of Mars & Callisto. The paper evaluates the required ideal launcher, calculates the minimum launch mass, time taken to reach Ganymede, and plots heliocentric & Julio centric plots along with B-plane targeting plots, all using MATLAB.

I. Nomenclature

μ	$= Gravitational\ Parameter$
T	$= Period$
ω	$= Rotational\ rate$
r	$= Radius$
G	$= Universal\ Gravitational\ Constant$
m	$= Mass$
h	$= Specific\ angular\ momentum$
v	$= Velocity$
v_r	$= Radial\ velocity$
$v_\perp$	$= Tangential\ Velocity$
SOI	$= Sphere\ Of\ Influence$
D	$= Orbital\ radius\ around\ Star/Planet$
e	$= Eccentricity\ of\ the\ Orbit$
a	$= Semi\ major\ axis$
v_∞	$= Hyperbolic\ excess\ velocity$
δ	$= Turn\ angle$
ϕ	$= Asymtote\ angle$
R	$= Radius\ of\ Planet's\ orbit\ around\ sun$
B	$= Aiming\ Radius$
v_*	$= Effective\ exhaust\ velocity$
m_0	$= Total\ launch\ mass$
m_f	$= Total\ fuel\ mass$

[1] Undergraduate Aerospace Engineering, Department of Aerospace, Physics, and Space Science
[2] Undergraduate Aerospace Engineering, Department of Aerospace, Physics, and Space Science
[3] Undergraduate Aerospace Engineering, Department of Aerospace, Physics, and Space Science
[4] Undergraduate Aerospace Engineering, Department of Aerospace, Physics, and Space Science
[5] Undergraduate Aerospace Engineering, Department of Aerospace, Physics, and Space Science

II. Introduction

Ganymede, the largest and most massive moon of Jupiter, has been an unexplored Galilean moon that has intrigued scientists, astronomers, and engineers for decades. In order to establish a Ganymede-bound spacecraft trajectory from Earth, we start by analyzing previous missions that have either flown to Jupiter or beyond.

We begin our analysis with the **Pioneer** [1][2][3][4][5] mission: Pioneer 10 and Pioneer 11. Launched in 1958 from Earth, Pioneer 1 travelled to Jupiter, Saturn, and Neptune while doing fly-bys around Callisto, Ganymede, Europa, and Io before travelling to the Heliopause. The 258.8 kg spacecraft had a mission duration of over 30 years in which it became the first spacecraft to travel through the asteroid belt and first to make direct observations of an outer planet. Launched in the same year, Pioneer 11 travelled to Jupiter and Saturn and did flybys around many of the planet moon including Callisto and Ganymede before travelling to the Heliopause. The 259 kg spacecraft had a mission duration of over 22 years. It allowed the first observation of Jupiter's polar region and identified the "Great Red Spot".

Starting in 1977, the **Voyager** [6] mission: Voyager 1 & 2, continue to relay information back to Earth to present day. Voyager 1, weighing at 721.9 kg spacecraft mass, had its initial trajectory planned for Earth-Jupiter-Saturn, with gravity assist flybys around Jupiter and Saturn. It was later extended to the Terminal shock and Heliopause. On the other hand, Voyager 2, weighing similar to Voyager 1, did gravity assist flybys around Jupiter, Saturn, Uranus, and Neptune for a planned trajectory Earth-Jupiter-Saturn-Uranus-Neptune before heading onto the terminal shock and Heliopause. The mission has been going for over 41 years and has been transformed into the Voyager Interstellar Mission (VIM) to discover the edge of the Sun's domain. During their flybys of the 4 gas giant's moons, the voyager mission discovered 22 new satellites and found active volcanos on Io, one of Jupiter's moon.

Galileo [7], launched in October of 1989, had its planned trajectory of Earth-Venus-Earth-Earth-Jupiter. The 2223 kg spacecraft did a Venus-Earth-earth gravity assist fly-by (VEEGA) to reach Jupiter where it did 7 flybys around Io, 8 around Callisto, 8 around Ganymede, 11 around Europa, and 1 around Amalthea. During its 14 years inside Jupiter's sphere of influence, the Galileo mission discovered thunderstorms on Jupiter, much more water on Europa compared to Earth under its icy surface, and a magnetic field around Ganymede.

With a spacecraft mass of 2523 kg & launch mass of 5712 kg, the **Cassini-Huygens** [8] mission completed its Earth-Venus-Venus-Earth-Jupiter-Saturn trajectory in about 20 years. The spacecraft did flybys around Venus twice, followed by Earth and Jupiter before doing an injection burn around Saturn. Huygens's landing on Titan made it the first probe to land on a moon of an outer planet in the solar system. During its flyby around Jupiter, Cassini captured images of Jupiter that helped scientists understand the red and white bands of gas around Jupiter.

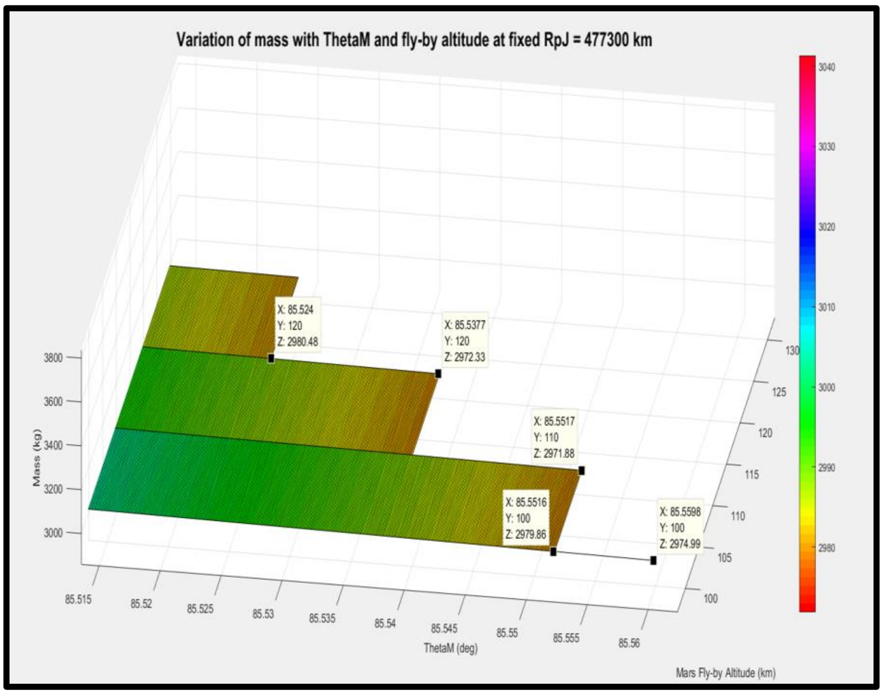
Projected to end its mission in July of 2021, **Juno** [9] [10] [11] has had a mission duration of about 10 years. Post launch, it did a gravity assist flyby boost around Earth and got boosted again during Jupiter arrival due to the planet's gravity. The total spacecraft mass was 3625 kg and had a planned trajectory of Earth-Earth-Jupiter. Its major goal was to reveal the story of Jupiter's formation and evolution. It revealed both of Jupiter's poles to be covered in Earth-sized swirling storms that are densely clustered and rubbing together. The Microwave Radiometer (MWR) data indicated that Jupiter's iconic belts and zones are mysterious, with the belt near the equator penetrating all the way down, while the belts and zones at other latitudes seem to evolve to other structures. The data suggest the ammonia is quite variable and continues to increase as far down as we can see with MWR, which is a few hundred miles or kilometers.

The aim of this report is to establish a Ganymede bound spacecraft trajectory yielding the lowest possible launch mass from Earth. A MATLAB based code, to calculate heliocentric & Julio centric trajectories, was built to run several possible iterations to realize this goal. An initial guess of roughly 3000 kg launch mass is estimated to get the given 500 kg spacecraft in a 200-1000 km orbit around Ganymede on a Falcon Heavy (Recovery). As mission time is not a constraint, we expect the total calculated time to be unrealistic. Moreover, with the several assumptions made while complaining this report, the results are expected to give a rough estimate, not the precise value for launch mass.

III. Approach

After our primary research on the space missions to or beyond Jupiter, we decided to test some of the similar approaches and see if it could be helpful to our mission to Ganymede. The first approach involved an interplanetary flyby around Venus and Mercury, and gain some more energy to go towards outer planets, but the energy gained by Venus flyby was not enough. A powered fly-by of Venus would have helped, but since our goal was to reduce the propellant mass used, we were limiting ourselves to one burn (our final burn). A Hohmann transfer to Mars and then a fly-by of Mars was also tried, but the energy after the fly-by was not enough to reach Jupiter after the fly-by.

At last, the final approach involved going from Earth to Mars on a non-Hohmann transfer followed by a trailing side flyby at a certain altitude of Mars. Then, from Mars to Callisto and a leading side flyby around Callisto to Ganymede. The trailing side flyby around Mars was an appropriate choice for our approach and we wanted more energy to reach the Jupiter Sphere of Influence. The leading side flyby around Callisto was a practical choice around Callisto as we wanted to slow our spacecraft as much as possible before reaching Ganymede.



The (figure 1) below shows a surface plot that was used to get optimum values for true anomaly (85.5517°) to reach mars and the flyby altitude (110 km). The periapse of Jupiter arrival hyperbola and Callisto fly-by altitude were optimized in a similar manner (See Appendix). The values chosen from the graph helped to get the minimum mass.

Figure 1 - Mass variation with change in Mars flyby altitude and true anomaly

NOTE: All the assumptions given in the project assignment were applied when coming up with the final approach.

