Interplanetary Trajectories for Multiple Satellite-Aided Capture at Jupiter

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Multiple-satellite-aided capture employs sequential gravity-assist flybys of more than one of Jupiter's Galilean moons. These flybys substantially reduce the amount of propellant required for a spacecraft to capture into orbit around Jupiter. The "average" plane of the Galilean satellites constrains the arrival V-infinity vector, which in turn constrains the interplanetary trajectories from Earth to Jupiter. The solution space of interplanetary trajectories that permit multiple-satellite-aided capture is explored, and trajectories that start from Earth and end at Jupiter capture are integrated.

I. Introduction

Satellite-aided capture is a mission design technique that is used to decrease the ΔV required to capture a spacecraft into orbit around a planetary body. The technique employs gravity-assist flybys of massive satellites of a planetary body, so only missions to planets with large moons can benefit from this technique. Hence, satellite-aided capture is only available to Earth-return missions and missions to Jupiter, Saturn, Uranus, or Neptune. Jupiter, in particular, has four massive Galilean moons that can be used for satellite-aided capture. These satellite-aided capture trajectories were first proposed for missions to Jupiter by Longman[1] and by Longman and Schneider.[2] Cline[3] determined the best use of a Ganymede gravity-assist to minimize the Jupiter insertion maneuver (JOI) ΔV required for capture into Jupiter orbit.

Nock and Uphoff[4] performed a tour-de-force of satellite-aided capture trajectories for the entire Solar System by varying several trajectory parameters, including perijove radius after flyby, flyby altitude, declination of the incoming satellite-centered hyperbola, and the distribution of ΔV between powered satellite flybys and the JOI maneuver. They also briefly investigated double-satellite-aided capture by determining the phasing and transfer orbit parameters necessary to achieve capture. Malcolm and McInnes[5] employ a vectorial targeting approach to solve the satellite-aided capture problem. Yam[6] and Okutsu et al.[7] present a central-body-changing algorithm that can model a satellite-aided capture using a patched-conic method. The algorithm accepts a planet-centered V_∞ vector and a moon's radius vector as input and outputs the phase angle between the incoming Jupiter-centered asymptote and the flyby. Landau et al.[8] proposed using solar electric propulsion (SEP) to reduce the Jupiter arrival V_∞ of interplanetary trajectories in order to ballistically capture an SEP spacecraft into orbit about Jupiter with gravity assists of one or two of Jupiter's Galilean moons.

The first implementation of a single-satellite-aided capture occurred during the Galileo mission to Jupiter.[9] Two proposed NASA missions to Jupiter (the Europa Orbiter Mission[10–12] and the Jupiter Icy Moons Orbiter[13]) had designed single-satellite-aided capture trajectories using Ganymede and Callisto, respectively. The planned Jupiter Europa Orbiter mission has a nominal trajectory that includes an Io-aided capture.[14] Lynam et al.[15] proposed the use of double-, triple-, or quadruple-satellite-aided capture as another method of capturing a spacecraft into orbit around Jupiter with still lower ΔV cost. That study focuses on the Jupiter capture phase of these trajectories and only briefly discusses the interplanetary trajectory phase of these missions. In this paper, we connect several of the multiple-satellite-aided capture sequences designed by Lynam et al. with interplanetary trajectories to form complete trajectories from Earth launch to Jupiter capture. Figure 1 shows a complete trajectory that begins at Earth launch and then performs gravity-assist flybys of Ganymede and Io as it approaches Jupiter. We also determine how often some of these capture trajectories are available for use in a future mission and how much total mission ΔV can be saved. As in Lynam et al., we assume that the (non-trivial) navigational challenges associated with these trajectories can be surmounted.

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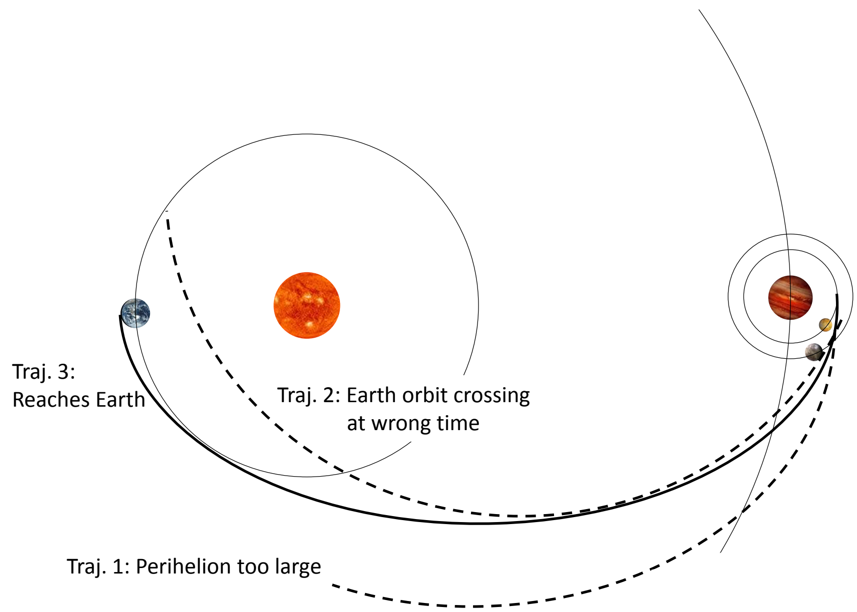

Figure 1. A schematic of a trajectory from Earth to Jupiter that uses gravity-assist flybys of Ganymede and Io to reduce the ΔV required to capture into orbit around Jupiter.

II. Patched-Conic Method

The ΔV savings of multiple-satellite-aided capture justify the effort required to find interplanetary trajectories that make use of such sequences. Lynam et al.[15] used a patched-conic method to calculate the ΔV required for the best multiple-satellite-aided capture trajectories using one, two, three, or four of Jupiter's Galilean moons. A compilation of their results is compared with the ΔV required for unaided capture (i.e. with no gravity assists) in Table 1.

