Impulsive Trajectories from Earth to Callisto-Io-Ganymede Triple Flyby Capture at Jupiter

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Triple-satellite-aided capture sequences use gravity-assist flybys of three of Jupiter's four massive Galilean moons to help capture a spacecraft into orbit about Jupiter. A novel triple-satellite-aided capture uses sequential flybys of Callisto, Io, and Ganymede to reduce the ΔV required to capture into orbit about Jupiter. An optimal broken-plane maneuver is added between Earth and Jupiter to form a complete chemical/impulsive interplanetary trajectory from Earth to Jupiter.

Nomenclature

a = semi-major axis (SMA)
B = B-plane miss radius
e = eccentricity (ECC)
i = inclination (INC)
RJ = radius of Jupiter
R_p = radius of perijove
V = velocity
θ = B-plane angle
ν = true anomaly (TA)
Ω = right ascension of the ascending node (RAAN)
ω = argument of periapsis (AOP)

I. Introduction

GRAVITY-assist trajectories have been used in a number of deep space missions. The Galileo and Cassini missions both used several gravity-assist flybys of planets to obtain enough orbital energy to reach their destinations (Jupiter and Saturn, respectively) [1-8]. As Galileo arrived at Jupiter, it captured into orbit about Jupiter using a gravity assist of Io and a sizable impulsive ΔV from its main engine. The Io gravity-assist reduced the ΔV required to capture into Jupiter orbit by 185 m/s [3]. After Galileo captured into Jupiter orbit, it performed dozens of gravity-assist flybys of Jupiter's Galilean moons, which have provided much scientific knowledge about the gravity fields and geology of each moon [9-12].

The use of gravity assists of planetary moons to reduce the ΔV required to capture into planetary orbit is called "satellite-aided capture". While most papers discussing satellite-aided capture have focused on using only one satellite gravity assist to aid in the capture [13-18], several have proposed using two [19-23] or three [21-26] of Jupiter's Galilean moons to capture a spacecraft into orbit about Jupiter. Using three gravity-assists of Jupiter's Galilean moons is called "triple-satellite-aided capture".

Since Jupiter has four massive Galilean moons and any three of these moons can be encountered in differing orders, there are numerous permutations for triple-satellite-aided capture. Lynam et al. [21-22] discovered four geometrically possible "Laplacian triple-satellite-aided capture" sequences that use gravity assists of each of the Galilean moons that are involved in the 4:2:1 Laplace resonance: Ganymede, Europa, and Io. While these sequences occur more frequently than other triple-satellite-aided captures, they have a few deficiencies that make them less useful than more optimal double- and triple-satellite-aided capture sequences. These deficiencies include having low

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perijoves (two have perijoves [R_p's] of slightly higher than 1 Jupiter radii [RJ]; two have R_p's of 2 RJ) that would increase radiation exposure and have lower ΔV savings for most mission scenarios.

In addition to Laplacian triple-satellite-aided capture, the other three combinations of satellites are Callisto-Ganymede-Io, Callisto-Ganymede-Europa, and Callisto-Europa-Io triple flybys. Of these combinations, Callisto-Europa-Io is the definitive worst since Callisto and Europa are the weakest satellites for gravity-assist capture and must have a perijove that is below 6 RJ to encounter Io (which is deep within Jupiter's radiation environment). Callisto-Ganymede-Europa sequences show some promise since they can have higher perijoves (since Europa has an orbit of about 9.4 RJ), however they still suffer from the weaknesses of Callisto and Europa as gravity-assist capture bodies. The most promising combination is Callisto-Ganymede-Io since Ganymede and Io are the strongest of the Galilean moons for gravity-assist capture, although they also suffer from low perijoves of less than 6 RJ.

Although Callisto, Ganymede, and Io are the best combination of three moons to use for triple-satellite-aided capture, since they can be encountered in different orders, there are actually eight geometrically possible permutations. Lynam [25-26] developed a method that was able to find promising trajectories for two of these eight permutations: Callisto-Ganymede-Io-perijove and Callisto-Ganymede-perijove-Io.

This paper builds on the work of Lynam by investigating one of the other six permutations: the Callisto-Io-perijove-Ganymede sequence. It refines the heuristic reduction methods that Lynam used to find triple-satellite-aided capture sequences. Further, this paper concentrates on finding ballistic trajectories from Earth to Jupiter that would use chemical propulsion rather than the low-thrust trajectories that Lynam [25-26] used. This paper features the use of a broken-plane maneuver (BPM) to ensure that the spacecraft's original trajectory plane intersects with an Earth encounter and that its final trajectory plane is coplanar with the orbits of the Galilean moons.

