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AN INVESTIGATION OF A JUPITER GALILEAN MOON ORBITER TRAJECTORY

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NASA's mission to send a single electric propulsion spacecraft to orbit Callisto, Ganymede, and Europa within a decade will require a very complex trajectory. Strong multi-body effects combined with low-thrust control of capture and escape will make the trajectory design challenging. This paper describes an optimal trajectory that begins in low Earth orbit and ends in low Io orbit. A spacecraft following this trajectory will orbit Callisto, Ganymede, and Europa in succession before orbiting Io. This trajectory highlights the complexity, some of the risks, and also some of the advantages that can be gained from using low-thrust in strong multi-body regimes. The optimization algorithm called Static/Dynamic Control was used to design the trajectory.

INTRODUCTION

NASA's Jupiter Icy Moons Orbiter is an ambitious mission with great potential for discovery at each of the three large icy moons of Jupiter. The large icy moons of Jupiter have the three ingredients essential for life on Earth: water, certain chemical compounds, and an energy source (tidal heating and radiation). The Galileo orbiter produced evidence for a liquid or slushy water layer present below the frozen crust of the icy moons. The Jupiter Icy Moons Orbiter science goals include finding the extent of liquid oceans, locate regions that may be capable of supporting life, and identify future landing sites.

The Jupiter Icy Moons Orbiter mission is the first space science mission of NASA's project Prometheus. Project Prometheus was established to develop technologies that enable a new class of deep space missions that cannot be achieved with chemical propulsion. Project Prometheus' goal is to develop the first reactor powered spacecraft and demonstrate it can be safely operated for long periods of of time on deep space missions.

The Jupiter Icy Moons Orbiter (JIMO) mission involves sending a single electric propulsion spacecraft to orbit Callisto, Ganymede, and Europa in succession. In addition, electric propulsion may be used to spiral away from a low Earth orbit. The enormous ΔV required for this mission (on the order of 30 $\frac{km}{s}$) necessitates the use of high efficiency of propulsion.

The trajectory described in this paper was developed for an advanced study before the JIMO mission was defined. The spacecraft parameters (for example, power and initial mass) used in this trajectory are likely to be different than those selected for the JIMO mission.

Trajectory Design Challenges

The trajectory required for a low-thrust Galilean moon orbiter mission is complex and challenging to design. Strong multi-body effects combined with low-thrust control of capture and escape

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around the icy moons make the trajectory optimization difficult, and introduce risks and opportunities not present in chemical propulsion trajectories.

Optimizing low-thrust trajectories, and in particular, trajectories that include escape and capture is inherently difficult. The continuous operation associated with low thrust significantly increases the optimization complexity. High fidelity modeling of escape and capture requires a multi-body force model. However, a multi-body force model compounds the optimization complexity. To fully optimize an escape or capture trajectory, the origin or destination of the trajectory must be taken into account. Typically this involves optimizing an interplanetary trajectory simultaneously with a moon or planet centered spiral trajectory. However, optimizing a trajectory involving both an interplanetary leg and a planet or moon centered spiral introduces two very different time and distance scales into mathematical formulation. Widely varying time and distance scales are known to create difficulty for optimization.

The duration and complexity of a Galilean moon orbiter mission will make detailed trade studies difficult. Individual complete trajectories require a great deal of time to construct. Trajectories will typically involve Earth centered spiral escape, a gravity assist from the Earth's moon, a long heliocentric trajectory to reach Jupiter, ten or more gravity assists from the Galilean moons, resonant orbits between the Galilean moons, and a total of four escape and capture trajectories. The trajectory described in this paper required more than 2 weeks of computer time and several weeks of human time to produce.

If there is an unexpected loss of spacecraft control at critical points during low-thrust capture or escape from the Galilean moons, then there will be an impact risk. The risk arises from strong multi-body effects near capture and escape. Impact with one of the Galilean moons can occur in as little as week and a half. Ultimately, the design of the trajectory must try to reduce this risk. Optimization formulations do not take this impact risk into account. There is no simple way to formulate this risk in optimization because it requires multiple multi-body propagations to assess the impact risk. Gradient based optimization methods require derivatives. Obtaining derivatives of the impact risk (if they are even meaningful) will require a significant amount of computational effort.

Besides making trajectory design more difficult, Multi-body effects can present opportunities to improve performance[1,2,3]. Finding and evaluating these opportunities requires time and advanced design tools, but the performance improvements can be large. For example, the distant retrograde escape (capture) described in this paper provides a dramatic boost or decrease in the spacecraft's orbital energy relative to a Moon's orbital energy. The performance increase does not require additional thrusting.

The number of possible pathways between the Galilean moons presents another difficulty. As many as 6 or 7 moon flybys may be employed during each transfer. The number of possible combinations of flybys and intermediate resonant orbits is very large. Most developments in the literature do not specifically address using low-thrust to transfer between Galilean moons. However several methods to analyze and sort pathways between the moons are useful in general. For example, the Tisserand graph method[4,5] provides a means to analyze alternate pathways.

APPROACH

This paper describes an optimal trajectory that begins in low Earth orbit and ends in low Io orbit. A spacecraft following this trajectory will orbit Callisto, Ganymede, and Europa in succession before orbiting Io. The optimization objective is to maximize the final spacecraft mass in Io's orbit, given a fixed initial spacecraft mass in low-Earth orbit. The optimization variables include the thrust vector as a function of time, flyby or multi-body interaction times, and arrival and departure times. The

optimization algorithm called Static/Dynamic Control[6] (SDC) embodied in the program "Mystic" was used to design the trajectory. SDC is a general, gradient-based optimization method that is distinct from both parameter optimization and the calculus of variations. Trajectories are integrated with a multi-body force model and finite burns. Optimizing capture and escape trajectories with a multi-body force model results in a significant improvement in the flight time and mass delivered compared to patched two-body formulations[2]. A strong point of the SDC approach is its ability to find and exploit multi-body phenomena and handle widely varying physical scales. It is not necessary to specify intermediate flyby bodies or multi-body interactions on input. This is in contrast to many other optimization methods.

The trajectory was optimized in the parts. The reason the trajectory was optimized in parts was because the trajectory is far too complex to optimize in a single step. The trajectory was divided in such a way as to minimize the impact of piecewise optimization. For example, there is little control freedom in the low-altitude spiraling portions of the trajectory. Hundreds of powered revolutions are required with little change from one revolution to the next. Full optimization provides negligible improvements in performance compared to the simple control law of thrusting parallel to the relative velocity vector. Since low-altitude spiraling is not dependent on body phasing and does not require optimization, it can be "separated" from the interplanetary and intermoon trajectory. Similarly moon to moon transfers can be optimized separately because the frequency of a repeated phasing between any two Galilean moons is on the order of only a few days. The trajectory was optimized piecewise as follows: I. Earth high orbit to Callisto mid-level orbit. II. Callisto mid-level orbit to Ganymede mid-level orbit, III Ganymede mid-level orbit to Europa mid-level orbit, and finally, IV. Europa mid-level orbit to Io mid-level orbit. Low-altitude spiraling around the Earth and the Galilean moons was integrated with a simple control law.

RESULTS

The trajectory begins in low Earth orbit (2500 km altitude) with an initial mass of 9400 kg. This mass corresponds to the launch capability of Boeing's Delta 4450 launch vehicle. The thruster specific impulse is $I_{sp} = 9000$ seconds, the thruster overall efficiency is $\nu = 74\%$, and the power available to the thrusters is assumed to be $P_o = 200$ kW. The thruster jet power is $\nu \times P_o = 148$ kW. The thrust magnitude is given by the following equation:

$$Thrust = 2\nu \frac{P_o}{gI_{sp}} = 3.353 \ \ Newtons \tag{1}$$

Launch is assumed to occur before September 3rd, 2011 so thrusting to escape Earth may begin on this date.

Earth Orbit to Callisto Orbit

The first end-to-end optimized portion of the trajectory begins in high Earth orbit and ends in mid-level Callisto orbit. Figure 1 illustrates the Earth escape and lunar flyby portion of the trajectory. A lunar flyby is used to achieve escape energy relative to the Earth. The use of the Earth's moon to escape is advantageous and may not be avoidable. Low-thrust escape spirals will inevitable spend a fair amount of time at radii where the Moon has a strong influence. Taking advantage of the Moon does not require a close (risky) flyby[2]. The lunar gravity assist in Figure 1 provides an effective ΔV of 800 $\frac{m}{s}$ relative to the Sun. Another way to evaluate, the performance of the gravity assist is by plotting the orbital energy of the spacecraft with respect to the Earth (see Figure 2.) This trajectory achieves nearly 1 $\frac{km^2}{s^2}$ boost in orbital energy.

