Optimal Gravity Assisted Orbit Insertion for Europa Orbiter Mission

Deepak Gaur[1], M. S. Prasad[2]

[1]M. Tech. (Avionics), Amity Institute of Space Science and Technology, Amity University, Noida, U.P., India

[2]Director, Amity Institute of Space Science and Technology, Amity University, Noida, U.P., India

ABSTRACT

The Europa Orbiter Mission is designed to search for subsurface liquid oceans on the third largest moon of Jupiter, Europa. The primary objective of this research is to analyze the optimal orbit insertion maneuver that will put the spacecraft into orbit around Jupiter. It was found that an impulsive velocity change of -1.33 km/s was required to put the spacecraft into an initial orbit. Using the gravity of Jupiter's largest moon, Ganymede, to slow the spacecraft upon arrival to Jupiter, reduced the change in velocity by approximately 30%. The initial orbits around Jupiter for the two cases were nearly identical. This suggests that this type of gravitational assists could be used to decrease the mass of fuel needed on board on the spacecraft. Possible problems with the assisted trajectory lie in the timing and relative phase angle of Jupiter's moon. If the spacecraft were to deviate from the optimal arrival by as little as 25 seconds, it could potentially collide with the moon. The position of the other moon of Jupiter must also be considered as they could affect the spacecraft's trajectory, or worst collide with the spacecraft.

Keywords: Europa, Ganymede, Spacecraft Trajectory, Hohmann Transfer.

1. INTRODUCTION

The Europa orbiter mission, was scheduled for Jupiter to look at one of the solar systems most promising locations for life beyond earth. There are three primary mission goals that have been outlined by the Europa Orbiter Science Definition Team. They are to determine the presence or absence of a subsurface liquid ocean, characterize the three-dimensional distribution of any subsurface liquid and its overlaying ice layers, and finally to understand the formation of surface features and identify possibly landing sites for future lander missions.

Scientists believe that a relatively young surface of ice, possibly only about 1 km thick exists on Europa. Internal heating due to Jupiter's tidal pull could melt the underside of the icepack, forming an ocean of liquid water underneath the surface. The presence of a liquid ocean on Europa could lead to the discovery of life. Micro-organisms have been found to exist at the bottom of the Earth's ocean with little to no sunlight. The organisms survive on the upwelling chemical nutrients from the interior of the planet. It is believed that similar organisms could survive at the bottom of the ocean on Europa.

The Europa Orbiter comprises of an instrument called a radar sounder to measure the thickness of ice. The instrument will bounce radio waves through the ice and measure the time delay for the signal to return. Other instruments would be used to examine the surface and interior characteristics. The mission could lead to a lander mission that would make detailed studies of the surface characteristics, such as composition, seismology, and physical state. The lander could then lead to another lander mission that would be designed to penetrate the ice and use robotic submarines to reach the bottom of the ocean for evidence of life.

Gravity assisted trajectories are an important part of astrodynamic applications, specifically for interplanetary missions. By using the gravity of other planets and moons, a space vehicle can travel through the solar system without the need for large amounts of fuel to be carried on board. Many interplanetary missions have utilized the effect of the planets' gravity to their advantage. One example is the Voyager 2 spacecraft. After leaving Earth, the spacecraft did not have enough velocity to escape the solar system, or even reach the outer planets, but by using the gravity of other plants during its flybys, it was able to obtain enough velocity to escape the solar system, see figure 1.

Interplanetary orbits can be calculated using the patched conic method. This method assumes a satellite to be in orbit around a local primary body. The primary body will have control of the satellite only if it is within the local sphere of influence. Other bodies, such as the sun or moon, will always have an influence on a satellite in orbit around earth but those influences will be small compared to the influence of Earth, the primary body.

The sphere of influence of a body will have a radius of approximately:

$$r_{SOI} = R*\left(\frac{M_2}{M_1}\right)^{2/5} \quad (1)$$

Where R is the distance between the primary body (1) and the other body (2), and M is the mass of the bodies respectfully.

