AAS 15-609

HIGH-FIDELITY LOW-THRUST SEP TRAJECTORIES FROM EARTH TO JUPITER CAPTURE

Sean Patrick[*] and Alfred E. Lynam[†]

Triple Satellite aided capture sequences use gravity-assists at three of Jupiter's four massive Galilean moons to capture into Jupiter orbit. In this paper, three solar electric propulsion (SEP), low-thrust trajectories from Earth to Jupiter capture are optimized using JPL's high-fidelity Mystic software. A Mars gravity assist is used to augment the heliocentric trajectories. Gravity assist flybys of Callisto, Ganymede, and Io or Europa are used to capture into Jupiter Orbit. With between 89.8 and 137.2-day periods, the orbits are shorter than most capture orbits. Thus, the main satellite tour of the Jupiter mission could begin sooner using this strategy.

INTRODUCTION

First proposed by Longman[1], satellite-aided capture uses gravity assists of satellites around a central body, in this case Jupiter, to capture a spacecraft into a planetocentric orbit. Gravity-assist flybys have proven useful in deep space missions such as Galileo and Cassini to obtain the orbital energy necessary to reach their destinations[2-9]. In addition to the use of planetary gravity assists, Galileo employed a gravity assist of Io to reduce the ΔV of Jupiter capture by 185 m/s[4]. After obtaining Jupiter orbit, dozens of other gravity-assist flybys of the Galilean moons were performed as part of the spacecraft's science mission, providing much scientific knowledge of the moons[10-13]. The use of a single satellite-aided capture in mission design is the most explored option[1,14-18]. Despite this, multiple papers have proposed using two[19-23] or three[21-26] of the Galilean moons to capture into orbit around Jupiter.

Because it is possible to encounter any three of the moons in differing order, there are numerous possible permutations for a triple satellite aided capture sequence. Lynam et al. have previously explored the use of three of the Galilean moons for a triple-satellite-aided capture as a means to further reduce the overall ΔV requirements of Jupiter insertion[21-25]. Of particular note are the so called "Laplacian triple-satellite-aided capture" sequences featuring Ganymede, Europa, and Io[21-22]. These trajectories are noteworthy due to 4:2:1 Laplace resonance of the three moons, which allows the capture sequences involving the three moons to occur more frequently. Despite the frequency of these trajectories, the low perijoves of such an approach makes them less than ideal. Of the other sequences explored, Lynam et al. note that the Callisto-Ganymede-Io sequence is the most promising. The efficiency of these sequences is due to Ganymede and Io being the most effectivet gravity-assist bodies of the Galilean Moons. Despite this the sequence does have a low perijove of less than 6 Jupiter radii (RJ). Callisto-Ganymede-Europa sequences

---

[*] Graduate Student, Mechanical and Aerospace Engineering, West Virginia University, ESB, Evansdale Dr., Morgantown, WV 26506.

[†] Assistant Professor, Mechanical and Aerospace Engineering, West Virginia University, ESB, Evansdale Dr., Morgantown, WV 26506.

occur less frequently and have worse (higher) capture orbit periods, but can have better (higher) perijoves of 8-9 RJ.

Previously, Patrick and Lynam have explored low-thrust trajectories utilizing a Callisto-Ganymede-perijove-Io capture sequence[26]. This trajectory was designed as an improvement upon previous work by Strange et al. on Earth-Mars-Jupiter Solar Electric Propulsion (SEP) trajectories[27]. The trajectory developed by Patrick and Lynam made use of the aforementioned Callisto-Ganymede-Io triple-flyby sequence to achieve a shorter period Jupiter capture orbit than that of the double flyby sequence employed by Strange et al. In addition to the triple flyby trajectory, Patrick and Lynam designed a low-thrust interplanetary trajectory as an expansion on previous work by Lynam and Longuski[25].

This paper expands on the work of Patrick and Lynam by performing a high-fidelity optimization of the low-fidelity trajectories devised in MALTO. To perform this optimization, the Mystic software program was employed in the design and modeling of the trajectory[28]. As in the previous, low-fidelity trajectory, Hall thrusters were employed using specific impulse and efficiency data as given by Kamhawi et al. for modeling[29]. Two other trajectories were also found in Mystic that use triple flybys of Callisto, Ganymede, and Europa. Along with this high-fidelity modeling, a comparison is made to the impulsive Earth to Jupiter capture trajectory, featuring a Callisto-Io-perijove-Ganymede triple-flyby capture sequence, as developed by Didion and Lynam[30].