Figure 3 illustrates the complete optimized trajectory from Earth orbit to Callisto orbit in a Sun centered frame. Figure 3 best illustrates the heliocentric phase of the trajectory. Jupiter capture is achieved after about one revolution around the Sun. A lower thrust to mass ratio than the one used

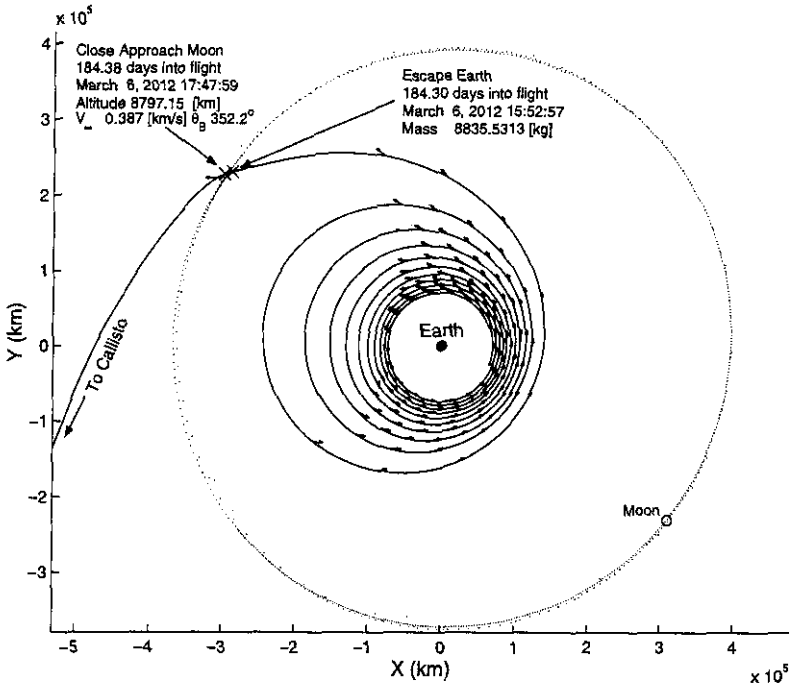

Figure 1: Optimal trajectory for the Earth escape spiral to Callisto orbit, illustrating the Earth escape portion. The arrows along the spacecraft trajectory indicate the thrust direction. The lack of arrows along the trajectory indicate optimal coasting periods.

here is likely for the JIMO mission. Hence, the JIMO mission will involve two or three revolutions around the Sun between Earth escape and Jupiter capture. At least one long coasting arc will be present in the heliocentric phase.

No gravity assist (other than the lunar gravity assist) is used to get to Jupiter. Using a planetary gravity assist will improve performance but will cost flight time and limit launching to certain years. An Earth gravity assist is likely to be ruled out for safety (reentry) reasons. A Venus gravity assist will add thermal design constraints and may be ruled out because such a trajectory must cross the Earth's orbit and hence lead to risk of reentry. A Mars gravity assist may be feasible, but requires correct phasing and provides less performance than either an Earth or Venus gravity assist.

Figure 4 is a Jupiter centered plot of the Earth orbit to Callisto orbit trajectory. The pinwheel of arrows near Callisto's orbit is the the Callisto centered spiraling thrust as viewed in the Jupiter centered frame. This part of the trajectory involves a "double capture:" first around Jupiter and then around Callisto. The trajectory includes a flyby of Callisto shortly before Callisto orbit insertion. This trajectory could be altered to include a flyby of Ganymede on the initial approach to improve performance and flight time. Future trajectory development will likely include at least one flyby of Ganymede and/or Callisto early in the Jupiter spiral.

Figure 5 is a Callisto centered plot of the Earth orbit to Callisto orbit trajectory. Figure 5 illustrates the use of an orbit *near* a well-known[7] three-body orbit called a "Distant Retrograde Orbit" or DRO. DROs are stable three-body orbits that encompass the secondary body and lie entirely outside the Lagrange points 1 and 2. An example of a DRO around Ganymede is provided in Figure 6. The DRO can be very stable, requiring no station keeping. The DRO in Figure 6 was propagated for 300 days or more than 40 Ganymede revolutions around Jupiter. The trajectory in

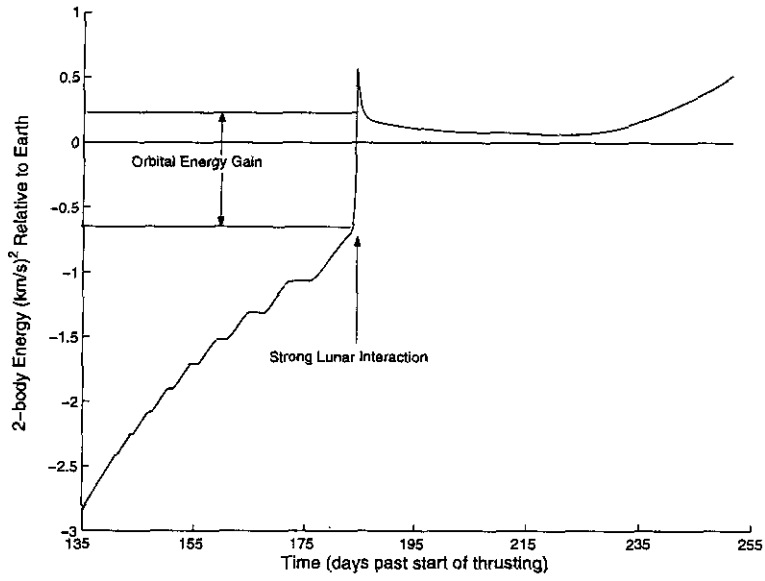

Figure 2: Optimal trajectory for the Earth escape spiral to Callisto orbit: orbital energy gain from the lunar gravity assist.

Figure 5 is not a stable DRO, but near a stable DRO for about one quarter of a revolution before "falling down" to a high altitude (essentially two-body) retrograde orbit. This type of capture is locally optimal and was identified (without human guidance) by the SDC optimization algorithm. The advantage to this type of capture verses other locally optimal capture types[2] is that it is highly efficient and ends in a two-body retrograde orbit around the moon. Retrograde orbits are preferred because they remain stable at higher altitudes than posigrade orbits. For example, compare the ballistic propagations in Figure 7. The only difference in the initial circular orbits is Figure 7 is one is retrograde (left) and one is posigrade (right). Impact occurs in the posigrade case in only 37 days whereas the retrograde case is stable.

While unstable or "near" DROs provide an excellent means of capture (and, also, escape - as will be shown) *stable* DROs provide a potentially useful parking orbit that is not captured (in a two-body sense) at any Galilean moon, but remains in the vicinity of a single moon. It is possible to depart the DRO with very little ΔV to a Jupiter centric orbit with either a significantly higher or lower energy than the central moon's orbital energy with respect to Jupiter. This feature of the DRO enables efficient stepping toward the moon below or above the parking orbit moon.

Callisto Escape to Ganymede Capture

The second, end-to-end optimized portion of the trajectory begins in a circular retrograde Callisto orbit at an altitude of 9841 km and ends in a nearly circular retrograde orbit around Ganymede. The trajectory involves two flybys of Callisto and two flybys of Ganymede before Ganymede orbit insertion. The flybys are set up to step between resonant orbits. Using flybys and resonant intermediate orbits greatly reduce the propellant required and often the time required to transfer between the Galilean moons when compared to a Jupiter centered low-thrust spiral.

The initial state for the Callisto to Ganymede transfer was obtained by propagation of the final state of the Earth to Callisto trajectory down to the Callisto science orbit (500 km circular orbit, stay time of 1 month) and back up to a Callisto orbit with altitude of 9841 km.

