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CHARACTERISTICS OF TRANSFERS TO AND CAPTURES AT EUROPA

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This paper explores the characteristics (i.e. stability and performance) of transfers to, and captures at Europa. We focus on optimal low-thrust transfers from Ganymede to potential science orbits at Europa and compare different capture types, transfer resonances, and thrust accelerations. The two types of capture methods we consider are capture in a distant retrograde orbit (DRO) and capture by targeting a state on a stable invariant manifold of a halo orbit. We show that each type has its advantages and disadvantages. The first part of DRO-type capture may be easier than a halo-type capture in some design schemes because DROs are generally extremely stable. However, halo-type captures using stable invariant manifolds typically result in fewer escapes even when full ephemeris is used. Moreover, changing the inclination to achieve a high inclination science orbit at Europa is much easier in a halo-type capture. We study these trade-offs in this paper.

INTRODUCTION

Europa has been and still remains a prime target for scientists. Low-thrust has been proposed to get to and orbit Europa. The benefit of such a method lies in the engine's high efficiency, which allows a larger payload mass to be delivered to Europa than with traditional chemical propulsion systems. However, low-thrust or low acceleration transfers to Europa from either Ganymede or from larger more distant orbits, is a complex and challenging mission design problem. Strong multi-body effects due to Jupiter and its moons coupled with little control authority of the spacecraft due to low thrust accelerations add complexity compared to chemical missions. In addition, for transfers between moons (i.e. Ganymede to Europa) the use of orbital resonances adds to the complexity of the design.

Another difficulty in the design process is the computational time required for optimization. In general, spiral-ins and -outs with hundreds of revolutions are very time consuming and complex to optimize. With the addition of multi-body effects and spherical harmonics effects, it is nearly impossible to design an optimal end-to-end transfer from, for example, Ganymede to Europa. Additional problems include orbits with very short life time if loss of control occurs, or an increase in shielding mass due to Jupiter's radiation environment if too much time is spent getting to Europa.

In this paper the characteristics of optimal low-thrust transfers from Ganymede to Europa and captures at Europa are explored using a real ephemeris. The path from Ganymede to Europa has many branches that are beyond the scope of this paper to investigate, but the paper will explore and compare those that are most relevant to the once planned NASA's Jupiter Icy Moons Orbiter (JIMO) reference trajectory.[1] The main objective of the transfers is to minimize the flight time from Ganymede to Europa. The secondary objective is to maximize the final spacecraft mass at Europa science orbits. Comparisons are made between capture types, transfer resonances, and different thrust accelerations for the spacecraft.

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METHOD AND APPROACH

This paper will focus on two distinct transfer and capture methods going from Ganymede to Europa: (1) DRO-type capture, which captures by means of a Distant Retrograde Orbit (DRO),[2] and (2) halo-type capture, which uses the invariant manifolds from a Jupiter-Europa L_2 halo orbit. The difference in the 3-body energy (the Jacobi constant in the circular restricted 3-body problem) of the two capture types consequently affects the available resonances of the transfers to Europa. The motivation for studying these two methods and not other methods of capturing at Europa is that the halo-type capture and the DRO-type captures represent two very different types of capture strategies – one being a low energy capture and the other being a high energy capture method (energy with respect to both the 2-body and 3-body energy). In undertaking this comparison we also wanted to test the following hypothesis in the context of using the full ephemeris : approaching a moon along a stable invariant manifold would result in fewer escapes. In this paper we show that this is indeed true. See for instance Figure 10 and 15 and compare these with Figures 13 and 18 respectively. It can be seen that the use of stable invariant manifold in the halo-type capture results in fewer escapes.

The halo-type capture method is a lower energy capture method, where the energy of the spacecraft is just enough to pass through the L_2 gate (of the forbidden region in the three-body problem) and get captured at Europa.[3,4] The DRO-type capture is a high energy capture, where the spacecraft's energy is hyperbolic even after the spacecraft is bounded to Europa. Previous capture designs which relied on low-thrust propulsion systems usually opted for a DRO-type capture due to its better stability and performance in getting captured (or bounded at Europa).[5] However the spacecraft will be required to spend more time spiraling down from the distant orbit to the science orbit. Moreover, since DROs are generally very planar orbits, more time will be required changing the inclination to one which is adequate for a science orbit, especially for a spacecraft with very low thrust acceleration levels. On the other hand, a halo-type capture requires an energy level near that of Europa's about Jupiter, thus it may take longer for the spacecraft to get captured at Europa than DRO-type captures. Halo-type capture requires less time for spiraling down. Due to its low relative energy of the capture with respect to Europa and due to spacecraft's crossing through the L_2 equilibrium point, one can capture in a smaller orbit about Europa and capture at nearly any inclination at Europa. To summarize, a DRO-type capture spends less time getting captured but more time spiraling toward the science orbit while a halo-type capture spends more time getting captured and less time spiraling toward the science orbit. Both methods have their strengths and weaknesses, and the decision of which to use is really dependent on the mission requirements and constraints.

Since a limited amount of work has been done on end-to-end transfers from Ganymede to Europa (or from any moon of Jupiter to another) in the real ephemeris, one cannot fully determine which capture method is better in performance and stability. In this paper we perform such a trade-off study and give characteristics and information about both capture types.

The rationale for characterizing a capture that uses the manifolds from the L_2-halo orbits, as a "halo-type capture" and not a "halo capture" is that the final capture transfer does not reside on any true manifolds from the L_2-halo orbit. This is a consequence of the real ephemeris being used, which causes many of manifolds to cease to exist. In addition, manifolds from the L_2-halo orbit are not used as the final transfer toward Europa, but are used as initial guesses for an optimizer (Mystic/SDC)[6] to provide a means to bring the spacecraft from a Jupiter centered orbit to a Europa centered orbit. Therefore "halo-type" describes the method and the general approach of the capture, but does not imply that a halo orbit is part of the final transfer.

Similarly, a DRO-type capture does not necessary follow the profile (i.e. velocity and position) of a DRO, but the general trend and shape of the capture orbit resembles a DRO. Unlike the halo-type captures, the manifolds of the DRO were not used as initial guesses to optimize a DRO-type capture. The rationale for this is that numerical experiments have shown that it is optimal, and computationally easy to capture into a DRO-type capture if the spacecraft's energy is large (i.e. hyperbolic) and planar with respect to Europa or if the final desired target orbit is a large distant orbit, in which case the SDC optimizer will usually fall into such local solution with a reasonable initial guess.[5]

All the analysis done in this paper was done numerically with Mystic, JPL's high fidelity low-thrust trajectory optimization tool developed and maintained by G. Whiffen and colleagues. Mystic is based on the

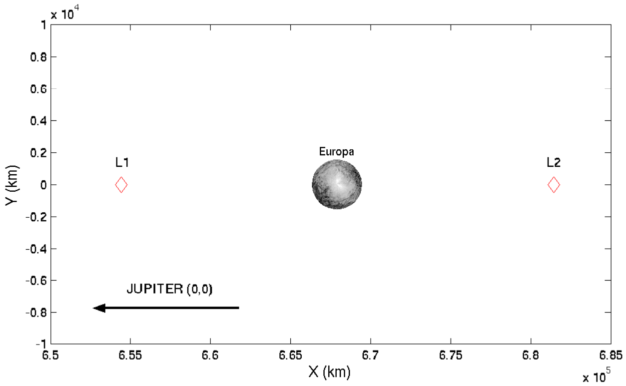


Figure 1 Orientation of Europa, Jupiter, and the L_1/L_2 libration points in the rotating frame.

Static/Dynamic Control (SDC) optimization algorithm.[6] In our analysis we use JPL's planetary ephemeris (DE405) and for the Jovian satellites we use the JUP100 satellite ephemeris. Gravitating bodies include all major planetary bodies with the exception of Pluto, and all 4 Galilean moons. In addition, a 2nd order gravity field, including $J_3 - J_6$, is activated for Jupiter, and a 4×4 gravity field is activated at Europa during the spiral-in segment.