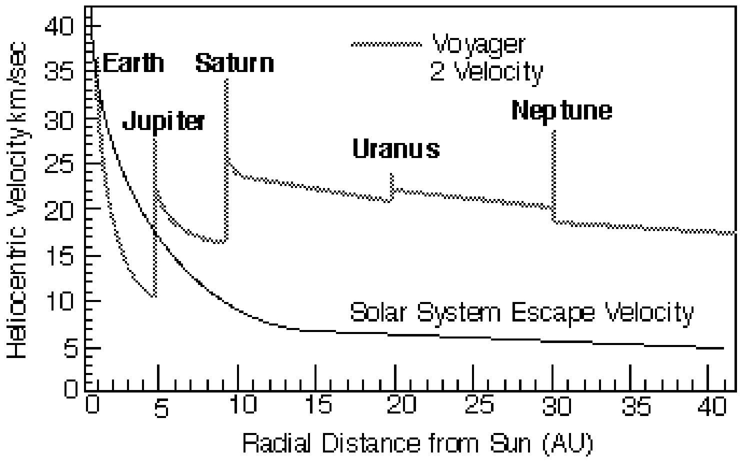

Figure 1 Voyager 2 Gravity Assist Velocity Changes

For interplanetary trajectories, a satellite must escape the pull of Earth and achieve an orbit around the sun. The velocity of a satellite when it leaves Earth's sphere of influence is called the hyperbolic escape velocity, $V_{\inf}$ in figure 2. The velocity the satellite has with respect to the sun will be the satellite's escape velocity with respect to the earth plus the velocity of the Earth with respect to the sun, equation 2.

$$V_{Sat/Sun} = V_{\inf/earth} + V_{earth/sun} \quad (2)$$

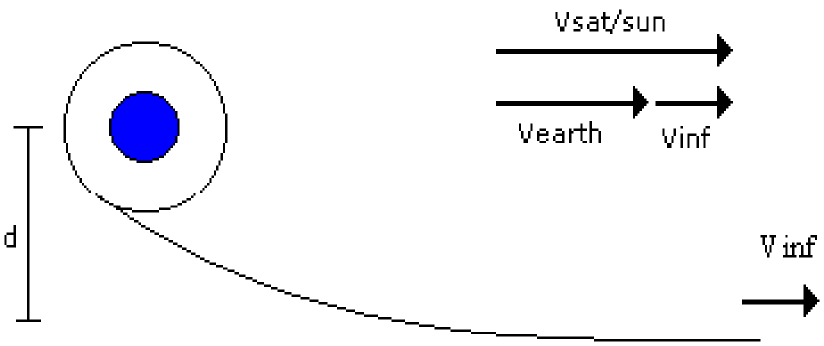

Figure 2 Hyperbolic Escape Geometry

The velocity that the satellite has with respect to the sun will then define the orbit the satellite has around the sun. If the desired velocity with respect to the sun is known, for example to initiate a Hohmann transfer, the required escape velocity, $V_{\inf}$, can be easily found. In figure 2, d is the distance between the body and the satellite's asymptote and is equal to:

$$d = \mu * \frac{\sqrt{e^2 - 1}}{V_{\inf}^2} \quad (3)$$

If a trajectory brings the satellite within another body's sphere of influence, the satellite's motion can be approximated by assuming a hyperbolic orbit around that object until it leaves that bodies sphere of influence. If a final orbit is desired around the body, then a change in velocity is required to put the satellite in a closed orbit around the body. If a simply flyby is desired, the body's motion can be used to speed up or slow down the satellite with respect to its primary

body. This is done by adding or subtracting energy from the satellite depending on which side of the body the satellite passes. If the satellite passes behind the body, the satellite will "slingshot" around the body and gain energy. If the satellite passes in front of the planet, the satellite will lose some of its energy to the body, figure 3.
The satellite's trajectory can also be computed by using the three-body equations of motion. This assumes the satellite to be in orbit around the primary body with the third body perturbing the satellites motion. The three-body equations of motion are developed from the two-body equation, Equation 4, to take the influence of the third body into account.

