Optimal SEP Trajectories from Earth to Jupiter with Triple Flyby Capture

Sean K. Patrick[1] and Alfred E. Lynam[2]

West Virginia University, Morgantown, WV, 26506

Triple-Satellite-aided-capture sequences use gravity-assists at three of Jupiter's four massive Galilean moons to reduce the ΔV required to enter into Jupiter orbit. A triple-satellite-aided capture at Callisto, Ganymede, and Io is proposed to capture a SEP spacecraft into Jupiter orbit from an interplanetary Earth-Jupiter trajectory that employs low-thrust maneuvers. The principal advantage of this method is that it combines the ISP efficiency of ion propulsion with nearly impulsive but propellant-free gravity assists.

Nomenclature

ΔV	= change in velocity
JOI	= Jupiter Orbit Insertion
SEP	= Solar Electric Propulsion
NBCP	= Non-body Control Point
CBE	= Current Best Estimate
V_x	= Velocity coefficient in the x direction
V_y	= Velocity coefficient in the y direction
V_z	= Velocity coefficient in the z direction
SOI	= Gravitational sphere of influence
TCM	= Trajectory Control Maneuver

I. Introduction

The use of gravity-assist flybys to reduce overall mission ΔV requirements have proven useful ever since Mariner 10 succeeded in reaching Mercury via gravity assist at Venus [1]. First proposed by Longman, the use of satellites to provide a gravity assist around a central planet such as Jupiter have been proposed for missions such as the Europa Orbiter Mission [2-3]. The use of such maneuvers, known as "satellite-aided capture", allows for significant advantages in mission design as these maneuvers reduce the total ΔV requirements for orbital insertion around the central body. The Galileo mission was able to reduce its JOI ΔV requirements by 175 m/s using an Io gravity assist [4].

While single gravity-assist trajectories are most commonly proposed [5], double gravity-assists have been proposed for some mission designs [6]. Further, the use of three of the Galilean moons for a triple-satellite-aided capture has been explored by Lynam et al. as a means to further reduce the overall ΔV requirements of Jupiter insertion [7-8]. This sequence begins with a hyperbolic arrival trajectory (from a low-thrust Earth-Jupiter trajectory) a few days before the triple-flyby gravity-assist sequence. The triple flyby sequence is designed such that each gravity assist occurs within one day of the previous assist. Following the three gravity-assists, a capture orbit is achieved with a period of one hundred days. The Callisto, Ganymede, and Io sequence is an excellent candidate for triple-satellite-aided capture as they are all much larger than Europa, so they can provide the strongest collective gravity-assist. Lynam and Longuski have shown that deep space broken-plane maneuvers must be used to target

[1] Graduate Student, Mechanical and Aerospace Engineering, ESB, Evansdale Dr., Morgantown, WV 26506, and AIAA Student Member.
[2] Assistant Professor, Mechanical and Aerospace Engineering, ESB, Evansdale Dr., Morgantown, WV 26506, and AIAA Member.

triple-satellite-aided capture sequences since the average orbital plane of the Galilean moons is different from the elliptical plane. If a chemical engine is used, these maneuvers often range from 40 m/s to 100 m/s [9]. In order to eliminate impulsive maneuvers that use low ISP chemical engines, low-thrust interplanetary trajectories are chosen for the triple-satellite-aided capture trajectories that are used in this paper. Furthermore, low-thrust interplanetary trajectories can have a much lower arrival V_∞ than chemical trajectories; we can remove the need for an impulsive JOI maneuver.

Strange et al. have proposed a SEP design which uses multiple Hall thrusters [6]. This design provides a reasonable choice for a triple-satellite-aided-capture sequence as it allows for optimal low thrust maneuvers at all stages of flight. The model used here assumes a BHT-600 thruster is used upon arrival at Jupiter from an interplanetary trajectory with a power range of 0.49 to 1 kW. Specific impulse and efficiency for the BHT-600 as given by Kamhawi et al. [10] are used in the modeling. CBE wet mass of 1970 kg and the margin mass value of 415 kg given by Strange et al. in the Mass Estimate List for their proposed mission was used as a baseline for the initial mass of the proposed craft.

This paper expands on the work of Lynam by exploring the feasibility of one of the proposed triple-satellite-aided capture sequences, specifically the Callisto-Ganymede-perijove-Io sequence [11]. This is accomplished by modeling the sequence using the low-thrust optimization program MALTO to determine feasibility and to refine the Callisto-Ganymede-perijove-Io sequence as it would be carried out using a SEP design. Further, this paper will expand upon the chemical interplanetary trajectories used by Lynam and Longuski [9], by developing a low-thrust interplanetary trajectory using robust low-thrust trajectory optimization software (MALTO).