Capture Method and Description

In either the halo-type or the DRO-type capture methods, the capture is best understood from a three-body perspective, specifically, by considering the Circular Restricted Three Body Problem (CR3BP). See Reference 7 for details on this model. In this model we have Jupiter and Europa located on the X-axis, the angular momentum vector along the Z-axis, and the Y-axis completing the right-hand rule in the cartesian coordinate system. In this rotating reference frame there are two well known equilibrium points near Europa which lie along the Jupiter-Europa line: L_1, which is toward Jupiter, and L_2, which is away from Jupiter. Both are approximately 13,500 km from Europa. See Figure 1. In the CR3BP, halo orbits and DROs are families of periodic orbit solutions. From dynamical systems theory we know that invariant manifolds exist for equilibrium points and for periodic orbits which bifurcate from equilibrium points, such as halo orbits.[7]

DRO-Type Capture Method

The design and optimization of a DRO-type capture are relatively simple in comparison to halo-type captures. The reason for this is the stability which surrounds the family of DROs. This stability remains fairly invariant in the real ephemeris model. With this capture approach for low-thrust optimal captures one can target a 6-state along a DRO, which requires prior knowledge of the DRO structure and its velocities. A much simpler approach is to target a loosely captured distant retrograde near circular orbit around Europa. In nearly all practical cases Mystic will converge to a DRO-type capture around Europa.

Halo-Type Capture Method

To understand the application of the stable manifold as capture orbits we must first look at the phase space near L_2. The phase space structure around L_2 provides a low energy corridor which connects Europa to the rest of the solar system, while the area around the L_1 point provides a low energy (small ΔV) means to travel between the inner Jovian system and Europa. It is the L_2 halo orbits which allow us to design low energy captures from Ganymede or from any other point past Europa's orbit to Europa itself.

Desiring a final science orbit which is near polar around Europa, we select a halo orbit with a large Z-amplitude and one that does not impact or come near Europa as our reference orbit. From this reference halo

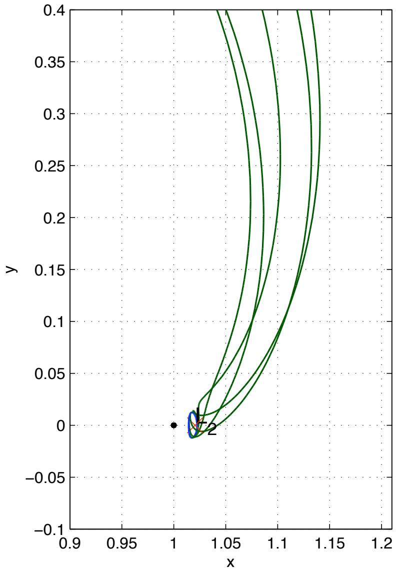


Figure 2 Some trajectories lying close to a stable invariant manifold originating from a halo orbit around Jupiter-Europa L_2 point. Europa is the dot at $(1 - \mu, 0)$ and Jupiter is off to the left at $(-\mu, 0)$ where μ is the ratio of Europa's mass to the sum of Jupiter and Europa mass. The distance unit is normalized so that 1 is the distance between Jupiter and Europa. The halo orbit is shown in blue and the stable manifold trajectories are shown in olive green. The halo orbit and its invariant manifolds exist in the circular restricted three body model. Taken together as a bundle, these trajectories form a tube in phase space for some distance. We pick a state on one such trajectory as the target state for halo-type capture. Since the invariant manifold is stable, a spacecraft with such a state will head towards the halo orbit in CR3BP model. This figure is in a frame with origin at center of mass and x-axis along the Jupiter-Europa line.

orbit we compute, then backwardly propagate, the stable invariant manifolds at selected intervals around the halo orbit, creating a tube-like structure. If we were to then propagate forward in time from any point along the tube (some position and velocity 6-state) we would then approach the halo orbit, and because halo orbits are unstable, the spacecraft will orbit the L_2 point a few times before it heads toward Europa. We note here that 2 sets of both stable and unstable invariant manifolds exist for the halo orbits.[7]

To compute trajectories that approximately lie on the invariant manifolds of a halo orbit one uses fairly standard techniques involving eigen analysis of the periodic orbits. In particular, given a periodic orbit, one computes the state transition matrix. In the case of 3 degrees of freedom systems, this involves integrating 36 differential equations. Starting from any point on the orbit and numerically integrating the state transition matrix for 1 period gives the monodromy matrix. The eigenvalues of this matrix determine the linear stability of the periodic orbit. To obtain the stable invariant manifold, one integrates backwards in time by offsetting the initial condition on the orbit by the corresponding scaled eigenvector. An example of such trajectories for a halo orbit is shown in Figure 2.

The rationale for testing this approach as an initial guess to capture at Europa instead of other approaches is that it is much easier for an optimizer to target and converge on a solution if the final target state is a position and velocity 6-state. For example, it is much more difficult (and computationally intensive) to target orbital elements around a body with an optimizer when one is 20-30 radii from the body, than it is to target a 6-state which is 20-30 radii from the body. In addition, the 6-state from the halo manifold guarantees (to some fidelity) that it will approach the L_2 point and be in close vicinity to the body. Another benefit of this method is that it provides intermediate target or break points for computationally long runs. Instead of having a transfer which goes from Ganymede to Europa in one leg, we can break the problem down into segments, with one segment being the targeted 6-state which resides on the stable manifold of L_2's halo orbit.

The states along the tube of stable manifolds provide 6-state targets for mission designers and ensure that the final state approaches Europa, since they are on or near a stable a manifold. We then choose a state along the manifold to be our target state. This state is an arbitrary state which needs to meet 2 criteria: (1) It must not be too close to Europa because otherwise the spacecraft's motion might be influenced by Europa's gravity or by some other periodic orbit near L_2, but (2) it must not be too far from Europa because otherwise when one propagates the state forward using the real ephemeris the spacecraft might stray far from Europa due to perturbations. Criteria (1) is important when one wishes to save computational time optimizing a trajectory to some 6-state target point. A suggested range to use in selecting target states along the manifolds is approximately 50,000 to 100,000 km.

After obtaining a state along a manifold for the L_2-halo orbit we then transition the state to the real ephemeris. As mentioned earlier, the example in this paper relies on low-thrust propulsion to control the spacecraft. We note that in the real ephemeris the tube structure will change slightly as a function of time due to the slight change between the distance between Jupiter and Europa (the normalization length) and the orbital period of Europa around Jupiter (the normalization period). For our example it is required that we have a good reference transfer as the one in Figure 3, which uses low-thrust propulsion to escape Ganymede, transition through a 2:3 to a 3:4 to about a 10:13 spacecraft-Europa resonance before arriving near Europa. At this resonance the spacecraft's energy is sufficiently near that of Europa's around Jupiter, and a direct (prograde) capture at Europa is possible. If one desired to capture into a DRO one can avoid getting into the 10:13 resonance and capture directly after the 3:4 resonance.

This paper does not attempt to discuss how we obtain the initial reference orbit or why certain resonances were used. The details required to fully address this concern would require an in-depth discussion that is beyond the scope of this paper. Further, the resonances used and the phasing of the transfer is a locally optimal solution to get into the vicinity of Europa's orbit and near Europa itself based on the constraints we have placed on the design. It should be stressed that the goal of this paper is not to explain the entire design process but to explain the general results and trends on transfers to and captures to Europa.

After a reference transfer has been selected, the transfer is then truncated at a state (in position space) which is near the targeted point on the stable invariant manifold, as in Figure 4. The state does not have to be exact or even close, but the transfer should be feasible and, thus, should have adequate coasting to shift around to reach the target point. We now let Mystic, the SDC optimizer, optimize the transfer along with the target state constraint. Figure 5 shows the trajectory after Mystic optimized it to the target state. Three days of coasting were added after the end state to show that the transfer does pass through L_2 and reach Europa. After converging on the transfer, one can now iterate on the flight time and the location of the targeted state for better performance. The final step to this process is to circularize the orbit and spiral down to a potential science orbit.