The following approach was finalized after multiple iterations to optimize the lowest spacecraft launch mass possible: Earth-Mars-Jupiter (Callisto-Ganymede)

1. Earth to Mars (Mars Flyby):

   i. Leave Earth's SOI at perihel (zero true anomaly) on a trajectory to Mars and reach Mars SOI at a specific true anomaly (optimized by iterations).
   ii. Calculate the eccentricity, specific angular momentum and semi major axis of the transfer orbit.
   iii. Calculate the speed of spacecraft at perihel of transfer orbit and earth's heliocentric Velocity.
   iv. Using (iii) Calculate the heliocentric excess velocity needed for the spacecraft to leave earth SOI.
   v. Calculate radial and tangential heliocentric velocities when entering Mars orbit around Sun.
   vi. Calculate transversal and radial components of hyperbolic excess velocity when entering Mars SOI.
   vii. Using (vi) calculate the flyby hyperbolic excess velocity.

2. Mars (mars flyby) to Jupiter

   i. Decide an altitude for Mars Flyby. (the altitude chosen was a result of multiple iterations)
   ii. Calculate the eccentricity of heliocentric orbit after mars flyby.
   iii. Calculate the turn angle because of the gravity assist of Mars.
   iv. Calculate the asymptote angles for the spacecraft to enter and leave Mars SOI. (Trailing side flyby was chosen as a higher heliocentric velocity was required to reach Jupiter's SOI)
   v. Calculate radial and tangential heliocentric velocities leaving Mars SOI
   vi. Calculate the angular momentum of the transfer orbit between Mars and Jupiter and the true anomaly leaving Mars orbit.
   vii. Calculate eccentricity, semi major axis, periapsis and apoapsis for the transfer orbit between mars and Jupiter.

3. Entering Jupiter (Callisto Flyby)

   i. Calculate the true anomaly of Transfer and Jupiter orbit intersection.
   ii. Calculate radial and tangential heliocentric velocities when entering Jupiter on a transfer orbit.
   iii. Calculate Jupiter's heliocentric velocity.
   iv. Calculate transversal and radial components of hyperbolic excess velocity when entering Jupiter SOI.
   v. Using (iv) calculate hyperbolic excess velocity.
   vi. Decide a periapsis radius around Jupiter for the incoming hyperbola. (The value used is result of multiple iterations until final lowest mass was achieved).
   vii. Calculate the aiming radius
   viii. Calculate the eccentricity, semi-major axis and angular momentum of the arrival hyperbola.

ix. Calculate the true anomaly of intersection of incoming hyperbola with Callisto's SOI.
x. Calculate the Intersection of Heliocentric ellipse with Jupiter's SOI.
xi. Calculate radial and tangential heliocentric velocities when entering Callisto's SOI.
xii. Calculate Callisto's orbital velocity around Jupiter.
xiii. Calculate transversal and radial components of hyperbolic excess velocity inside Callisto's SOI.
xiv. Decide an altitude for Callisto Flyby. (the altitude chosen was a result of multiple iterations)
xv. Decide an altitude for Callisto's Flyby. (the altitude chosen was a result of multiple iterations)
xvi. Calculate the eccentricity of Callisto's flyby orbit.
xvii. Calculate the turn angle because of the gravity assist of Callisto.
xviii. Calculate the asymptote angles for the spacecraft to enter and leave Callisto SOI. (Leading side flyby was chosen because a slower Julio centric velocity is desired before reaching Ganymede.)

4. <u>Callisto (Callisto Flyby) to Ganymede</u>

i. Calculate radial and tangential heliocentric velocities leaving Callisto's SOI.
ii. Calculate the angular momentum of the transfer orbit between Callisto and Ganymede and the true anomaly leaving Callisto's SOI.
iii. Calculate eccentricity, semi major axis, periapsis and apoapsis for the transfer orbit between Callisto and Ganymede.
iv. Calculate the true anomaly of Transfer and Ganymede orbit intersection.
v. Calculate radial and tangential heliocentric velocities when entering Ganymede SOI.
vi. Calculate Ganymede's orbital velocity around Jupiter.
vii. Calculate transversal and radial components of hyperbolic excess velocity inside Ganymede SOI.
viii. Using (vii) calculate hyperbolic excess velocity.
ix. Decide a periapsis altitude around Ganymede for the incoming hyperbola and Circular orbit for spacecraft insertion. (The value used is result iteration between 200 Km and 1000 km to achieve lowest mass possible).
x. Calculate the eccentricity of the arrival hyperbola.
xi. Calculate the velocity at periapsis of the incoming hyperbola.
xii. Calculate the velocity of circular orbit around Ganymede.
xiii. Calculate the required change in velocity for the spacecraft insertion in the circular orbit.

5. <u>Mass Calculation</u>

i. Use the calculated velocity change to calculate the mass.
ii. For each 1 kg of propellant mass, 0.1 kg of structural mass is added.
iii. Rocket equation is used to calculate the final mass.

Look-up values:

G	$= 6.67408 \times 10^{-20}\ m^3 kg^{-1} s^{-2}$	Gravitation constant
r_{earth}	$= 6378\ km$	Radius of Earth
r_{Mars}	$= 3396\ km$	Radius of Mars
$r_{Jupiter}$	$= 71490\ km$	Radius of Jupiter
$r_{Callisto}$	$= 2410.3\ km$	Radius of Callisto
$r_{Ganymede}$	$= 2631.2\ km$	Radius of Ganymede
D_{Earth}	$= 149600000\ km$	Semi-major axis of Earth's orbit
D_{Mars}	$= 227900000\ km$	Semi-major axis of Mars's orbit
$D_{Jupiter}$	$= 778600000\ km$	Semi-major axis of Jupiter's orbit
$D_{Calisto}$	$= 1882709\ km$	Semi-major axis of Callisto's orbit
$D_{Ganymede}$	$= 1070412\ km$	Semi-major axis of Ganymede's orbit
μ_{sun}	$= 132712000000\ km^3 s^{-2}$	Standard gravitational parameter of Sun
μ_{Earth}	$= 398600\ km^3 s^{-2}$	Standard gravitational parameter of Earth
μ_{Mars}	$= 42828\ km^3 s^{-2}$	Standard gravitational parameter of Mars
$\mu_{Jupiter}$	$= 126686000\ km^3 s^{-2}$	Standard gravitational parameter of Jupiter
SOI_{Earth}	$= 925000\ km$	Radius of Earth's Sphere of Influence
SOI_{Mars}	$= 577000\ km$	Radius of Mars's Sphere of Influence
$SOI_{Jupiter}$	$= 48200000\ km$	Radius of Jupiter's Sphere of Influence
$m_{Jupiter}$	$= 1.899 \times 10^{27}\ kg$	Mass of Jupiter
$m_{Callisto}$	$= 10759000 \times 10^{16}\ kg$	Mass of Callisto
$m_{Ganymede}$	$= 14819000 \times 10^{16}\ kg$	Mass of Ganymede
g_0	$= 9.81\ m/s^2$	Earth gravitational acceleration

Equations used:

Orbit Equation (1)

$$r = \frac{\frac{h^2}{\mu}}{1 + e\ cos\theta}$$

Specific Angular momentum (2)

$$h = rv_\perp = \sqrt{\mu a(1 - e^2})$$

Radial Velocity (3)

$$v_r = \frac{\mu}{h} e \sin(\theta)$$

Tangential Velocity (4)

$$v_\perp = \frac{\mu}{h}(1 + e\cos(\theta))$$

Vis-viva Equation (5)

$$\frac{v^2}{2} - \frac{\mu}{r} = -\frac{\mu}{2a}$$

Orbital Velocity for circular orbit (6)

$$v = \sqrt{\frac{\mu}{r}}$$

Semi major axis (7)

$$a = \frac{r_p + r_a}{2} = \frac{h^2}{\mu(1 - e^2)}$$

Non Hohmann Transfer

Eccentricity (8)

$$e = \frac{r_A - r_B}{r_B \cos\theta_B - r_A \cos\theta_A}$$

Angular Momentum (9)

$$h = \sqrt{\mu r_A (1 + e\cos\theta_A)}$$

Fly-by Equations:
Gravity Assist / Turn angle (10)

$$\delta = 2\sin^{-1}\left(\frac{1}{e}\right)$$

Eccentricity (11)

$$e = 1 + \frac{r_p v_\infty^2}{\mu}$$

Transversal Excess Velocity before flyby (12)

$$v_{\infty 1,v} = v_{\perp,1} - v_{planet/moon}$$

Radial Excess Velocity before flyby (13)

$$v_{\infty 1,s} = -v_{r,1}$$

Asymptote Angle before flyby (14)

$$\phi_1 = \tan^{-1}(\frac{v_{\infty 1,v}}{v_{\infty 1,s}})$$

Asymptote Angle after flyby (15)

$$\phi_2 = \phi_1 \pm \delta$$

Tangential velocity after flyby (16)

$$v_{\perp,2} = v_{planet} + v_\infty \cos\phi_2$$

Radial velocity after flyby (17)

$$v_{r,2} = -v_\infty \sin\phi_2$$

Angular momentum after flyby (18)

$$h_2 = R v_{\perp,2}$$

True anomaly after flyby (19)

$$\theta_2 = \tan^{-1}\left[\frac{h_2}{v_{r,2} R} - \frac{\mu}{v_{r,2} h_2}\right]$$

Eccentricity after flyby (20)

$$e_2 = \frac{v_{r,2} h_2}{\mu \sin\theta_2}$$

Kepler Equations for Timeline
Kepler Equation (21)

$$M_e = E - e\sin E$$

Mean Anomaly (22)

$$M_e = \frac{\mu^2}{h^3}(1 - e^2)^{\frac{3}{2}}(t - t_p) = \frac{2\pi}{T}\Delta t$$

Eccentric Anomaly (23)

$$E = 2\tan^{-1}\left(\sqrt{\frac{1-e}{1+e}}\tan\frac{\theta}{2}\right)$$

True Anomaly (24)

$$\theta = 2\tan^{-1}\left(\sqrt{\frac{1-e}{1+e}}\tan\frac{E}{2}\right)$$

Hyperbolic Eccentric Anomaly (25)

$$F = 2\tanh^{-1}\left(\sqrt{\frac{e-1}{e+1}}\tan\frac{\theta}{2}\right)$$

True Anomaly (26)

$$\theta = 2\tanh^{-1}\left(\sqrt{\frac{e+1}{e-1}}\tan\frac{F}{2}\right)$$

Hyperbolic Mean Anomaly (27)

$$M_h = \frac{\mu^2}{h^3}(1-e^2)^{\frac{3}{2}}\left(t-t_p\right)$$
$$M_h = e\sinh F - F$$