Section II of this paper details the methodology and theory of the methods employed in this paper, covering the initial design of the proposed Callisto-Ganymede-perijove-Io triple flyby and interplanetary trajectories. Following this, Section III discusses the resulting optimized trajectories while Section IV discusses and expands upon these results

II. Theory & Methodology

To develop an optimal Triple-flyby trajectory, the MALTO low-thrust optimization software was employed [12]. MALTO was chosen to be used for trajectory optimization as it provides an intuitive interface along implementing SNOPT optimization. MALTO separates the trajectory into discrete segments around a match point in which the segment is propagated forward from the initial control node and backwards from the later control node. Generally, these propagations are done using the patched-conic method with lo-thrust modeled as impulsive maneuvers placed at discrete segments. For low-thrust trajectories, MALTO can model multiple power and propulsion sources such as NEP and SEP as well as differing launch vehicles [12]. Of particular interest to Jupiter missions, solar perturbations were recently added to increase fidelity of MALTO's patched-conic propagations in the Jupiter System. These solar perturbations are particularly necessary when modeling the 100 day capture orbit. These factors allow MALTO to model an array of potential missions.

The Callisto-Ganymede-perijove-Io sequence was modeled in MALTO as a single trajectory using an initial NBCP to represent the initial approach towards Jupiter from the interplanetary trajectory. Following the flyby sequence and a 100 day capture orbit, a second flyby of Ganymede is included. This second flyby represents the start of an extended Jupiter science mission following the initial insertion into Jupiter orbit using the triple flyby sequence. Once set up, the trajectory is optimized using MALTO. The initial conditions for the initial guess of this trajectory are provided below in Table 1.

Parameter	Value	Units
X	3329325.508140922	km
Y	-1043254.126368165	km
Z	-475214.4864968658	km
V_x	-7.528551861244786	km/s
V_y	4.963528973952879	km/s
V_z	2.2581649229118	km/s

Table 1: Initial Jupiter-centered, ecliptic J2000 parameters for the NBCP used in the Triple Flyby. These values were obtained via GMAT and used as an initial guess for the MALTO optimization.

The initial conditions chosen were based on previous work by Lynam [11]. The initial flyby dates for the Callisto-Ganymede-perijove-Io flyby, each one day after the previous, were chosen such that each of the three moons would be in the proper sequence for the triple flyby. The follow up flyby to Ganymede has been chosen to be approximately100 days after the initial Io flyby.

Once an optimal solution to the Callisto-Ganymede-perijove-Io sequence was found in MALTO, an interplanetary trajectory was developed. The sequence was initialized as an Earth-Mars-Jupiter, low-thrust trajectory. The initial values for the interplanetary trajectory were based of previous work by Lynam [11] as well as Strange et al. [6]. The interplanetary trajectory was initially designed as an Earth to Jupiter trajectory with a single gravity-assist of Mars. This initial trajectory was optimized in MALTO and, once optimized, modified to use the NBC point that was back propagated from the triple-flyby trajectory as the final control point instead of Jupiter.

The NBCP used in the interplanetary trajectory represents the point at which the spacecraft enters Jupiter's SOI. This point was determined by back propagating the trajectory of the spacecraft from the NBCP of the optimized triple-flyby trajectory. This back propagation was accomplished using GMAT. The GMAT software was chosen for the back propagation over MALTO due to the nature of the task. Specifically, MALTO and other patched-conic optimizers and propagators have notably low-fidelity n propagating trajectories for long time periods when two gravitating bodies both impart significant acceleration on the spacecraft. During the trajectory region between the Jupiter-centered NBCP and the heliocentric NBCP at Jupiter's SOI, both Jupiter and the Sun have a significant influence on the spacecraft's trajectory. Modeling the trajectory as a series of Jupiter-centered conic sections does not account for the gravitation of the Sun within this regime. Although the addition of solar perturbations within MALTO does mitigate this inaccuracy, the general perturbations-based method that MALTO uses to model solar perturbations has an implicit assumption that Jupiter's gravity is much stronger than the Sun's gravity within this regime. While this assumption may be warranted in the portions of the regime that are much closer to Jupiter, the assumption breaks down when the spacecraft is closer to Jupiter's SOI where the gravitational accelerations of Jupiter and the Sun are approximately equal. GMAT can accurately model this regime by using direct numerical integration of the trajectory with the full gravity of Jupiter and the Sun throughout this regime.