RESULTS

In this section we will compare transfers that start from Ganymede and eventually end at Europa's science orbit. The two transfers types we are comparing are DRO-type captures and halo-type captures. For the DRO-type captures our desired target is at 100 km altitude and an inclination of 110°. For the halo-type captures our desire altitude target is the same, but our final inclination target is 90° instead of the 110°. The rationale for targeting different inclinations for the two methods is as follows. We are interested in overall performance comparison between the methods while meeting the mission objective. Since both orbits are adequate science orbits for Europa, the final inclination will be that which utilizes the capture method for better delivered mass. If one were to actually fly the spacecraft using a DRO-type capture method, one would not expend extra propellant to reach an exact polar orbit, but settle on a reasonable off-polar science orbit. In the case for the halo-type capture, the spacecraft can easily capture at various prograde (direct) inclinations, and even slightly retrograde ones, and thus a polar orbit was selected for potential science observation reasons.

The results section will be divided into 3 subsections in order of progression toward a detailed end-to-end design starting with results for (1) transfers from distant orbits around Ganymede to distant orbits around

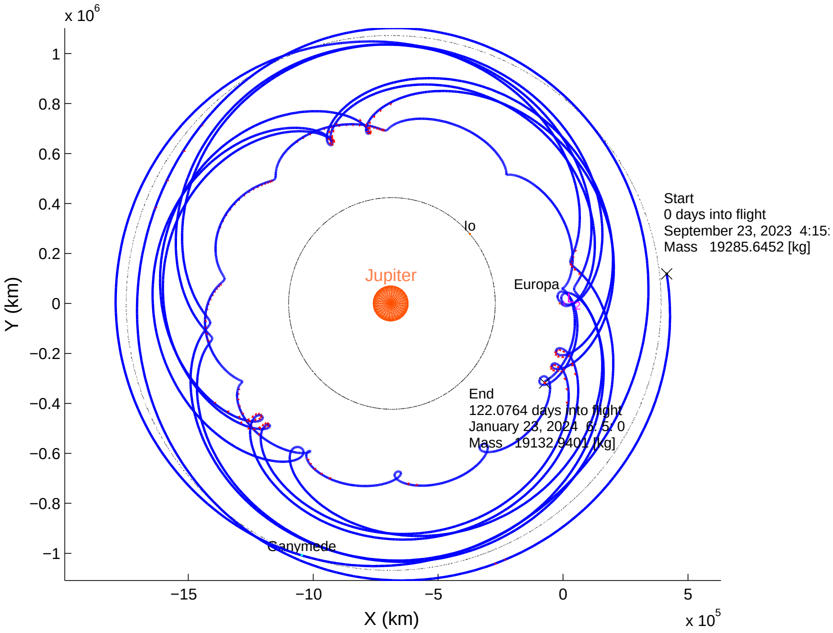
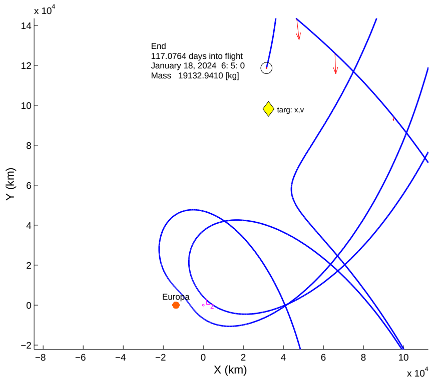


Figure 3 A reference transfer from Ganymede which arrives near Europa. The transfer is a very efficient transfer which takes advantage of the different resonances (2:3 to 3:4 to 10:13 spacecraft-Europa) to arrive, but not capture, near Europa. This will be truncated at a point near a target state on stable invariant manifold trajectory of Figure 2. See Figure 4 for a close-up view of the truncated trajectory.



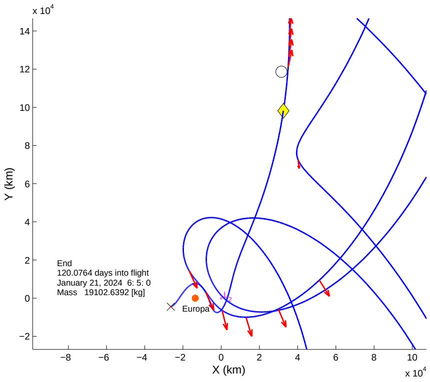


Figure 4 Close-up view of the reference transfer trajectory of Figure 3 after truncating it to a state near the desired target state. End state = ◯, target state = ◊. Target state lies on or near a stable invariant manifold of a halo orbit around L_2.

Figure 5 Same reference transfer trajectory after optimization to target state. We have added 3 days of coasting to check that the trajectory ends up around Europa. End state before coasting = ◯, target state = ◊.

Europa, where we will look at various thrust acceleration levels, resonances, and flight times. (2) Look at examples of halo-type and DRO-type captures at Europa with final orbiting radius of 5,000 km. Although 5,000 km is still far from Europa's surface, the examples provide great insights to the problem without the huge computational time that is required to get down to 100 km altitude. (3) Look at examples of halo-type and DRO-type captures to Europa's science orbit.

Ganymede DRO to Europa DRO

Before looking at a complete transfer from Ganymede to Europa's science orbit, we attempt to analyze the characteristics (flight time, ΔV, etc.) of the transfers by first looking at transfers to a distant orbit around Europa. This allows us to look at the stability and performance of the better performing transfers and resonances without getting too deep into Europa's gravity well. This also allows us to save computational and optimization time and perform necessary trades before getting to the science orbit.

Due to the nature of prograde orbits, distant prograde orbits do not exist and thus, in this subsection, our analysis will focus on transfers from DROs around Ganymede to DROs around Europa.[8] Our initial orbit around Ganymede is a 30,000 km near-planar (175°) DRO, and our target orbit is also a 30,000 km near-planar DRO around Europa. For this analysis we looked at the effects of 3 main trades, (1) the effect of the spacecraft's thrust-acceleration, (2) the effect of the different transfer resonances, and (3) the effect of the time to the first Europa flyby after escaping Ganymede. In our analysis we also note the minimum orbital lifetime of the transfer.

The transfers between Ganymede and Europa were designed as minimum duration transfers. Many other transfers were possible for a given thrust level, and were often more optimal in terms of ΔV, but in all cases the goal was to escape from Ganymede and capture at Europa in a minimum time. All transfers began in a 30,000 km near-planar orbit about Ganymede. The spacecraft thrusts until it is in a large elliptical orbit as viewed the rotating frame. The final rev before escape includes a close flyby of Ganymede (Figure 6) which acts to decrease the energy of the spacecraft trajectory. After escape, the spacecraft thrusts so that it is in an elliptical orbit about Jupiter with perijove near the radius of Europa's orbit. Figure 7 shows a typical Ganymede to Europa transfer in the rotating frame. The locations of perijove passages along the trajectory are marked 1, 2, and 3 and indicate possible locations on the transfer trajectory where the first close flyby of Europa is targeted. To minimize the transfer time, an early flyby of Europa is desired, however this is not possible with all acceleration levels.

After the first close Europa flyby, the spacecraft thrusts so that it is on a resonant transfer trajectory. For this study, two resonances were chosen: (1) an initial 2:3 resonance followed by a 3:4 resonance and (2) a 3:4 resonance. Other resonant transfers are possible but these were chosen to give the shortest transfer time possible.

The final close approach of Europa before capture (Figure 8) resembles the Ganymede escape (Figure 6). The spacecraft makes a close flyby of Europa and is captured into a 30,000 km DRO after 1, 2, or 3 orbits after the close flyby.