II. Methodology

In order to generate high-fidelity orbit simulations and formulate optimal conditions for a triple-satellite-aided capture maneuver, the NASA General Mission Analysis Tool (hereafter referred to as GMAT) software is used. The GMAT software was chosen due to its adaptability to such esoteric mission profiles such as that described in this paper as well as its open source availability and computational flexibility and accuracy. While less widely used than other similar astrodynamical propagation software, it is easily reconfigured to fit mission specifics (such as addition of the Galilean moons), provides a simple GUI and script editing interface, and is capable of interfacing with MATLAB in order to use its optimization subroutines.

A. Software Configuration & Setup

The GMAT software provides a default environment which includes the sun, each of the eight planets, Pluto, and the earth's moon. Additionally, the default scenario includes multiple Earth-centered coordinate systems and an Earth-orbiting generic spacecraft. For the purposes of this mission, the default spacecraft can be disposed of in favor of a customized spacecraft while the Earth-centered coordinate systems can be ignored. In order to model the Jovian system and its Galilean moons, additional celestial bodies are added with the gravitational parameter, equatorial radius, texture map and SPICE ephemeris data corresponding to each of the four major moons. All interplanetary propagation will incorporate gravitational effects of point masses representing the sun, all of the planets, and Pluto, while all propagation within the Jovian sphere of influence will incorporate such effects from the sun, Jupiter, and the four Galilean moons. To properly display each of the three flyby maneuvers and provide relevant orbital parameters, an "orbit view" graphical output window is created corresponding to each of the three new moon coordinate systems as well as a Jupiter-centered and Sun-centered coordinate system. Because the Galilean moons must be added manually into the simulation environment, their precise radii and gravitational parameters are required. These parameters are set according to the values provided in the JPL Solar System Dynamics planetary satellite physical parameters table [27-30].

To propagate astrodynamical systems, GMAT employs a numerical integrator which can be adjusted with custom integrator types, step sizes, and stopping tolerances (acceptable accuracy), among other parameters. As is common practice with close flyby maneuvers, the default "RungeKutta89" integrator is changed to the "PrinceDormand78" integrator, which is specifically designed for the required type of adaptive step sizing, yielding higher accuracy as the spacecraft approaches the stronger gravitational field close to celestial bodies and higher computational speed in interplanetary voids where large steps can be taken. Using these specially tailored tools, GMAT will be used to refine initial guess parameter approximations into a complete orbital profile with precise ΔV and moon body-plane (B-plane) targets based on intense numerical calculation and detailed ephemeris data. It is important to note that with integration techniques that use adjustable step sizing, such as PrinceDormand78, safeguards must be inserted into the script to stop propagation if the solution breaches the surface of a celestial body.

If this is not done and the solution approaches the core of a body, its gravitational singularity, the adjustable step size will shrink exponentially and severely hinder the solving process. In this situation, such safeguards will be accomplished by causing the solver to revert to the “JupiterOnly” propagator if the spacecraft is below the surface of a moon. This propagator neglects the gravitational effects of the moons and the spacecraft will drift through the moon to be reset and that run deleted without slowing down the process.

B. Definition of Flyby Coordinate Systems

Moon flyby maneuvers will be described throughout this analysis using the flyby body plane (B-plane) parameters. The parameters of most importance are the “BdotT” and “BdotR” dot products (as denoted in GMAT), shown in Figure 1 below, which quantify respectively the horizontal and vertical components of the “B” miss radius of the incoming hyperbola. These quantities, it will be shown, can be correlated to the change in the spacecraft’s Jupiter-centered orbital energy and inclination, respectively. This means that flybys with lower BdotT values will serve to drastically change the orbital energy of the spacecraft’s Jupiter-centered orbit while, similarly, high BdotR flybys will drastically change the inclination of the orbit. In this figure, the “S” vector is simply the unit vector centered on the moon parallel to the incoming velocity asymptote, from which “R” and “T” are orthogonally derived. These vectors, with the miss radius, B, and B-plane angle, ϴ, fully describe a celestial flyby.