Using GMAT, a script was employed to back propagate from the initial Jupiter centered NBC point to Jupiter's SOI. As mentioned earlier, the numerical integrator for this script used the point mass gravity of both Jupiter and the Sun (For added fidelity, the script also added the point mass gravity of other planets and Pluto). Once the script successfully back propagated the NBCP, the new location was converted to heliocentric coordinates and used in MALTO for the interplanetary trajectory. The back propagation allows for more accurate formulation of the interplanetary trajectory in MALTO. By moving the NBCP out of Jupiter's SOI, more accurate heliocentric coordinates could be determined for use in MALTO. Once the new NBCP is found using GMAT, the interplanetary trajectory is optimized in MALTO based on this new point. The parameters of the new NBCP are given below in Table 2.

Parameter	Value	Units
X	-662176330.18765	km
Y	-462209124.57349	km
Z	16146115.180484	km
V_x	4.1570208980255	km/s
V_y	-7.3053291606423	km/s
V_z	0.0003191673957	km/s

Table 2: Initial heliocentric, ecliptic J2000 parameters of the back propagated NBCP at Jupiter's SOI.

The work of Strange et al. was chosen as a basis for the mass and power and propulsion systems for both the triple-flyby and interplanetary trajectories. This choice was made due to the sample mission provided by the authors who provide detailed reasoning for the choices made regarding the power, propulsion as well as the mass allowance of the sample mission.

The power and propulsion system used by Strange et al. [6] included BPT-4000 and BHT-600 Hall-thrusters along with SEP, which provides an optimal set up for triple-flyby sequences. As Strange et al. point out; Hall thrusters provide higher thrust but lower specific impulse than ion engines for the same power consumption. This fact, as well as the fact that Hall thrusters can be magnetically shielded, makes Hall thrusters the more attractive option for use at Jupiter as the solar power supply would be limited at 5.2 AU [6].

The BHT-600 and BPT-4000 thrusters used in the sample mission were picked specifically based on the efficiency curve of the thrusters. By using two BPT-4000 thrusters for the interplanetary trajectory and a BHT-600 for the Jupiter mission, Strange et al. have designed a propulsion set up that allows for efficient thrust at all points of the mission. To power the Hall thrusters, an Ultraflex Solar Array with a reference power of 30 kW at 1 AU was employed. This array will provide sufficient power to the Hall thrusters for the interplanetary trajectory as well as the triple-flyby trajectory. SEP is an attractive option for long term Jupiter missions compared to NEP due to the fact that, as Strange et al. mention, multiple radioisotope power systems would be required to produce the necessary 1 kW of power the BHT-600 requires at Jupiter [6].

To model the BHT-600 and BPT-4000 Hall-thrusters in MALTO, the values given bellow in Table 3 were used. In addition to these values, the default solar model for MALTO was employed along with the Ultraflex solar array model values included with MALTO. In addition, for thruster modeling a Pmax of 5 and a Pmin of 2.2 were employed.

Thruster	Cthrust(2) [N/kW]	Cmdot(2) [kg/s/kW]
BPT-4000	0.066281553843565	$4.224273442228 \cdot 10^{-06}$
BHT-600	0.056084391713786	$2.8595081762776 \cdot 10^{-06}$

Table 3: Coefficients used to model BPT-4000 and BHT-600 hall thrusters. All other coefficients were not utilized and set to zero.

For the interplanetary trajectory, the launch mass was chosen to be 2385 kg and the launch V_∞ was capped at 3.55 km/s. For the BPT-4000 thrusters, the power and propulsion system was set such that two thrusters were used until the power dropped below 4.8 kW. Once the power dropped below 4.8 kW one thruster would be shut down. These Values correspond to those of the Falcon 9 and of the thruster configuration used by Strange et al. [6].

III. Results

Using MALTO, the Callisto-Ganymede-perijove-Io trajectory was successfully optimized. The follow up Ganymede trajectory was also successfully optimized with the resulting trajectory including both the triple flyby sequence and the follow up tour displayed in Figures 1 and 2. The triple flyby approach forms an expected hyperbola hitting the three gravity assists in succession. The Callisto and Ganymede flybys are at their lower bounds (300 km) while the Io flyby dips below this to 258 km. While low, the Io flyby distance is still within a safe distance. The follow-up flyby to Ganymede is, at 106.3 days, very near the targeted 100 day orbit. This orbit puts the Ganymede arrival position very near that of the original Ganymede gravity-assist.