Table 1 shows the results for the four acceleration levels – 0.15 mm/s^2, 0.2 mm/s^2, 0.25 mm/s^2 and 0.3 mm/s^2, the three possible locations of the first Europa flyby, and the resonant transfer types. For each acceleration, the first column corresponds to the $2:3 \rightarrow 3:4$ type of transfer. The second column for each acceleration level (except 0.15 mm/s^2) corresponds to the $3:4$ type transfer. The 3:4 transfer is not possible at the lowest acceleration level of 0.15 mm/s^2 which is why that has only 1 column. Other locations of the first Europa flyby and other resonance transfers are possible, and may even be more desirable in terms of ΔV, but these transfers were designed to minimize the total transfer time to Europa. The first row shows the location of the first Europa flyby. Higher thrust levels allow for a Europa flyby at perijove passage 1. At lower thrust levels the spacecraft must thrust longer and encounter Europa at perijove locations 2 or 3. The next row gives the time from Ganymede escape to the first Europa flyby. Row 3 gives the time from Ganymede escape to the time of Europa close approach prior to capture in the DRO. This time varies as a function of acceleration and the transfer type chosen. The $2:3 \rightarrow 3:4$ transfer type is longer than the 3:4 transfer. The

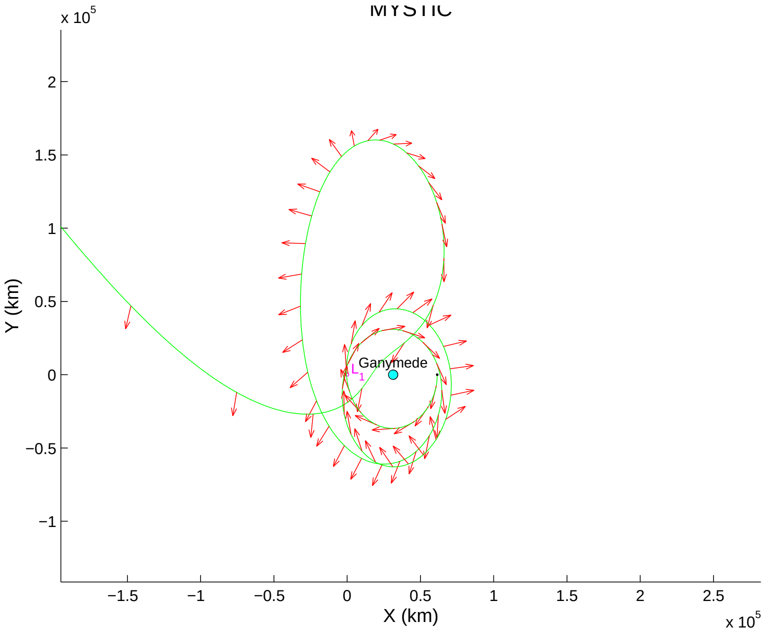


Figure 6 **Escape trajectory from Ganymede starting initially from a 30,000 km DRO at 175°. After escape the transfer goes into either a 2:3 or 3:4 spacecraft-Europa resonance depending on the desired flight time.**

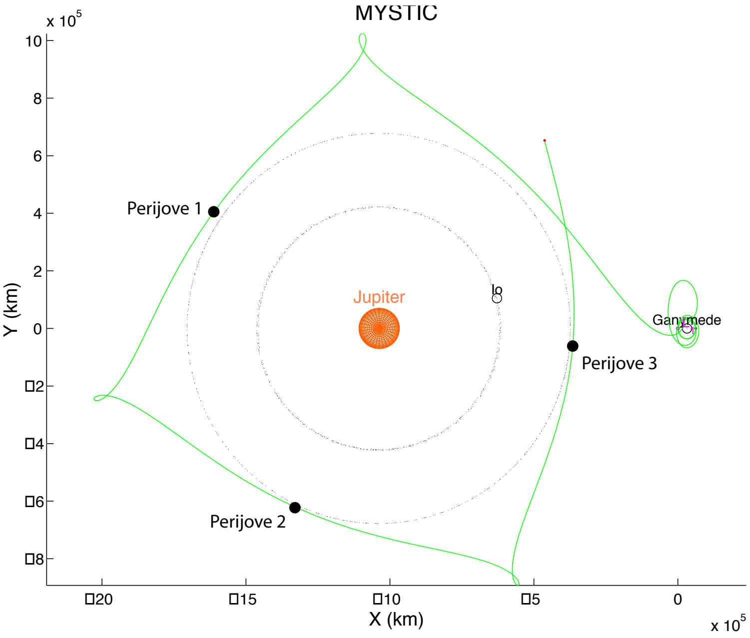


Figure 7 **Ganymede to Europa transfer in the rotating frame. The locations of perijove passages along the trajectory are marked 1, 2, and 3 and indicate possible locations on the transfer trajectory where the first close flyby of Europa can occur.**

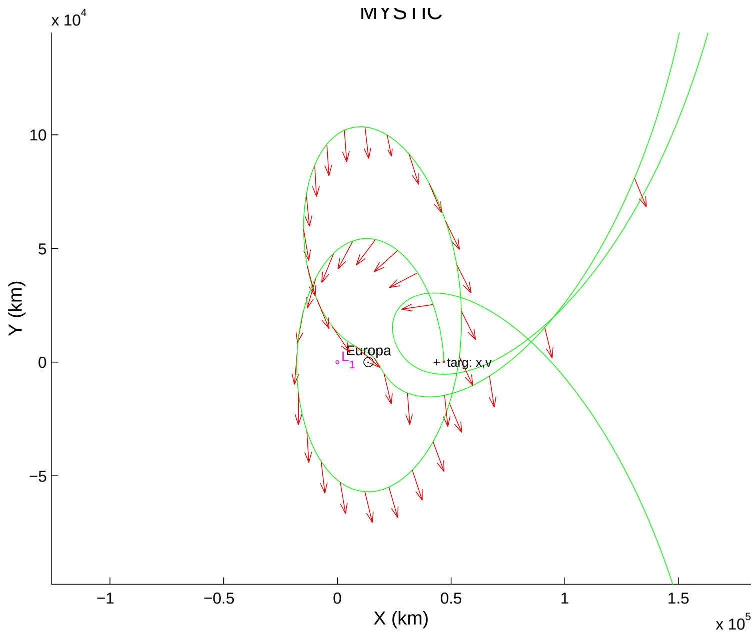


Figure 8 **A representative DRO-type capture at Europa. Note that a final close approach of Europa is required prior to being capture. The spacecraft captures into a 30,000 km DRO at 175°.**

Table 1 **Results for transfers from Ganymede DRO (30,000 km) to Europa DRO (30,000 km)**

Acceleration (m/s^2)	0.30	0.30	0.25	0.25	0.20	0.20	0.15
Location of 1st Europa Flyby*	1	1	1	1	2	2	3
Time to Ganymede Escape (days)	13.34	13.34	19.61	19.61	23.17	23.17	22.13
Time to 1st Europa Flyby (days)	20.06	20.06	22.26	22.26	36.35	36.35	40.73
Time to Europa Capture (days)	45.66	34.60	52.46	41.90	61.60	50.42	65.68
Time to Europa DRO (days)	51.06	39.96	57.76	54.21	70.10	58.75	74.45
Total ΔV (m/s)	678.8	814.2	735.1	1,131.4	605.5	736.1	408.9
Minimum Orbital Lifetime (days)	4.7	4.7	4.7	5.8	5.1	5.1	5.4

$*$ See Figure 7

table also shows the total time from Ganymede escape to the time to DRO capture.

Ganymede DRO to 5,000 km Around Europa

In this subsection we will compare transfers starting from a 60,000 km DRO at Ganymede to 5,000 km circular orbits around Europa. The spacecraft parameters assumed for these analyses are listed on Table 2. A rationale for initially ending the transfer at 5,000 km is the assumption that the transfer will be a simple two-body spiral-down below 5,000 km and the flight time and ΔV should be comparable for all transfer segments thereafter. The methods used to capture into the circular 5,000 km orbit around Europa was described in the previous section. Results for the analysis are listed in Table 3. Each ID represents a different case.

As stated previously, Jupiter's harsh radiation environment near Europa causes shielding mass to increase on the spacecraft. Therefore, even if we spend very little propellant to get to Europa, but spend too much time time to get there, our overall final net mass at Europa might be less than if we spend more propellant to get to Europa fast. This is a simple trade between final net mass and flight time, and Table 3 shows that it is usually better to arrive at Europa fast. Table 3 also shows the basic trends of halo-type and DRO-type captures. Halo-type captures tend to have slightly lower minimum lifetime during their transfer to Europa. Here we define lifetime as the time it would take to impact Europa if complete loss of control and thrust occurred anywhere along its nominal trajectory. We will later see that these minimum lifetimes for the halo-type capture occur during the Europa approach phase of the transfer, near the L_2 point.