B-Plane targeting (28)

$$r_p = -\frac{\mu}{v_\infty^2} + \sqrt{\left(\frac{\mu}{v_\infty^2}\right)^2 + B^2}$$
$$B = \sqrt{\left(r_p + \frac{\mu}{v_\infty^2}\right)^2 - \left(\frac{\mu}{v_\infty^2}\right)^2}$$
$$B = \frac{r_p v_p}{v_\infty}$$

Rocket equation (29)

$$\Delta v = v_* \ln\left(\frac{m_0}{m_f}\right) = -v_* \ln\left(\frac{\varepsilon+\lambda}{1+\lambda}\right)$$

Specific Impulse (30)

$$I_{sp} = v_* g_0^{-1}$$

IV. Heliocentric trajectory

The graph, on the left, shows the heliocentric trajectory of the spacecraft on its way to Ganymede. The green trajectory is the first transfer ellipse on which the spacecraft leaves Earth's SOI at a true anomaly of 0° and enters Mars' SOI at a true anomaly of 85°. The spacecraft then leaves Mars SOI on a second transfer ellipse with a true anomaly of 73.1° and arrives at Jupiter's SOI at a true anomaly of 179.9°.

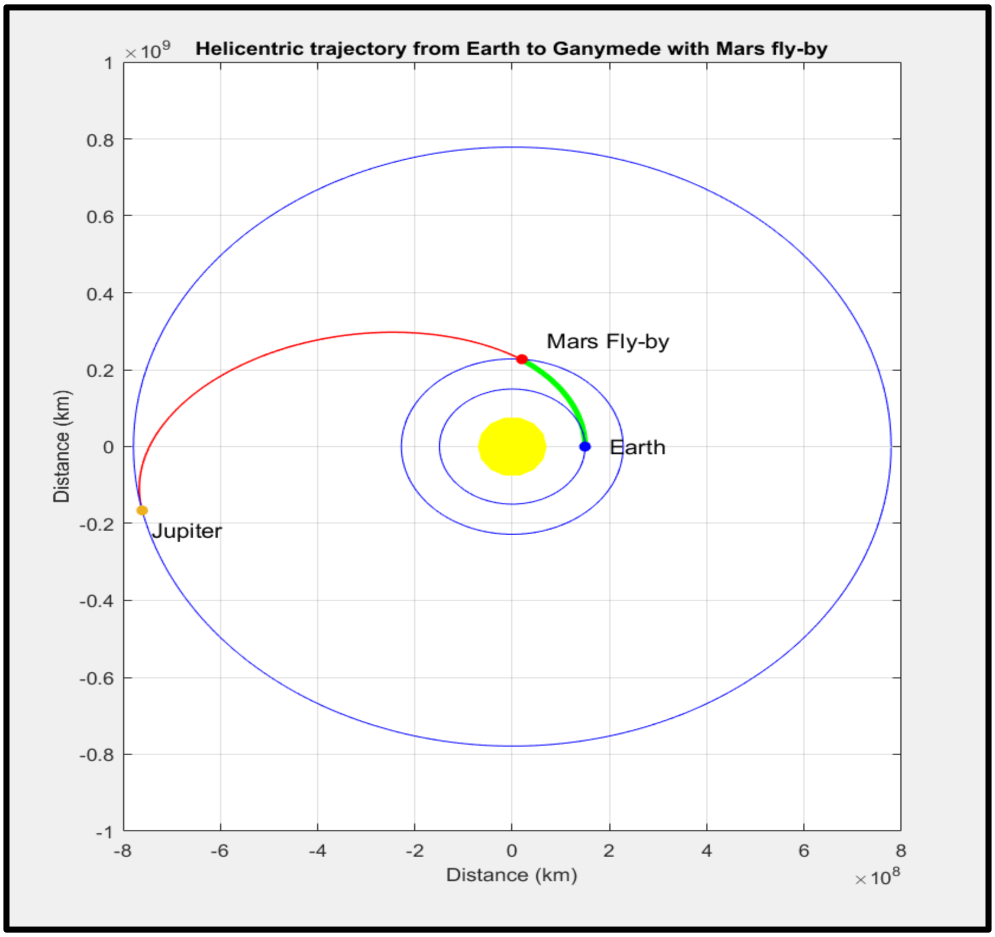


Figure 2 – Heliocentric Trajectory of Spacecraft

V. Planet Centric trajectory & B-Plane Targeting

The following plots show the planet centric trajectories of the spacecraft as it leaves Earth's sphere of influence (SOI) on a heliocentric transfer ellipse, performs a Mars fly-by, then enters Jupiter's SOI to perform a fly-by with Callisto, and finally arrives in Ganymede's SOI and inserts itself into a circular orbit around it.

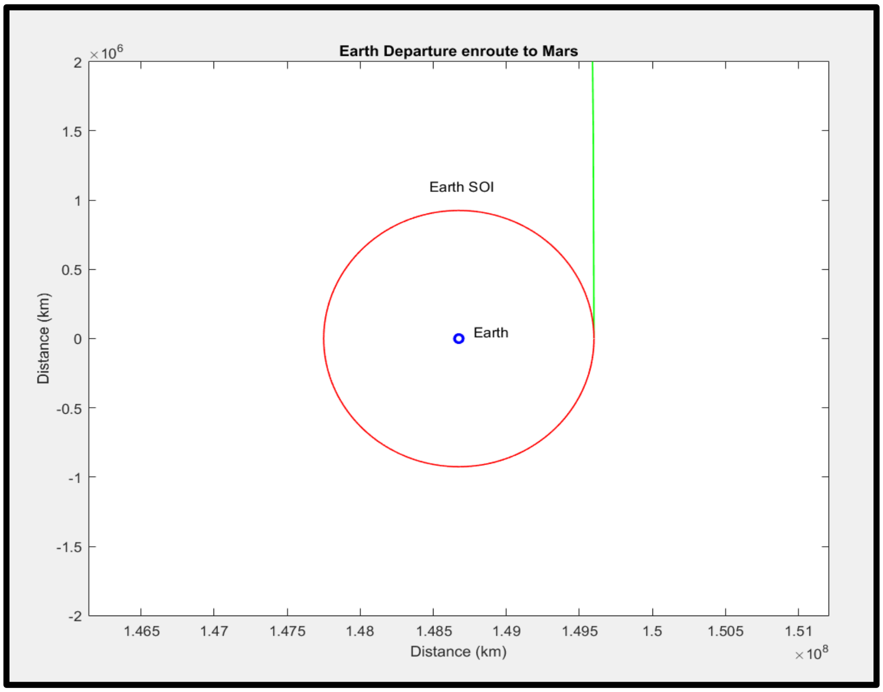


Figure 3 – Earth Departure and its SOI

The following plot shows the Mars fly-by trajectory in which the hyperbolic periareum is at an altitude of 110 km.

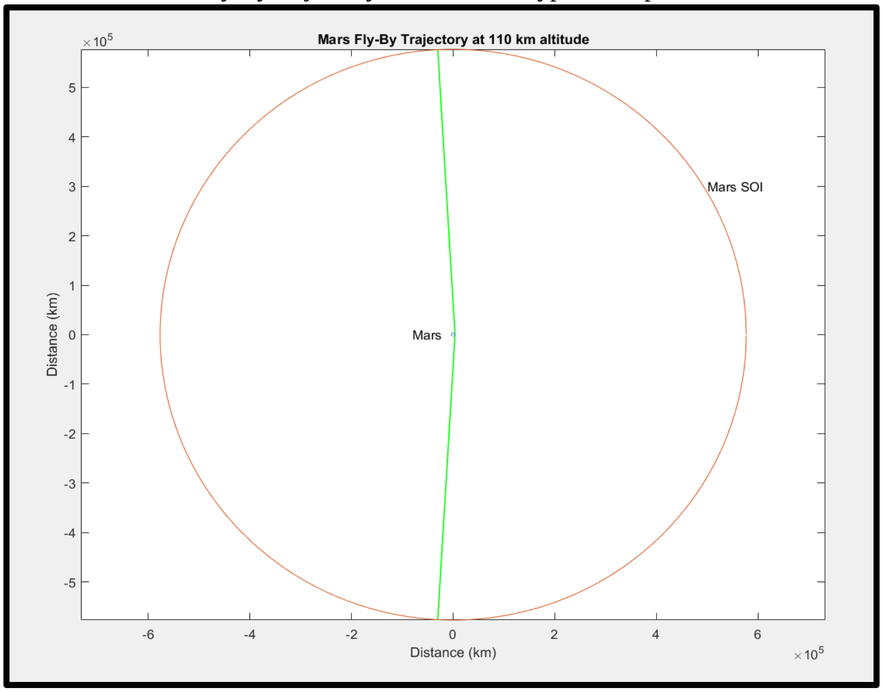


Figure 4 - Mars SOI showing flyby

The plots below show the trajectory of the spacecraft as it enters Jupiter's SOI. Inside the SOI the spacecraft performs a fly-by with Callisto and then arrives at Ganymede.