METHODOLOGY

The trajectory design started, as stated above by using previously developed trajectories by Patrick and Lynam[26] as a basis for the current design work. These trajectories were devised using the MALTO design software developed by NASA Jet Propulsion Laboratory (JPL) as a means of performing low-fidelity trajectory optimization and mission planning. The trajectories derived using MALTO show promising results, the capture trajectory used a Callisto-Ganymede-perijove-Io capture sequence to obtain direct Jupiter capture with a period of 106.3 days with negligible SEP ΔV expenditure. The interplanetary trajectory conversely showed a distinct possibility of improvement.

Patrick and Lynam's interplanetary trajectory had a final mass 135.9 kg lower than the interplanetary trajectory devised by Strange et al. that was used as a basis of comparison. A few possibilities were proposed as to the reasons for this. The most important reason, as far as this paper concerned, is that MALTO does not allow for the changing of central bodies in a single optimization run. Because of this factor the interplanetary and triple flyby trajectories could not be simultaneously optimized in MALTO. To correct this, the high fidelity optimization software Mystic was employed to design a new trajectory incorporating both the interplanetary and triple flyby trajectories into one trajectories allowing for simultaneous optimization.

Mystic vs MALTO

Mystic, also developed at JPL, employs a "Static/Dynamic Optimal Control (SDC)" algorithm for optimization. The SDC algorithm is a nonlinear optimization method that is designed to optimize both static and dynamic variables at the same time. The Mystic software applies the SDC algorithm to computing optimal low-thrust trajectories by way of either maximizing the final net mass of the spacecraft or by minimizing user defined infeasibility by way of the magnitude of a constraint violation.

In addition, Mystic allows for the central body of the trajectory to be changed mid-trajectory, this allowed for the integration of the triple-flyby trajectory with that of the interplanetary trajectory to create a single trajectory starting from Earth launch and ending in Jupiter capture orbit. By creating a single, continuous trajectory, Mystic reduces the overall error in the trajectory by eliminating the need to match end points of trajectories. This fact is relevant to the trajectory devised by Patrick and Lynam as the GMAT program was required to back propagate the start of the MALTO triple flyby trajectory to Jupiter's sphere of influence (SOI) to allow for matching with the MALTO interplanetary trajectory.

Beyond the fact Mystic allows for the changing of the central body for the trajectory, Mystic also allows for more control over trajectory end states. MALTO, for example, builds trajectories by defining trajectory segments each ending with an approach of a pre-defined body or control point. Mystic conversely allows for a wider range of intermediate and end states by allowing for simple creation of bodies via ephemeris or orbital element definitions as well as custom orbit constraints as defined around a specific central body.

Despite its disadvantages, MALTO does provide two benefits over Mystic. First, MALTO is better at finding trajectories without initial guesses than Mystic is. Secondly, MALTO allows for the definition of custom launch vehicles inside the GUI in a much more user-friendly manner. Mystic conversely does not allow for custom launch vehicle definitions in the GUI. Mystic does, however, allow for a greater degree of control over launch parameters as well as more in-depth launch mass curve manipulation for the predefined launch vehicles.

Trajectory Design

Much like the previous MALTO trajectory design, the triple flyby trajectory was designed first to ensure feasibility of the capture with the interplanetary trajectory designed afterwards. Once the triple flyby was developed and a feasible interplanetary trajectory was developed, the two were combined to further optimize the full trajectory.

The optimized MALTO trajectory was used to provide reasonable initial guesses for the trajectory design. The triple flyby was designed using the optimized Non-body control point (NBCP) from MALTO as the starting conditions leading into the Callisto-Ganymede-perijove-Io sequence. One major change to the design is the change in end state for the trajectory. Due to previously discussed limitations in the MALTO software, a second Ganymede flyby representing the Jupiter capture orbit and the start of a subsequent science mission was used as the end state for the trajectory. Here, Mystic allows the end state to be represented by an energy constraint representing achievement of a 100-day Jupiter capture orbit.

Once the triple flyby trajectory was developed and optimized, the interplanetary trajectory was developed using the newly optimized Non-body control point as the initial target location. This optimization was achieved through an iterative design process starting with an Earth to Mars trajectory and working up to an Earth-Mars-Jupiter and finally Earth-Mars-NBCP trajectory. This iterative method was employed due to the highly constrained nature of the trajectory (the constraint requirements can be seen in the previous work by Patrick and Lynam). By iterating the trajectory piecewise, a greater degree of control over the optimization can be achieved.