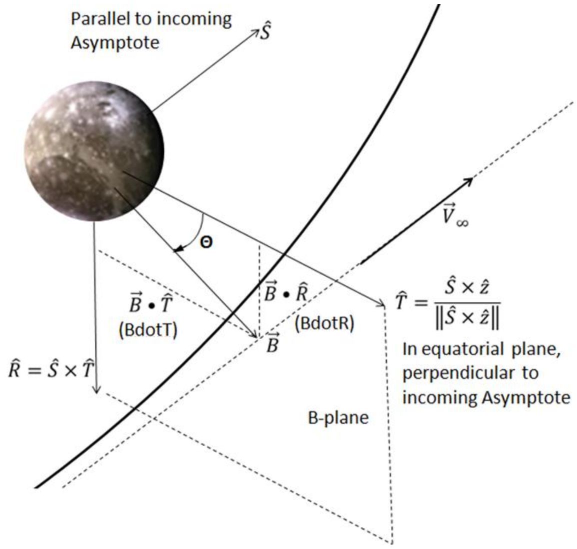

Figure 1: Flyby body B-plane parameters, used in GMAT to fully describe a celestial flyby.

C. Initial Parameter Selection & Goal Definitions

To begin, a suitable candidate was chosen from a collection of approximately twenty thousand theoretically feasible capture orbits between the year 2024 and 2028 by sorting according to desirable properties. (This collection of trajectories was generated using a similar method to that of Lynam [25-26].) By prioritizing parameters such as Callisto B-plane angle, required interplanetary ΔV, and incoming perijove radius R_p, the options were reduced to approximately six hundred, from which a candidate was chosen for having the highest R_p. The chosen candidate’s initial parameters are detailed in Table 1 and Table 2 in Cartesian and Keplerian elements respectively.

Table 1: Initial guess for Jupiter-centered Cartesian elements.

Parameter	Symbol	Value	Units
Epoch	[N/A]	2025 FEB 03 02:01:24	UTC G
X Position	X	-4589880.285	[km]
Y Position	Y	-8789.404	[km]
Z Position	Z	-61966.500	[km]
X Velocity	Vx	9.240	[km/s]
Y Velocity	Vy	-1.843	[km/s]
Z Velocity	Vz	0.067	[km/s]
V infinity	V_∞	5.622	[km/s]

Table 2: Initial guess for Jupiter-centered Keplerian elements.

Parameter	Symbol	Value	Units
Epoch	[N/A]	30709.584	MJD
Semi-major Axis	a	-3774011.246	[km]
Eccentricity	e	1.07364	[N/A]
Inclination	i	1.950	[deg]
RAAN	Ω	336.747	[deg]
AOP	ω	347.910	[deg]
True Anomaly	ν	215.465	[deg]
Hyperbolic Perijove	R_p	3.887	[RJ]

Prior to any targeting, the GMAT default script is modified as previously discussed, adding the Galilean moons into the simulation environment and creating the necessary coordinate systems to accurately display the solution. An initial propagation of the approximation candidate yields a rough triple flyby trajectory through the Jupiter system which does not achieve the stated goals, so targeting must be performed in order to refine the trajectory to a usable state. To define "usable state", some reasonable but adjustable parameters were set as targets for the triple flyby trajectory. These target values are detailed in Table 3 below, and represent the features of a feasible, efficient capture sequence to place a spacecraft into a desirable two-hundred day equatorial science orbit around Jupiter. It is important to note here two things: first, recall that the sequence includes a ballistic double flyby, followed by a purely retrograde Jupiter Orbit Insertion (JOI) burn at perijove which then allows the spacecraft to ballistically fly by Ganymede for the exact assist necessary to place it in a relatively equatorial, two-hundred day Jupiter orbit. Secondly, the B-plane angles (ϴ's) are listed in degrees to ease understanding, but GMAT accepts these angles only in terms of radians. Table 4 also details the parameters that will be referred to as describing a "desirable", marketable final orbit. These parameters ensure that the final science orbit is useful and that the incoming trajectory does not expose the spacecraft to excessive amounts of Jupiter's radiation.

Table 3: Altitude and ΔV targets for a desirable trajectory.

Parameter	Value	Units
Callisto Altitude	100.0	[km]
Callisto θ	0.0	[deg]
Io Altitude	300.0	[km]
Io θ	0.0	[deg]
JOI Burn Magnitude	0.230	[km/s]
Ganymede Altitude	100.0	[km]
Ganymede θ	180.0	[deg]

Table 4: Desirable trajectory limits and recommendations.