$$\frac{\partial^2 \vec{r}}{\partial t^2} = -\mu * \frac{\vec{r}}{r^3} \tag{4}$$

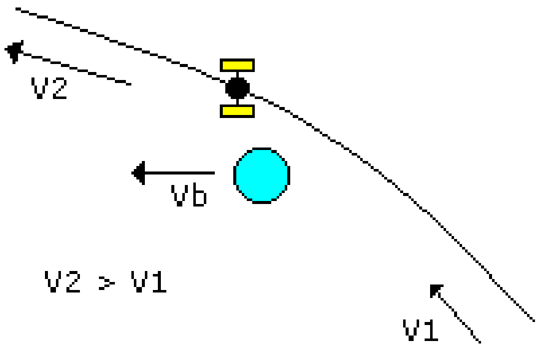

Figure 3 Satellite flyby

In the two-body equation r is the vector in the inertial frame from the primary body to the orbiter, and m is the gravitational parameter for the primary body. The three-body equation, Equation 5, introduced two perturbations to the two-body equation, the direct effect and indirect effect. The first effect, direct, is the gravitational acceleration due to the third body on the orbiter. The second, indirect, is the acceleration of the third body on the primary body.

$$\frac{\partial^2 \vec{r}_{12}}{\partial t^2} = -\mu_1 * \frac{\vec{r}_{12}}{r_{12}} + \mu_3 \left(\frac{\vec{r}_{23}}{r_{23}^3} - \frac{\vec{r}_{13}}{r_{13}^3} \right) \tag{5}$$

In the three-body equation, r_{12} is the vector from the primary body to the orbiter, r_{23} is the vector from the orbiter to the third body, r_{13} is the vector from the primary body to the third body, and finally m_1 and m_3 are the gravitational parameters for the primary and third bodies respectively. Numerical integration of the three-body equation of motion will determine a satellite's position with respect to the primary body as a function of time. Analysis of this output can be used to determine the effect the third body had on the motion of the satellite.

2. PROBLEM OF INTEREST

As the Europa Orbiter enters the sphere of influence of Jupiter, it will have a velocity, $V_{\inf}$, with respect to Jupiter. This velocity will be the difference between the spacecraft's velocity with respect to the sun minus Jupiter's velocity with respect to the sun. The first step in the Jupiter orbit insertion is to calculate this velocity.
The spacecraft's velocity when it reaches Jupiter will be the velocity at apoapsis of the Hohmann transfer from the Earth to Jupiter. The semi-major axis of this orbit will be the orbit radius of Earth plus the orbit radius of Jupiter divided by two. This is assuming that Earth and Jupiter have circular orbits about the sun. The velocity at apoapsis will then be defined by the vis-visa equation:

$$V = \sqrt{\mu_{Sun} * \left(\frac{2}{r} - \frac{1}{a} \right)} \tag{6}$$

Using the appropriate vales for m_{Sun}, r, and a, the velocity at apoapsis is calculated to be 7.4 km/s. The velocity of Jupiter, assuming a circular orbit, is:

$$V_C = \sqrt{\frac{\mu_{Sun}}{r_{JUP}}} \tag{7}$$

This value turns out to be 13.1 km/s. The difference yields the relative velocity of the spacecraft with respect to Jupiter as –5.6 km/s. The satellite is assumed to have a closest approach to Jupiter of 7*10^5 km. This implies that the asymptote distance, d in figure 1, will be 2.46*10^6 km, from Equation 3. This is found by first calculating e, the eccentricity of the hyperbolic orbit, from Equation 8.

$$e = 1 + \left(r_P * \frac{V_{\inf}^2}{\mu_{JUP}} \right) \tag{8}$$

In Equation 8, r_P is the closest approach (periapsis radius), $V_{\inf}$ is the approach velocity with respect to Jupiter, and finally μ_{JUP} is the gravitational parameter for Jupiter. The spacecraft position is assumed to be the asymptote distance in the y direction and the radius of Jupiter's sphere of influence in the x direction, with respect to Jupiter, as it enters Jupiter's sphere of influence, figure 4.