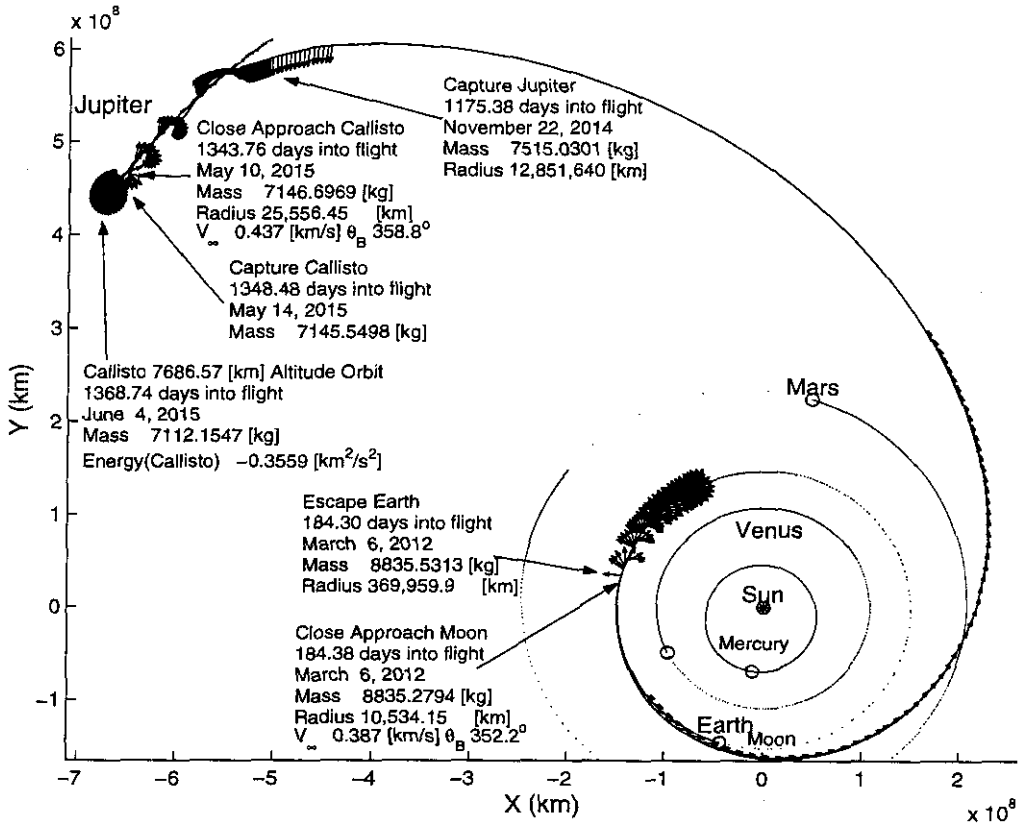

Figure 3: Optimal trajectory for the Earth escape spiral to Callisto orbit, illustrating the heliocentric portion of the trajectory. The arrows along the spacecraft trajectory indicate the thrust direction. The lack of arrows along the trajectory indicate optimal coasting periods. The pinwheels of arrows near Earth and Jupiter are Earth, Jupiter and Callisto centered spiraling as viewed in the heliocentric frame.

Figure 8 illustrates the optimal Callisto to Ganymede transfer in a Jupiter centered frame. The trajectory uses DRO type escape to reach a 4:3 Callisto resonant orbit. The DRO escape (see Figure 9) is the escape analogue of the DRO type capture in Figure 5. The analogy between the DRO escape and capture is apparent when comparing the DRO escape illustrated in the L_1 centered plot in Figure 9 to the DRO capture illustrated in the L_2 centered plot in Figure 5. The DRO escape is the mirror reflection of the DRO capture. In both the capture and escape cases, the trajectory approximates a DRO for about one third of a revolution. In the capture case, a flyby of Callisto occurs before the one third revolution around a DRO. In the escape case, the one third revolution around the DRO is established using low thrust, then the spacecraft "falls off" the DRO and flys by Callisto between Callisto and L_1.

After the DRO escape from Callisto, Callisto is re-encountered after 4 revolutions around Jupiter (3 revolutions for Callisto). The Callisto flyby reduces perijove to Ganymede's orbit. Ganymede is encountered after 1/2 revolution around Jupiter. The Ganymede flyby reduces the spacecraft orbital energy around Jupiter such that the resulting orbit is a 3:4 Ganymede resonance. After 3 revolutions around Jupiter (4 revolutions for Ganymede) Ganymede is re-encountered and a DRO type capture at Ganymede is completed in about 4 days. Note that most of the transfer does not require thrusting.

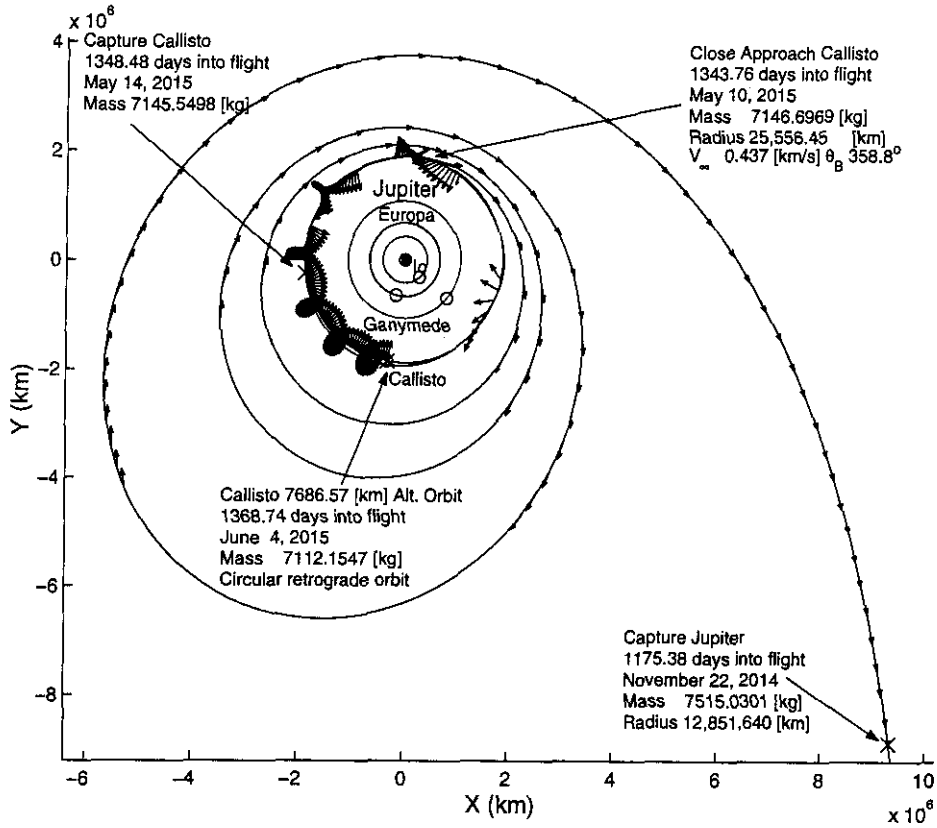

Figure 4: Optimal trajectory for the Earth escape spiral to Callisto orbit, illustrating the Jupiter centered portion of the trajectory. The arrows along the spacecraft trajectory indicate the thrust direction. The pinwheels of arrows near Callisto's orbit are Callisto centered spiraling thrust as viewed in the Jupiter centered frame.

Many other locally optimal transfers involving different resonant intermediate orbits are possible. This particular transfer utilizes the DRO escape to reach the lowest energy resonance possible with a short resonant period (4:3 Callisto resonance.) Using the DRO escape to reach the 4:3 Callisto resonance represents a single point in the trade between reducing overall flight time and maximizing the ballistic performance of the DRO type escape.

An orbit with perijove equal to Ganymede's orbital radius apparently can not be directly reached from a DRO type escape. Therefore, only Callisto resonances need to be searched. This is in contrast to a DRO type escape attempting to reach Europa from Ganymede, as will be discussed below. These results are somewhat independent of the thrust to mass ratio because the transfer to the first resonant orbit from the DRO escape is essentially ballistic once the near DRO orbit is achieved using low-thrust.