The initial design of the trajectory was based on the optimized interplanetary MALTO trajectory with a few changes. The largest change to the trajectory is in the use of an Atlas V with constrained launch V_∞ vs Falcon 9 for the initial earth centered launch. This change was made for optimization simplification. The only parameter of the trajectory that was affected by this change is that of the initial launch mass, by switching to the Atlas V a larger starting mass value can be assumed.

Once the triple-flyby and interplanetary trajectories were developed the combined trajectory was developed by adding 30 days to the Earth-Mars-NBCP interplanetary trajectory. In addition, the Callisto, Ganymede and Io gravity assists were inserted and optimized.

As mentioned previously, each trajectory was based on the previous MALTO trajectories derived by Patrick and Lynam. From these the following initial conditions as displayed in Tables

1 and 2 were developed for the triple flyby and interplanetary trajectories. The combined trajectory's initial conditions were developed based on those of the triple-flyby and interplanetary trajectories.

Following the optimization of the final combined trajectory, two more trajectories were developed similarly to the combined trajectory. The optimized Earth-Mars trajectory was then used as a base and expanded up to complete Earth-Mars-Jupiter capture orbits with inserted and optimized Callisto, Ganymede and Europa gravity assists. The two additional trajectories differ in the placement of the Europa flyby, which is either before or after perijove.

RESULTS

Following the optimization of the individual triple-flyby and interplanetary trajectories for the first solution, an optimal combined trajectory was found using Mystic. This trajectory demonstrates a complete, Earth to Jupiter capture orbit over the course of 1848.875 days (5.0619 years). The trajectory includes a successful gravity assist of Mars as well as a complete triple-flyby capture using of Callisto, Ganymede, and Io (with each flyby one day apart). Table 1 below gives a complete timeline of this trajectory.

Table 1. Earth-Mars-Callisto-Ganymede-perijove-Io mission timeline

Event	Date
Earth Launch	November 16, 2024 01:43:58
Mars Gravity Assist	April 5, 2026 21:41:48
Callisto Gravity Assist	December 1, 2029 14:44:14
Ganymede Gravity Assist	December 2, 2029 09:43:25
Perijove	December 3, 2029 02:57:57
Io Gravity Assist	December 3, 2029 7:05:56
Jupiter Capture	December 8, 2029 22:42:48

The optimized trajectory results in a space craft final mass of 3779.7238 kg out of the launch mass of 5024.9739 kg along with a capture orbit period of 89.8 days. Figure 1 below shows the overall Sun-centered trajectory, and with Figure 2 shows the Jupiter-centered triple-flyby.

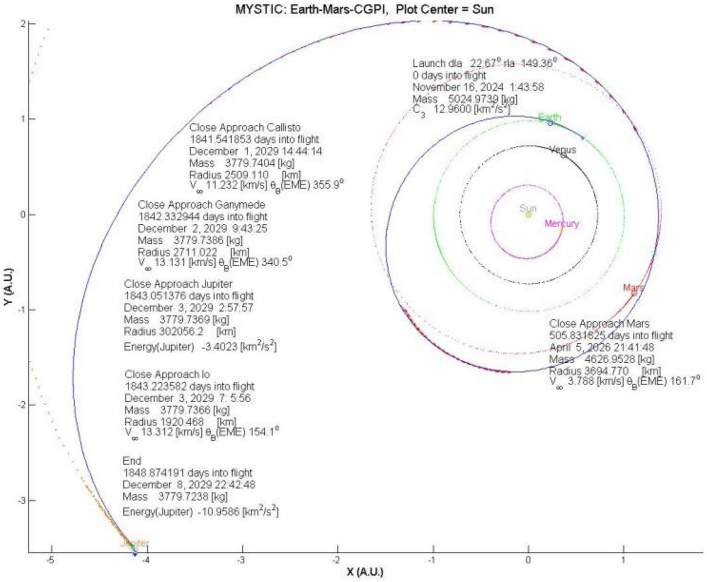

Figure 1. Expanded view of complete Earth-Mars-CGPI trajectory following optimization.