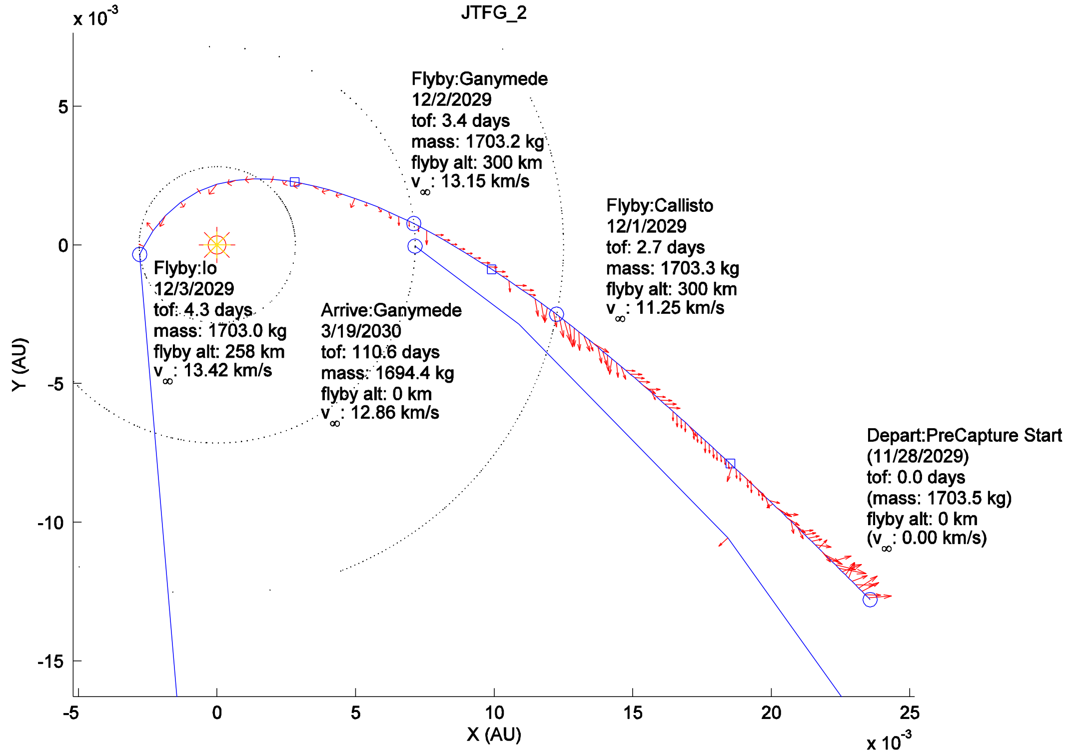

Figure 1: Callisto-Ganymede-perijove-Io triple-flyby with follow-up Ganymede tour. The excessive amount of red thrust arrows are artifacts of the MALTO optimization process and would be removed in higher-fidelity mission design.

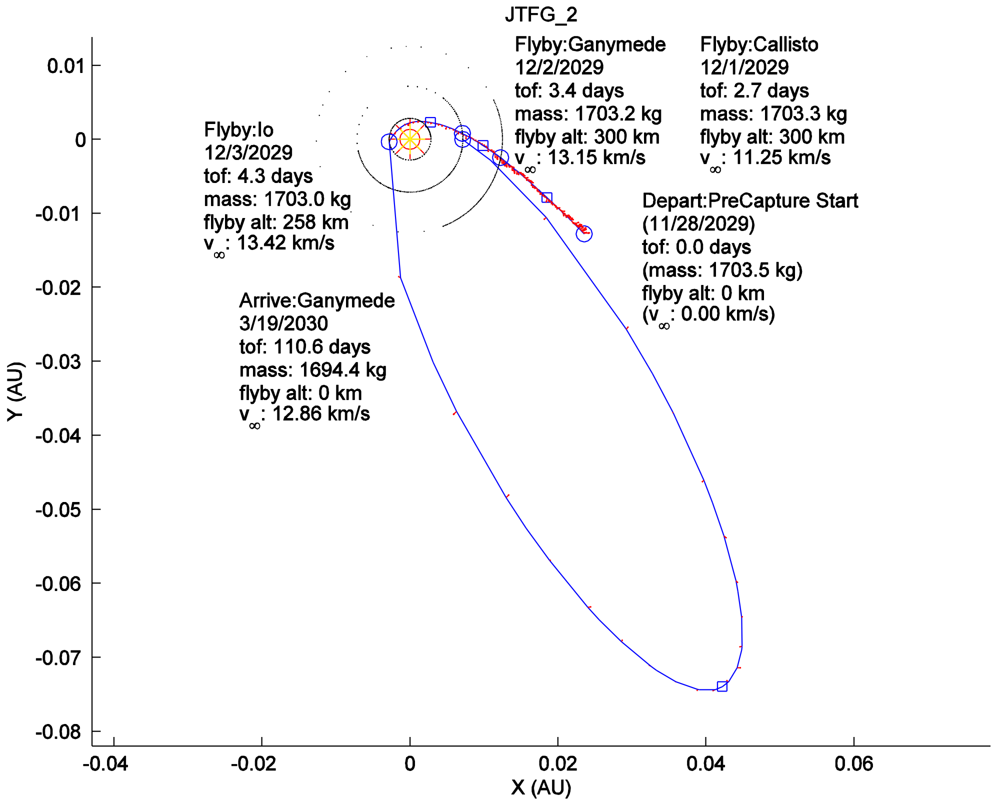

Figure 2: Expanded view of Callisto-Ganymede-perijove-Io flyby following optimization. This figure shows the full follow-up capture orbit

As shown above, the triple-flyby trajectory expels very little mass, 9.1 kg, the majority of which is expended during the capture orbit.