There exist different locally optimal Ganymede captures. The SDC optimization algorithm does not require a good guess to begin the optimization. It is this feature that was used to explore the complex optima space of capture at Ganymede. A number of poor initial guesses were generated to begin separate optimizations. The purpose of this procedure is to investigate (with as little bias as possible) the range of available, locally optimal capture trajectories. Four different local minima were obtained from the same initial condition in Callisto orbit and same sequence of resonant intermediate

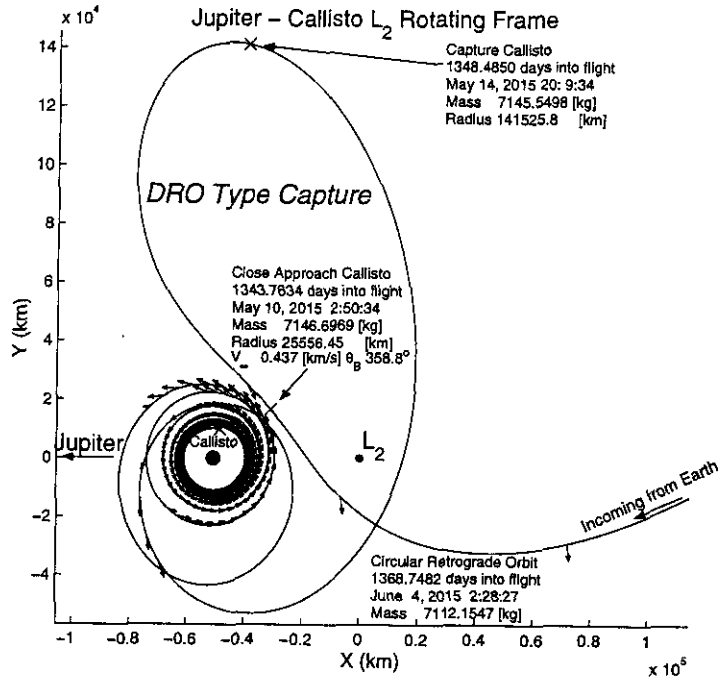

Figure 5: The Callisto capture portion of the Earth orbit to Callisto orbit optimal trajectory. The trajectory is plotted in Jupiter-Callisto rotating coordinates to illustrate the DRO type capture.

orbits. The four locally optimal trajectories are illustrated in Figure 10. Three posigrade captures (Figures 10a, b, and c) were obtained, and one DRO retrograde capture (Figure 10d) was obtained. The performance for each locally optimal trajectory is provided in Table 1. The DRO type capture is the most efficient of the four minima and is particularly useful if a low retrograde orbit is the ultimate target. The Ganymede DRO capture trajectory was used in the final tour design.

Table 1

RELATIVE PERFORMANCE OF OPTIMAL GANYMEDE CAPTURES

Ganymede Capture Type	Propellant From Callisto Escape to Ganymede Capture [kg]	Time of Flight From Callisto Escape to Ganymede Capture [d]
(a) Direct	39.3572	92.1231
(b) L_2 Halo	35.5338	93.2301
(c) L_2 Halo	46.0681	94.3010
(d) DRO	29.9031	94.2511

Ganymede Escape to Europa Capture

The third, end-to-end optimized portion of the trajectory begins in a circular retrograde Ganymede orbit at an altitude of 8651 km and ends in a nearly circular retrograde orbit around Europa. The trajectory involves one flyby of Ganymede and two flybys of Europa before Ganymede orbit insertion. The flybys are set up to step between a Europa crossing and a Europa resonant orbit. The initial state for the Ganymede to Europa transfer was obtained by propagation of the final state of the Callisto to Ganymede trajectory down to the Ganymede science orbit (500 km circular orbit, stay time of 1 month) and back up to a Ganymede orbit with altitude of 8651 km. Figure 11 illustrates

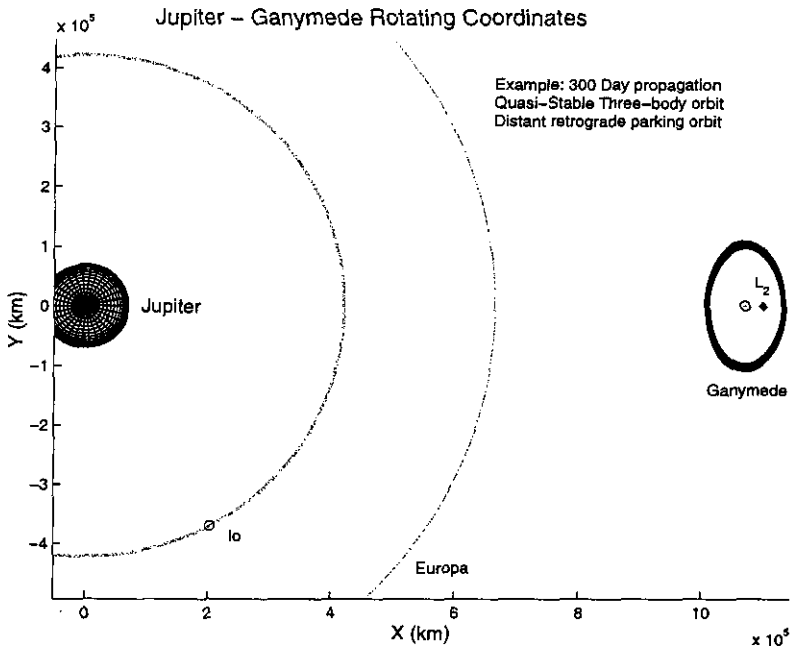

Figure 6: An example of an uncontrolled Distant Retrograde Orbit or DRO around Ganymede. The trajectory is propagated for 300 days with no station keeping. The coordinate frame rotates with Ganymede.

the optimal Ganymede to Europa transfer in a Jupiter centered frame. The trajectory uses a DRO type escape from Ganymede (Figure 12) to enter into a Jupiter centered orbit that crosses Europa's orbit. Europa is encountered after 1.5 revolutions around Jupiter. The Europa flyby reduces the spacecraft orbital energy around Jupiter such that the resulting orbit is a 6:7 Europa resonance. After 6 revolutions around Jupiter (7 revolutions for Europa) Europa is re-encountered and a DRO type capture (Figure 13) at Europa is completed in about 5 days.

Note that the the DRO type escape *can* result in a Europa crossing orbit, however, a DRO escape from Callisto *can not* result in a Ganymede crossing orbit. It also turns out that a DRO escape from Europa *can not* result in a Io crossing orbit. This was determined by using SDC to optimize the DRO escape with the single objective of minimizing the resulting orbital energy with respect to Jupiter. The minimum energy solution has a perijove above the next lowest moon in the case of Callisto and Europa and below the next lowest moon in the case of Ganymede.

Europa Escape to Io Capture

The fourth, end-to-end optimized portion of the trajectory begins in a circular retrograde Europa orbit at an altitude of 6664 km and ends in a nearly circular retrograde orbit around Io. The trajectory involves two flybys of Europa and three flybys of Io before Ganymede orbit insertion. The flybys are set up to step between resonant orbits. The initial state for the Europa to Io transfer was obtained by propagation of the final state of the Ganymede to Europa trajectory down to the Europa science orbit (500 km circular orbit, stay time of 1 month) and back up to a Europa orbit with altitude of 6664 km.

The decrease in orbital energy between Europa and Io is much greater than any other two adjacent Galilean moons. As a result, more resonant orbit intermediate steps are required for the Europa to Io transfer than for either the Callisto to Ganymede transfer or the Ganymede to Europa transfer. Figure 14 illustrates the optimal Europa to Io transfer in a Jupiter centered frame. The

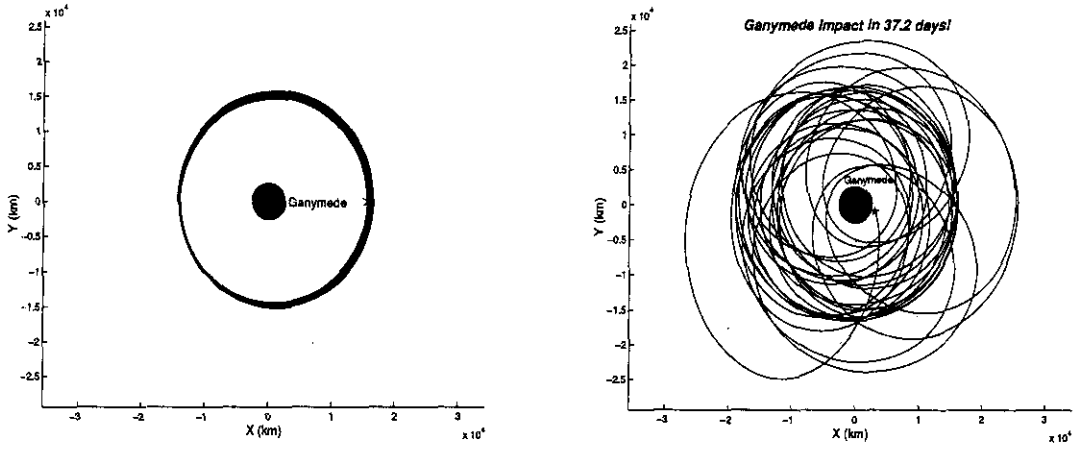

Figure 7: An example of an uncontrolled circular retrograde orbit (left) and an uncontrolled circular posigrade orbit (right) around Ganymede with an initial altitude of 12,866 km. Note that both orbits lie well inside of the Lagrange points unlike the DRO three-body orbit in Figure 6.