We will now analyze and compare the best performing DRO-type and halo-type captures from Table 3, which are ID-1 and ID-4, respectively. As shown in Table 3, we note that both these best performing transfer types have comparable flight times and net delivered mass, and both have very low minimum orbital lifetimes of about 2.5 days.

Figure 9 shows the transfer and capture for the best performing halo-type capture in an L_2 centered view of rotating coordinates. Figure 9 also clearly shows the resonance flyby used to reduce the energy and the capture at Europa. This trajectory spirals-out and escapes Ganymede (initial orbit = 60,000 km DRO around Ganymede), goes through a 2:3 to 3:4 to a low-energy long flight time 12:13 spacecraft-Europa resonance, crosses though the L_2 point approximately 118 days from the start of the transfer, and ends up in a 5,000 km circular orbit around Europa with a final inclination of about 54.6°. We note here that the 54.6° is far from the desired science inclination, but since it does go though the L_2 point the cost of targeting other inclination is negligible compared to the entire propellant consumed for the transfer. Table 4 shows results for the halo-type captures to various targeted inclinations at 5,000 km around Europa using transfer ID-4 on Table 3 as the reference transfer. As can be seen in Table 4 the flight times and and ΔV required to obtain different inclinations vary a little bit and these two variables can be traded for each other.

As we stated earlier, the benefit of such a method is the shorter time spent in spiraling in to Europa's science orbit, but one pays the price of spending a much longer time in long low-energy resonances to reduce the energy so that such close capture may occur.

Figure 10 shows the stability or the safety of the transfer using the halo-type capture. If the spacecraft were to lose thrusting capability anywhere between 0 and 90 days from the start of its transfer then, from Figure 10, the spacecraft would not impact Europa for at least 50 days. We define a point with orbital lifetime 50 days or greater as a stable point along the transfer. We also classify a path as an escape if it is beyond 50,000 km from Europa. From the figure we notice that the transfer remains quite stable until a short bands of impacts occur approximately prior to 118 days. This band of impacts also represents the location at which the lowest lifetime of the entire transfer occurs, and occurs when the spacecraft is approaching Europa just before crossing the L_2 point. As mentioned earlier, this approach segment is usually the least stable segment of the transfer. Figure 10 also shows a number of escapes and captures after crossing the L_2 point (118 days TOF). These escapes and impacts represent the instability of the region due to third-body perturbations. The high number of impacts exist until a more traditional two-body regime is encountered around Europa, which one sees by the series of "green squares" representing stability during the latter part of the transfer to 5,000 km.

The better performing DRO-type capture from Table 3 escapes Ganymede, goes through a series of resonances with Europa (2:3, 9:13, and 4:5 resonance) before capturing at Europa in a retrograde direction (Figure 11). From Figure 11 we also note the general "shape" of a DRO-type capture by the upper right distant loop of the trajectory which occurs during the last flyby of Europa before capturing permanently at

Table 2 Initial spacecraft parameters

Parameters	Values
Initial Mass	19,285.6 kg
Initial Acceleration	0.2176 mm/s^2
Specific Impulse	6,000 sec
Power for Propulsion	180 kW
Efficiency	70 %
Duty Cycle	98 %

Table 3 Results for transfers from Ganymede (60,000 km) to circular orbits around Europa at 5,000 km

ID	Capture Type	Resonances	Flight Time (days)	ΔV (m/s)	Min. Lifetime (days)	Final Net Mass (kg)
1	DRO	2 : 3 → 9 : 13 → 4 : 5	127.94	747.92	2.72	15,513.95
2	DRO	2 : 3 →∽3:4	147.40	1,646.43	4.03	14,903.54
3	DRO	2 : 3 → 3 : 4	150.79	1,100.23	8.08	-$^{\alpha}$
4	Halo	2 : 3 → 3 : 4 → 12 : 13	130.79	659.85	2.18	15,512.69
5	Halo	2 : 3 → 3 : 4 → 9 : 10	135.69	604.21	1.81	15,471.84
6	Halo	2 : 3 → 3 : 4	150.29	771.37	1.65	15,215.63
7	Halo	2 : 3 → 5 : 7 → 10 : 13 → 11 : 12	159.90	363.19	2.72	15,256.63
8	Halo	2 : 3 → 5 : 7 → 3 : 4 → 7 : 9 →∽11:12	160.51	512.17	2.94	15,188.25
9	Halo	2 : 3 → 5 : 7 → 10 : 13 → 11 : 12	171.34	629.53	1.15	15,000.76

$^{\alpha}$Data was lost

Table 4 Results for halo-type captures for selected inclinations: references transfer = ID-4 (Table 3)

ID	Capture Type	Resonances	Flight Time (days)	ΔV (m/s)	Min. Lifetime (days)	Final Incl. (deg)
4	Halo	2 : 3 → 3 : 4 → 12 : 13	130.79	659.85	2.18	54.60
4b	Halo	2 : 3 → 3 : 4 → 12 : 13	130.79	756.61	2.18	62.34
4c	Halo	2 : 3 → 3 : 4 → 12 : 13	133.79	564.71	2.30	73.36
4d	Halo	2 : 3 → 3 : 4 → 12 : 13	138.59	549.51	1.96	86.42
4e	Halo	2 : 3 → 3 : 4 → 12 : 13	135.79	704.25	1.69	88.89
4f	Halo	2 : 3 → 3 : 4 →∽13:14	129.79	624.88	1.74	103.04
4g	Halo	2 : 3 → 3 : 4 →∽12:13	135.39	592.83	4.46	115.61

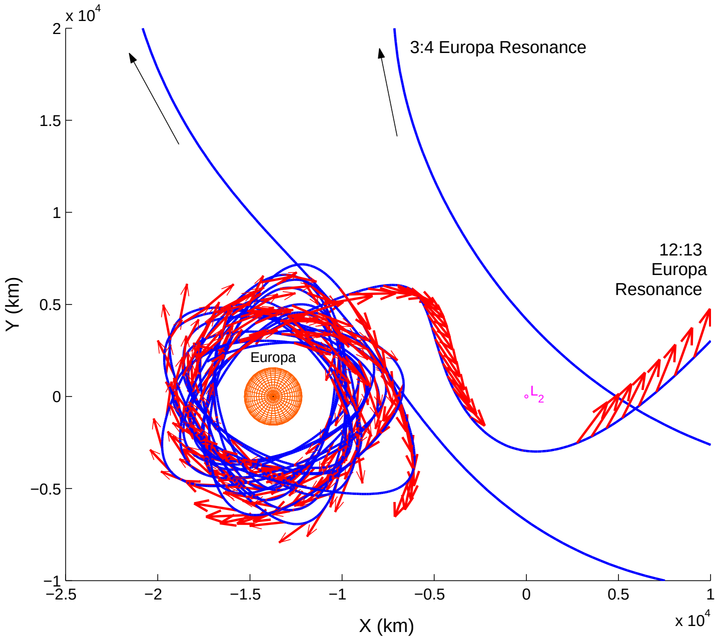


Figure 9 Halo-Type Capture. Ganymede to Europa 2:3 to 3:4 to ∽12:13 low-thrust transfer which captures at Europa at 55 deg and 5,000 km.