Table 1. ΔV for Best Jupiter Capture Sequences Using Gravity Assists of No Moons, One Moon, or Multiple Moons[a], m/s

Flyby Sequences	JOI (5 R_J) ΔV, m/s	JOI (4 R_J) ΔV, m/s	JOI (3 R_J) ΔV, m/s	JOI (2 R_J) ΔV, m/s	JOI (1.01 R_J) ΔV, m/s
Unaided	825	735	641	524	371
Best Single	556	526	483	416	308
Best Double	330	340	333	299	228
Best Triple	202	232	245	234	190
Best Quadruple	—	—	—	175	160

[a] Arrival V_∞ is 5.6 km/s, flyby altitudes are fixed at 300 km, and the spacecraft captures into a 200-day orbit. R_J=71,492 km.

As an example, the fourth row of Table 1 gives ΔV values for the best triple-satellite-aided capture sequences at various perijoves (closest approach distances to Jupiter). The entry in column 1 of row 4 indicates that the best triple-satellite-aided capture sequence with a perijove of 5 Jupiter radii has a Jupiter orbit insertion (JOI) ΔV of 202 m/s. This sequence saves about 75% of the ΔV cost of unaided capture at that particular perijove, so it is the most efficient sequence at reducing ΔV. If three consecutive 10-km flybys (rather than the safer 300-km flybys given in the table) of Ganymede, Io, and Callisto could be safely executed, this sequence could capture a spacecraft into a 560-day orbit without any deterministic ΔV.

III. STK Trajectory Integration

Lynam et al.[15] used the patched-conic results as initial guesses for high-fidelity integration. They integrated these multiple-satellite-aided-capture trajectories using AGI's STK software.[16] In order to simplify the problem, they began the integration from an arbitrary initial state inside Jupiter's sphere-of-influence, propagated the gravity-assist flybys of each of the targeted moons, modeled a Jupiter orbit insertion (JOI) maneuver, and ended the trajectory at a point inside the spacecraft's capture orbit. Since the initial state of the spacecraft was arbitrary, the modeled spacecraft could approach Jupiter from any direction. Hence, most of these trajectories could not originate from Earth and thus are not available to actual Jupiter missions. Lynam et al.[15] did create a few "petal plots" to quickly rule out flyby sequences that have no chance of connecting to an interplanetary trajectory, but they did not actually integrate any transfers from Earth. In this paper, these rough petal plots are used as a first step to determine which multiple-satellite-aided-capture trajectories may have a chance of connecting to an interplanetary trajectory from Earth. These selected trajectories are then modified via STK such that they can be back-propagated to an Earth encounter.

A. Propagation Model and Initial State

We define a spacecraft propagation model for the Jupiter-centered regime that is the same as that used by Lynam et al.[15] This model includes the best known gravity fields of the Sun, Jupiter, and the Galilean moons.[17–20] General relativity perturbations and solar radiation pressure perturbations were added to the propagator to increase its fidelity. The high-fidelity of this propagator was necessary because of the dynamic sensitivity of these multiple-satellite-aided capture sequences.[15] Before the spacecraft approaches Jupiter, the fidelity of the trajectory is not as important because interplanetary trajectories are not as dynamically sensitive and they can be easily navigated. Thus, for the interplanetary trajectory, we use a heliocentric propagation model that includes only the point-mass gravity of the Sun and the eight planets.

The initial state of the STK trajectory is defined as a point in a hyperbolic orbit a few days before the spacecraft approaches Jupiter. STK's "target vector incoming asymptote" coordinate system is used to define this initial state. As illustrated in Fig. 2, the target vector incoming asymptote coordinate system includes four angular coordinates (declination, right ascension, velocity azimuth at perijove, and true anomaly), one distance coordinate (radius of perijove), one energy coordinate (C_3), and the initial time (Epoch). The incoming V_∞ vector is described in terms of its spherical components: its magnitude is described by the square root of C_3 and its direction is described by the declination and right ascension angles in Fig. 2. (Even though they do not have incoming asymptotes, elliptical orbits can also be defined in this system: the declination and right ascension angles of an elliptical orbit describe the direction of a vector pointing toward an elliptical orbit's apoapsis and the negative C_3 value of an elliptical orbit can be used to determine its semi-major axis.) Another coordinate, the radius of perijove, is the scalar distance between Jupiter's center and the spacecraft's position at closest approach (before any of the flybys modify the perijove of the spacecraft). A third angular coordinate, the velocity azimuth at perijove, describes the angle between the z-axis of the reference system and the velocity vector of the spacecraft at perijove. The fourth and final angular coordinate is true anomaly which defines the angular distance from the spacecraft at the initial time (Epoch) to its perijove. Each of the seven coordinates that represent the spacecraft's initial state can be used as control parameters within targeting sequences.

B. Defining B-plane parameters

Double satellite-aided capture sequences can be precisely targeted within STK by using the B-plane parameters of the two moons as target variables. The spacecraft is propagated from its initial state to its periapsis (closest approach distance) with respect to the first moon in the sequence. At periapsis, the spacecraft has two B-plane parameters that are used to characterize each flyby: $\mathbf{B} \cdot \mathbf{T}$ and $\mathbf{B} \cdot \mathbf{R}$. (This description of the B-plane is similar to that given by Malcolm and McInnes.[5]) In Fig. 3, the B-plane parameters are defined. The $\mathbf{S}$ vector is defined as a unit vector parallel to the spacecraft's incoming hyperbolic asymptote (with respect to the moon, not Jupiter). We define the $\mathbf{T}$ vector as the normalized cross product of the $\mathbf{S}$ vector and the moon's orbit normal, $\mathbf{N}$:

$$\mathbf{T} = \frac{\mathbf{S} \times \mathbf{N}}{|\mathbf{S} \times \mathbf{N}|} \tag{1}$$

As illustrated in Fig. 3, the $\mathbf{R}$ vector is orthogonal to $\mathbf{T}$ and $\mathbf{S}$ such that

$$\mathbf{R} = \mathbf{S} \times \mathbf{T} \tag{2}$$

The B-plane is a plane defined by the $\mathbf{R}$ and $\mathbf{T}$ vectors and centered at the moon's center of mass. The B-plane is, by definition, perpendicular to the incoming moon-centered asymptote. The $\mathbf{B}$ vector is the distance from the center of mass of the moon to the incoming moon-centered asymptote's intersection with the B-plane (as shown in Fig. 3). The B-plane parameters, $\mathbf{B} \cdot \mathbf{T}$ and $\mathbf{B} \cdot \mathbf{R}$, are the two components of the $\mathbf{B}$ vector in the $\mathbf{T}$ and $\mathbf{R}$ directions, respectively.