trajectory uses a DRO type escape to reach a 5:4 Europa resonant orbit (A DRO escape can not be used to cross Io's orbit). After the DRO escape from Europa, Europa is re-encountered after 5 revolutions around Jupiter (4 revolutions for Europa). The Europa flyby reduces perijove to Io's orbit. Io is encountered after 2 1/2 revolutions around Jupiter. The Io flyby reduces the spacecraft orbital energy around Jupiter such that the resulting orbit is a 5:7 Io resonance. After 5 revolutions around Jupiter (7 revolutions for Io) Io is re-encountered. The Io flyby reduces the spacecraft orbital energy around Jupiter such that the resulting orbit is a 10:11 Io resonance. After 10 revolutions around Jupiter (11 revolutions for Io) Io is re-encountered and a DRO type capture at Io is completed in about 2 days.

Of the three moon to moon transfers, the Europa to Io transfer probably has the greatest number of transfers involving different resonant intermediate orbits that should be investigated. The accumulated radiation dose is high inside of Europa so there will be great incentive to find short flight time transfers probably at the expense of some performance. The JIMO mission (as it is currently defined) will not continue to Io.

SUMMARY AND CONCLUSIONS

A summary of the performance of the complete trajectory from Earth low orbit to Io low orbit is provided in Tables 2 and 3. Table 2 lists the flight times, propellant usage, and ΔV required for different phases of the trajectory. Table 3 compares the efficiency of the inter-moon transfers to both Hohmann transfers and integrated, continuous low-thrust spirals from one moon's orbit to the next. The optimized trajectories between the moon's presented in this paper require only 15% of the propellant to achieve the transfer compared to both a Hohmann type transfer and an integrated low-thrust spiral. Even better performance can be achieved but more flight time will be needed.

Improving the Performance of the Trajectory

Table 2 can be used to decided where to place more effort on improving the trajectory. For example, a 50% reduction in propellant required for the inter-moon transfers will have only a minimal impact on the overall trajectory performance. This is because the propellant required for the inter-moon transfers is currently small (accounting for only only 4% of the overall ΔV) Large consumers of the ΔV budget are the Earth to Jupiter phase and the Jupiter spiral down phase. Additional Callisto flybys or Ganymede flybys can be used to improve the Jupiter spiral down performance.

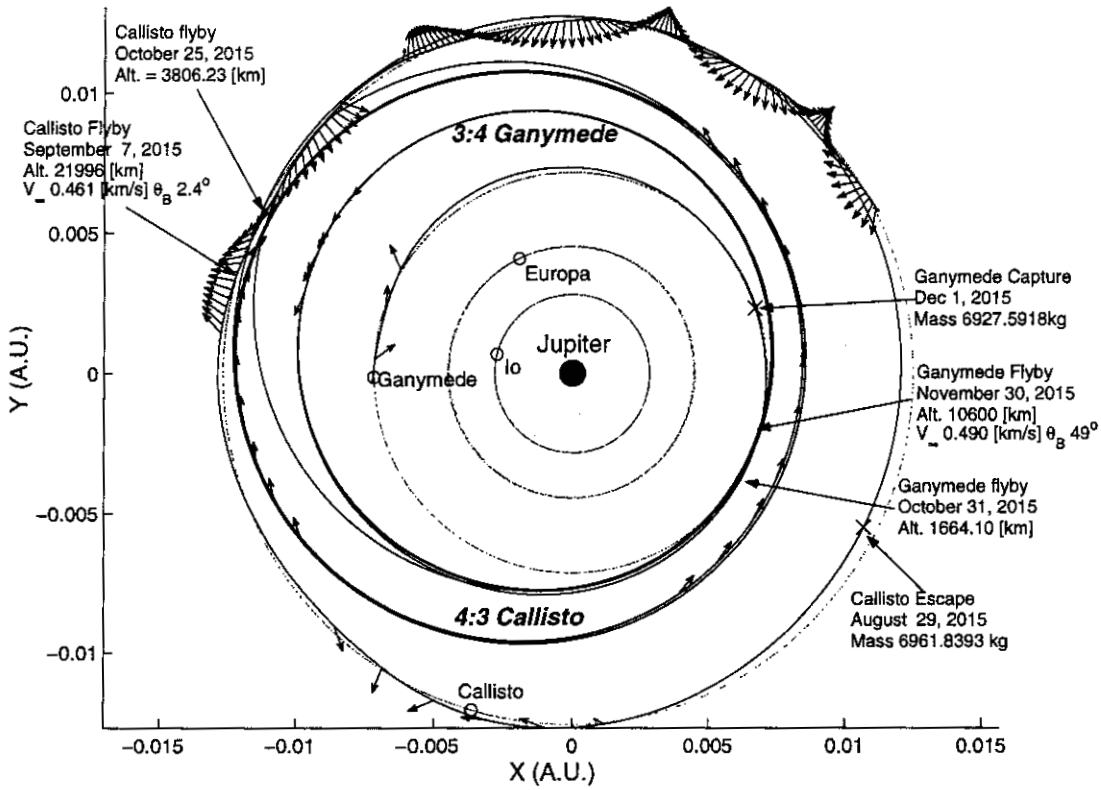

Figure 8: The optimal trajectory for the Callisto retrograde orbit to Ganymede retrograde orbit transfer is illustrated in a Jupiter centered frame. 4:3 Callisto and a 3:4 Ganymede resonant intermediate orbits are used as steps in the transfer. The pinwheel of arrows near Callisto's orbit are Callisto centered spiraling thrust vectors as viewed in the Jupiter centered frame.

This portion of the trajectory accounts for 14% of the overall ΔV. An indirect trajectory to Jupiter can provide significantly better performance with a flight time to Jupiter capture of 6 or more years. Since the trajectory from Earth to Jupiter capture accounts for 43% of the total ΔV in the trajectory, savings in this portion of the trajectory will have a large impact on the overall ΔV. For lower power or larger initial masses, an indirect trajectory will probably be necessary. The ΔV required for moon centered "deep-gravity-well" spirals cannot be significantly improved. The moon centered spirals account for 23% of the overall ΔV in the trajectory.

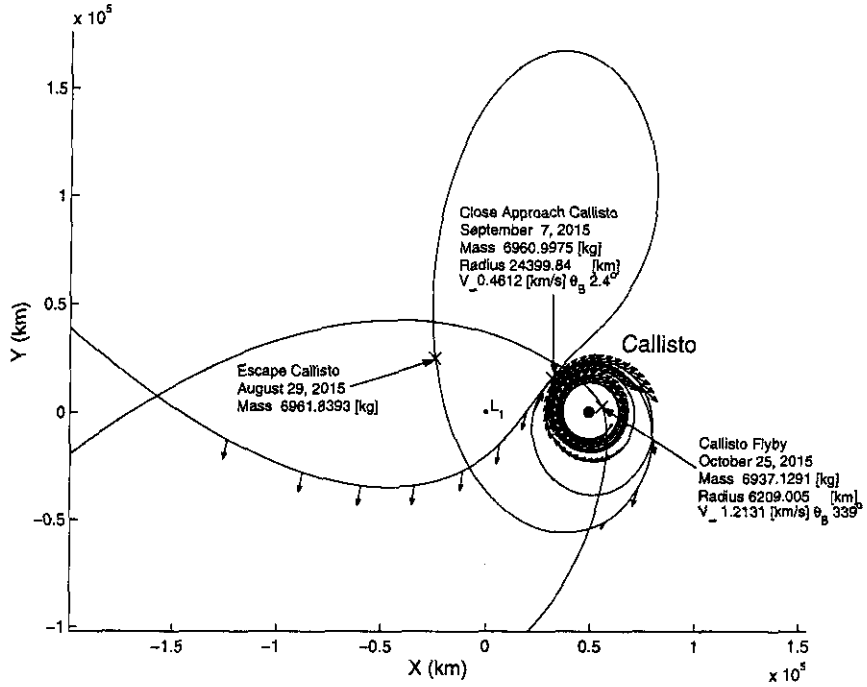

Figure 9: The optimal trajectory for the Callisto retrograde orbit to Ganymede retrograde orbit transfer is illustrated in a Jupiter-Callisto rotating frame centered on L_1. A DRO type escape is used to depart Callisto and reach the 4:3 Callisto resonance. Callisto is re-encountered on October 25, 2015. The flyby on October 25, establishes an orbit that encounters Ganymede on October 31.