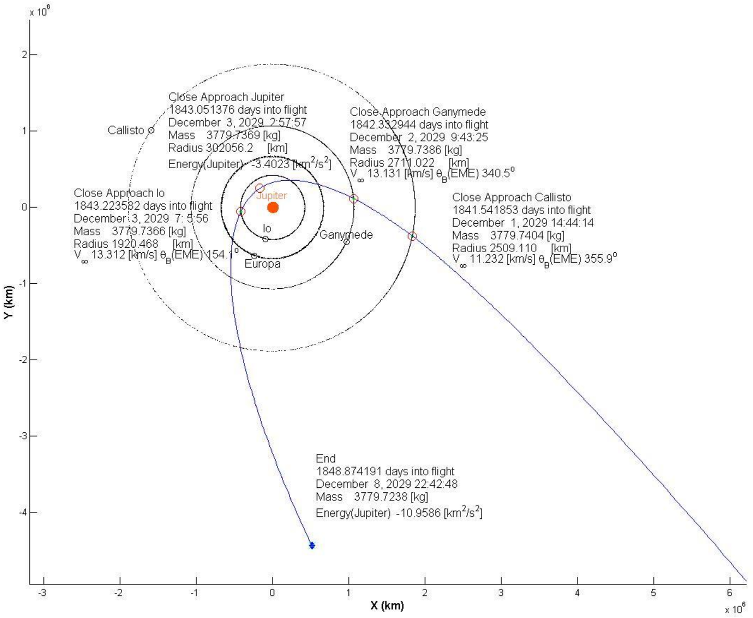

Figure 2. Close view of CGPI section of trajectory.

With minimal effort, the combined trajectory was found to be able to model the feasibility of other Jupiter approach sequences involving triple-flyby maneuvers of the Galilean moons. To demonstrate, a Callisto-Ganymede-Europa-perijove sequence was developed as shown in Figure 3 and Figure 4 along with a Callisto-Ganymede-perijove-Europa sequence as shown in Figure 5 and Figure 6.