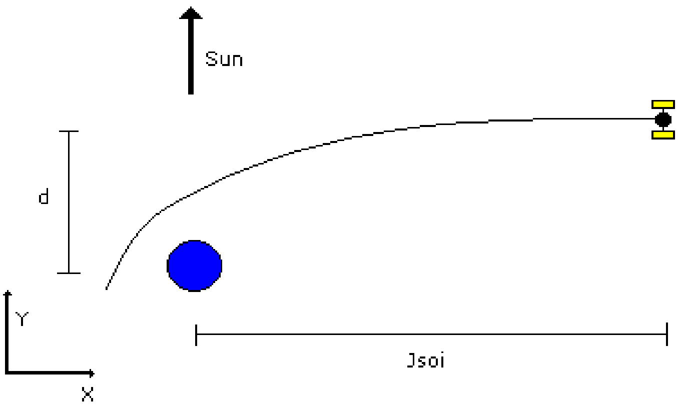

Figure 4 Spacecraft Approach Geometry

The initial desired orbit around Jupiter after insertion is defined to have a periapsis radius of 7*10^5 km and an apoapsis radius of 10^6 km. To get to this orbit, a change in velocity must be applied at the spacecraft's closest approach. To calculate the ΔV required to place the spacecraft in orbit around Jupiter, the velocity at periapsis must be found. Using Equation 9, with the appropriate values, the velocity of the spacecraft at periapsis is 19.9 km/s.

$$V_P = \sqrt{V_{\inf}^2 + 2 * \frac{\mu_{JUP}}{r_P}} \tag{9}$$

The desired velocity at that point can be found from the vis-visa equation, Equation 6, with the appropriate values for the orbit. The calculated velocity is 18.4 km/s. This implies that an impulsive ΔV of -1.45 km/s must be applied to put the satellite into the desired orbit around Jupiter, figure 5.

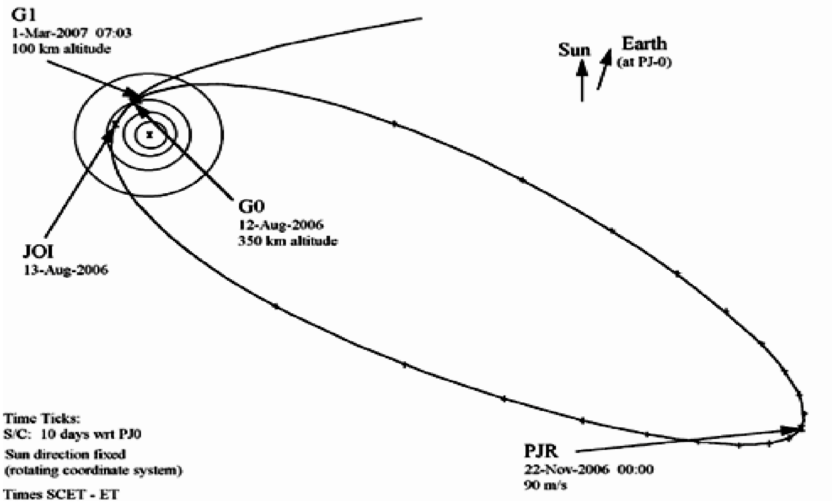

Figure 5 Initial Orbit about Jupiter

The calculations of the spacecraft's path have assumed that all orbits lie within the same plane. Any plane change manoeuvres that would be required have been neglected for simplicity.