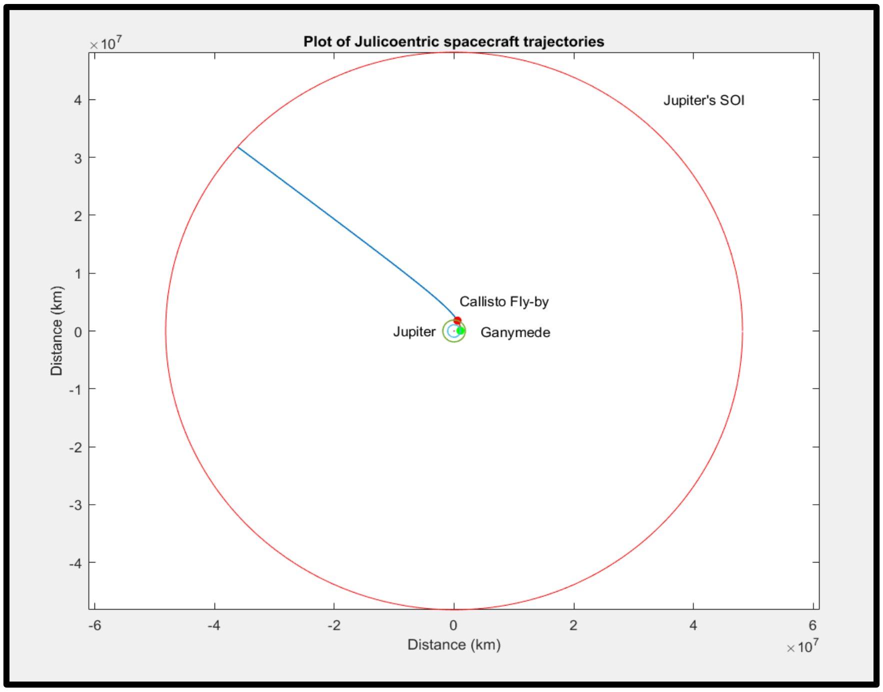


Figure 5 - Jupiter Arrival and SOI

Below is a close-up view of the Julio centric trajectory of the spacecraft inside Jupiter's SOI.

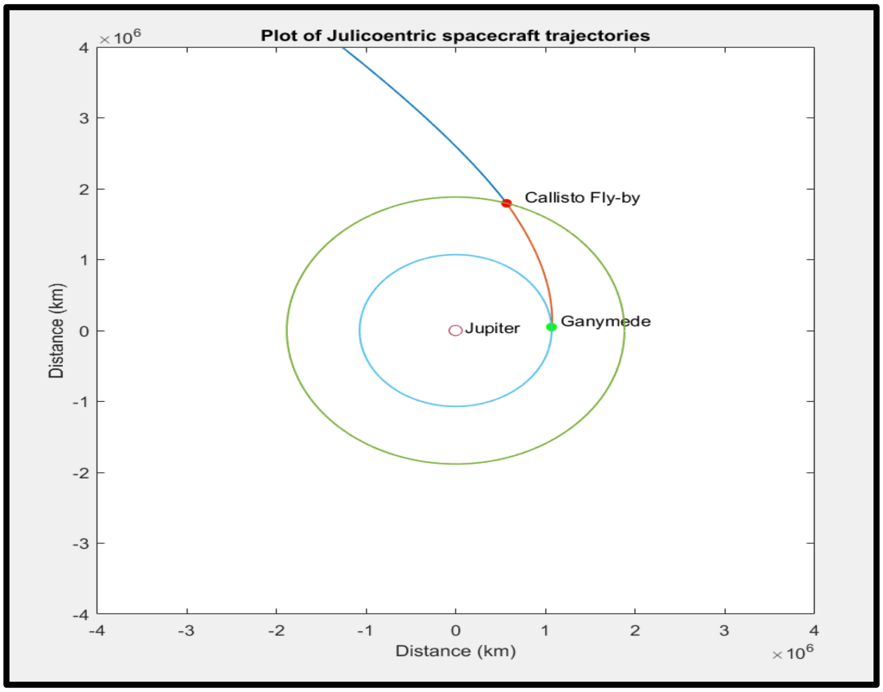


Figure 6 - Julio centric Trajectory (Note: Jupiter's SOI has not been drawn because it is so large that the details above are reduced to small dots in the screen)

The spacecraft trajectory during Callisto fly-by is illustrated in the figure below. The periapse of the hyperbolic fly-by trajectory is at an altitude of 660 km.

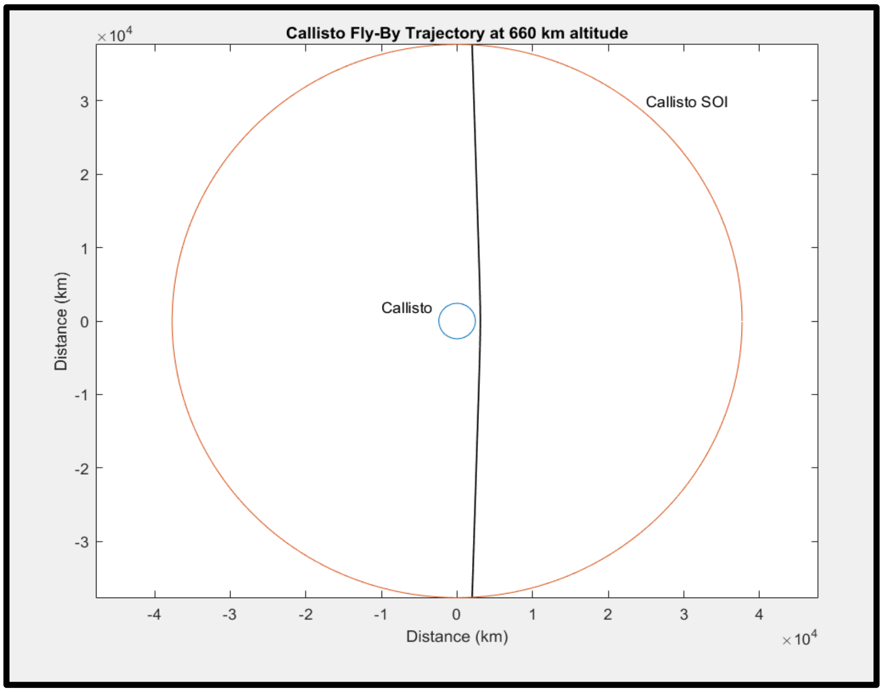


Figure 7 - Callisto Fly-by maneuver

Finally, the spacecraft arrives inside Ganymede's sphere of influence on a hyperbola and inserts itself into a circular mission orbit with an altitude of 200 km.

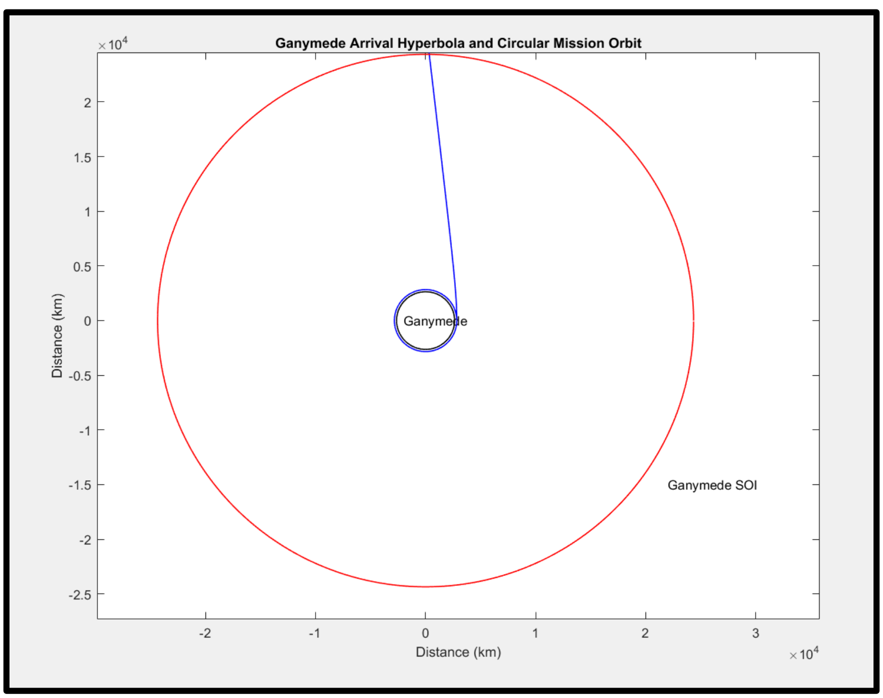


Figure 8 – Ganymede Arrival and insertion into circular mission orbit

The following figures shows the B-plane targeting of Mars, Jupiter, Callisto, and Ganymede. First, the spacecraft aims at 3719 km away from the center of Mars. The Mars targeting plot is presented in figure 9.

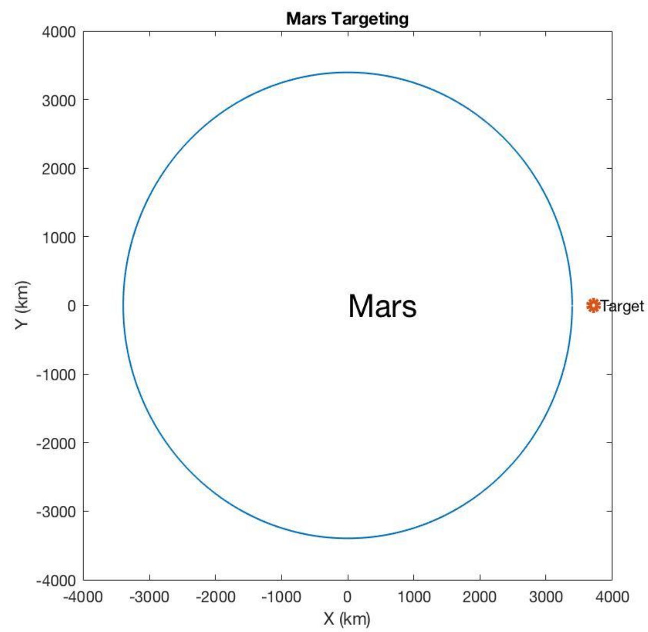


Figure 9 Mars Targeting

For Jupiter, the spacecraft aims at 3,389,766 km away from the center. Figure 10 shows the aiming location.