Parameter	Value	Units
Orbital Period (final)	~ 200	[days]
Inclination (final)	~ 0	[deg]
Perijove (burn)	> 3.0	[RJ]

The flyby altitudes will be fairly low to make the most use of the gravity assists as well as to gather science data during close approaches of the moons, especially while passing through the volcanic plumes of Io, which can exceed the 300 km targeted periapsis of this mission. The BdotR values at Callisto and Ganymede are both targeted to be approximately zero; this will help ensure that the interplanetary and final trajectories, respectively, are approximately equatorial with respect to their central body. The Io flyby will use an off-plane BdotR value to reconcile the resulting inclination differences between the two extremes, using Io's large gravity assist potential in place of the equivalent large ΔV that would be required. The flyby altitudes will mainly dictate appropriate BdotT values, which are the most influential geometric factor in acquiring equivalent ΔV from gravity assist maneuvers.

D. Trajectory Targeting & Optimization

To attempt to meet these conditions, initial rough targeting scripts will be formulated that aim to determine an initial state that would ballistically complete a suitable flyby of Callisto and Io without additional ΔV adjustment. In order to achieve this, it is necessary to identify all variables available and examine those whose adjustment would serve to achieve different target parameters. By examining the desired mission profile, it becomes clear that these variables are the six Keplerian elements and starting epoch of the flyby trajectory as it enters Jupiter's sphere of influence (SOI), the three flyby altitudes, the JOI burn ΔV magnitude, and the Io B-plane angle. The Jupiter SOI elements will then be ballistically back-propagated to a broken-plane maneuver to flyby Earth. This yields variables in the interplanetary scenario of time of flight (TOF) from Jupiter SOI to the BPM and the three BPM burn Cartesian elements. It should be obvious that the BPM burn elements and TOF are of importance primarily to the interplanetary cruise scenario. Furthermore, the Jupiter SOI-state (or incoming) semi-major axis will greatly influence the interplanetary trajectory, but the flyby sequence will be hardly affected by its alteration. Likewise, the Callisto flyby will be strongly governed by the incoming state's epoch, inclination, right-ascension of the ascending node, and argument of periapsis; the subsequent Callisto flyby altitude will dictate the Io flyby parameters. The subsequent Io flyby altitude and B-plane angle will dictate the Ganymede flyby parameters, fully ballistic with the exception of a pure retrograde JOI burn at perijove. All of these parameters, with Ganymede's flyby included, will then determine the final orbit's elements and the most important parameters: the orbital period, R_p, and inclination.

Because of the somewhat disjoint nature of the effects of the variables in the problem, a "nested loop" structure will be used to target individual phases of the trajectory, organized as follows. The interplanetary and triple flyby trajectories are mostly disjoint, patched only by the Keplerian elements at the exact epoch of "initial state" on the

Jupiter approach hyperbola as defined by the initial guesses. Therefore, to simplify the programming approach, the triple flyby is modeled in a forward propagated script while the interplanetary trajectory is modeled in a completely separate, backwards propagated script sharing the spacecraft “initial state”. The triple flyby trajectory is split into a nested double loop structure, with an internal differential corrector loop varying the incoming epoch, inclination, right ascension of the ascending node, and argument of periapsis. This inner loop is set to achieve given targets for Callisto and Io flyby BdotT and BdotR values. The outer differential corrector loop will vary incoming eccentricity and the Io B-plane angle. Each outer loop iteration will also then run the inner loop until convergence and propagate the results to perijove where it will execute the chosen ΔV and continue propagating to Ganymede. There, it will attempt to achieve a proper Ganymede flyby altitude to achieve the desired final orbital period. It is important to note that in this structure, each iteration of the outer loop will require a complete convergence cycle of the inner loop, and so the outer loop can require considerable time and computational power to converge. The script logic for the triple flyby solver is shown the form of a flow chart in Figure 2.