Since all of the multiple-satellite-aided capture trajectories that we studied are nearly within Jupiter's equatorial plane, $\mathbf{S}$ is nearly perpendicular to $\mathbf{N}$ such that $\mathbf{N}$ and $\mathbf{R}$ are nearly anti-parallel. Under the anti-parallel assumption, we informally refer to $\mathbf{B} \cdot \mathbf{T}$ as the equatorial component of $\mathbf{B}$ and $\mathbf{B} \cdot \mathbf{R}$ as the polar or out-of-plane component of $\mathbf{B}$. Under the aforementioned conditions, a flyby with a $\mathbf{B} \cdot \mathbf{T}$ component of zero and a large $\mathbf{B} \cdot \mathbf{R}$ component would be a polar flyby. Similarly, a flyby with a large $\mathbf{B} \cdot \mathbf{T}$ component and a $\mathbf{B} \cdot \mathbf{R}$ component of zero would be an equatorial flyby.

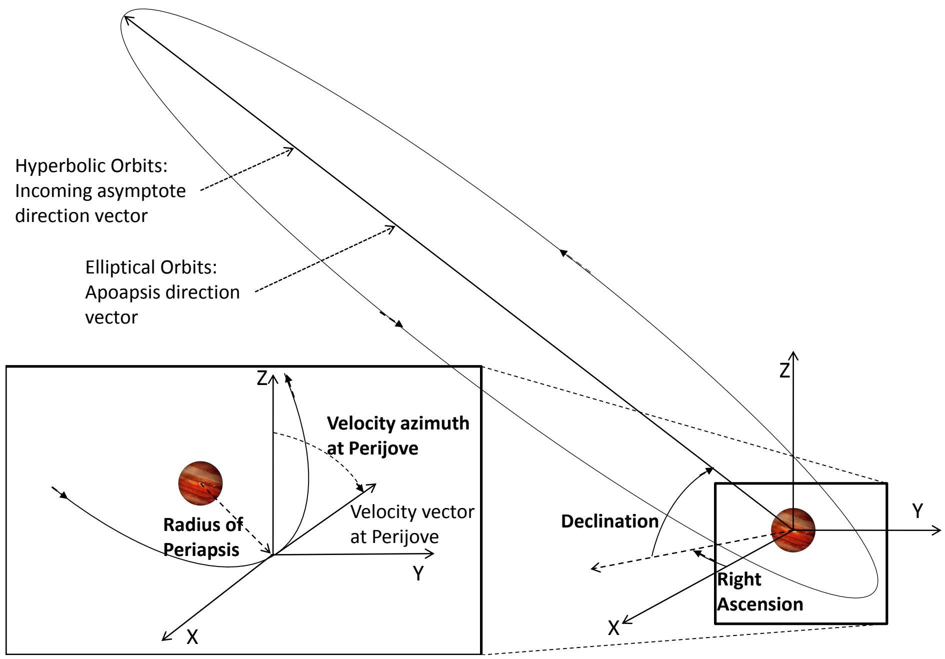

Figure 2. A graphical depiction of the four states of the "seven-state" that is used to define "target vector incoming asymptote" coordinates within STK. In addition to the four states that are depicted, there are Epoch (the spacecraft's initial time), C_3 (twice the specific orbital energy), and True Anomaly (the angular position of the spacecraft within the orbit at Epoch)

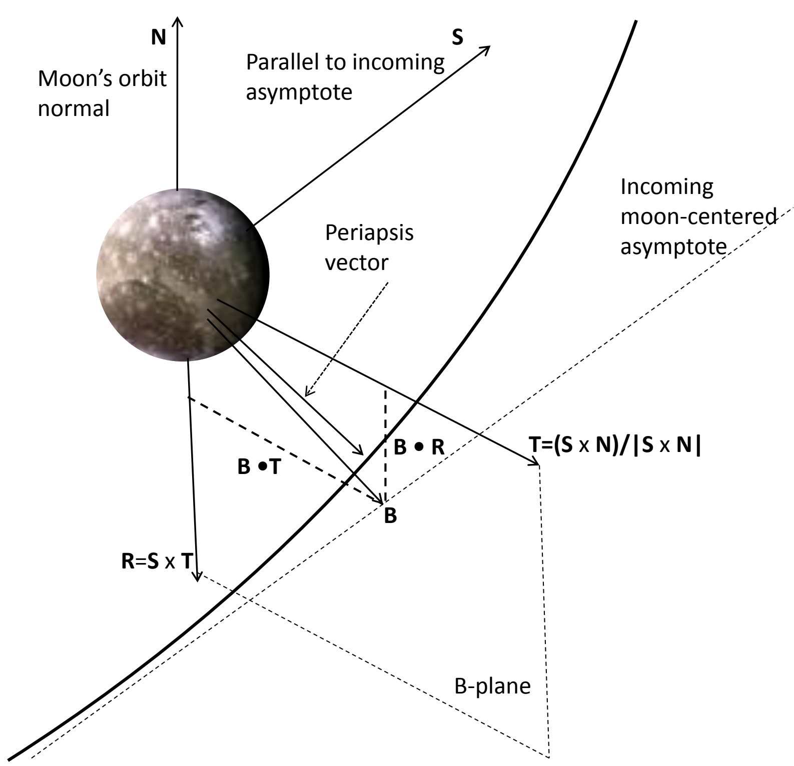

Figure 3. A graphical depiction of the B-plane used to describe the spacecraft's flyby of a Galilean moon.