The successful Ganymede flyby shows that an extended science mission following the triple-flyby sequence is possible. The values for the NBCP are given in Table 4.

Parameter	Value	Units
X	3525495.932	km
Y	-1913671.4535083	km
Z	-29262.11	km
V_x	-6.1082620057458	km/s
V_y	6.1629269494039	km/s
V_z	0.17901096148155	km/s

Table 4: Parameters of the initial Jupiter-centered, ecliptic J2000 NBCP after optimization

Following the optimization of the triple-flyby, the interplanetary trajectory was successfully optimized regarding the initial Earth-Mars-Jupiter trajectory and was then subsequently optimized for the Earth-Mars-NBCP trajectory. The NBCP used was first determined using the back propagation method described above in Section II. The optimized trajectory is given below in Figure 3.

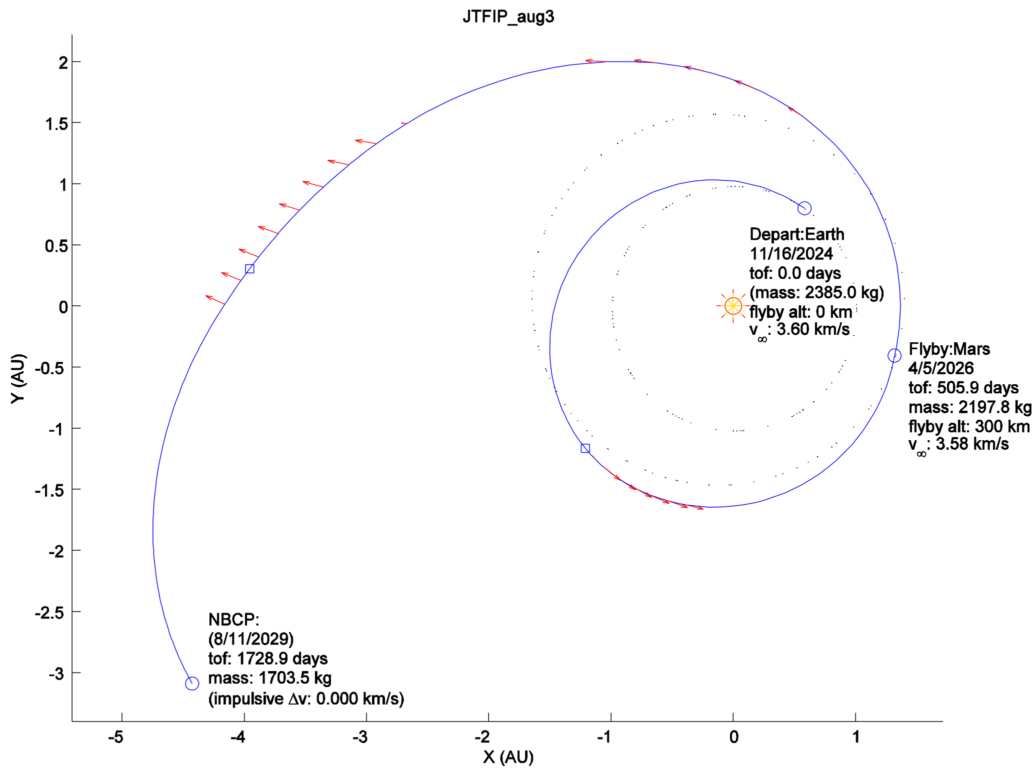

Figure 3: Earth-Mars-NBCP interplanetary trajectory following optimization

In Figure 3, the spacecraft launches from Earth on November 16, 2024 on a SpaceX Falcon 9 rocket and begins its interplanetary trajectory with a mass of 2385 kg and a launch V_∞ of 3.6 km/s. The spacecraft coasts until it nearly reaches aphelion. Near aphelion, the SEP engines provide a low-thrust analog of a V_∞-leveraging maneuver that raises the perihelion of the spacecraft to near Martian orbit (see red arrows in Figure 3). On April 5th, 2026, the spacecraft flies by Mars at its lower bound altitidue of 300 km. This Martian gravity assist increases the aphelion of the spacecraft and enables it to reach Jupiter with less thrusting (and therefore less mass expenditure).