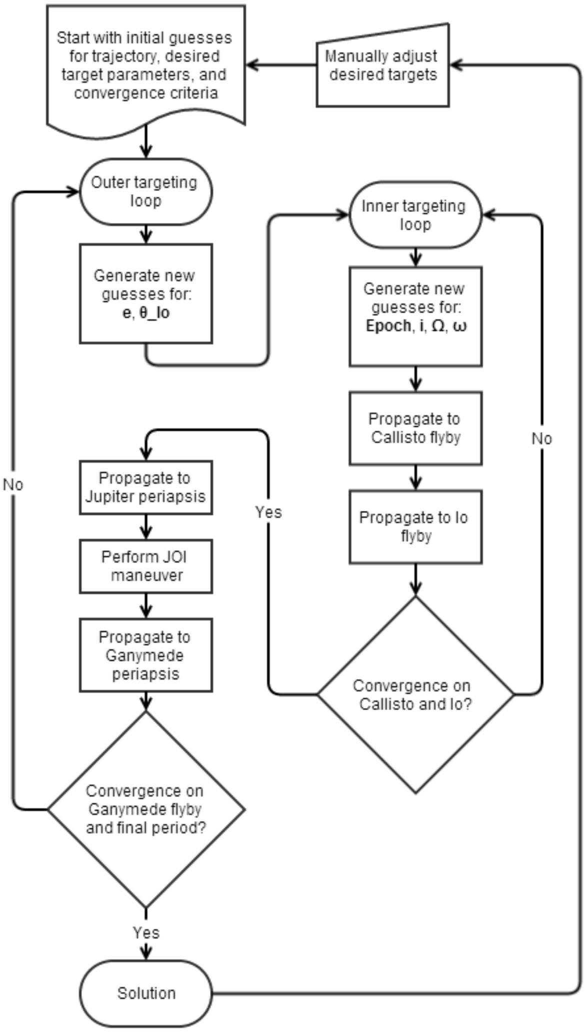

Figure 2: The triple flyby “nested solver” script refines the initial guess state to a useful solution.

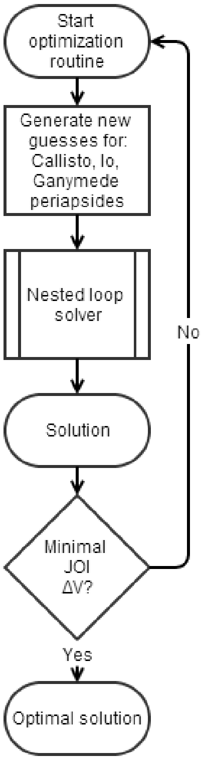

Figure 3: The triple flyby optimizer script finds the most efficient possible triple flyby.

The interplanetary trajectory’s script consists of only one loop which varies the time of flight to BPM, and Jupiter centered semi-major axis at the initial state. It then propagates backwards to and executes the BPM before propagating further back to achieve an Earth encounter. Backwards propagation is identical to the previously used forward propagation, but with negative time steps. This “split-propagation” scheme, with two scripts propagating in opposite directions, allows the two scripts to achieve the two halves of the mission independently and meet at a common point in space and time.

By using a MATLAB script interface, GMAT can solve problems with non-linear constraints through an optimization routine included in the MATLAB optimization toolbox, known by the handle "FminconOptimizer". This optimization routine allows GMAT to solve for the orbital parameters that most closely satisfy a constraint without having to achieve a direct goal; it can find a minimum difference rather than a precise match. This function is used in this analysis to find the minimum possible Earth periapsis radius when targeting Earth during the interplanetary back-propagation phase. It cannot be expected that the script find a flyby of specific radius on such a scale, but it is simple for the optimizer to find the minimum possible by varying the semi-major axis of the Jupiter-centered hyperbola. The optimizer is also used on the triple-flyby trajectory to find the lowest possible maneuver ΔV possible to achieve the desired orbit, while varying moon flyby altitudes. This ensures that no solution is chosen with largely arbitrarily chosen constraints, but that every value within the simulation has been carefully optimized and proven to provide the best possible trajectory in terms of minimal propellant usage and adequate flyby altitude. The optimizer script logic for the triple flyby and interplanetary trajectories can be seen in Figure 3 and Figure 4 respectively.

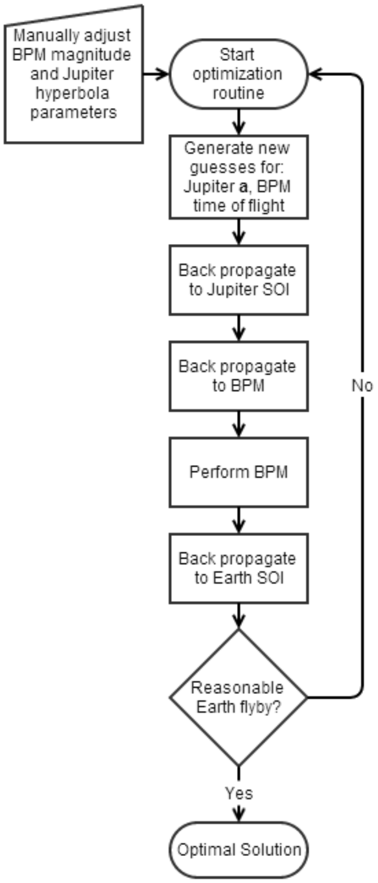

Figure 4: The interplanetary trajectory optimizer finds a reasonable Earth escape from the specified trajectory entering the Jovian system.