3. ANALYSIS AND RESULTS

In an effort to reduce the velocity change required to put the Europa Orbiter in orbit around Jupiter, a gravitational assist around Jupiter's largest moon, Ganymede, was considered. Ganymede orbits Jupiter at a distance of $1.07*10^6$km, with a radius of 2360 km and has a mass of $1.48*10^{23}$ kg. Putting the spacecraft on a path that would bring it in front of Ganymede would slow the craft down requiring a smaller velocity change to put it into the desired orbit.
The first step in the gravity-assisted orbit was to find the position of the moon, Ganymede, with respect to Jupiter as a function of time. The orbit was assumed to be circular with a semi-major axis of $1.07*10^6$ km with zero inclination. A Matlab® function was created to predict the moon's position and velocity by solving Kepler's Equation, Equation 10, for the given time. The resulting orbit elements were then converted to position and velocity in a Jupiter centred inertial frame.

$$M = E + e * \sin E \tag{10}$$

After the moon's position had been defined, the three-body equations of motion, Equation 5, could be numerically integrated. The initial conditions were defined as the position and velocity of the spacecraft as it entered Jupiter's sphere of influence. These were calculated in the previous section for arrival to Jupiter on a Hohmann transfer from Earth. The spacecraft's motion was assumed to remain in the $x - y$ plane.

The spacecraft's position was calculated and plotted to show its position relative to the moon. The initial position of the moon was adjusted and the simulation was re-run until the spacecraft came to a minimum altitude of approximately 300 km from the surface of the moon. The position vector from the centre of the moon to the spacecraft was also calculated and plotted to verify that the orbiter did not collide with the moon, figure 6.

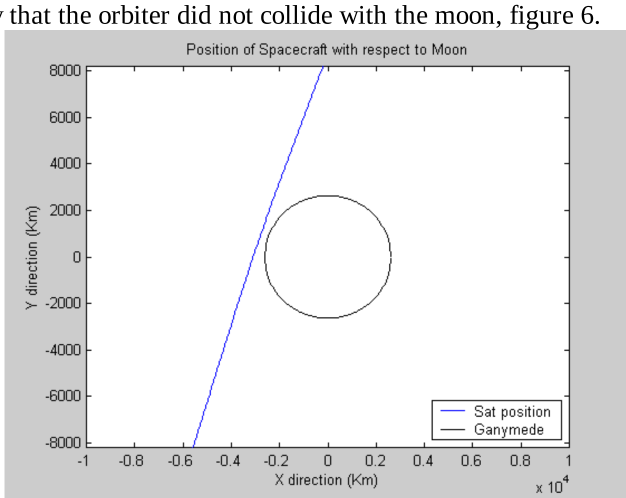

Figure 6 Europa Orbiter course

The two-body equations of motion, Equation 4, were also numerically integrated to show the path the spacecraft would take without consideration to the presence of the moon. The two paths show what effect the third body had on the spacecraft's position, figure 7. An animation of the spacecraft's motion, as well as the moon, was made to help visualize the interaction between the three bodies.