Equatorial flybys cause the maximum change of a spacecraft's Jupiter-centered orbital energy, while polar flybys cause the maximum change of a spacecraft's Jupiter-centered inclination. The objective of multiple-satellite-aided capture is to minimize the required ΔV to capture a spacecraft into orbit around Jupiter. Since equatorial flybys can maximally reduce the spacecraft's Jovicentric orbital energy, they also maximally reduce the amount of Jupiter orbit insertion(JOI) ΔV required to capture a spacecraft into orbit around Jupiter. Polar flybys are not useful within multiple-satellite-aided capture sequences because they add complexity and dynamical sensitivity to the sequences without significantly aiding in the capture process.

IV. Targeting Double-satellite-aided Capture Sequences

Double-satellite-aided capture sequences require the targeting of flybys of two of Jupiter's Galilean moons. Since the precise timing of these flybys is not critical, we describe the flyby conditions of each flyby using only the B-plane parameters, $\mathbf{B} \cdot \mathbf{T}$ and $\mathbf{B} \cdot \mathbf{R}$. Thus, executing two flybys requires four target variables: $\mathbf{B} \cdot \mathbf{T}$ and $\mathbf{B} \cdot \mathbf{R}$ for the first moon and $\mathbf{B} \cdot \mathbf{T}$ and $\mathbf{B} \cdot \mathbf{R}$ for the second moon. In order to precisely target these variables, we need to define four control variables that can have a direct effect on the four target variables. We chose all four of these control variables from the initial state: epoch, declination, right ascension, and velocity azimuth at perijove. (Since the initial state can vary greatly during a targeting sequence, it is not prudent to constrain the initial state such that it must align with an interplanetary trajectory at this stage of the problem.)

STK's differential-corrector targeter varies each of the four control variables from the initial state until each of the four B-plane parameters are precisely targeted. As discussed earlier in the "Defining B-plane parameters" section, each flyby is maximally efficient at reducing JOI ΔV when it is equatorial, so the $\mathbf{B} \cdot \mathbf{R}$ parameters of both flybys are targeted to be zero. The $\mathbf{B} \cdot \mathbf{T}$ parameters are chosen so that they are positive for inbound flybys (where the trajectory is moving toward Jupiter) and negative for outbound flybys (where the trajectory is moving away from Jupiter) so that they maximally decrease the orbital energy. In our simulations, the $\mathbf{B} \cdot \mathbf{T}$ parameters are chosen to be consistent with flybys that are constrained to have altitudes of exactly 300 kilometers for consistency, but this choice is somewhat arbitrary and the flybys can be targeted to any altitude. (We note that all of the targeting described in this section refers to the deterministic targeting of nominal trajectories that mission designers perform and not the statistical targeting of trajectory correction maneuvers that navigators perform.)

The above procedure is only numerically effective if the flybys are either both inbound flybys or both outbound flybys. If the desired trajectory sequence contains both an inbound and an outbound flyby, only three of the four required B-plane parameters can be targeted. In this case, three of the control variables should be used to target three of the B-plane parameters. The fourth control variable can either be manually modified to target the fourth target variable or included within the upper-level targeter of a nested targeting sequence. (A nesting targeting sequence would use one upper-level targeter to target one of the parameters and one lower-level targeter to target the other three.) Once the targeting sequence for the two flybys converges within STK, a JOI maneuver is added to capture the spacecraft into its desired capture orbit. In our simulation, we used 200-day capture orbits to reflect the capture orbit that was used by Galileo[9], but this period can also be modified by changing the ΔV magnitude of the JOI maneuver.

A. Interplanetary Trajectory Windows for Double-satellite-aided capture sequences

Interplanetary trajectories for these double-satellite-aided capture trajectories can be found by backward-propagating (running STK's propagators backward in time) the initial states of these trajectories until they reach Earth. Unfortunately, a vast majority of the Jupiter-centered, double-satellite-aided capture trajectories will not reach Earth via back-propagation. Each available interplanetary trajectory has a constrained Jupiter-centered arrival V_∞ vector. The double-satellite-aided capture targeting sequence separately constrains the Jupiter-centered arrival V_∞ vector because its right ascension and declination are used as control variables. Because satellite-aided capture cannot be implemented on an actual space mission unless the spacecraft arrives at Jupiter from an interplanetary trajectory beginning at Earth, multiple-satellite-aided capture sequences must be found whose V_∞ vectors align with the V_∞ vectors associated with interplanetary trajectories from Earth. The remainder of this paper explores methods of aligning multiple-satellite-aided capture sequences with interplanetary trajectories.

Since double-satellite-aided capture targeting sequences only require four of the initial state variables, two variables remain that can be used as control variables for targeting the interplanetary portion of these trajectories: C_3 and radius of perijove. (True anomaly is not useful because true anomaly and epoch are not independent variables—changing the true anomaly would only force the epoch to change and vice versa.) The first method we explore, "the interplanetary-trajectory-window method", involves varying only the radius of periapsis to (roughly) determine if it is possible to align an interplanetary trajectory with a double-satellite-aided capture sequence for a given period of time. This method narrows the set of all possible double-satellite-aided capture sequences to the set of all double-satellite-aided capture sequences that could possibly align with an interplanetary trajectory. Once the set is narrowed, the second method, "nested backward targeting", uses both C_3 and radius of perijove as control variables to backwards-target Earth's two B-plane parameters, thereby explicitly solving for the interplanetary trajectories that align with double-satellite-aided capture sequences.

The interplanetary-trajectory-window method is predicated on finding the right ascension angle of a V_∞ vector that corresponds to a Hohmann transfer that is near Earth's orbital radius about the Sun. In this rough method, the right ascension angle of an initial state is used to backward-target a heliocentric radius of perihelion that is equivalent to Earth's mean orbital radius. The right ascension angle whose backward-propagated interplanetary trajectory's perihelion is smallest is defined as the "Hohmann" angle at that particular epoch. Another Hohmann angle is found at a later epoch, and we linearly interpolate to find the Hohmann angles that occur between the two epochs.