Table 2: Base Jupiter NEP Galilean Tour (200 kW, I_{sp} 9000 s) - Summary

Leg Description	**Flight Time** [days]	**Propellant Usage** [kg]	ΔV $[\frac{km}{s}]$
LEO to Earth escape	185	565.0162	5.47
Earth escape to Jupiter capture	991	1318.7548	14.26
Jupiter capture to Callisto capture	172	372.4372	4.48
Callisto centered spiral	73	181.9525	2.28
Callisto escape to Ganymede capture	95	34.2475	0.43
Ganymede centered spiral	77.6	209.0125	2.70
Ganymede escape to Europa capture	40.2	31.4629	0.41
Europa centered spiral	46.7	125.9449	1.68
Europa escape to Io capture	53.7	39.7308	0.54
Io centered spiral down	19.5	61.7659	0.84
TOTAL	**1849**	**2940**	**33.09**

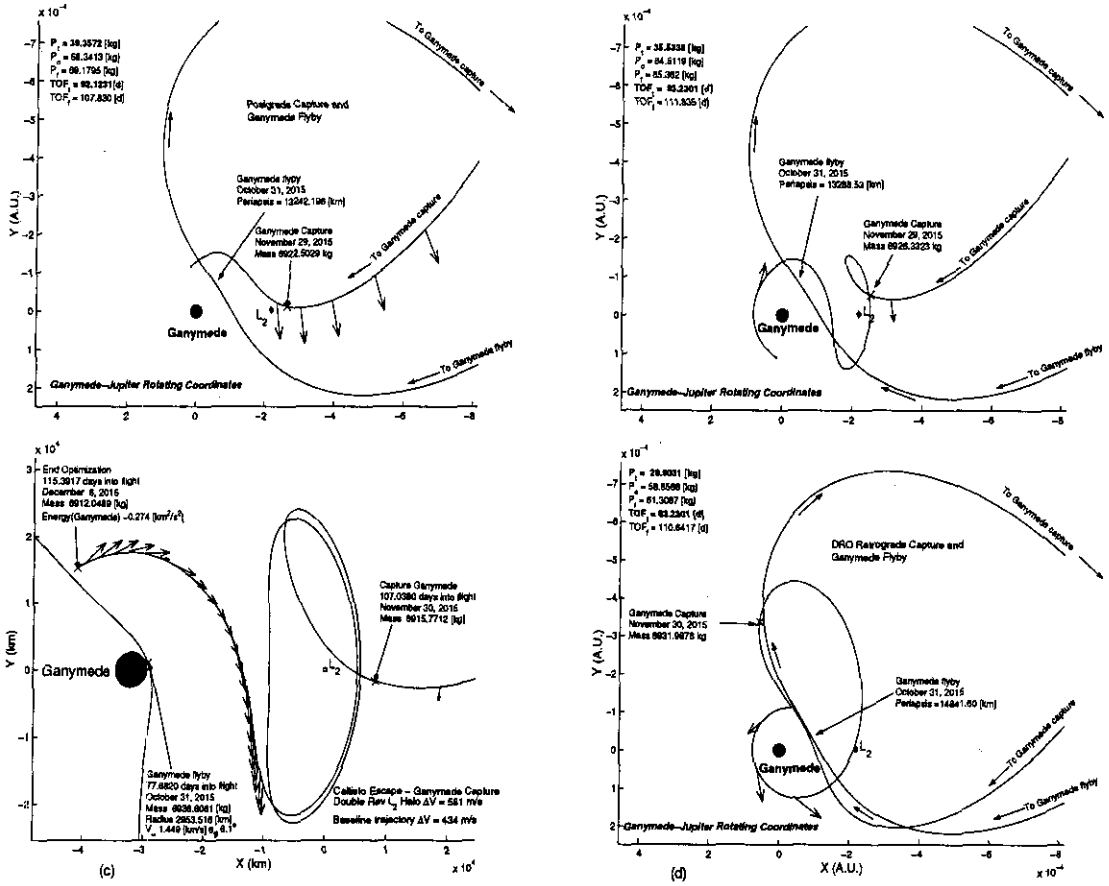

Figure 10: Four different, locally optimal Ganymede Captures. All trajectories are plotted in a Ganymede-Jupiter rotating frame centered on L_2. Each trajectory begins with the same initial condition in orbit around Callisto and utilize the same sequence of resonant intermediate orbits to reach Ganymede. The four minima obtained are (a) a direct posigrade capture, (b) a single revolution L_2 Halo type capture, (c) a double revolution L_2 Halo type capture, and (d) a DRO type retrograde capture.

Table 3: Transfer Efficiency Between Galilean Moons (200 kW, I_{sp} 9000 s)

Leg Description	ΔV Achieved $[\frac{km}{s}]$	ΔV Hohmann $[\frac{km}{s}]$	ΔV Spiral $[\frac{km}{s}]$	ΔV Savings $[\frac{km}{s}]$
Callisto escape to Ganymede capture	0.43	2.62	2.67	**2.24, (84%)**
Ganymede escape to Europa capture	0.41	2.82	2.86	**2.45, (86%)**
Europa escape to Io capture	0.54	3.58	3.63	**3.09, (85%)**
TOTAL	**1.38**	**9.02**	**9.16**	**7.78, (85%)**

Conclusions

A low-thrust Galilean moon orbiter mission design will require end-to-end optimization of trajectories involving an Earth centered spiral, an interplanetary leg, Jupiter centered spiral, and a Callisto centered spiral. The trajectory from Earth to Callisto has a dynamic scale change factor of 10,000 (the extremes are the heliocentric phase and the Callisto orbit phase). Widely varying

time and distance scales are known to create great difficulty for numerical optimization. The SDC algorithm embodied in the program Mystic has been shown to be capable of optimizing high fidelity trajectories with as much dynamic variation as occurs in the Galilean moon orbiter mission. Even though the SDC algorithm is capable of optimizing a Galilean moon orbiter trajectory, the duration and complexity of the mission will make detailed trade studies difficult. Individual complete trajectories require a fair amount of time to construct, and optimize.

The impact risk resulting from unexpected loss of spacecraft control at critical points during low-thrust capture or escape requires more analysis. Ultimately, the design of the trajectory must respond to this risk. The current maximize-final-mass objective used for optimization does not take this impact risk into account. Further research should be conducted to evaluate and reduce the impact risk.

SDC is well suited to explore the optimal trajectories that exist in capture and escape. SDC does not require a good guess to begin the optimization. It is this feature that can be used to explore the optima space of capture and escape. The process of evaluating alternate capture and escape trajectories resulted in the identification of the DRO type capture and escape. The DRO type capture and escape is the most efficient of several identified local optima and is particularly useful if a low retrograde orbit is the ultimate target. In the Jovian system, it was found that the DRO type escape from Ganymede can result in a Europa crossing orbit, however, a DRO escape from Callisto *can not* result in a Ganymede crossing orbit. Similarly, a DRO escape from Europa *can not* result in a Io crossing orbit.