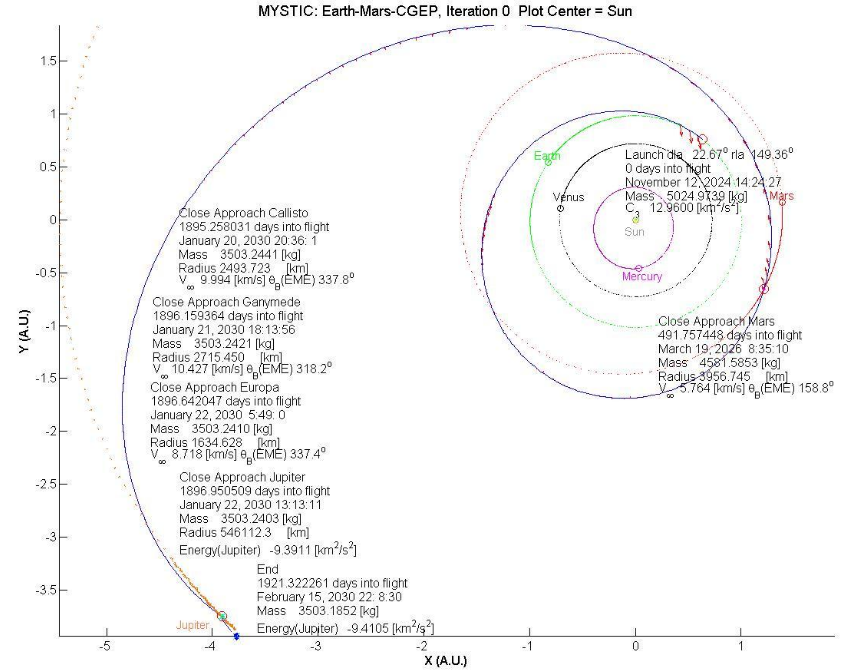

Figure 3. Complete Earth-Mars-CGEP trajectory following optimization

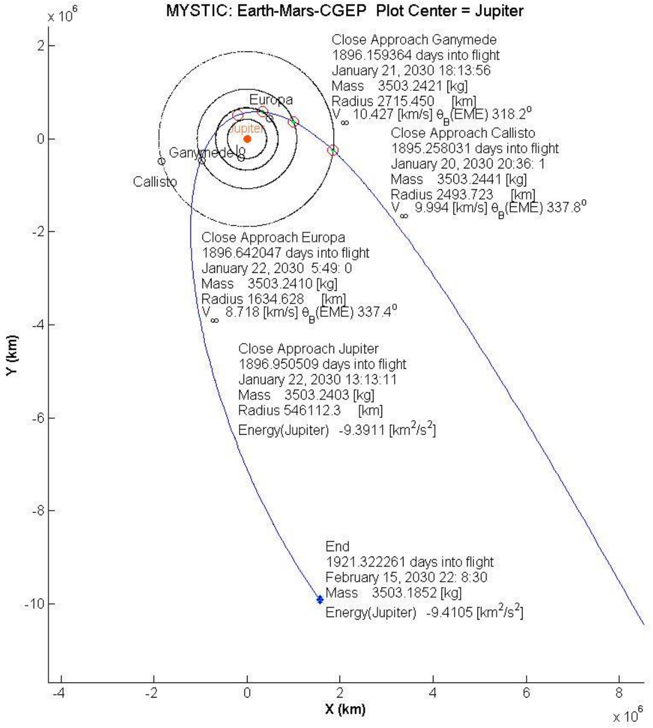

Figure 4. Close view of CGEP section of trajectory

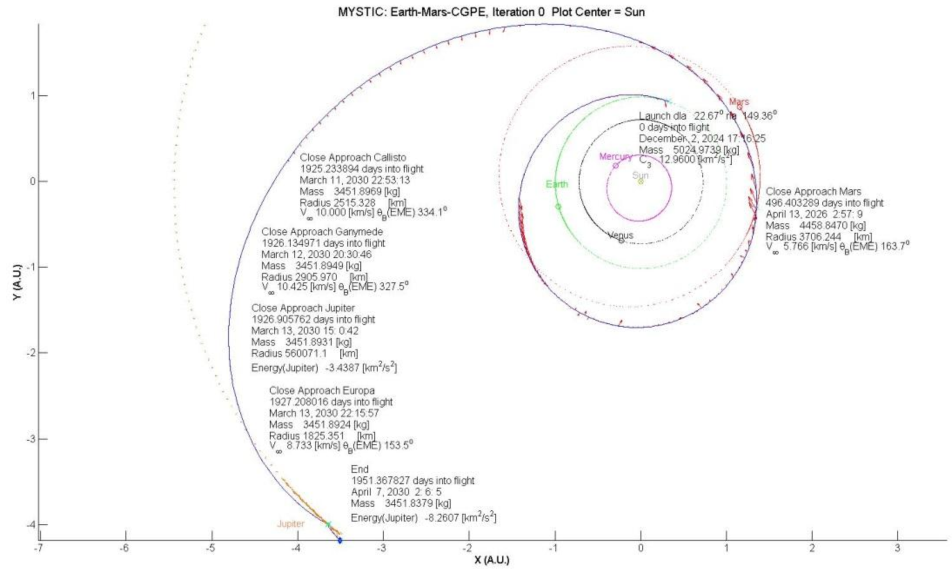

Figure 5. Complete Earth-Mars-CGPE trajectory following optimization

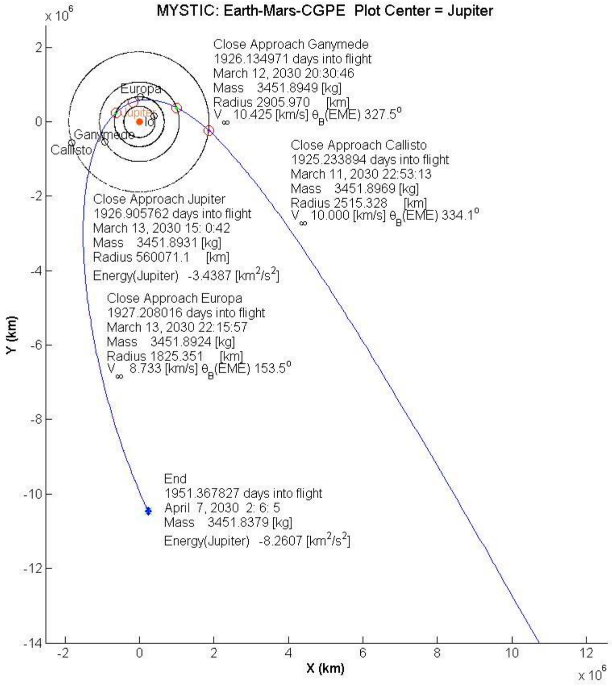

Figure 6. Close view of CGPE section of trajectory

A complete mission timeline of both trajectories has been included below in Table 2 and Table 3. The Earth-Mars-Callisto-Ganymede-Europa-perijove trajectory was successfully optimized to have a final mass of 3503.2 kg and a capture orbit period of 112.8 days. Additionally, the Earth-

Mars-Callisto-Ganymede-perijove-Europa trajectory has an optimized final mass of 3451.8 kg and a capture orbit period of 137.2 days.