Next, two separate double-satellite-aided capture sequences are calculated: one with the minimum radius of perijove near Jupiter's atmosphere and one with the maximum radius of perijove near the orbital radius of the innermost moon in the two-moon sequence. The corresponding two right ascension angles are recorded and subtracted from the Hohmann angle at that particular epoch. This process gives the rough angular difference between the V_∞ vectors for these two sequences and the V_∞ vector for a Hohmann transfer at this epoch. The subtraction is equivalent to transforming the right ascension angles into the Sun-Jupiter rotating frame, so new angles are called "normalized right ascension" angles.

The normalized right ascension angles for the maximum and minimum perijove solutions of a Ganymede-Io sequence are plotted as the edges of the triangles that represent each flyby window in the polar "petal" plot in Fig. 4. We interpolate the continuum of solutions for radii of perijove (and consequently normalized right ascension angles) that are between the maximum and minimum perijoves. This continuum is represented by the area inside each of the petals in Fig. 4. For Ganymede-Io-satellite-aided capture sequences, there are three unique interplanetary trajectory windows every week that are shifted about 120 degrees from each other. Since the right ascension angles are normalized, we can easily determine that an interplanetary trajectory is unavailable during this time period (July 11-July 23) because none of the of the triangular petals encompass the region around the Hohmann angle (of zero degrees). However, the petals precess by about 6 degrees every week (due to the Laplace resonance and the orbit of Jupiter around the Sun), so we know that an interplanetary trajectory will become available within about 8 weeks.[15] Additionally, there are three other Ganymede-Io double-satellite-aided capture sequences that can be propagated backward to Earth: Ganymede-JOI-Io, Io-JOI-Ganymede, and JOI-Io-Ganymede. (We also note that Ganymede-JOI-Io could be sequenced as a Ganymede flyby, perijove, Io flyby, JOI maneuver sequence to avoid having a JOI maneuver between flybys.) One of these four Ganymede-Io flyby sequences is available at virtually any Jupiter arrival date, so double-satellite-aided capture is almost always possible for any Jupiter mission.

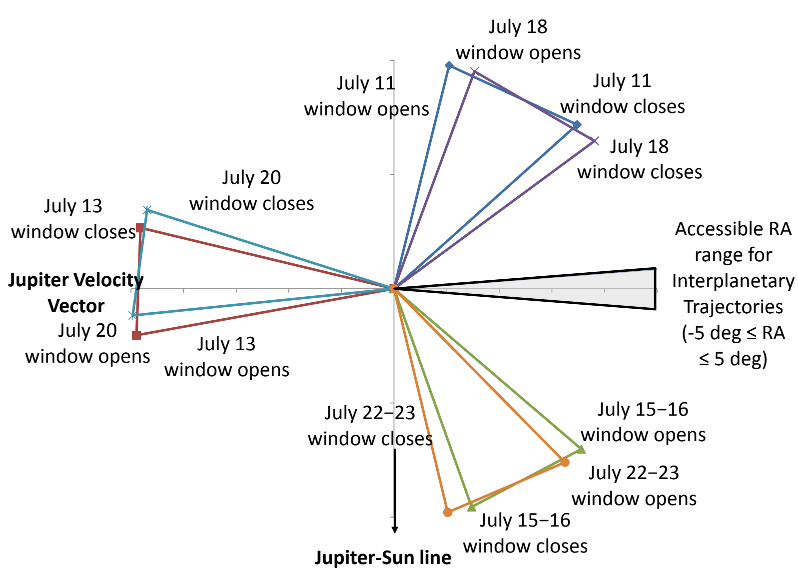

Figure 4. Polar plot of the normalized right ascension angles of Ganymede-Io-JOI flyby windows. The Jupiter-Sun line points downward. The area near the Hohmann right ascension angle (shaded region) is not encompassed by a (triangular) petal, so a Ganymede-Io-JOI capture sequence is not available for an interplanetary trajectory from Earth during this arrival time frame. The petals rotate about 6 degrees every week, so a Ganymede-Io-JOI sequence will become available in about 8 weeks.

B. Nested Backward Targeting for Double-satellite-aided Capture Sequences

Once the interplanetary-trajectory-window method provides a window that encompasses the area around the Hohmann angle, a more precise nested backward targeting method is used to solve for an interplanetary trajectory that aligns with a double-satellite-aided capture sequence. A flowchart of this method is given in Fig. 5. The large blue arrows in Fig. 5 represent the flow of time of the spacecraft: it starts at Earth, propagates to an initial state at an incoming asymptote near Jupiter, propagates to the first flyby of a double-satellite-aided capture sequence, and then propagates to the second flyby. The small black arrows describe the targeting algorithm within STK. Four of the variables within the initial state are used to target the four B-plane parameters that describe the two flybys. This targeting sequence occurs via forward propagation and is the inner loop of the nested targeter. Two of the variables within the initial state (C_3 and radius of perijove) are used to backward target the two B-plane parameters of Earth within the upper loop of the nested targeter. (Thus, each time the C_3 or radius of perijove is changed in the outer loop, the double-satellite-aided capture sequence in the inner loop must be re-solved.)