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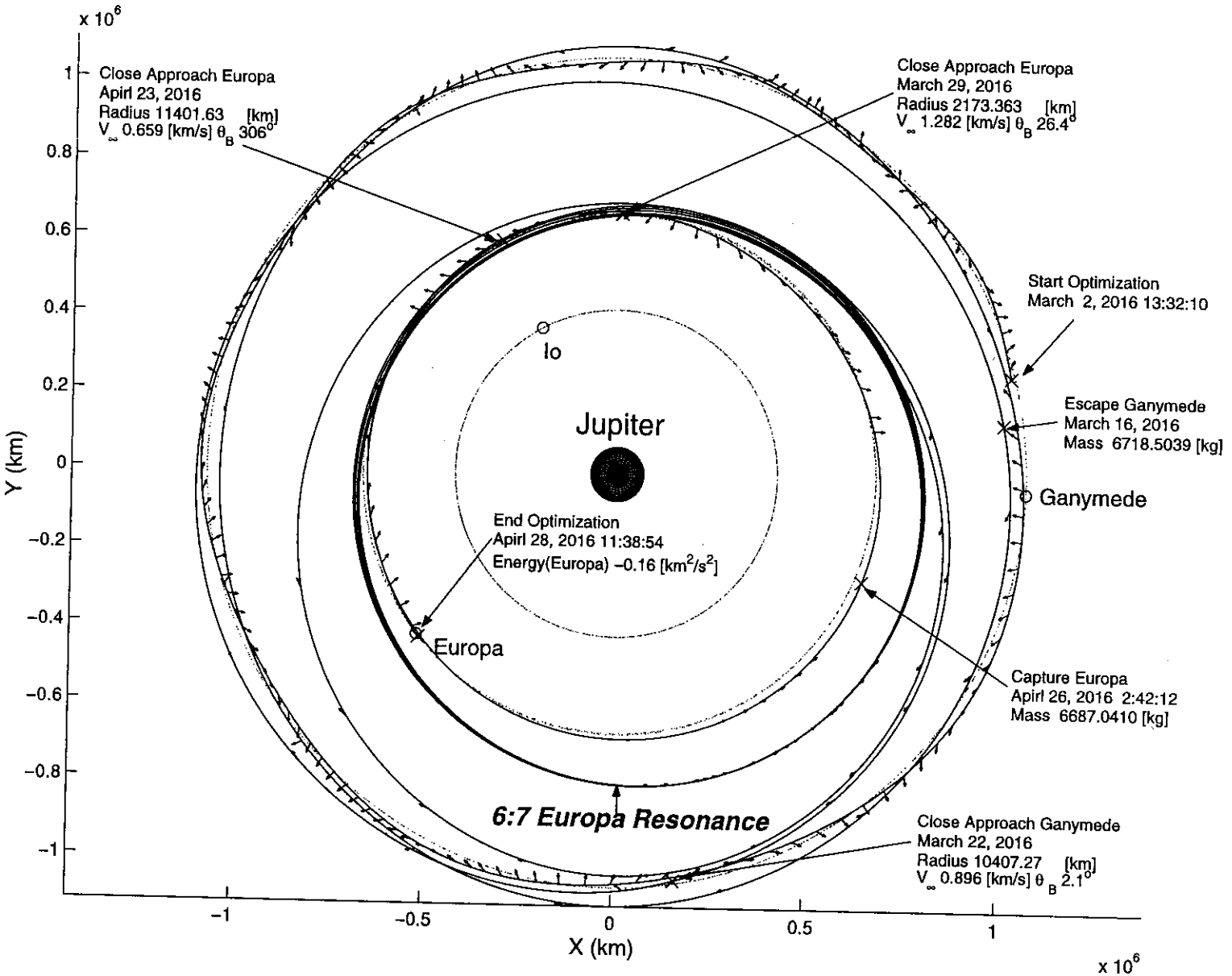

Figure 11: The optimal trajectory for the Ganymede retrograde orbit to Callisto retrograde orbit transfer is illustrated in a Jupiter centered frame. A 6:7 Europa resonant intermediate orbit is used in the transfer.

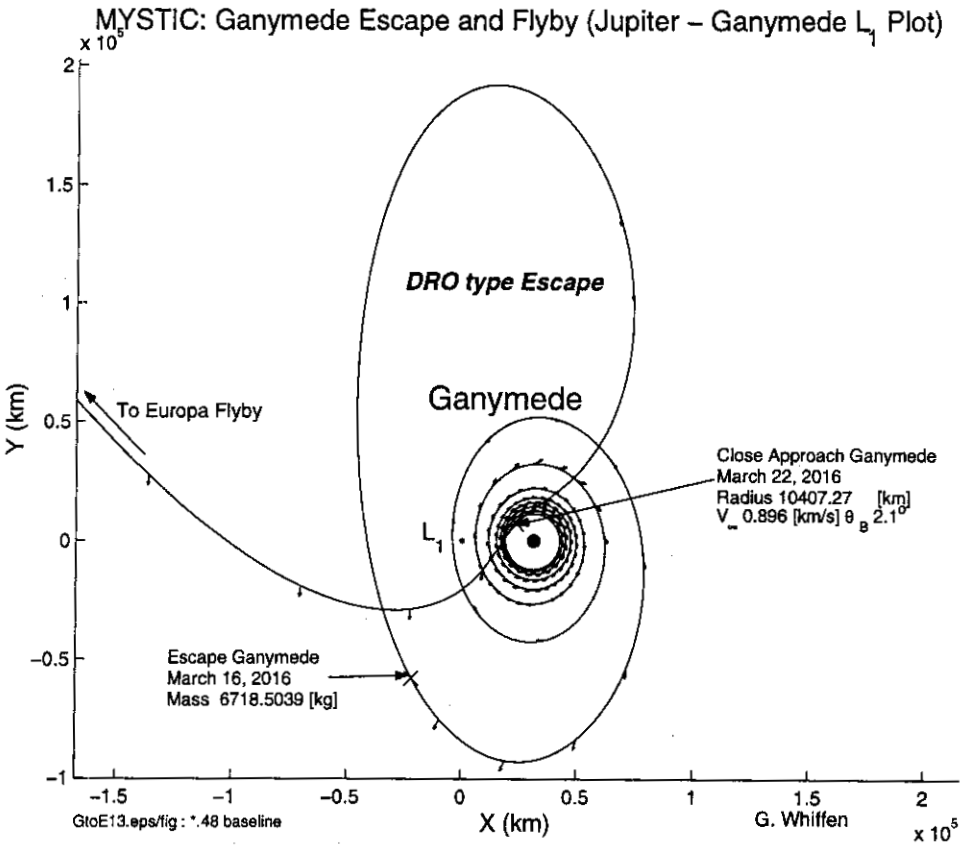

Figure 12: Part of the optimal trajectory for the Ganymede retrograde orbit to Europa retrograde orbit transfer is illustrated in a Jupiter-Ganymede rotating frame centered on L_1. A DRO type escape is used to depart Ganymede and reach a Europa crossing intermediate orbit around Jupiter .