The spacecraft coasts for several more months after the Martian gravity assist before thrusting again with its Hall thrusters. These maneuvers are near perihelion and nearly tangent to the spacecraft's trajectory, so they efficiently raise the aphelion of the spacecraft toward Jupiter's orbit. The spacecraft coasts again until it reaches a second set of SEP maneuvers. These maneuvers are mostly perpendicular to the spacecraft's trajectory, so they are not efficient in the sense that they do not directly raise the spacecraft's aphelion. However, these SEP maneuvers are necessary to ensure that the spacecraft enters Jupiter's SOI on a trajectory that is consistent with the highly constrained triple flyby sequence in Figure 1. The total mass cost of the SEP trajectory leg from Mars to Jupiter SOI NBCP is 494.3 kg. It is possible that further optimization work would remove some of these inefficient maneuvers and allow a more mass-efficient interplanetary trajectory.

Below, Table 5 details a complete mission timeline for the interplanetary and triple-flyby trajectories. The GMAT propagation from Jupiter SOI to Jupiter NBCP was ballistic, so it is assumed that no mass would be used in that leg.

Node	Date	Mass (kg)
Earth Launch	11/16/2024	2345
Mars Gravity-Assist	04/05/2026	2197.8
Jupiter SOI arrival	08/11/2029	1703.5
Jupiter NBCP	11/28/2029	1703.5
Callisto flyby	12/01/2029	1703.3
Ganymede flyby 1	12/02/2029	1703.2
Io flyby	12/03/2029	1703.0
Ganymede flyby 2	03/19/2030	1694.4

Table 5: Timeline detailing the time and mass at each major node for the entire 5.3 year length of the mission.

IV. Discussion

A. Comparison with SEP Double Flyby Capture at Jupiter

Since the modeling choices for this paper were based on those of Strange et al. [6], the partial mission designed in this paper can be directly compared to the appropriate portions of the mission designed by Strange et al. The optimized Earth-Mars-NBCP interplanetary trajectory was found to be very comparable to the Earth-Mars-Jupiter interplanetary trajectory depicted in Figure 3 of Strange et al. The first point of comparison is that the shapes of the two interplanetary trajectories are similar. This similarity is due to the similar MALTO design methodology used in the two trajectories. The second point of comparison is that their times of flight are similar. The interplanetary trajectory of Strange et al. had a time of flight from Earth to Callisto flyby of 4.86 years while the time of flight of the interplanetary trajectory in this paper from Earth to Callisto flyby was 4.96 years. Hence, this paper's trajectory only took slightly more than 1 month longer to arrive at Jupiter than that of Strange et al.

Although the shape, design methodology, and time from Earth to Jupiter of the two interplanetary trajectories were very similar, Strange et al.'s interplanetary trajectory resulted in a final mass of 1839.4 kg while the trajectory presented here in Figure 2 resulted in a final mass of 1703.5 kg. However, this comparison is somewhat misleading since Strange et al. did not use the GMAT integration used in this paper to patch their interplanetary trajectory to their Jupiter-centered trajectory. If they had, it is possible they would have also obtained a less optimal solution. While considered optimal by MALTO's optimizer, the trajectory in this paper could potentially be improved to further reduce the amount of mass spent. This suboptimality, along with the excessive amount of thrust arrows in the triple-flyby, can partially be attributed to artifacts in the low-thrust optimization of MALTO. Additionally, the optimality of the completed trajectory was reduced due to the fact that the triple flyby and the interplanetary trajectory could not be simultaneously optimized in MALTO since MALTO cannot change central bodies within a single optimization run. To correct this in further mission design, higher fidelity optimization software such as Mystic could be employed.

The principal difference between the mission design in this paper and that of Strange et al. [6] is that this paper uses a triple flyby of Callisto, Ganymede and Io while Strange et al. used a double flyby of Callisto and Ganymede. There is several design tradeoffs associated with using double vs triple flybys to capture into Jupiter orbit. First, the triple flyby is better than the double flyby at quickly reducing Jupiter-centered orbit period of the spacecraft due to its larger number of gravity assists. The capture orbit used in this paper had a period of 106.3 days before the second Ganymede flyby (which would ostensibly reduce the orbit period to a reasonable value if the full tour was modeled). Strange et al.'s Jupiter-centered mission required a 350.4 day capture orbit, a second Callisto flyby a second 84.1 day orbit, and a third Callisto flyby before capturing into a reasonable 33.4 day orbit.

Combining the interplanetary trajectory time with the time required to obtain a low-period orbit for both approaches gives the following total times. The approach used by Strange et al. would reach a low-period Jupiter orbit on 9/7/2028, roughly 6 years from the initial 8/18/2022 launch date. Comparatively, this approach would achieve low-period Jupiter orbit on 3/19/2030, about 5.3 years following the 11/16/2024 launch date. Hence, the triple flyby approach does save a substantial amount of mission time.