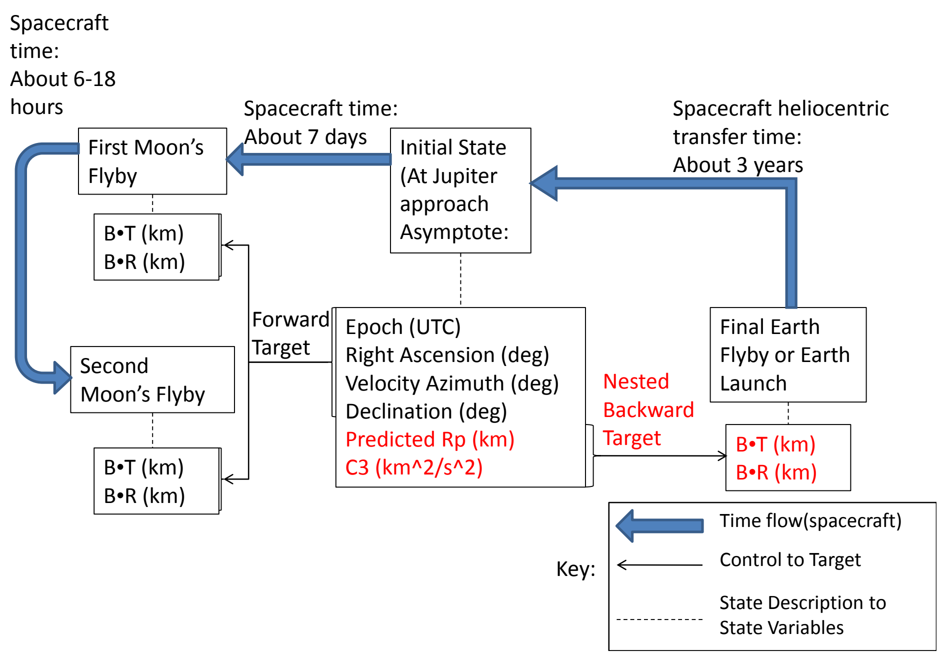

Figure 5. A flowchart describing both the trajectory propagation (large blue arrows) and the numerical targeting (small black arrows) of a mission from Earth to Jupiter that uses a double-satellite-aided capture sequence.

One of the only problems with the nested backward targeting method is that it requires a good initial guess to converge within a reasonable amount of time (due to numerical problems within STK's targeter). We circumvent this problem by using a manual targeting method for finding initial guesses that are close to the actual solutions and then applying the nested backward targeting method. We varied the C_3 and radius of perijove manually, recorded the back-propagated B-plane parameters of Earth, and interpolated to find a good initial guess. This rough interpolation gave a good enough initial guess to obtain convergence within the nested backward targeter for a trajectory that began at Earth with specified B-plane parameters. The encounter parameters of this converged trajectory are given in Table 2.

Table 2. Integrated GIJ Flyby Sequence: Flyby Parameters

Encounter Times (UTC)	Encounter	Θ (deg)	$B \cdot R$ (km)	$B \cdot T$ (km)
15 June 2022 4:29	Earth	0.0019	0.680	19998.1
29 Aug 2024 19:19	Ganymede	0.0	0.0	2967
30 Aug 2024 5:48	Io	0.0	0.0	2175
JOI Time (UTC)	R_{p} (R_{J})	ΔV(m/s)		Capture Orbit Period (days)
30 Aug 2024 10:05	2.0439	347.22		200

The converged trajectory in Table 2 notably requires no deterministic ΔV between Earth departure and the Ganymede-Io flyby sequence. The spacecraft does, however, require a ΔV_{JOI} of 347 m/s in order to capture into a 200-day orbit after it executes its two flybys.

V. Targeting Triple-satellite-aided Capture Sequences

Targeting triple-satellite-aided capture sequences is computationally more difficult than targeting double-satellite-aided capture sequences. Each of the four Galilean moons orbit Jupiter with slightly different inclinations, so it is unlikely that three flybys would occur within the same orbital plane. The initial state can specify the plane of the first and second flybys. In order to find a third flyby, the second flyby must be able to change the plane of the trajectory such that the new plane is coplanar with the second and third flybys. Thus, the second flyby is rarely an efficient equatorial flyby with a $\mathbf{B}\cdot\mathbf{R}$ of zero. Instead, part of the second gravity-assist flyby's equivalent ΔV (the part associated with its $\mathbf{B}\cdot\mathbf{R}$ component) changes the inclination of the spacecraft's orbital plane and part of the second gravity-assist flyby's equivalent ΔV (the part associated with its $\mathbf{B}\cdot\mathbf{T}$ component) reduces the orbital energy of the spacecraft in order to minimize the required ΔV_{JOI}.

The targeting process for triple-satellite-aided capture sequences involves a nested inner loop that targets the first and second flybys of the sequence and a nested outer loop that targets the third flyby of the sequence. The inner loop uses the same initial state control variables that double-satellite-aided capture sequences use: epoch, declination, right ascension, and velocity azimuth at perijove. The outer loop uses the radius of perijove at the initial state and the $\mathbf{B}\cdot\mathbf{R}$ component of the second flyby to target the two B-plane components of the third flyby. Because one of the B-plane components of the first two flybys is used to target the third, only five of the initial states are needed to target the triple-flyby sequence. Thus, the control variable C_3 is still available to backward target interplanetary trajectories.

A. Interplanetary Trajectory Windows for Triple-satellite-aided Capture Sequences

A slightly modified version of the "interplanetary trajectory window" method is available for triple-satellite-aided capture sequences. Since the radius of perijove is used as a control variable in the targeting of the third flyby of these sequences, full "windows" of solutions are not available. Instead, only a few unique solutions are available during a given time period. Figure 6 shows the normalized right ascension angles for Callisto-Ganymede-Io-JOI triple-flyby sequences for the date range from August 2023 to May 2024. (There do not exist any Callisto-Ganymede-Io-JOI sequences for 1.5 years prior to this date range or 1.5 years after this date range.[15]) Since none of these sequences have normalized right ascension angles that are near the Hohmann angle, near-Hohmann interplanetary transfers are not available. However, modifying the C_3 of the sequence that has the closest normalized right ascension angle to zero does permit a less ideal interplanetary trajectory to be found.

Varying the C_3 to larger values (which drastically increases the JOI ΔV required for capture) can enable the triple-satellite-aided capture trajectory to align with an interplanetary trajectory. However, a deep-space maneuver (DSM) is needed to back-target the trajectory to specified B-plane parameters. The total ΔV required for this trajectory was 607 m/s which is far greater than the 347 m/s that was required for the double-satellite-aided capture trajectory.