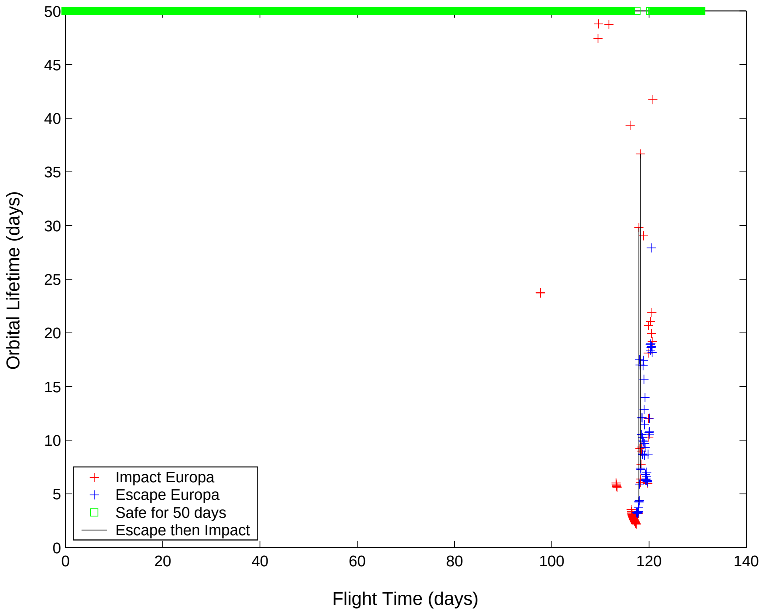


Figure 10 Orbital lifetime of the halo-type capture if the spacecraft loses all control and thrust capabilities. This shows Ganymede DRO escape to about 5000 km around Europa. Note that the band of escapes and captures does not appear until the capture and spiral-down segment at Europa. Compare with Figure 13 and note that DRO-type capture shown there has more escapes during early part of the trajectory compared to what is shown here for halo-type capture along stable invariant manifold. This confirms our hypothesis about this advantage of captures along stable invariant manifolds.

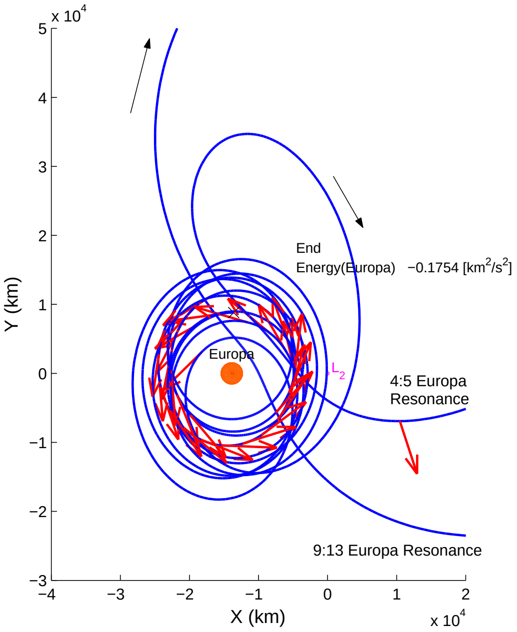


Figure 11 Distant Retrograde Orbit (DRO) Type Capture. Ganymede to Europa 2:3 to 9:13 to 4:5 low-thrust transfer which captures at Europa at 130 deg and 5,000 km.

Europa (looking down upon the orbit plane in the rotating frame). The trajectory ends in a 5,000 km orbit around Europa with an inclination of $128.2°$. One clear difference between the DRO-type capture and the halo-type capture is the size of the capture orbit. From Figure 11 we note the the initial capture orbit is approximately 15,000 km from Europa. If this orbit was in the prograde direction it would clearly escape the system within a few revolutions around Europa, but due to the stability of DROs and the periodic families which surrounds them the orbit remains bounded to Europa. Comparing this 15,000 km to the initial capture orbit using the halo-type capture approach which is approximately 7,000 km (Figure 9), we notice a large difference in the capture radius, and thus the capture energy.

To analyze the orbital lifetime of this particular transfer, one can first look at the transfer plotted against the "Red Sea Plot" (Figure 12). The Red Sea Plot is a plot which depicts stability for circular retrograde orbits near Europa and from DRO around Europa as a function of inclination for small circular orbit and DRO-periapsis distances (the distances from Europa to the semi-minor axis of the DRO or the radius). The color bar on Figure 12 is the orbital lifetime in days. In the figure we overlay our trajectory's path onto the Red Sea Plot and notice that the spacecraft follows along the edge of the blue and red upon capture till the peninsula of the stable region about $135°$ and about 7,500 km from Europa. Since the trajectory is oscillating between the red and blue we expect the orbital lifetime of this transfer to switch between regions of low lifetime and that of long lifetime. The transfer then spends most of its time spiraling down to the 5,000 km. The small white squares on Figure 12 represents division or break points of the transfer for optimization. We note that the transfer ends in a region which is orange representing lifetimes of about 10 to 20 days.

The Red Sea Plot allows us to look at the stability of the transfer from a mission design perspective, allowing us to see visually the orbital lifetime of a trajectory without ballistically propagating each point along the nominal trajectory. Although the method is only an approximation to the stability of the transfer it provides good insight into the stability and ways to improve the stability, i.e., stay in the blue region. But for direct comparison between the stability of DRO-type capture methods and halo-type capture methods one still needs to plot the orbital lifetime as a function of flight time. This is because our Red Sea Plot is limited to only retrograde orbits (note the inclination scale on Figure 12).

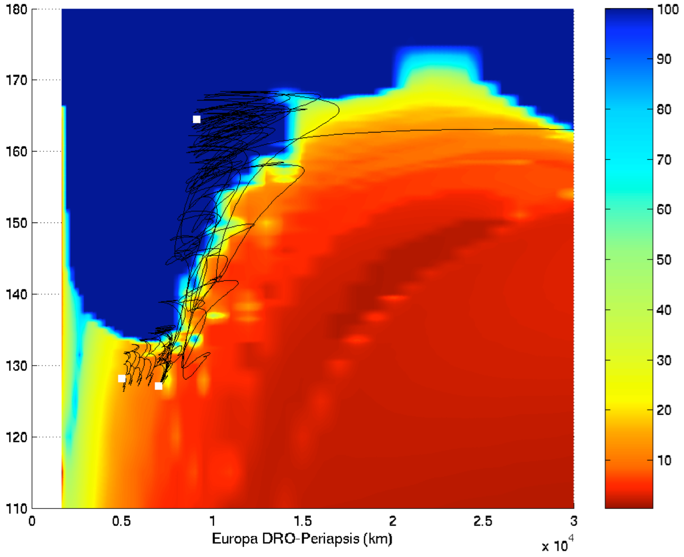


Figure 12 DRO-type capture against the Red Sea Plot, which depicts stability for retrograde orbits and distant retrograde orbits (DROs) as a function of inclination and distance along the rotating x-axis. The color bar scale indicates orbital lifetime in days. Break points in the trajectory = □.

Now looking at the actual propagated lifetime, Figure 13 shows the orbital lifetime of the DRO-type capture to 5,000 km as a function of flight time. Here we note a few bands of potential impacts and escapes prior to capturing at Europa. An interesting result of this plot shows a few isolated impacts with Ganymede while spiraling out marked by the red $*$. The first large band of impacts and escapes starting around 45 days into the flight is due to the approach of the 9:13 spacecraft-Europa resonance flyby. After about 80 days into the start of the transfer the spacecraft is loosely bounded around Europa in a quasi-DRO state. This loosely bounded state is slightly unstable and shows up as the second band of impacts and escapes around 80 days on Figure 13. The last band of impacts and escapes is due to the spiraling down process to the targeted 5,000 km. We note that the final few days prior to and at capture have lifetimes which are approximately 20-40 days, which is somewhat higher then that predicted by the Red Sea Plot (Figure 12).

Ganymede DRO to 100 km Altitude Around Europa

Taking the better performing DRO-type transfer from Table 3 and transfer ID-4e from Table 4 (halo-type capture to approximately $90°$), we will re-optimize these transfers down to the science orbits - circular 100 km altitude orbit. In the process of doing so the resonances of the transfers will shift slightly to more optimal solutions. From Table 3, looking at the final net delivered mass and the corresponding flight time, we note that it is better to have a short trip time to Europa, again due to radiation shielding. Therefore, for the next couple of examples we attempt to arrive at Europa with the shortest flight time possible while optimizing the final mass. Our solutions are not minimum time solutions, which usually have poor performances, but “short” flight times meaning that we try to minimize the number of revolutions about Jupiter and attempt to thrust as much as possible during the spiral-in, spiral-out, and moon transfer phases. Again, the spacecraft parameters used for the runs are on Table 2.