Table 2. Earth-Mars-Callisto-Ganymede-Europa-perijove mission timeline

Event	Date
Earth Launch	November 12, 2024 14:24:27
Mars Gravity Assist	March 19, 2026 08:35:10
Callisto Gravity Assist	January 20, 2030 20:36:01
Ganymede Gravity Assist	January 21, 2030 18:13:56
Europa Capture	January 22, 2030 05:49:00
Perijove	January 21, 2030 13:13:11
Jupiter Capture	February 15, 2030 22:08:30

Table 3. Earth-Mars-Callisto-Ganymede-perijove-Europa mission timeline

Event	Date
Earth Launch	December 2, 2024 17:16:25
Mars Gravity Assist	April 13, 2026 02:57:09
Callisto Gravity Assist	March 11, 2030 22:53:13
Ganymede Gravity Assist	March 12, 2030 20:30:46
Perijove	March 13, 2030 15:00:42
Europa Gravity Assist	March 13, 2030 22:15:57
Jupiter Capture	April 7, 2030 02:06:05

DISCUSSION

The optimized Earth-Mars-Callisto-Ganymede-perijove-Io trajectory developed in Mystic shows a marked improvement over the previous separated interplanetary and triple-flyby trajectories designed by Patrick and Lynam using MALTO. Specifically, the combined Mystic trajectory reduces the overall mission SEP ΔV requirements by roughly 1.0 km/s from 6.602 km/s to 5.587 km/s.

Each of the three trajectories found using Mystic have nearly equatorial Jupiter-centered orbits. Because of this, in all three trajectories, the spacecraft will travel through Jupiter's equatorial region where the radiation environment is the worst. The radiation exposure is most severe below 5 RJ and progressively improves at higher radii. The initial Earth-Mars-Callisto-Ganymede-perijove-Io trajectory has a radius of perijove of 4.225 RJ, exposing the spacecraft to high levels of radiation. The subsequent Earth-Mars-Callisto-Ganymede-perijove-Europa and Earth-Mars-Callisto-Ganymede-Europa-perijove trajectories have perijove radii of 7.834 RJ and 7.639 RJ respectively. These higher radii expose the spacecraft to much less radiation than that of the Earth-Mars-Callisto-Ganymede-perijove-Io trajectory, about 1/3 as much exposure. The lower radiation exposure does come with a trade off in regards to the period of the capture orbits and the SEP ΔV requirements. While exposing the craft to higher radiation, the Earth-Mars-Callisto-Ganymede-perijove-Io (EMCGPI) trajectory has a period of 89.8 days. This is much shorter than the Earth-Mars-Callisto-Ganymede-perijove-Europa (EMCGPE) trajectory at 137.2 days and the Earth-Mars-Callisto-Ganymede-Europa-perijove (EMCGEP) trajectory at 112.8 days.

The EMCGPI trajectory requires 5587.3 m/s of SEP ΔV, while the EMCGPE and EMCGEP trajectories require 7367.8 m/s and 7077.8 m/s, respectively. However, this difference is mostly due to the fact that the MALTO interplanetary trajectory that all three were based on was optimized for the EMCGPI trajectory, rather than the other two. Also, the other two are less optimal in terms of their heliocentric flight path angle as they approach Jupiter. Thus, we cannot draw general conclusions from these specific examples about whether EMCGPI trajectories require more SEP ΔV than the other two captures. Other EMCGPE trajectories may very well require less SEP ΔV than other EMCGPI trajectories. The other conclusions about perijoves, the radiation, and capture orbit period are more generalizable because they are based on the fact that Io has a larger mass and a smaller perijove than Europa.

Previously, Patrick and Lynam briefly explored some of the navigation challenges related to a SEP triple-flyby trajectory. Specifically, Patrick and Lynam compared the applicability of the navigation analysis performed by Lynam and Longuski relating to triple flyby capture trajectories assuming impulsive maneuvers to SEP triple satellite aided capture sequences. The main navigation challenge was determined to be that continuous application of thrust from a SEP source would be unable to provide enough ΔV over the short intervals between flybys. Because of this there is insufficient control authority to guide a SEP craft through the given triple flyby sequences.