A finial comparison of the two approach strategies involves this paper's use of an Io flyby to aid in capture. In order to use Io as a gravity-assist body, the spacecraft must have a perijove that is below Io's orbital radius of 5.9 Jupiter radii. Such a close approach to Jupiter would expose the spacecraft to increased levels of radiation from the "Io torus" that would need to be mitigated. Furthermore, in a more complete mission design, the spacecraft would have to perform more SEP thrusting during the capture orbit to raise its perijove in order to compensate for the effects of solar perturbations and reduce the radiation exposure of the spacecraft in future orbits. This SEP thrusting was modeled by Strange et al. [6], but not in this paper due to tis focus on the interplanetary trajectory and capture.

B. Navigation Challenges

This analysis strongly focuses on the mission design of SEP triple flyby capture trajectories and does not directly address the navigational challenges of triple satellite aided capture in general or SEP triple satellite aided capture in particular. Lynam and Longuski [7] performed a preliminary navigation analysis for chemical triple satellite aided capture, so their results will be contextualized to SEP triple satellite aided capture. Lynam and Longuski showed that using only radiometric navigation would require two trajectory correction maneuvers (TCMs) with a total impulsive ΔV of about 5-9 m/s to precisely guide a spacecraft through a triple flyby trajectory. Using both radiometric and optical navigation, they showed that it would take 2-4 m/s. For both cases, they assumed an expedited ground processing loop that can determine the spacecraft's orbit after each flyby, calculate a trajectory correction maneuver (TCM), and command the spacecraft to perform that maneuver within 4.5-5.8 hours after each flyby. Due to the 30-50 minute one-way light time between Earth and Jupiter, achieving these results in an operational mission would be challenging.

Since Lynam and Longuski's results [7] assumed impulsive maneuvers, it is difficult to predict their applicability to SEP triple satellite aided capture. Strange et al. [6] stated that their BHT-600 Hall thruster has a control authority of 1.6 m/s/day applied continuously rather than impulsively. Since there is about 1 day between flybys and the continuous application of ΔV would be less efficient at correcting the flyby errors than an impulsive ΔV, it is clear that only using radiometric navigation would not be sufficient for guiding an SEP spacecraft through a triple flyby. Using both radiometric and optical navigation to guide the spacecraft through the triple flyby from the ground would be extremely challenging, but not necessarily impossible. However, the spacecraft would probably require an extremely powerful imaging telescope such as Deep Impact's High Resolution Imager (HRI) and the use of stereophotoclinometry [13-15], which would complicate the payload choices and the operation of the mission. The use of autonomous navigation is another option which would save hours of light time delay, but also would require a robust onboard navigation system and probably still require an HRI-level imager. Another possible strategy would be to use low Isp RCS attitude control thrusters to navigate the flybys, but use the high Isp SEP thrusters for every other maneuver in the mission. Despite the challenge of the TCM maneuvers involved, the SEP propulsion employed would not require an impulsive JOI maneuver (that would also add operational difficulty and statistical uncertainty to the capture). A full GNC analysis of SEP triple flybys would be an interesting topic for further research, but is beyond the scope of this paper.

V. Conclusion

Triple gravity-assist flybys of the Galilean moons, in association with SEP propulsion, allows for a lower ΔV requirement to enter Jupiter orbit. Here, an application of the previous work by Lynam and Strange et al. is proposed in which a spacecraft approaches Jupiter orbit using an Earth-Mars-Jupiter low-thrust trajectory into a Callisto-Ganymede-perijove-Io triple flyby. This application shows that the proposed triple-flyby method, in conjunction with SEP, is feasible for insertion into Jupiter orbit while providing ample mass reserves (1703.5 kg) for an extended Science mission once orbit is achieved. In addition to the mass reserves, the proposed trajectory requires less time to achieve low-period Jupiter orbit at only 5.3 years compared to the trajectory proposed by Strange et al. at 6 years.

The optimized trajectory while, comparable to that of Strange et al., can possibly be improved. The triple-flyby trajectory includes excessive thrust arrows while the interplanetary trajectory could further reduce mass expenditure. These may be a product of the fact that MALTO cannot simultaneously optimize both trajectories and requires two separate trajectories to optimize both the Jupiter centered triple flyby and heliocentric interplanetary trajectories. Follow up work could expand upon the interplanetary and triple-flyby trajectories using higher fidelity optimization software (Mystic) to reduce suboptimalites.

In addition, the benefits of the use of triple-flyby capture trajectories would require trajectory correction maneuvers with challenging navigation requirements or the addition of RCS control thrusters to the spacecraft. Along with the difficulty of the TCMs required for the triple-flyby the proposed trajectory requires a perijove lower than Io's orbital radius (5.9 Jupiter radii), exposing the spacecraft to increased radiation that must be accounted for in mission design. Despite these issues, the low-thrust SEP design does not require an impulsive JOI maneuver lowering the operational difficulty and statistical uncertainty of the mission. In addition to the lack of an impulsive JOI maneuver, the patched Earth-Ganymede trajectory proposed here is faster than the similarly designed mission given by Strange et al.