Figure 14 shows the resulting transfer for the halo-type capture which started from a 60,000 km DRO at Ganymede, goes through a 2:3 to a 3:4 to a 11:13 resonance transfer before capturing at Europa at 4,500 km and at an inclination of about $87°$. From this leg of the transfer we then add two additional leg which optimize the transfer further down and then continuously spirals-down to the science orbit of about 100 km altitude and an inclination of $89.48°$. From the rotating view we see that the transfer flyby the Jupiter-Europa

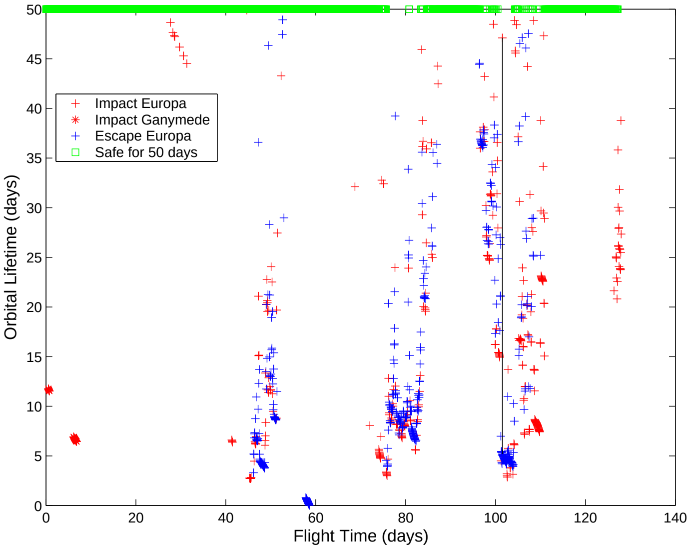


Figure 13 Orbital lifetime of the DRO-type capture if the spacecraft loses all control and thrust capabilities. This shows Ganymede DRO escape to about 5000 km around Europa. The first band of escapes and impacts is due to the 9:13 Europa flyby resonance. The second band of escapes and impacts is due to the loose capture state around Europa. The third band of escapes and impacts is due to the spiraling down process to 5,000 km at a high inclination. Compare this with Figure 10 and note that the use of stable invariant manifold shown there results in fewer escapes in the early part of that trajectory.

L_2 point and loops near L_1 before capturing at Europa. The ΔV for this transfer is 1,553 m/s and the total flight time from Ganymede's DRO to Europa's science orbit is 167.25 days (78.39 days of coasting).

The stability or the orbital lifetime of the transfer is plotted on Figure 15. In the plot we note that there exist two main segments during the transfer where the orbital life time is low. The first band of potential impacts between 70-80 days is due to the 3:4 to 11:13 resonance flyby at Europa (Figure 16). The minimum lifetime of this segment is 2.14 days. During this flyby the spacecraft comes as close as 2000 km from Europa during the flyby. We should also note, visually, that it is possible to get captured loosely into a DRO-type orbit instead of a halo-type orbit after crossing the L_2 point and flying by Europa. This could eliminate the need for the 11:13 resonance leg. The drawback of such a method is the required propellant to go from a planar orbit to a reasonably inclined science orbit.

We would also like to note that the one can remove the first band of impacts by increasing the minimum flyby radius constraint. Increasing the minimum flyby radius to 2,500 km at a cost of 6 m/s in ΔV can increase the minimum lifetime of that segment to 9.53 days instead of the 2.14 days.

The second band of impacts occur during the approach and spiral-in phase to Europa science orbit (1665 km radius and 90°). The minimum lifetime of the entire transfer is 0.84 days, which occurs approximately 120 days into the flight. This small band of impacts prior to the minimum lifetime point is during the approach phase just before crossing the L_2 point. In the figure we note that the lifetime steadily increases as we approach Europa, this is due to the reduction of third body perturbations during the spiral-in. In a few cases lifetime increases to at least 50 days. As we approach within a few hundreds of kilometers from Europa its harmonics begin to dominate the lifetime of the orbits, which one observed in Figure 15 by the steady decrease in lifetime as we approach the 100 km altitude orbit.

Figure 17 shows the resulting solution for the DRO-type capture that started from a 60,000 km DRO at Ganymede. The transfer goes through a 2:3 to a 11:16 to a final 4:5 resonance before capturing at Europa with a high inclination of 137° at about 7,000 km radius. This inclination and radius corresponds to a stable

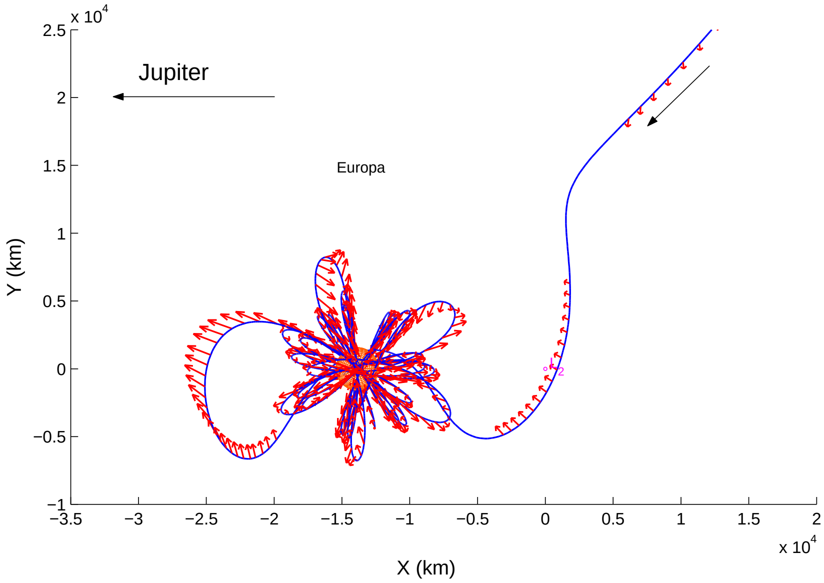


Figure 14 Halo-type capture which started from a 60,000 km DRO at Ganymede, goes through a 2:3 to 3:4 to 11:13 resonance transfer before capturing at Europa at approximately 4,500 km radius and $87°$. The transfer was continued from this end state down to 1671.98 km and $89.48°$.

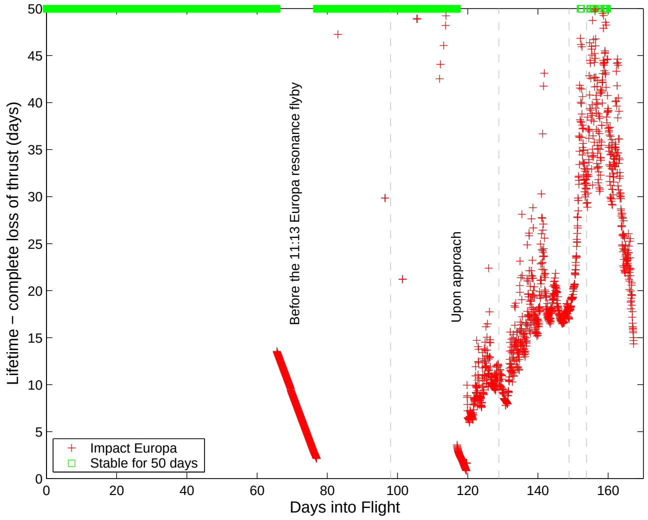


Figure 15 Orbital lifetime of the halo-type capture if the spacecraft lost control and thrusting capabilities. This shows departure from Ganymede DRO to arrival at about 100 km science orbit around Europa. Note the existence of two main segments during the transfer where the orbital life time are low. The first band of potential impacts between 70-80 days is due to the 3:4 to 11:13 resonance flyby at Europa. These disappear if a minimum flyby altitude constraint of about 900 km is used. The second band is due to the Europa approach phase which is inherently dangerous for the halo-type capture. Compare with Figure 18 which shows many escapes in the DRO-capture method. The halo-type capture used here uses a stable invariant manifold which results in fewer escapes.