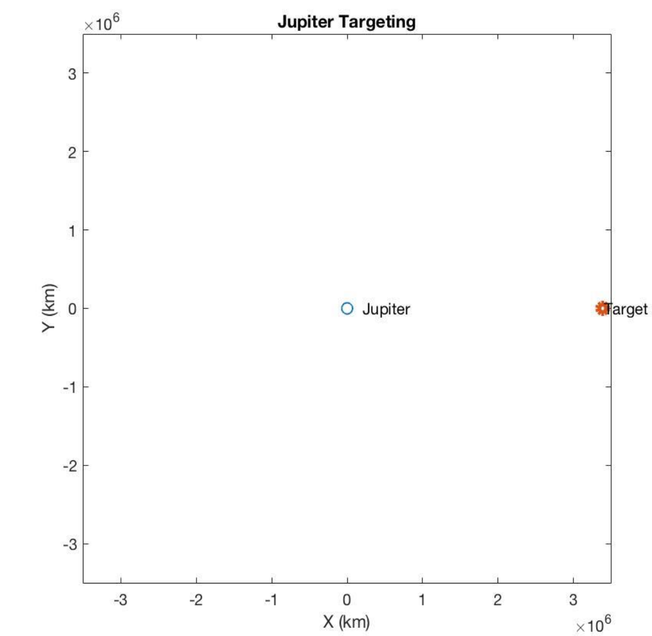


Figure 10 Jupiter Targeting

Next, the spacecraft aims at 3,114 km away from the center of Callisto for a flyby as shown in figure 11.

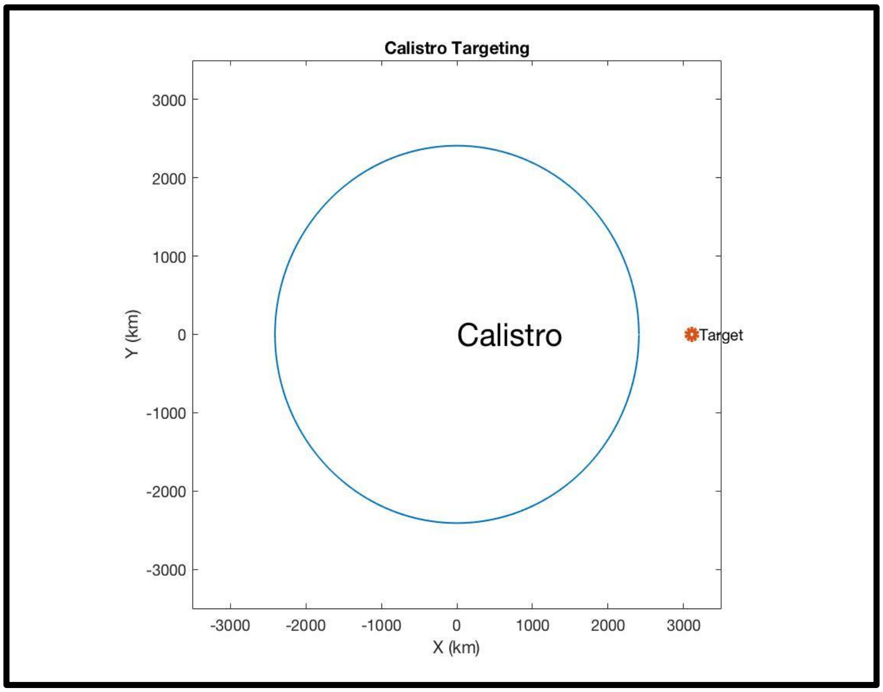


Figure 11 Callisto Targeting

Ultimately, figure 12 shows the targeting distance at 3,187 km away from the center of Ganymede before entering the SOI and injecting into the circular orbit.

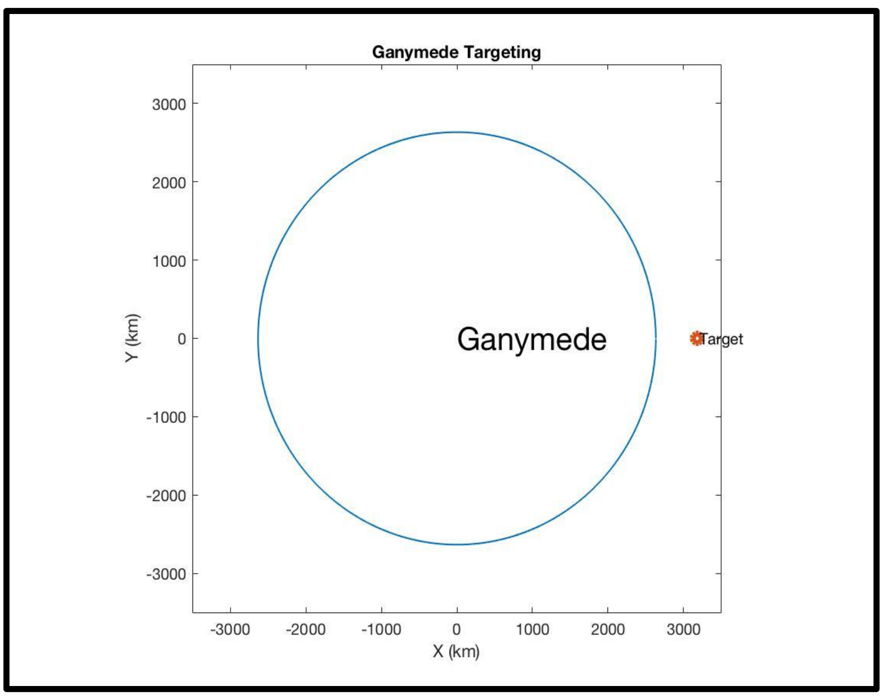


Figure 12 Ganymede targeting

VI. Mission Timeline

The total estimated time for this mission is 3.05 years or 1114 days. On day zero, the spacecraft is launched and sent to a heliocentric orbit. 94 days later, the spacecraft does a flyby at Mars to gain its velocity. After the flyby, the spacecraft spends 934.47 days, 2.56 years, coasting to Jupiter. The spacecraft enters the SOI of Jupiter on day 1029 of the mission. 83.55 days after entering the SOI of Jupiter, a flyby at Callisto, one of the Jupiter's moons, is performed to slow down its velocity on day 1112. Finally, the spacecraft is injected into a circular orbit around Ganymede on day 1114. For the ease of understanding, the mission timeline is summarized in table 1 below:

Day	Time (days)	Position	
0	-	Earth departure	STARTING POSITION
94	93.99	Mars flyby	
1029	934.47 (2.56 years)	Entering Jupiter SOI	
1112	83.55	Callisto flyby	
1114	1.61	Orbit around Ganymede	FINAL POSITION
Total Mission Time		1114 days = 3.05 years	

Table 1 - Mission timeline

VII. Mass budget

The goal of the mission is to send a spacecraft to Ganymede with the least launch mass. The mass constraints of the mission are to have a payload mass of $500kg$, and having a tank mass which is 10% of the total propellant used. To reduce the amount of fuel used, our team planned to burn at the very end (after reaching the final orbit), and this goal was achieved as the two fly-bys were used to reach the $200km$ orbit around Ganymede. The following table is the mass breakdown for the complete mission:

Ganymede's orbit burn	
Final mass after burn	$692.536g$
Initial mass before burn	$2618.1kg$

Table 2 - Mass budget table

The initial mass before the burn is the payload mass for the launcher which will be attached to the upper stage of the launch vehicle. The launcher which must produce a characteristic energy ($C_3 = v_\infty^2$) of $61.06\ km^2/s^2$ based on our calculation and support the launch mass is **Falcon Heavy (Expendable)** based on the plot provided. The propellant used for the mission is $1925.6\ kg$, which needs a tank with mass of $192.6\ kg$.

VIII. Conclusion

The mission of the project was to send a spacecraft to Ganymede. This was achieved with a heliocentric path: Earth < Mars < Jupiter (E < M < J), and once the spacecraft reached Jupiter's SOI, the path was: Callisto < Ganymede (C < G). There were two fly-bys which were added to the path to help reduce our propellant mass: 1) A trailing side fly-by of Mars, 2) A leading side fly-by of Callisto. Overall, our launch mass of the spacecraft came out to be $\mathbf{2618.9}\ \boldsymbol{kg}$. The time taken by the spacecraft leaving Earth's SOI and reaching a $200\ km$ orbit around Ganymede was $\mathbf{1114}\ \boldsymbol{days}$ ($\mathbf{3.05}\ \boldsymbol{years}$).

The following tables are the important parameters of our transfer orbits going from Earth to the final orbit around Ganymede:

Earth's SOI to Mars' SOI:

True anomaly at Earth departure	0°
True anomaly at Mars' SOI	85.55°
Eccentricity of transfer orbit	0.5935
Excess velocity required for departure	$7.814\ km/s$

Mars' fly-by:

Mars' fly-by altitude	$110km$
Eccentricity of hyperbola	16.98
Turning angle	6.7517°

Mars' SOI to Jupiter's SOI:

True anomaly after fly-by	73.103°
Eccentricity of transfer ellipse after fly-by	0.6518
True anomaly at Jupiter's SOI	179.86°

Jupiter's SOI to Callisto's SOI:

Perilume radius of the incoming orbit	$1149700km$
Eccentricity of the incoming hyperbola	1.26
True anomaly at intersection of incoming hyperbola and Callisto's orbit around Jupiter	72.44°

Callisto's fly-by:

Callisto's fly-by altitude	$660km$
Eccentricity of hyperbola	31.961
Turning angle	3.586°

Callisto's SOI to Ganymede's SOI:

True anomaly after fly-by	78.4953°
Eccentricity of transfer hyperbola after fly-by	1.1689
True anomaly at Ganymede's SOI	0.1278°

Final Orbit Insertion around Ganymede:

Eccentricity of the hyperbola inside SOI	8.58
Target altitude around Ganymede	$200km$
Velocity of the spacecraft on the hyperbola at the perilume altitude of $200km$	$5.7816\ km/s$
Last burn (Δv)	$3.92137\ km/s$

Our mission shared similarities with other missions to the Jovian system and beyond (seen in the introduction of the report). Most of the missions seen in the introduction had paths to the Jupiter moons and they used moon fly-bys in their mission.