B. Interplanetary Trajectories for Laplacian Triple-satellite-aided Capture Sequences

Another class of capture sequences are the Laplacian triple-satellite-aided capture sequences.[15] These sequences do not use Callisto gravity assists and are designed by exploiting the dynamics of the Laplace resonance among Io, Europa, and Ganymede.[15,21–23] The Laplace resonance is a perfect 1:2:4 orbital resonance, so the various types of triple-satellite-aided capture sequences always have the same perijove: Ganymede-Io-JOI-Europa and Europa-JOI-Io-Ganymede sequences have perijoves of around 2.1 R_J while Ganymede-Europa-JOI-Io and Io-JOI-Europa-Ganymede sequences have perijoves of around 1.15 R_J. (For details see Table 8 of Lynam et al.[15]) The Laplace resonance precesses in the Jupiter-Sun rotating frame by about 6 degrees per Laplace resonance period (7.05 days), so each of the four sequences align with a Hohmann transfer about once every 60 weeks. Additionally, there are several trajectories that are close to a Hohmann that can be optimized to find the minimum DSM ΔV required to backward target a Laplacian triple-satellite-aided capture sequence to Earth.

A set of four Ganymede-Io-JOI-Europa capture sequences (each with perijoves that are about 7 days apart) near the Hohmann region were used as example trajectories. For a fixed C_3 value of 33.0625 $\mathrm{km}^2/\mathrm{s}^2$, the back-propagated Earth B-plane parameters of these four trajectories are given in Table 3. The August 30 trajectory is the best trajectory (i.e. will require the lowest ΔV) because the B-plane parameters are closest to zero (although they are still much too large for a gravity assist of Earth). Next, the C_3 value of the August 30 trajectory is varied to reduce the magnitude of the back-propagated B-plane paramters. Once an optimal C_3 is found, a deep-space maneuver (DSM) is added 0.2 years before the spacecraft approaches Jupiter to backward-target a more precise Earth B-plane. The final converged interplanetary trajectory has a DSM with a ΔV of 39 m/s and a JOI maneuver with a ΔV of 327 m/s. The total mission ΔV is thus about 367 m/s. (We note that the final row of Table 3 lists B-plane parameters in kilometers while the top seven rows list them in millions of kilometers.)

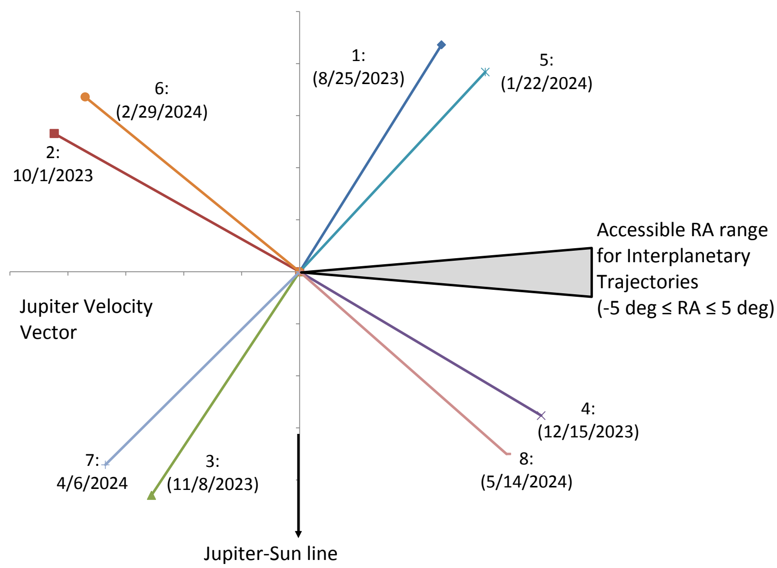

Figure 6. Polar plot of the normalized right ascension angles of Callisto-Ganymede-Io-JOI flybys. Note that (unlike in Fig. 4) only unique solutions exist (lines) not continua of solutions (petals). None of the trajectories have normalized right ascension angles within the area near the Hohmann right ascension angle (shaded region), so a Callisto-Ganymede-Io-JOI capture sequence is not available for a Hohmann interplanetary trajectory from Earth during this arrival time frame. However, a less ideal interplanetary trajectory can still be found.

Table 3. Backward-propagated GIJE Flyby Sequences

Perijove Time (UTC)	Perijove (R_J)	C_3 (km^2/s^2)	Earth $B \cdot R$ (km $\times 10^6$)	Earth $B \cdot T$ (km $\times 10^6$)	
16 Aug 2024 7:43	2.1201	33.0625	0.949	47.0	
23 Aug 2024 8:57	2.1199	33.0625	1.35	18.7	
30 Aug 2024 10:10	2.1198	33.0625	-3.29	10.5	
6 Sep 2024 11:23	2.1191	33.0625	-4.74	52.8	
30 Aug 2024 10:10	2.1182	34.0625	-1.05	0.425	
30 Aug 2024 10:10	2.1180	34.2125	-3.29	10.5	
30 Aug 2024 10:10	2.1177	34.4125	0.0273	-11.0	
Perijove Time (UTC)	Perijove (R_J)	C_3 (km^2/s^2)	Earth $B \cdot R$ (km)	Earth $B \cdot T$ (km)	Total ΔV (m/s)
30 Aug 2024 10:10	2.1190	34.4125	0.0427	20000	366.58

C. Quadruple-satellite-aided Capture

Interplanetary trajectories for quadruple-satellite-aided capture are possible but rare. Only one quadruple-satellite-aided capture sequence has been discovered so far and it did not align with an interplanetary trajectory.[15] We estimate the frequency of possible quadruple-satellite-aided capture sequences using the following reasoning. Each of the eight possible quadruple-satellite-aided capture sequences can be modeled as an extension of the four possible Laplace-resonant, triple-satellite-aided capture sequences. Because the Laplace resonance precesses by about 6 degrees every Laplace resonance period, every flyby window is separated from the next window by about 60 Laplace resonance periods (430 days). As indicated in Table 3, there are about 4 potential interplanetary trajectories in each window. Multiplying four interplanetary trajectories per window by four types of Laplace-resonant, triple-satellite-aided capture sequences and dividing by 430 days gives one triple-satellite-aided capture sequence per 27 days.