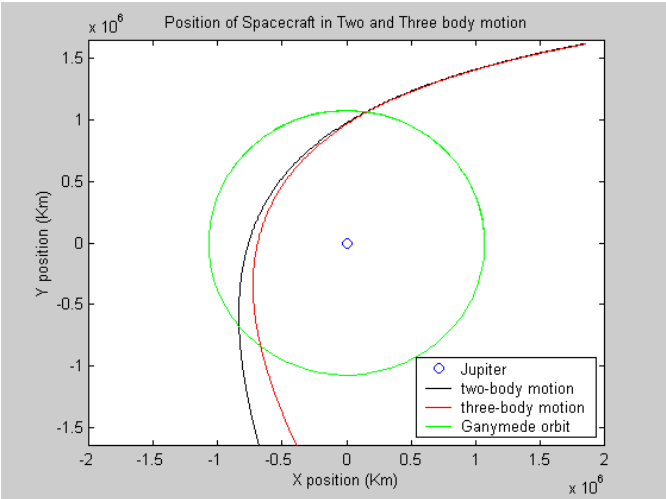

Figure 7 Europa Orbiter position in two and three body position

Once the satellite's position and velocity are found as it passes by Jupiter, the orbit insertion velocity can then be found. This was done by finding the closest approach to Jupiter and assuming this to be the periapsis radius. This was found for both the two-body and three-body solutions. The apoapsis radius was given as 10^6 km. Using these two radii to define the orbit, the required velocity to put the spacecraft on this orbit was found by the vis-visa equation, equation 6. The spacecraft's velocity at that point was subtracted from the required velocity to return the change needed to put the spacecraft in the correct orbit. The calculations were repeated for the two-body orbit for comparison. It was found that the two-body orbit required a delta V of -1.33 km/s while the three-body orbit required only -0.94 km/s, a reduction of 29.5%. The orbit of the satellite around Jupiter, for both the two-body and three-body motion, is calculated for one full orbit, figure 8.

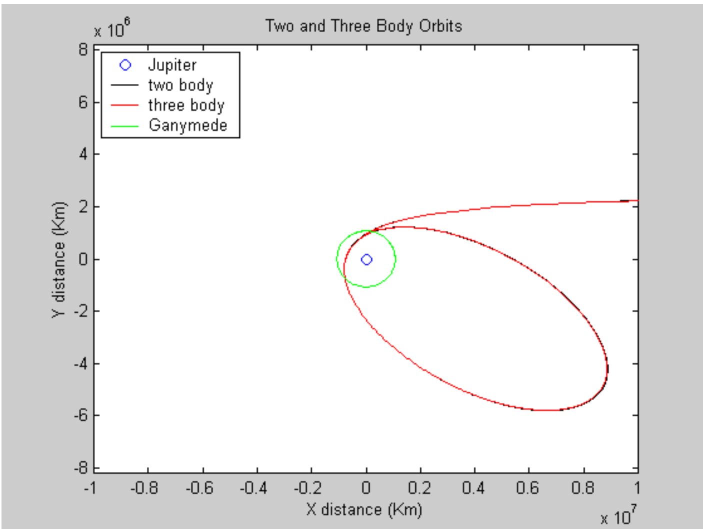

Figure 8 Two and three body orbits for Europa Orbiter

It can be seen that the two approaches and ensuing orbits are nearly identical with the three-body motion requiring approximately 30% less velocity change. A final calculation made was to find the eccentricity of the orbit during the approach and initial orbit around Jupiter. This was done by converting the position and velocity each time to classical orbit elements. Because the orbits lie solely in the $x-y$ plane, the only orbit elements of interest are the semi-major axis and eccentricity. A plot of the eccentricity, figure 9, shows the effect that the moon had on the orbit of the spacecraft.

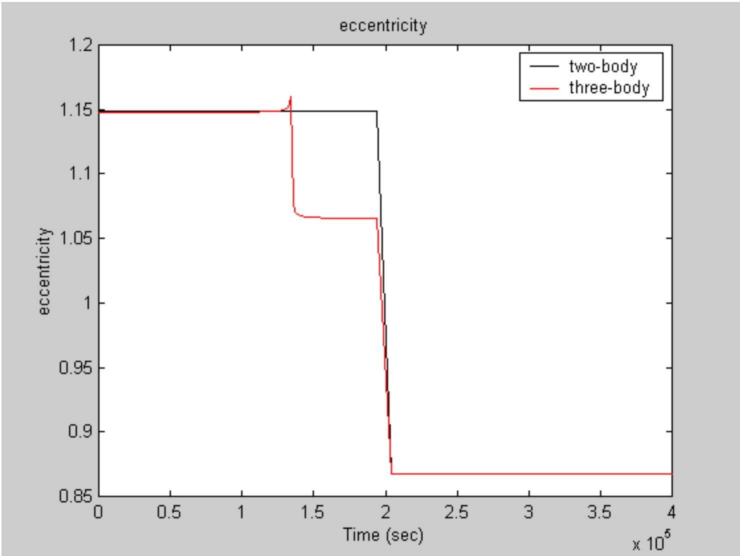

Figure 9 Eccentricity plot

The first dip in eccentricity of the three-body orbit is due to the gravitational effect of Ganymede. The second dip, for both orbits, is a result of the applied impulsive change in velocity. The velocity change brought the eccentricity below one, for both orbits, indicating similar closed orbits around Jupiter. Once the spacecraft is in orbit around Jupiter, further manoeuvres, possible gravitationally assisted, will be required to place the spacecraft in orbit around Europa to achieve the scientific goals.