III. Results

With proper setup, the patched, nested-loop optimizer script architecture produces a full impulsive trajectory from Earth to a precise triple-satellite-aided Jovian capture using only a minimal retrograde perijove maneuver and a single interplanetary broken plane maneuver. The mission successfully escapes Earth, cruises to Jupiter and captures using less propellant than comparable missions and guarantees science opportunities in the form of close flybys to three of the four Galilean moons and Jupiter prior to completion of the first Jupiter orbit and a desirable final orbit for the extent of the mission. The analysis concludes with the spacecraft at first apojove. At which point, the orbit can be further adjusted to raise perijove and target a specific science flyby.

Achieved mission parameters are detailed below in Tables 5-8; these can be compared to the initial guesses and goals as previously detailed in Tables 1-4. It can be seen that some restrictions have been relaxed both manually and by the solver routine in order to achieve the ultimate final period goal. Most notably so is the Callisto flyby altitude, allowed to fluctuate low in order to converge on the necessary Io flyby to achieve the desired Ganymede parameters.

Table 5: Targeted initial Jupiter-centered Cartesian elements for the triple flyby phase.

Parameter	Symbol	Value	Units
Epoch	[N/A]	02 Feb 2025 21:19:19	UTC G
X Position	X	-4714128.923	[km]
Y Position	Y	68943.330	[km]
Z Position	Z	-60914.940	[km]
X Velocity	Vx	9.078	[km/s]
Y Velocity	Vy	-1.970	[km/s]
Z Velocity	Vz	0.060	[km/s]
V infinity	V_∞	5.704	[km/s]

Table 6: Targeted initial Jupiter-centered Keplerian elements for the triple flyby phase.

Parameter	Symbol	Value	Units
Epoch	[N/A]	30709.388	MJD
Semi-major Axis	a	-3894011.246	[km]
Eccentricity	e	1.07342	[N/A]
Inclination	i	1.956	[deg]
RAAN	Ω	336.929	[deg]
AOP	ω	346.780	[deg]
True Anomaly	ν	215.465	[deg]
Hyperbolic Perijove	Rp	3.999	[km]

Table 7: Achieved altitudes and propellant consumption for the triple flyby phase.

Parameter	Value	Units
Callisto Altitude	54.8	[km]
Callisto θ	0.0	[deg]
Io Altitude	279.0	[km]
Io θ	-26.3	[deg]
JOI Burn Magnitude	0.264	[km/s]
Ganymede Altitude	97.3	[km]
Ganymede θ	168.6	[deg]

Table 8: Achieved final orbit characteristics.

Parameter	Value	Units
Orbital Period (final)	198.913	[days]
Inclination (final)	2.329	[deg]
Perijove (JOI)	3.237	[RJ]

As shown, the optimization sequence was unable to achieve both the desired period and the ΔV recommendation within flyby altitude restrictions, and the choice was made to sacrifice more propellant in favor of the lower orbital period. However, the perijove at which the JOI maneuver is performed is above the desired minimum (of 3 RJ), safeguarding the spacecraft from unnecessary radiation exposure. The periapsis altitude of the final orbit, however, is low and will require adjustment for a small amount of prograde ΔV at the moment of first apoapsis, which has not been modeled here. Such periapsis adjustment has been left to those tailoring the mission to their specific objectives. A graphic representation of the capture orbit through the Jovian system can be seen in Figure 5. In this figure, the incoming hyperbola intersects each moon's orbit (except Europa) at the point of each respective flyby and the spacecraft is captured into a final closed orbit with the apojove out of frame. Each flyby is shown individually in Figure 6.