The position of Callisto must be aligned very closely with a trajectory of a Laplace-resonant, triple-satellite-aided capture sequence in order for a quadruple-satellite-aided capture sequence to occur. As a rough estimate, a spacecraft on a Laplace-resonant, triple-satellite-aided capture sequence would have to pass within 30,000 km of Callisto in order for a quadruple-satellite-aided capture trajectory to be possible. Since this distant flyby could occur either before or after the triple-satellite-aided capture sequence and the spacecraft could pass in front of Callisto or behind Callisto, the position of Callisto would have to be within a 120,000 km range for a quadruple-satellite-aided capture trajectory to be possible. Since the semi-major axis of Callisto's orbit is 1,882,700 km, its orbital circumference is $2\pi(1,882,700\text{km})$. Since Callisto's orbit is not commensurate with the Laplace resonant, the probability that Callisto will align with any given Laplace-resonant, triple-satellite-aided capture sequence is 120,000 km divided by $2\pi(1,882,700\text{km})$, which is about one percent. Dividing 27 days (the period between triple-satellite-aided captures) by one percent gives the period between one quadruple-satellite-aided captures, i.e. 2,700 days or 7.4 years. The above calculations are summarized in Eq. 3.

$$\text{Quad Frequency} = \frac{\text{4 Interp. Trajs.}}{\text{Seq.}} \times \frac{\text{4 Types of Triple-Seqs.}}{\text{430days}} \times \frac{\text{120000km}}{2\pi(\text{1882700km})} = \frac{\text{1 Quad-Seq.}}{\text{7.4years}} \tag{3}$$

VI. Discussion

Interplanetary trajectories for double-satellite-aided capture sequences occur much more frequently (nearly always) than interplanetary trajectories for triple-satellite-aided capture sequences (a few times per year). Additionally, triple-satellite-aided capture sequences require a deep-space maneuver (DSM) in order to precisely backward-target an Earth flyby while double-satellite-aided capture sequences can backward-target a ballistic interplanetary trajectory from Earth. Double-satellite-aided capture sequences also have an advantage in that both satellite flybys can always occur in the same plane. Since the third flyby of a triple-satellite-aided capture sequence is rarely in the same plane as the first two flybys, a plane-change maneuver is required. Either some of the effective ΔV of the second flyby must be expended to change the plane, or an out-of-plane component must be added to the JOI manuever. Applying either available "maneuver" will increase the total JOI ΔV required to capture the spacecraft into orbit about Jupiter.

Due to the above considerations, the example Ganymede-Io-JOI double capture sequence has a total ΔV of 347 m/s (as indicated in Table 2), while the example Ganymede-Io-JOI-Europa triple capture sequence has a total ΔV of 367 m/s (in Table 3) due to its DSM and its non-equatorial Io flyby. Furthermore, triple-satellite-aided capture sequences are more dynamically sensitive than double-satellite-aided capture sequences,[15] so triple-satellite-aided capture would also require greater navigational capabilities to implement. Even taking all of the above advantages of double-satellite-aided capture into account, triple-satellite-aided capture sequences can still require less ΔV than double-satellite-aided capture sequences under ideal conditions (i.e. if the three flybys occur in nearly the same plane or the back-propagated Earth B-plane parameters are close to Earth without adding a DSM). Under such conditions, the ΔV required for triple-satellite-aided capture would be considerably less than that required for double-satellite-aided capture and would be similar to the patched-conic ΔV estimates (of Table 1).

Quadruple-satellite-aided captures that align with interplanetary trajectories have not been integrated, but they are predicted to occur once every 7.4 years. If a quadruple-satellite-aided capture sequence that aligned with an interplanetary trajectory was discovered, it would likely have drawbacks that are similar to those of triple-satellite-aided capture sequences. In order to construct four flybys, a trajectory would require two orbital plane changes. Additionally, C_3 is often needed as a target variable in order to converge on quadruple-satellite-aided capture sequences, so the DSM required to backward-target the Earth flyby for quadruple-satellite-aided capture sequences would probably counter any potential ΔV-savings. It is possible that a quadruple-satellite-aided capture sequence exists with all four flybys in nearly the same plane and a backward-propagated Earth flyby with only a small DSM. Such a sequence would require a similar amount of ΔV to the patched-conic estimates (of Table 1), but these ideal trajectories would occur very infrequently since quadruple-satellite-aided capture sequences are predicted to occur only once every 7.4 years and it is even less likely that the planes of the flybys would align during one of these sequences.

VII. Conclusions and Future Work

We developed methods for finding interplanetary trajectories for multiple-satellite-aided capture sequences assuming that the navigational challenges can be met. Double-satellite-aided capture trajectories occur the most often and have ΔV costs that are low and similar to patched-conic estimates. Triple- and quadruple-satellite-aided capture sequences occur much less often and frequently require more ΔV than double-satellite-aided capture sequences due to deep-space and plane-change maneuvers. For most Jupiter missions, double-satellite-aided capture would be the best choice, but sometimes triple-satellite-aided capture may offer a lower ΔV cost. The Jupiter arrival window of any future Jupiter orbiter mission should be checked for the availability and optimality of all three types of multiple-satellite-aided capture sequences before a final mission-design decision is made.

Now that the basic mission-design methods have been developed to find interplanetary trajectories for multiple-satellite-aided capture sequences, there are several extensions of this work that should be explored. The backward-targeting method was applied to Earth, but the same method could be used to backward-target Venus or Mars flybys. Regardless of which body is backward-targeted first, a longer planetary tour involving several flybys of planets in the inner Solar System can be developed using trajectory optimization software. Finding such a tour would give a better estimate of the total launch energy and ΔV required to execute a complete mission using multiple-satellite-aided capture.

Because we predict that quadruple-satellite-aided capture sequences occur only once every seven years, another potential application of these techniques would be to find every quadruple-satellite-aided capture trajectory over a Jupiter arrival window of several decades. If one of those trajectories has similar ΔV requirements to the patched-conic estimates, it would likely be the globally ΔV-optimal Jupiter capture sequence within that timeframe. Also, systematically searching through triple-satellite-aided capture trajectories involving either Callisto, Ganymede, and Io or Ganymede, Europa, and Io could also give some of the lowest available capture ΔV's. Once the lowest ΔV trajectories are found for a given timeframe, missions could be planned around when these trajectories are available.

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