All the calculations preformed have used the assumption that all orbits lie in the same plane and the path of Ganymede is circular. These approximations are not good enough to define mission parameters but they are useful for mission planning of total ΔV required. One downfall to the mission plan is the close proximity required to Ganymede, approx. 300 km. If the spacecraft arrives at Jupiter too late, as little as 25 seconds, the orbiter may collide with the moon. The positions of the other moons of Jupiter were not considered. There could be possibilities of other collisions or perturbations to the spacecraft that could affect the orbit path. The phase angle of the moon must also be considered to achieve the correct alignment of the moon when the spacecraft arrives at Jupiter. Ganymede has a period of approximately 7 days so it should come into alignment very frequently compared to the alignment required between Earth and Jupiter for a Hohmann transfer.

4. CONCLUSION

The Europa Orbiter mission could possibly be the first step in the discovery of life outside of Earth. Micro-organisms could be living near underwater volcanoes in a subsurface ocean on the third moon of Jupiter. The mission's primary objective is to determine if a liquid ocean does indeed exist beneath the ice sheets. To do this the orbiter must first depart from the Earth all the way to Jupiter and in-orbit around Europa. This is a difficult task with many complicated manoeuvres and possible failures.

The primary objective of this investigation was to determine the effect of a gravity-assisted trajectory for the insertion of the Europa Orbiter spacecraft into an initial orbit around Jupiter. By comparing the spacecraft's path considering first only two-body motion around Jupiter, the three-body motion taking the mass of Jupiter's largest moon into account, it was found that a 30% decrease in the required velocity change was needed to put the craft into orbit around Jupiter. This decrease could be very significant for the mission plan. A larger payload could be taken, or a significant cost could be saved in launch and subsequent orbit manoeuvres by requiring a smaller mass be sent to Jupiter. The primary difficulty in this approach is the phase angle and timing of the planets and moons. Small deviations from the optimal flight path could result in an insignificant assist from the moon or worst a collision. A realistic mission plan would have to consider any plane change manoeuvres required as well as the influence of other bodies into the spacecraft's motion.

This project has shown that gravitational assists from other celestial bodies can have a significant impact on the spacecraft's mission. The assists can be used to propel a craft beyond the solar system, or slow it down to place it into orbit around a planet or moon. The gravitational assists reduce the mass of fuel that must be carried along, and allows more scientific instruments at a lower cost.

References

[1] D. A. Vallado, "Fundamentals of Astrodynamics and Applications," McGraw-Hill, 1997.

[2] B. Wie, "Space Vehicle Dynamics and Control," AIAA, 1998.
[3] W. E. Wiesel, "Spaceflight Dynamics," Irwin/McGraw-Hill, 1997.
[4] Baker, M. L. Robert, "Astrodynamics: Applications and Advanced Topics," New York: Academic Press, 1967.
[5] V. A. Chobotov, "Spacecraft Attitude Dynamics and Control," Orbit Foundation Series, Malabar FL: Krieger Publishing Company, 1991.
[6] V. A. Chobotov, editor, "Orbital Mechanics (Second Edition)," AIAA Education Series, Reston VA: American Institute of Aeronautics and Astronautics, 1996.
[7] N. M. Harwood, G. G. Swinerd, "Long-Periodic and Secular Perturbations to the Orbit of a Spherical Satellite Due to Direct Solar Radiation Pressure," Celestial Mechanics and Dynamical Astronomy, 62:71-80, 1995.
[8] T. S. Kelso, "Orbit Propogation: Part II," Satellite Times, 1(4):80-81, 1995.