To correct for this, Patrick and Lynam proposed low Isp RCS thrusters dedicated to attitude control, that are also capable of performing Trajectory Correction Maneuvers (TCM). Additionally, autonomous navigation was suggested as a solution to save hours of light time delay, but it would require a robust onboard Navigation system.

While unexplored here, Didion and Lynam explored the use of autonomous navigation for an impulsive Callisto-Io-perijove-Ganymede Jupiter capture trajectory and by inserting reasonable, random errors into the propagation model[31]. The focus of this aspect was to determine if autonomous mission navigation of a triple-flyby trajectory was feasible after taking into account trajectory correction. Didion and Lynam determined that an autonomous navigation routine is feasible when dealing with reasonable error. The maneuvers required for trajectory correction are infeasible for the use in an SEP trajectory as presented here, but they could be performed with the addition of a Hydrazine thruster dedicated to attitude control and TCMs.

CONCLUSION

Triple gravity-assist flybys of the Galilean moons, in conjunction with SEP propulsion, have previously been shown by Patrick and Lynam to allow for a lower ΔV requirement to enter Jupiter Orbit. Here, an expansion on this work has been proposed in which a Jupiter approach is designed based on the previous Earth-Mars-Jupiter low-thrust trajectory with a Callisto-Ganymede-perijove-Io triple-flyby designed by Patrick and Lynam. This trajectory was modified and expanded using the Mystic software developed by JPL into a complete Earth-Mars-Callisto-Ganymede-perijove-Io trajectory. In addition an Earth-Mars-Callisto-Ganymede-Europa-perijove trajectory and an Earth-Mars-Callisto-Ganymede-perijove-Europa trajectory were developed.

Once optimized, these trajectories show a marked improvement over the original MALTO trajectories developed by Patrick and Lynam. The fact that Mystic allows for a complete Earth to Jupiter orbit capture in a single high-fidelity trajectory reduces uncertainty and error as compared to the need for separate patched-conic Jupiter-centered and heliocentric trajectories in MALTO.

While the optimized Mystic trajectories do show an improvement over the MALTO trajectories, the navigation challenges presented by Patrick and Lynam are still present. In addition, the Mystic EMCGPI trajectory still has the issue of exposing the spacecraft to high levels of radiation due to having a perijove lower than Io's orbital radius. However, the EMCGEP and EMCGPE trajectories, with a higher radii of perijove, have about 1/3 as much radiation exposure.

REFERENCES

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

[2] Potts, C. L., Wilson, M. G., "Maneuver Design for the Galileo VEEGA Trajectory," *AAS/AIAA Astrodynamics Specialist Conference,* AAS Paper No 93-566, Victoria, BC, Canada, August 1993.

[3] Barber, T. J., Krug, F. A., Froidevaux, B. M., "Initial Galileo Propulsion System In-flight Characterization," *AIAA/SAE/ASME/ASEE 29th Joint Propulsion Conference and Exhibit,* AIAA Paper No: 93-2117, Monterrey, CA, June 1993.

[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] Haw, R. J., Antreasian, P. G., McElrath, T. P., and Lewis, G. D., "Galileo Prime Mission Navigation," *Journal of Spacecraft and Rockets*, Vol. 37, No. 1, 2000, pp. 56-63.

[6] Goodson, T. D., Gray, D. L., Hahn, Y., Peralta, F., "Cassini Maneuver Experience: Finishing Inner Cruise", *AAS/AIAA Spaceflight Mechanics Meeting,* AAS Paper No 00-167, Clearwater, FL, January 2000.

[7] Roth, D., Antreasian, P., Bordi, J., Criddle, K., Ionesescu, R., Jacobson, R., Jones, J., Meed, M. C., Roundhill, I., Stauch, J., "Cassini Orbit Reconstruction from Jupiter to Saturn", *AAS/AIAA Astrodynamics Specialist Conference,* AIAA Paper No 05-311, Lake Tahoe, CA, August 2005.

[8] Ballard, C. G., Attieta, J., Hahn, Y., Stumpf, P. W., Wagner, S. V., Williams, P. N., "Cassini Maneuver Experience: Ending the Equinox Mission," *AIAA/AAS Astrodynamics Specialist Conference,* Toronto, ON, Canada, August 2010.