There were parts in our mission path which could have been improved. More planet fly-bys would have helped us by reducing the propellant mass used. Multiple fly-bys of the same planet and moons by adding phasing would have potentially helped in further reducing our mass. Also, based on the mission statement where mass was a constraint, an addition of time constraint like reaching Ganymede with the least amount of time possible would have encouraged us to add powered fly-bys to our approach.

Appendix

FINAL CODE

```
%FINAL CODE FOR EARTH-MARS-JUPITER

clear all;
clc

%Radius of planets and moons
rEarth=6378; %Radius of earth
rMars=3396;  %Radius of Mars
rJupiter=71490; %Radius of Jupiter
rGanymede = 2634.49613; %Radius of Ganymede
rCallisto = 2410; %Radius of Callisto

%Semi-major axis of planets and moons
rSEarth = 149600000; %Radius of Earth's orbit wrt Sun
rSMars = 227900000; %Radius of Mar's orbit wrt Sun
rSJupiter = 778600000; %Radius of Jupiter's orbit wrt Sun
rSCallisto = 1882709; %Radius of Callisto's orbit wrt Jupiter
rSGanymede = 1070412; %Radius of Ganymede's orbit wrt Jupiter

%Graviational parameters of sun, planets, and moons
G = 6.67408*10^-20; % Universal gravitational constant
muSun=132712000000; %Standard gravitational parameter of Sun
muMars=42828; %Standard gravitational parameter of Mars
muJupiter=126686000; %Standard gravitational parameter of Jupiter
muEarth=398600; %Standard gravitational parameter of Earth
muCallisto = G *10759000*10^16; %Standard gravitational parameter of Callisto
muGanymede = G *14819000*10^16; %Standard gravitational parameter of Ganymede

thetaM=(85.5517*pi)/180;% Optimized value of true anomaly for Mars fly-by

%Orbital elements of the transfer orbit
eT1=   (rSEarth   -   rSMars)   /   ((rSMars   *   cos(thetaM))-(rSEarth   *
cos(0)));%Eccentricity of transfer orbit between Earth SOI to Mars SOI
hT1=sqrt(muSun * rSEarth * ( 1 + (eT1 * cos(0))));%Angular momentum for transfer
orbit between Earth SOI and Mars SOI
aT1 = (hT1^2)/((muSun)*(1 - (eT1^2)));

vP1= (muSun / hT1) * (1 + eT1 * cos(thetaM) );
vR1= (muSun / hT1) * (eT1 * sin(thetaM) );
v_Mars_beforeflyby = (((vP1)^2)+((vR1)^2))^0.5;
vM = sqrt(muSun / rSMars);% Speed of Mars in the heliocentric plane

v_d = sqrt(muSun*((2/rSEarth)-(1/aT1)));
vE = sqrt(muSun/rSEarth);
v_inf_dep = v_d - vE;

%Entereing Mars' Sphere of influence
vInfinityV= vP1 - vM;
vInfinityS= -1 * vR1;

vInfinity1 = sqrt( (vInfinityV)^2 + (vInfinityS)^2 );

%Mars flyby
```

```
rp= 110 + rMars; %Perilume radius around Mars (Optimized)

eF= 1 + ((rp * (vInfinity1)^2 ) / muMars); %Flyby orbit's eccentricity

delta1 = 2 * asin(1/eF); %Turning angle

phi1= (atan(vInfinityS / vInfinityV)) + (2*pi);

%Trailing side calculations
% This is the practical choice since we want to have a higher heliocentric
% speed after the flyby.

phi2= phi1 + delta1;

vP2= vM + (vInfinity1 * cos(phi2) );
vR2= - vInfinity1 * sin(phi2) ;

v_Mars_afterflyby = (((vP2)^2)+((vR2)^2))^0.5;
hT2= rSMars * vP2;% Angular momentum for transfer orbit between Mars SOI and
Jupiter SOI

theta2 = atan(( ( hT2 / (vR2 * rSMars)) - (muSun / (vR2 * hT2)))^-1);
eT2= (vR2 * hT2) / (muSun * sin(theta2));% Eccentricity for transfer orbit
between Mars SOI and Jupiter SOI
aT2 = (hT2^2) / ( muSun * ( 1 - (eT2)^2));% SEMI_MAJOR_AXIS after Mars flyby

theta3 =  (acos( (((hT2)^2 / (rSJupiter * muSun)) - 1) / eT2));

% True anomaly for Jupiter and transfer orbit intersection

vP3 = (muSun / hT2) * (1 + eT2 * cos(theta3) );
vR3= (muSun / hT2) * (eT2 * sin(theta3) );

vJ = sqrt(muSun / rSJupiter);% Velocity of Jupiter in the heliocentric plane

%Entereing Jupiter's Sphere of influence
vInfinityV2= vP3 - vJ;% HYPERBOLIC EXCESS VELOCITY TRANSVERSE entering Jupiter's
SOI
vInfinityS2= -1 * vR3;% HYPERBOLIC EXCESS VELOCITY RADIAL entering Jupiter's
SOI
vInfinity2 = sqrt( (vInfinityV2)^2 + (vInfinityS2)^2 );

rpJ = 1149700; %Perilume radius around Jupiter (Optimized)

%Jupiter Arrival
eJupiter = 1 + ((rpJ .* (vInfinity2).^2)./ muJupiter);
a_jupiter = (-muJupiter) ./ (vInfinity2).^2;
h_Jupiter = ( muJupiter .* a_jupiter .* ( 1 - eJupiter.^2)).^(0.5);

theta_intersection= acos ( (1./eJupiter) .* ( ((h_Jupiter.^2)./(muJupiter .*
rSCallisto)) - 1 ) );%Intersection of incoming hyperbola with Callisto's SOI
SOI_Jupiter = 48200000; %SOI radius of Jupiter
theta_intersection1= acos ( (1./eJupiter) .* ( ((h_Jupiter.^2)./(muJupiter .*
SOI_Jupiter)) - 1 ) );%Intersection of heliocentric ellipse with Jupiter's SOI

%Callisto SOI orbit - Jupiter incoming hyperbola
v_hyp_aR = (muJupiter./h_Jupiter).*eJupiter.*sin(theta_intersection);
```

```
v_hyp_aT = (muJupiter./h_Jupiter).*(1 + (eJupiter.*cos(theta_intersection)));
v_SpaceCraft_Jupiter = sqrt ( (v_hyp_aR).^2 + (v_hyp_aT).^2 );
vCallisto = sqrt(muJupiter./rSCallisto);

%Velocities inside Callisto's SOI
v_inf_CallistoV = v_hyp_aT - vCallisto;
v_inf_CallistoS = - v_hyp_aR;
v_inf_Callisto = ((v_inf_CallistoV).^2 + (v_inf_CallistoS).^2 ).^0.5;

rp_C= 660 + rCallisto;% perilume radius around Callsito (Optimized)
eF_a= 1 + ( (rp_C .* (v_inf_Callisto).^2 ) ./  (muCallisto));% Flyby orbit's
eccentricity
delta2 = 2 .* asin(1./eF_a);% Aiming angle
phi3= (atan(v_inf_CallistoS ./ v_inf_CallistoV)) + (2*pi);

%Leading side calculations
% This is the practical choice since we want to have a slower juliocentric
% speed after the flyby.

phi4= phi3 - delta2;

%Leaving Callisto's SOI interface
vP_Callisto= vCallisto + (v_inf_Callisto .* cos(phi4));
vR_Callisto= - v_inf_Callisto .* sin(phi4) ;

hT_Callisto= rSCallisto * vP_Callisto;% Angular momentum for transfer orbit
between Amlathea SOI and Callisto SOI
theta_Callisto_flyby = (atan(( ( hT_Callisto / (vR_Callisto * rSCallisto)) -
(muJupiter / (vR_Callisto * hT_Callisto)))^-1));
eT_Callisto_Ganymede=  (vR_Callisto  *  hT_Callisto)  /  (muJupiter  *
sin(theta_Callisto_flyby));% Eccentricity for transfer orbit between Callisto
SOI and Ganymede SOI
aT_Callisto_Ganymede  =  (hT_Callisto^2)  /  (muJupiter  *  (  1  -
(eT_Callisto_Ganymede)^2));% SEMI_MAJOR_AXIS after Amalthea flyby
v_SpaceCraft_Callisto =  ( (vP_Callisto).^2 + (vR_Callisto).^2 )^0.5;

% True anomaly for Ganymede and transfer orbit intersection
theta_ganymede =  (acos( (((hT_Callisto)^2 / (rSGanymede * muJupiter)) - 1) /
eT_Callisto_Ganymede));

%Velocities entering Ganymede's SOI interface
vP_ganymedeSOI  =  (muJupiter  /  hT_Callisto)  *  (1  +  eT_Callisto_Ganymede  *
cos(theta_ganymede) );
vR_ganymedeSOI  =  (muJupiter  /  hT_Callisto)  *  (eT_Callisto_Ganymede  *
sin(theta_ganymede) );

v_ganymede  =  sqrt(muJupiter  /  rSGanymede);%  Velocity  of  Jupiter  in  the
heliocentric plane

%Entereing Ganymede's Sphere of influence
vInfinityVganymede= vP_ganymedeSOI - v_ganymede;
vInfinitySganymede= -1 * vR_ganymedeSOI;
v_inf_ganymede = sqrt( (vInfinityVganymede)^2 + (vInfinitySganymede)^2 );


r_p = 200 + rGanymede; %Target radius around Ganymede (Optimized)
```

```
e_hyperbolic_into_ganymede = 1 + ( (r_p .* (v_inf_ganymede).^2) ./ muGanymede);
%Eccentricity of the hyperbola inside Ganymede SOI
v_p_around_ganymede = sqrt ( (v_inf_ganymede).^2 + ((2 .* (muGanymede))./r_p)
); %Velocity at the perilume of the hyperbola
v_final_orbit = sqrt(muGanymede./r_p); %Velocity of the 200km orbit around
Ganymede
lastburnV = v_p_around_ganymede - v_final_orbit; %Burn to get into the 200km
around Ganymede

%Propellant Mass calculations
vstar = 300 * 9.81; %Exit velocity

%Mass calculation using rocket equation
a = exp(lastburnV.*1000./vstar);
spacecraft_drymass = 500; %Given
mp = ((spacecraft_drymass .* a) - spacecraft_drymass) ./ (1.1 - (0.1 .*a));
%Mass of the propellant
m_0 = spacecraft_drymass + mp + (0.1.*mp); %Total spacecraft launch mass
m_f = m_0 - mp; %Mass after burn
```