Acknowledgements

The Authors wish to thank Dr. Anastassios Petropoulos for his expertise and support regarding the set up and use of MALTO. In addition, the authors wish to thank Alan Didion for his assistance and advice in the use of GMAT and general support in relation to the project.

References

[1] McConaghy, T. T, Debban, T. J., Petropoulos, A. E., Longuski, J. M., "Design and Optimization of Low-Thrust Trajectories with Gravity Assists", *Journal of Spacecraft and Rockets*, Vol. 40, No. 3, May-June 2003, pp.380-387.

[2] Longman, R. W., "Gravity Assist from Jupiter's Moons for Jupiter-Orbiting Space Missions", The RAND Corp., Santa Monica, CA, 1968.

[3] Johannesen, J. R., D'Amario, L. A., "Europa Orbiter Mission Trajectory Design", *AAS/AIAA Astrodynamics Specialist Conference,* AAS Paper No 99-330, Girdwood, AK, August 1999.

[4] Wilson, M. G., Potts, C. L., Mase, R. A., Halsell, C. A., Byrnes, D. V., "Maneuver Design for Galileo Jupiter Approach and Orbital Operations", *12th International Symposium for Spaceflight Dynamics,* Darmstadt, Germany, June 1997.

[5] Cline, J. K., "Satellite Aided Capture", *Celestial Mechanics,* Vol. 19, 1979, pp. 405-415.

[6] Strange, N., Landau, D. F., Hofer, R., Snyder, J. S., Randolph, Campagnola, S., Szabo, J., Pote, B., "Solar Electric Propulsion Gravity-Assist Tours for Jupiter Missions", *AIAA/AAS Astrodynamics Specialist Conference,* AIAA Paper No 2012-4518, Minneapolis, MN, August 2012.

[7] Lynam, A. E., Longuski, J. M., "Preliminary Analysis for the Navigation of Multiple-satellite-aided capture at Jupiter", *Acta Astronautica,* Vol. 70, 2012, pp. 33-43.

[8] Lynam, A. E., Kloster, K. W., Longuski, J. M., "Multiple-satellite-aided Capture Trajectories at Jupiter using the Laplace Resonance", *Celestial Mechanics and Dynamical Astronomy,* Vol. 109, 2011, pp. 59-84.

[9] Lynam, A. E., Longuski, J. M., "Interplanetary Trajectories for Multiple-satellite-aided Capture at Jupiter", *Journal of Guidance, Control, and Dynamics,* Vol. 34, 2011, 1485-1494.

[10] Kamhawi, H., Soulas, G., Pinero, L., Herman, D., VanNoord, J., Huang, W., Shastry, R., Haag, T. Yim, J., "Overview of Hall Thruster Activities at NASA Glenn Research Center", *32nd International Electric Propulsion Conference,* Wiesbaden, Germany, September 2011.

[11] Lynam, A. E., "Broad-search Algorithms for the Spacecraft Trajectory Design of Callisto-Ganymede-Io Triple Flyby Sequences from 2024 to 2040, Part II: Lambert Pathfinding and Trajectory Solutions", *Acta Astronautica,* Vol. 94, Issue 1, January-February 2014, pp. 253-261.

[12] Sims, J. A., Finlayson, P., Rinderle, E., Vavrina. M., Kowalkowski, T., "Implementation of a Low-Thrust Trajectory Optimization Algorithm for Preliminary Design," AIAA/AAS Astrodynamics Specialist Conference, Paper AIAA 2006-6746, Aug. 2006

[13] Gaskell, R. W., "Automated Landmark Identification for Spacecraft Navigation", AAS Paper 01-422, *AAS/AIAA Astrodynamics Specialist Conference*, Quebec City, Canada, 2001.

[14] Gaskell R.W., Barnuin-Jha O.S., Scheeres D.J., Konopliv A.S., Mukai T., Abe S., Saito J., Ishiguro M., Kubota T., Hashimoto T., Kawaguchi J., Yoshikawa K., Kominato T., Hirata N., Demura H. "Characterizing and navigating small bodies with imaging data", Meteoritics & Planetary Science Vol. 43, No. 6, 2008, pp. 1049-1061.

[15] Mastrodemos, M., Rush, N., Vaughan, D., Owen, W., Jr., "Optical Navigation for Dawn at Vesta", AAS Paper 11-222, *AAS/AIAA Space Flight Mechanics Meeting*, New Orleans, Louisiana, 2011.