[9] Williams, P.N., Ballard, C. G., Gist, E. M., Goodson, T. D., Hahn, Y., Stumpf, P. W., Wagner, S. V., "Flight Path Control Design for the Cassini Equinox Mission," *AAS/AIAA Spaceflight Mechanics Meeting,* Savannah, GA, February 2009.

[10] Anderson, J. D., Lau, E. L., Sjogren, W. L., Schubert, G., and Moore, W. B., "Gravitational Constraints on the Internal Structure of Ganymede," *Nature*, Vol. 384, 1996, pp. 541–543.

[11] Anderson, J. D., Jacobson, R. A., McElrath, T. P. Moore, W. B., Schubert, G., and Thomas P. C., "Shape, Mean Radius, Gravity Field, and Interior Structure of Callisto," *Icarus*, Vol. 153, 2001.

[12] Anderson, J. D., Jacobson, R. A., Lau, E. L., Moore, W. B., Schubert, G., Io's gravity field and interior structure. *Journal of Geophysical Research*, Vol. 106, 2001.

[13] Anderson, J. D., Schubert, G., Jacobson, R. A., Lau, E. L., Moore, W. B., and Sjogren, W. L., "Europa's differentiated internal structure: Inferences from four galileo encounters," *Science*, Vol. 281, 1998.

[14] Longman, R. W., Schneider, A. M. "Use of Jupiter's Moons for Gravity Assist", *Journal of Spacecraft and Rockets*, Vol. 7, 1970, pp. 570-576.

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

[16] Nock, K. T., Uphoff, C., "Satellite Aided Orbit Capture", *AAS/AIAA Astrodynamics Specialist Conference,* AAS Paper No 79-165, Provincetown, MA, June 1979.

[17] 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.

[18] Yam, C. H., "Design of Missions to the Outer Planets and Optimization of Low-thrust, Gravity-assist Trajectories via Reduced Parameterization", PhD. Dissertation, Purdue University, 2008.

[19] Landau, D. F., Strange, N., Lam, T., "Solar Electric Propulsion with Satellite Flyby for Jovian Capture", *AAS/AIAA Spaceflight Mechanics Conference,* San Diego, CA, February 2010.

[20] 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.

[21] Lynam, A. E., Kloster, K. W., Longuski, J. M., "An Assessment of Multiple-Satellite-Aided Capture", *AAS/AIAA Astrodynamics Specialist Conference,* AAS Paper No 09-424, Pittsburgh, PA, August 2009.

[22] 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.

[23] Lynam, A. E., Longuski, J. M., "Interplanetary Trajectories for Multiple-satellite-aided Capture at Jupiter", *Journal of Guidance, Control, and Dynamics,* Vol. 34, 2001, 1485-1494.

[24] 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.

[25] Lynam, A. E., "Broad-search Algorithms for the Spacecraft Trajectory Design of Callisto-Ganymede-Io Triple Flyby Sequences from 2024 to 2040, Part I: Heuristic Pruning of the Search Space", *Acta Astronautica,* Vol. 94, Issue 1, January-February 2014, pp. 246-252.

[26] Patrick, S. K., Lynam, A. E. "Optimal SEP Trajectories from Earth to Jupiter with Triple Flyby Capture." *AAS/AIAA Astrodynamics Specialist Conference*, AIAA Paper No 2014-4218. Sandiego, CA, Aug 2014.

[27] 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.

[28] Wiffen, G. J. "Mystic: Implementation of the Static Dynamic Optimal Control Algorithm for High-Fidelity, Low-Thrust Trajectory Design." *AAS/AIAA Astrodynamics Specialist Conference,* AIAA 2006-6741, Keystone, Co, Aug 2006.

[29] 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.

[30] Didion, A., Lynam, A. E. “Impulsive Trajectories from Earth to Callisto-Io-Ganymede Triple Flyby Capture at Jupiter.” *AAS/AIAA Astrodynamics Specialist Conference*, AIAA Paper No 2014-4106. Sandiego, CA, Aug 2014.

[31] Didion, A., Lynam, A. E. “Guidance and Navigation of a Callisto-Io-Ganymede Triple Flyby Jovian Capture.” *AAS/AIAA Astrodynamics Specialist Conference*, AAS 15-624. Vail, CO, Aug 2015.