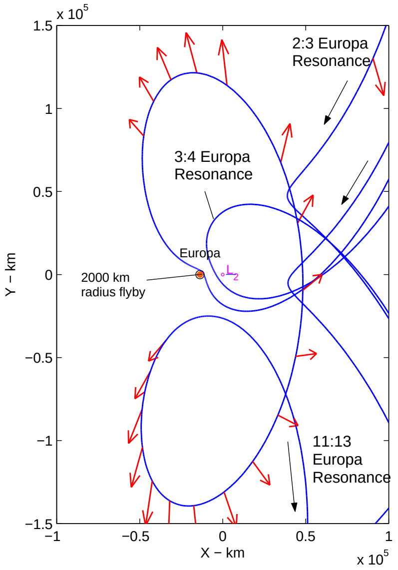


Figure 16 Halo-type capture transfer during the 3:4 to 11:13 Europa resonance flyby. From Figure 15 we notice a band potential impacts with Europa if we were to lose complete control of the spacecraft. From this figure we clearly note that the cause of such potential impacts are due to the very close flyby (approximately 2,000 km) with Europa during the 3:4 to 11:13 resonance hop. One way of improving the orbital lifetime of this transfer is to constrain the optimizer to larger flyby distances.

region around Europa, which can be seen on the Red Sea plot. From this radius and inclination we optimize the transfer down to approximately 2,500 km before spiraling in continuously down to the science orbit. Although not shown in Figure 17, the final orbit is a circular 1665.27 km radius orbit at 109.78°. The total ΔV for this transfer is 1,560 m/s and the total flight time is 166.34 days (76.9 days of coasting).

The orbital lifetime of the DRO-type capture transfer is plotted on Figure 18. Here we clearly note 3 bands of potential impacts and escapes. In the first band we note a few impacts with Ganymede and Europa on our way up. The second band of impacts and escapes around 80 days is due to the 4:5 resonance flyby which eventually causes the spacecraft to capture. The third band of impacts is during the spiral down portion down to the science orbit (1665 km radius and 110°). The minimum lifetime (3.03 days) of the entire transfer occur at about 77 days into flight which is during the capture flyby of Europa.

We would like to summarize this section by stating that the ΔV and flight time for both transfer types down to Europa's science orbit from a DRO around Ganymede are quite comparable. The overall differences between the optimal DRO-type and the optimal halo-type capture method is less than 10 m/s in ΔV and about 2 days in total flight time. Although the performance differences are small the stability or orbital lifetime of the transfer are more significant. In both transfer types the overall trend near Europa is the same, but the lifetime trend prior to Europa capture differs. For the halo-type capture, no significant impacts or escapes occur until the very close flyby of Europa around 70 days into flight. This confirms our hypothesis about the use of stable invariant manifolds to reduce escapes.

After the 10 day band of low lifetime impacts, the lifetime, generally, remain around 50 days until the spacecraft approaches the L_2 point near Europa. In the case of the DRO-type transfer and capture approach, we see that there are a few impacts early on the transfer, which can be removed by allowing the flight time to increase as little as 5 days. We also note that during capture (at around 70 days) numerous potential escapes occur, followed by a series of high lifetime orbits until about 110 days into the transfer, when the low-altitude (approx. 6,000 km) occurs.

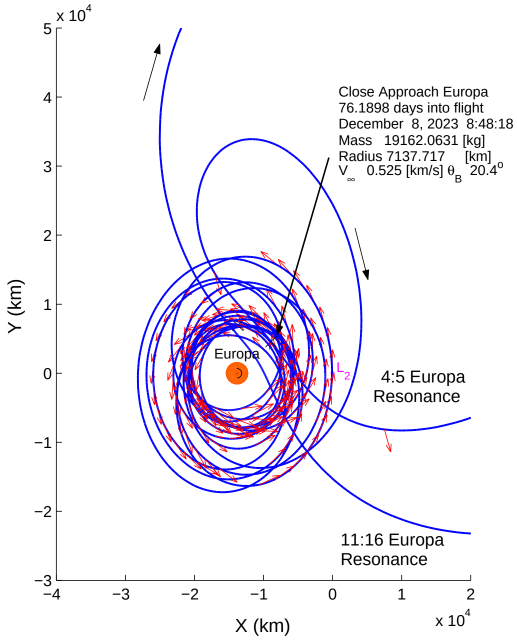


Figure 17 DRO-type capture which started from a 60,000 km DRO at Ganymede, goes through a 2:3 to 11:16 to a 4:5 resonance transfer before capturing at Europa at approximately 7,000 km and at 137°.

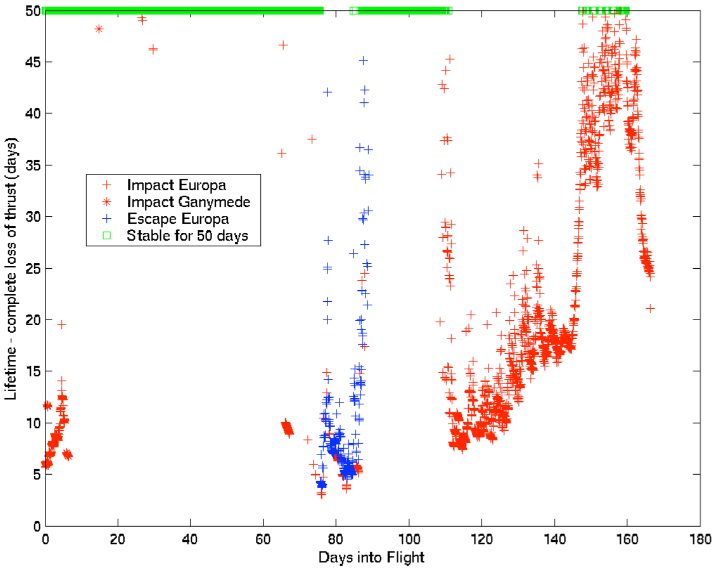


Figure 18 Orbital lifetime of the DRO-type capture if the spacecraft was to lose all control and thrusting capabilities. This shows departure from Ganymede DRO to arrival at about 100 km science orbit around Europa. There are 3 bands of potential impacts and escapes: (1) impacts associated with a Ganymede spiral-out, (2) a band of escapes around 80 days due to the 4:5 resonance flyby prior to Europa capture, and (3) band of impacts associate with spiraling down to the science orbit (1665 km radius and 110°). Compare with halo-type capture results shown in Figure 15. The use of a stable invariant manifold there reduces the number of escapes.

In either transfer type, one can improve the lifetime and stability of the transfer by adding additional flight time and re-optimizing. With the case of the halo-type transfer and capture one can also increase the orbital lifetime by targeting a final orbit which is off-polar.

CONCLUSIONS AND COMMENTS

The characteristics of optimal low-thrust transfers from Ganymede to Europa and captures at Europa are explored using a real ephemeris. Our objective was to design a transfer which minimizes fuel consumption, orbital lifetime in case of the lost of thrust control, and to minimize the trip time to Europa due to radiation dose levels. To meet such objective this paper compares different capture types, transfer resonances, and different thrust acceleration levels for the spacecraft. The two capture types compared were the lower energy halo-type capture method and the higher energy DRO-type capture method. We have shown in this paper that halo-type captures may be as stable as DRO-type captures around Europa. This is due to the instability of inclined retrograde orbits as seen on the Red Sea Plot. In addition, we have shown that since stable invariant manifolds are used in the halo-type captures, there are fewer escapes during loss of thrust in the early part of the trajectory. We have also shown that the ΔV and flight times for the two capture approaches are also quite comparable. In the paper we also briefly describe methods for improving orbital lifetime at critical points along the transfer from Ganymede to Europa. By no means are the trades conducted in this paper complete, but it does provide mission designers some understanding on key characteristics of transfers to and captures at Europa.

ACKNOWLEDGMENTS

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