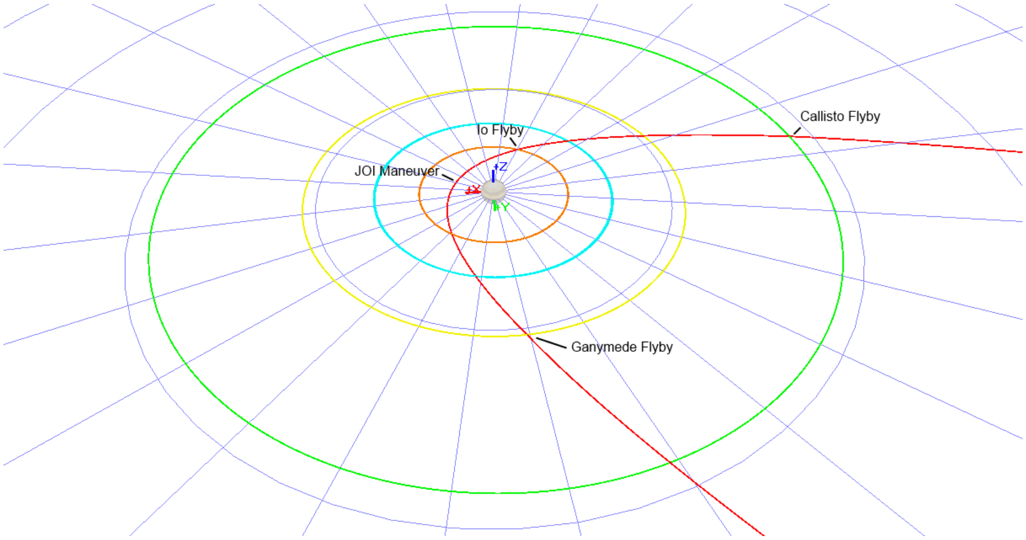

Figure 5: Triple flyby orbit plot.

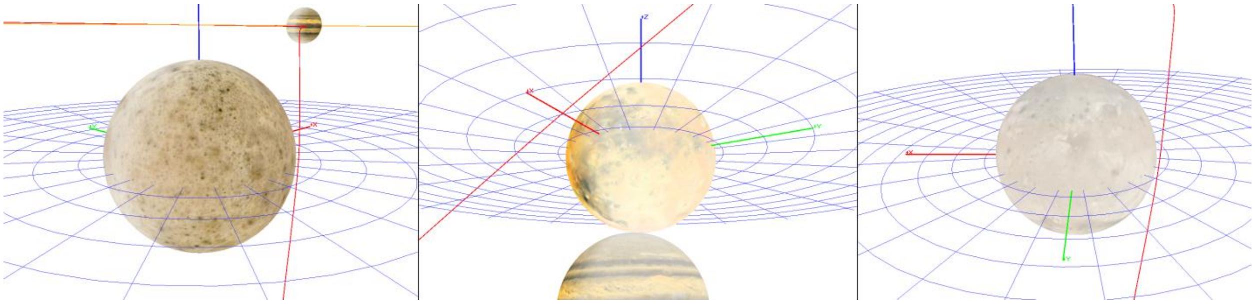

Figure 6: Graphical representations of the Callisto, Io, and Ganymede flybys respectively.

Back-propagating from the "targeted initial state" given in Tables 5-6, the interplanetary transfer trajectory is optimized to provide a suitable Earth escape. The Earth escape parameters are somewhat arbitrary and can be adjusted to suit the specific target mission or launch capabilities. For the purpose of rough targeting, an arbitrary Earth escape from a circular, 20,000 km orbit was used. The BPM specifics are detailed below in Table 9, next to the Earth escape specifics in Table 10. As shown, the BPM requires a total of approximately 12 m/s of ΔV to connect the Jupiter state with the Earth state given in Table 10. The resultant Earth V_∞ is approximately 9.253 km/s, requiring a NASA Space Launch System (SLS) launch. The interplanetary transfer, Earth and Jupiter intercepts, and BPM location are shown in a heliocentric view in Figure 7.

Table 9: BPM specific parameters.

Parameter	Value	Units
TOF	610.0	[days]
ΔV_x	7.50	[m/s]
ΔV_y	-8.36	[m/s]
ΔV_z	3.50	[m/s]
ΔV	11.76	[m/s]

Table 10: Spacecraft state just after Earth escape maneuver.

Parameter	Symbol	Value	Units
Epoch	[N/A]	29755.579	MJD
Semi-major Axis	a	-4655.913	[km]
Eccentricity	e	5.31685	[N/A]
Inclination	i	165.032	[deg]
RAAN	Ω	273.631	[deg]
AOP	ω	181.598	[deg]
True Anomaly	ν	0.000	[deg]