CODE FOR HELIOCENTRIC & PLANET CENTRIC PLOTS

```
%GRAPH

% Plot of heliocentric trajectory using values that yield best mass (by
inspection of surface plot)

% BEST POSSIBLE VALUES:
% fly by altitude: malt = 110 km
% rp_alt = 200 km
% thetaM = 85.5517 deg
% Corresponds to element 1018 for all other 1x1018 arrays at malt = 110

% Plot of first transfer orbit from Earth to Mars
th = 0:0.01:85.3*pi/180;
R1 = (hT1(1018)^2/muSun)./(1+eT1(1018)*cos(th));
x1 = cos(th).*R1;
y1 = sin(th).*R1;
plot(x1,y1,'g','linewidth',3)
ylim ([-10*10^8 10*10^8]);
grid on
hold on

% The following are the 1018th element of their respective arrays that yield
% lowest mass (for Mars fly-by altitude = 110 and ThetaM= 85.5177))
thetaM = 85.551699999999997;
theta2 = 1.275897618738569;
theta3 = 3.139098908060187;
eT2 = 0.651843179630087;
hT2 = 5.997924774895925e+09;

% Calculate offset angle between apse lines of the transfer orbits
t = (thetaM*pi/180)-theta2;

% Plot of second transfer orbit to Jupiter after Mars fly-by
```

```
theta = (theta2+t):0.01:(theta3+t);                         % Offset angle
included
R2 = (hT2^2/muSun)./(1+eT2*cos(theta-t));
x2 = cos(theta).*R2;
y2 = sin(theta).*R2;
plot(x2,y2,'r','linewidth',1)
xlabel('Distance (km)');
ylabel('Distance (km)');
title ('Helicentric trajectory from Earth to Ganymede with Mars fly-by')

% Plot circular orbits for Earth, Mars and Jupiter
thm = 0:0.01:2*pi;
xe = rSEarth*cos(thm);
ye = rSEarth*sin(thm);
plot(xe,ye,'b')

xm = rSMars*cos(thm);
ym = rSMars*sin(thm);
plot(xm,ym,'b')

xj = rSJupiter*cos(thm);
yj = rSJupiter*sin(thm);
plot(xj,yj,'b')

% Draw the planets
% Earth
ex = rSEarth*cos(0);
ey = rSEarth*sin(0);
scatter(ex,ey,'b','filled','linewidth',4);
text(ex+50000000, ey, 'Earth', 'Fontsize', 12);

% Mars
mx = rSMars*cos(85*pi/180);
my = rSMars*sin(85*pi/180);
scatter(mx,my,'r','filled','linewidth',2);
text(mx+50000000, my+50000000,'Mars Fly-by', 'Fontsize', 12);

% Jupiter
jx = rSJupiter*cos((theta3+t));
jy = rSJupiter*sin((theta3+t));
scatter(jx,jy,'o','filled','linewidth',6);
text(jx+20000000, jy-50000000, 'Jupiter', 'Fontsize', 12);

%Sun
scatter(0,0,'y','linewidth',29)


% Planet-Centric Trajectories

% Earth Departure
figure;
thE = 0:0.01:20*pi/180;
R = ((hT1^2)/muSun) ./ (1 + (eT1 .* cos(thE)));
xE= cos(thE).*R;
yE= sin(thE).*R;
plot(xE,yE,'g','linewidth',1)   % plot heliocentric trajectory
ylim([-2*10^6, 2*10^6]);
```

```
xlabel('Distance (km)');
ylabel('Distance (km)');
title('Earth Departure enroute to Mars')
axis equal
hold on

% Plot Earth
scatter(R(1)-925000,0,'b','linewidth',2);
text(R(1)-925000+100000, 0+50000,'Earth', 'Fontsize', 10);

hold on
theta= 0:0.01:2*pi;
xgsE=925000*cos(theta)+R(1)-925000;
ygsE=925000*sin(theta);
plot(xgsE,ygsE,'r','linewidth',1);          % Plot Earth's SOI
text(R(1)-1125000, 0+1100000,'Earth SOI', 'Fontsize', 10);
hold off

figure;
% Plot Mars Fly-By
thF = -93.1*pi/180:0.01:93.5*pi/180;
R = ((hF^2)/muMars) ./ (1 + (eF .* cos(thF)));
xMF= cos(thF).*R;
yMF= sin(thF).*R;
plot(xMF,yMF,'g','linewidth',1)
xlabel('Distance (km)');
ylabel('Distance (km)');
title('Mars Fly-By Trajectory at 110 km altitude')
axis equal

hold on
%Plot Planet Mars
theta= 0:0.01:2*pi;
x = rMars*cos(theta);
y = rMars*sin(theta);
plot(x,y)
text(-0.8*10^5, 0,'Mars', 'Fontsize', 10);

hold on
% Plot Mars SOI
theta= 0:0.01:2*pi;
x = 577000*cos(theta);
y = 577000*sin(theta);
plot(x,y)
ylim([-577000,577000]);
text(5*10^5,3*10^5,'Mars SOI', 'Fontsize', 10);
hold off

figure;

%Jupiter incoming hyperbola
theta = theta_intersection1:-0.01:theta_intersection;
%theta = 0:0.01:theta_intersection1;
R= ((h_Jupiter^2)/muJupiter) ./ (1 + (eJupiter .* cos(theta)));
x= R.* cos(theta);
y= R.* sin(theta);
plot(x,y,'linewidth',1)
```

```
xlabel('Distance (km)');
ylabel('Distance (km)');
title('Plot of Julicoentric spacecraft trajectories')
hold on



%Callisto-Ganymede transfer orbit
offset = theta_intersection-theta_Callisto_flyby ;
theta = (theta_ganymede+offset):0.01: (theta_Callisto_flyby+offset);
R= ((hT_Callisto^2)/muJupiter) ./ (1 + (eT_Callisto_Ganymede .* cos(theta-
offset)));
x= (R.* cos(theta));
y= (R.* sin(theta));
plot(x,y,'linewidth',1)
hold on

%Plotting Callsito
xc=1882709*cos(theta_intersection);
yc=1882709*sin(theta_intersection);
scatter(xc,yc,'r','filled','linewidth',3)
text(xc+200000, yc+100000,'Callisto Fly-by', 'Fontsize', 10);

%Plotting Ganymede
xg=1070412*cos(theta_ganymede);
yg=1070412*sin(theta_ganymede);
scatter(xg,yg,'g','filled','linewidth',3)
text(xg+100000, yg+100000,'Ganymede', 'Fontsize', 10);

%Callisto's orbit
theta= 0:0.01:2*pi;
xco=1882709*cos(theta);
yco=1882709*sin(theta);
plot(xco,yco,'linewidth',1)
axis equal
hold on

%Ganymede's orbit
theta= 0:0.01:2*pi;
xgo=1070412*cos(theta);
ygo=1070412*sin(theta);
plot(xgo,ygo,'linewidth',1)
axis equal
hold on

%Plot of Jupiter
theta= 0:0.01:2*pi;
x = rJupiter*cos(theta);
y = rJupiter*sin(theta);
plot(x,y)
text(100000, 50000,'Jupiter', 'Fontsize', 10);

% xlim([-4000000 4000000])
% ylim([-4000000 4000000])
hold on

% Plot of Jupiter's SOI
```

```
theta= 0:0.01:2*pi;
x = 48200000*cos(theta);
y = 48200000*sin(theta);
plot(x,y,'r')
text(3.5*10^7, 4*10^7,'Jupiter''s SOI', 'Fontsize', 10);
hold off

figure;
% Plot Callisto Fly-By
thF = -90*pi/180:0.01:90*pi/180;
R = ((hF_a^2)/(G*m_Callisto)) ./ (1 + (eF_a .* cos(thF)));
xCF= cos(thF).*R;
yCF= sin(thF).*R;
plot(xCF,yCF,'k','linewidth',1)
xlabel('Distance (km)');
ylabel('Distance (km)');
title('Callisto Fly-By Trajectory at 625 km altitude')
axis equal

hold on
%Plot Planet Callisto
theta= 0:0.01:2*pi;
rCallisto = 2410.79;
x = rCallisto*cos(theta);
y = rCallisto*sin(theta);
plot(x,y)
text(-1*10^4, 0.2*10^4,'Callisto', 'Fontsize', 10);

hold on
% Plot callisto SOI
theta= 0:0.01:2*pi;
m_J = 1.899*10^27;
D_Callisto = 1882709;
rSOI_Callisto = D_Callisto * (m_Callisto/m_J)^(2/5);
x = rSOI_Callisto*cos(theta);
y = rSOI_Callisto*sin(theta);
plot(x,y)
ylim([-rSOI_Callisto,rSOI_Callisto]);
text(2.5*10^4,3*10^4,'Callisto SOI', 'Fontsize', 10);
hold off


% Plot Arrival hyperbola to Ganymede
figure;
thG = 0*pi/180:0.01:93*pi/180;
R = ((h_hyperbola_G^2)/mewGanymede) ./ (1 + (e_hyperbolic_into_ganymede .*
cos(thG)));
xAG= cos(thG).*R;
yAG= sin(thG).*R;
plot(xAG,yAG,'b','linewidth',1)   % plot heliocentric trajectory
xlabel('Distance (km)');
ylabel('Distance (km)');
title('Ganymede Arrival Hyperbola and Circular Mission Orbit')
axis equal
hold on

 % Plot Ganymede
```

```
 theta = 0:0.01:2*pi;
 rGanymede = 2634.5;
 x = rGanymede*cos(theta);
 y = rGanymede*sin(theta);
 plot(x,y,'k','linewidth',1)
 text(-0.2*10^4, 0,'Ganymede', 'Fontsize', 10);

 hold on
 % Plot mission orbit
 r_p = 200 + 2634.49613;
 x = r_p*cos(theta);
 y = r_p*sin(theta);
 plot(x,y,'b','linewidth',1)

hold on
% Plot Ganymede SOI
theta= 0:0.01:2*pi;
D_Ganymede = 1070412;
m_Ganymede = 14819000*10^16;
m_J = 1.899*10^27;
rSOI_Ganymede = D_Ganymede * (m_Ganymede/m_J)^(2/5);
xSG=rSOI_Ganymede*cos(theta);
ySG=rSOI_Ganymede*sin(theta);
plot(xSG,ySG,'r','linewidth',1);          % Plot Earth's SOI
text(2.2*10^4, -1.5*10^4,'Ganymede SOI', 'Fontsize', 10);
hold off
```