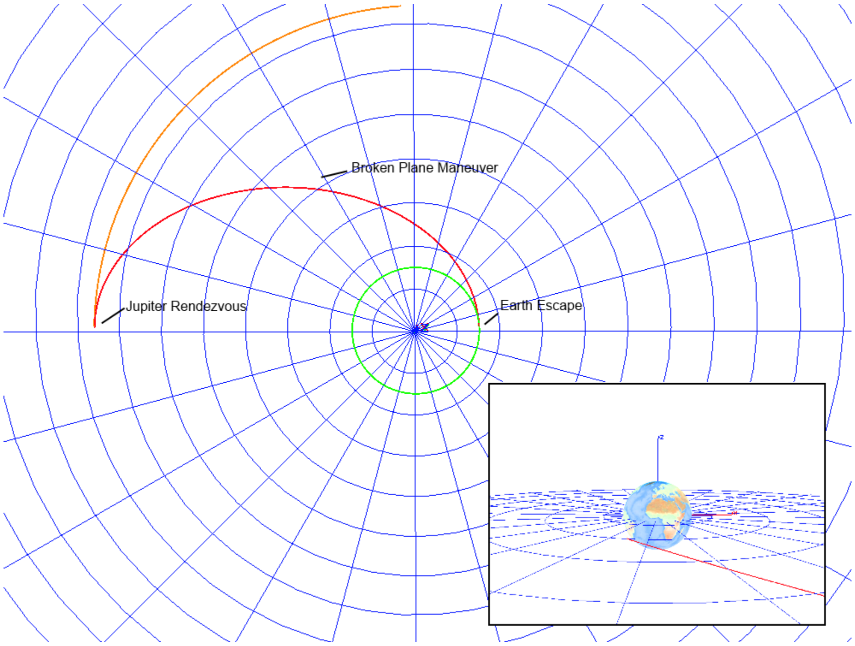

Figure 7: Graphical representation of the interplanetary transfer and Earth escape.

The mission is further detailed below in Table 11, a final orbit state at first apojove, where this analysis concludes. This state represents the "starting point" for final adjustment to a desired science orbit, starting at the first apojove after capture. Also, the entire mission is chronicled in Table 12 in the form of a mission timetable covering the events from Earth SOI escape to the first apojove. Both mission elapsed time (MET) and coordinated universal time (UTC) are given for each event. The full trajectory from Earth escape maneuver to first apojove takes a total of approximately 2.9 years to complete.

Table 11: Achieved Jupiter-centered Keplerian elements at first perijove.

Parameter	Symbol	Value	Units
Epoch	[N/A]	30813.663	MJD
Semi-major Axis	a	9823607.400	[km]
Eccentricity	e	0.98388	[N/A]
Inclination	i	2.329	[deg]
RAAN	Ω	8.044	[deg]
AOP	ω	317.780	[deg]
True Anomaly	ν	180.000	[deg]
Perijove	Rp	2.215	[RJ]

Table 12: Timetable of important mission events.

Event	MET (T+)	UTC Time
Earth Escape Maneuver	0/00:00:00	25 Jun 2022 01:53:32
SC Leaves Earth SOI	1/03:17:59	26 Jun 2022 05:11:31
BPM Performed	501/09:09:01	08 Nov 2023 11:02:34
SC Enters Jupiter SOI	878/04:38:27	19 Nov 2024 06:31:59
Callisto Periapsis	957/00:11:48	06 Feb 2025 02:05:20
Io Periapsis	958/05:09:06	07 Feb 2025 07:02:38
JOI Maneuver	958/09:35:35	07 Feb 2025 11:29:08
Ganymede Periapsis	959/02:01:04	08 Feb 2025 03:54:36
First Apojove	1058/02:00:34	18 May 2025 03:54:06

IV. Conclusions & Continued Work

This approach is designed to function for a variety of initial states leading to a Callisto-Io-perijove-Ganymede flyby sequence. With the inclusion of an optimized broken plane maneuver, the total interplanetary and capture ΔV for this mission is 275.8 m/s, as compared to 330 m/s for a Ganymede-Io-JOI double-satellite-aided capture. In the future, the scripts generated here can be used to find additional triple flyby missions to Jupiter by choosing any of the unused initial guesses in different time windows than the one refined here. Additionally, the sequence can be altered to solve for the other triple flyby scenarios such as Callisto-Ganymede-Io triple flybys.

As was shown, this particular mission scenario allows for multiple close flybys of Galilean moons, which provide the opportunity to perform large amounts of scientific observation during close approach, especially through the volcanic plumes of Io. Additionally, the triple flyby maneuver allows for a fuel-efficient entry into the Jovian system which has not been accomplished thus far. However, this scenario could greatly benefit from a longer multiple-flyby or low-thrust tour of the inner solar system before arrival at Jupiter, akin to the mission of the Juno spacecraft. Further refinement of this mission may include such elements to produce a fully efficient, albeit longer, low-thrust mission from Earth to Jupiter on minimal resources to achieve maximum science. However, the impulsive mission described here requires minimal propellant after detachment from the launch vehicle after Earth escape. Furthermore, the elapsed time between Earth escape and Jupiter capture (at Ganymede) is only 2.6 years, which is considerably shorter than comparable mission designs.

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