<u>CODE FOR B-PLANE TARGETTING</u>

```
%% B_plane Targeting Plot

%Mars Flyby
figure()
B_Mars = rp*vp_Mars/vInfinity1;
X_Mars = rMars*cos(theta);
Y_Mars = rMars*sin(theta);
plot(X_Mars,Y_Mars,'LineWidth',1)
hold on
scatter(B_Mars,0,'LineWidth',5)
axis equal
hold off
text(0, 0,'Mars', 'Fontsize', 20)
text(B_Mars+100, 0,'Target', 'Fontsize', 10)
title('Mars Targeting')
xlabel('X (km)')
ylabel('Y (km)')
xlim([-4000 4000])
ylim([-4000 4000])

%Jupiter Approach
figure()
%b_1
X_Jup = rJupiter*cos(theta);
Y_Jup = rJupiter*sin(theta);
plot(X_Jup,Y_Jup,'LineWidth',1)
hold on
scatter(b_1,0,'LineWidth',5)
```

```
axis equal
hold off
text(200000, 0,'Jupiter', 'Fontsize', 10)
text(b_1+10000, 0,'Target', 'Fontsize', 10)
title('Jupiter Targeting')
xlabel('X (km)')
ylabel('Y (km)')
xlim([-3500000 3500000])
ylim([-3500000 3500000])

%Calistro Flyby
figure()
X_Cal = 2410*cos(theta);
Y_Cal = 2410*sin(theta);
plot(X_Cal,Y_Cal,'LineWidth',1)
hold on
B_Cal=sqrt( (rp_a + ((G *10759000*10^16)./(v_SpaceCraft_Jupiter).^2)).^2 -
(((G *10759000*10^16)./(v_SpaceCraft_Jupiter).^2).^2) );
scatter(B_Cal,0,'LineWidth',5)
axis equal
hold off
text(0, 0,'Calistro', 'Fontsize', 20)
text(B_Cal+100, 0,'Target', 'Fontsize', 10)
title('Calistro Targeting')
xlabel('X (km)')
ylabel('Y (km)')
xlim([-3500 3500])
ylim([-3500 3500])

%Ganymede Entry
figure()
X_Gan = 2634.49613*cos(theta);
Y_Gan = 2634.49613*sin(theta);
plot(X_Gan,Y_Gan,'LineWidth',1)
hold on
B_Gan=sqrt( (r_p + (mewGanymede./v_inf_ganymede.^2)).^2 -
((mewGanymede./v_inf_ganymede.^2).^2) );
scatter(B_Gan,0,'LineWidth',5)
axis equal
hold off
text(0, 0,'Ganymede', 'Fontsize', 20)
text(B_Cal+100, 0,'Target', 'Fontsize', 10)
title('Ganymede Targeting')
xlabel('X (km)')
ylabel('Y (km)')
xlim([-3500 3500])
ylim([-3500 3500])
```

MISSION TIMELINE CODE

```
%% Time Line

    %Earth to Mars (Ellipse)
    T_EM = 2*pi*sqrt(aT1*aT1*aT1/muSun);
    E_EM = 2*atan(sqrt((1-eT1)/(1+eT1))*tan(thetaM/2));
    M_EM = E_EM-eT1*sin(E_EM);
    Dt_EM = M_EM*T_EM/2/pi / (60*60*24);
```

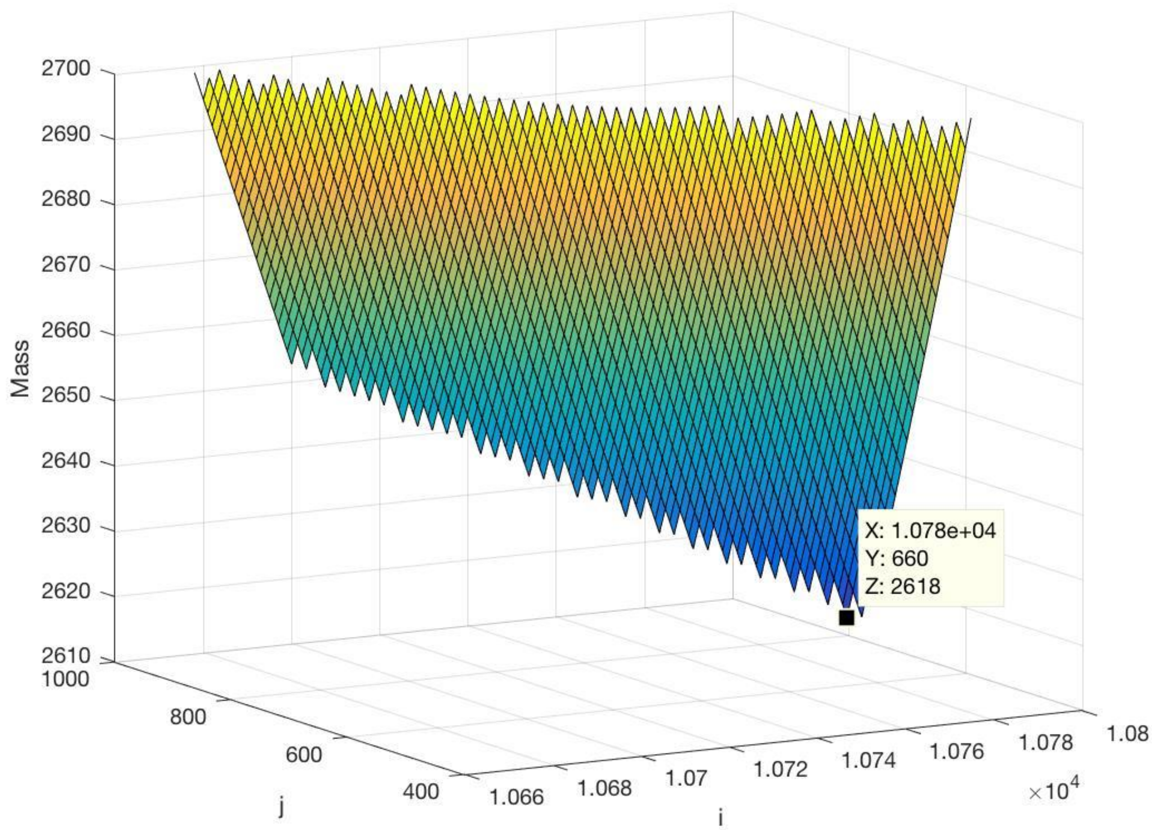
```
    %Mars to Jupiter
    T_MJ = 2*pi*sqrt(aT2*aT2*aT2/muSun);
    E_MJ_1 = 2*atan(sqrt((1-eT2)/(1+eT2))*tan(theta2/2));
    M_MJ_1 = E_MJ_1-eT2*sin(E_MJ_1);
    E_MJ_2 = 2*atan(sqrt((1-eT2)/(1+eT2))*tan(theta3/2));
    M_MJ_2 = E_MJ_2-eT2*sin(E_MJ_2);
    DM_MJ = M_MJ_2 - M_MJ_1;
    Dt_MJ = DM_MJ*T_MJ/2/pi / (60*60*24);

    %Jupiter to Calistro
    FJ1 = 2*atanh(sqrt((eJupiter-
1)/(eJupiter+1))*tan(theta_intersection1/2));
    FJ2 = 2*atanh(sqrt((eJupiter-1)/(eJupiter+1))*tan(theta_intersection/2));
    MJ1 = eJupiter*sinh(FJ1)-FJ1;
    MJ2 = eJupiter*sinh(FJ2)-FJ2;
    DMJ = MJ1-MJ2;
    Dt_J = DMJ/(muJupiter*muJupiter/(h_Jupiter^3)*(eJupiter*eJupiter-1)^1.5)
/ (60*60*24);

    %Calistro to Ganemyde
    F_CG_1 = 2*atanh(sqrt((eT_Callisto_Ganymede-
1)/(eT_Callisto_Ganymede+1))*tan(theta_Callisto_flyby/2));
    F_CG_2 = 2*atanh(sqrt((eT_Callisto_Ganymede-
1)/(eT_Callisto_Ganymede+1))*tan(theta_ganymede/2));
    M_CG_1 = eT_Callisto_Ganymede*sinh(F_CG_1)-F_CG_1;
    M_CG_2 = eT_Callisto_Ganymede*sinh(F_CG_2)-F_CG_2;
    DM_CG = M_CG_1-M_CG_2;
    Dt_CG =
DM_CG/(muJupiter*muJupiter/(hT_Callisto^3)*(eT_Callisto_Ganymede*eT_Callisto_
Ganymede-1)^1.5) / (60*60*24);

    %Total Mission Time
    Dt_total = (Dt_EM + Dt_MJ + Dt_J + Dt_CG);
```

OPTIMIZATION GRAPH
In addition to figure 1, the following graph was used to optimize the periapse of Jupiter arrival hyperbola and Callisto fly-by altitude:



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