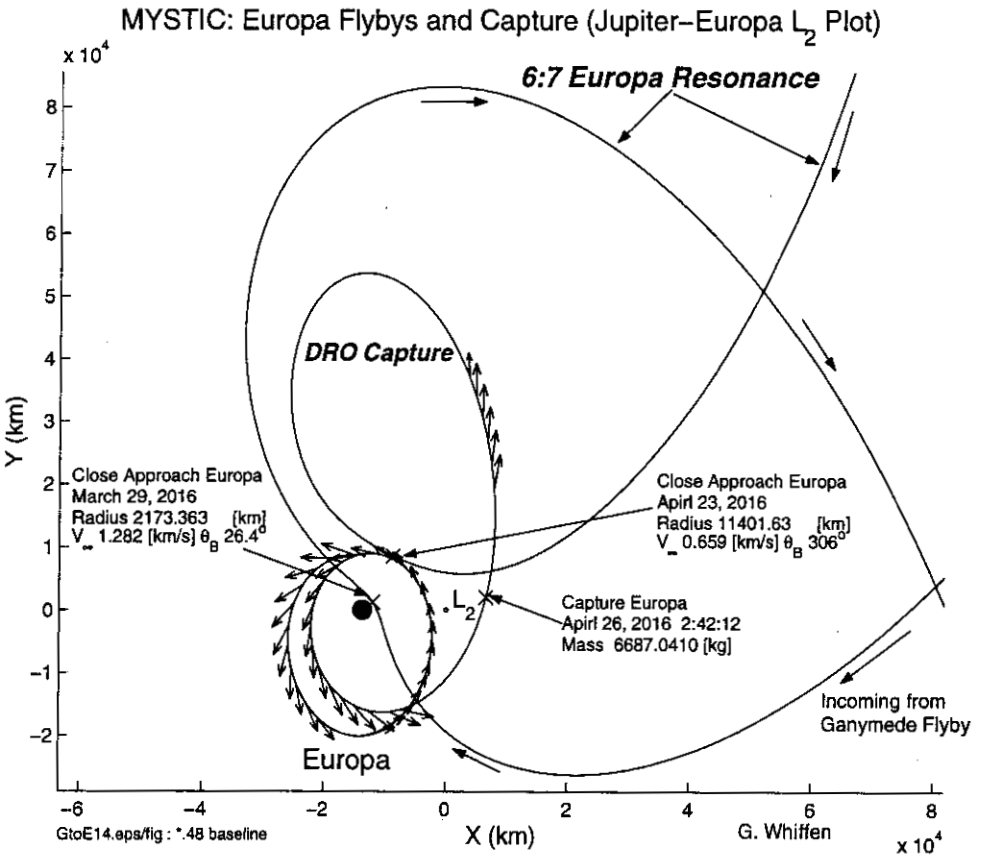

Figure 13: Part of the optimal trajectory for the Ganymede retrograde orbit to Europa retrograde orbit transfer is illustrated in a Jupiter-Europa rotating frame centered on L_2. A DRO type capture is used to enter into Europa orbit.

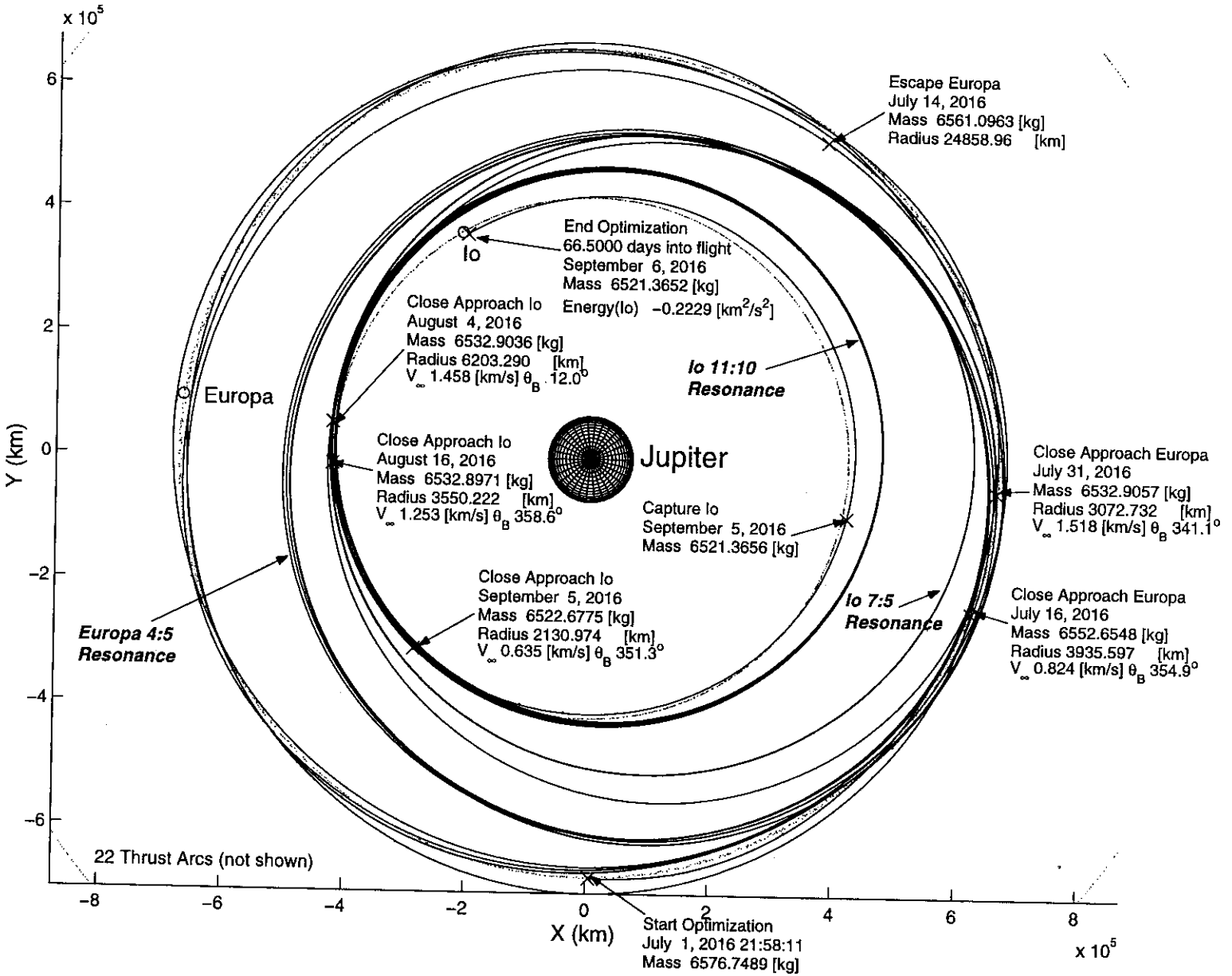

Figure 14: The optimal trajectory for the Europa retrograde orbit to Io retrograde orbit transfer is illustrated in a Jupiter centered frame. 5:4 Europa, 5:7 Io, and a 10:11 Io resonant intermediate orbits were used in the transfer.

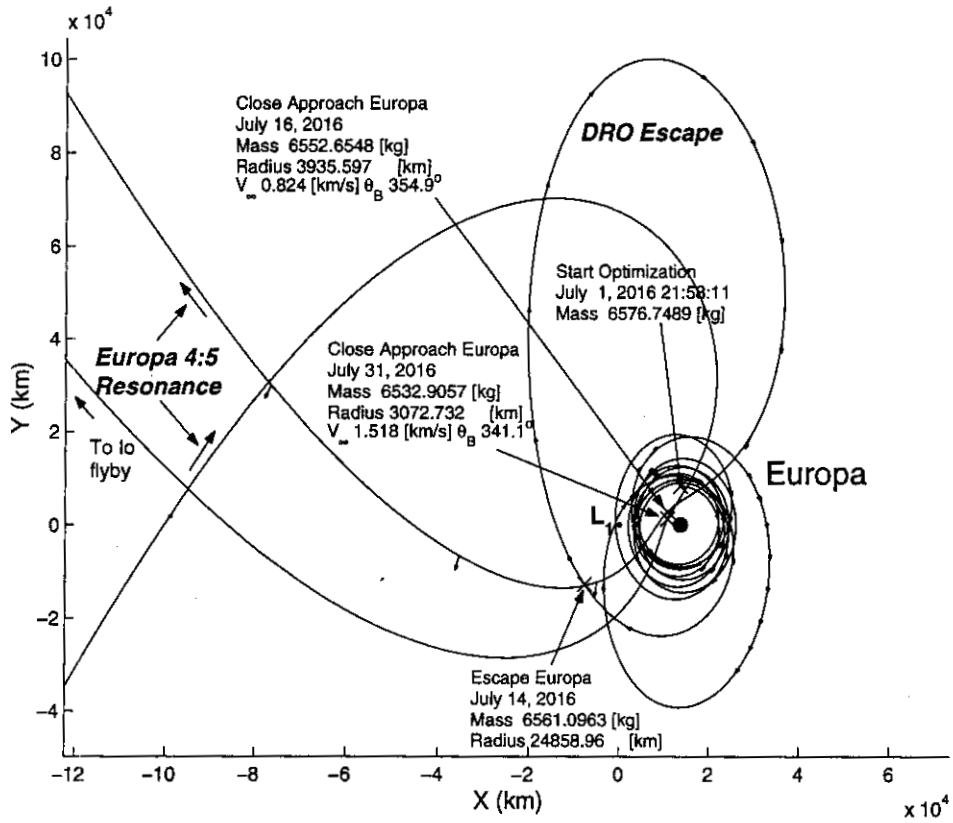

Figure 15: Part of the optimal trajectory for the Europa retrograde orbit to Io retrograde orbit transfer is illustrated in a Jupiter-Europa rotating frame centered on L_1. A DRO type escape is used to depart Europa and reach a 5:4 Europa resonant orbit around Jupiter .

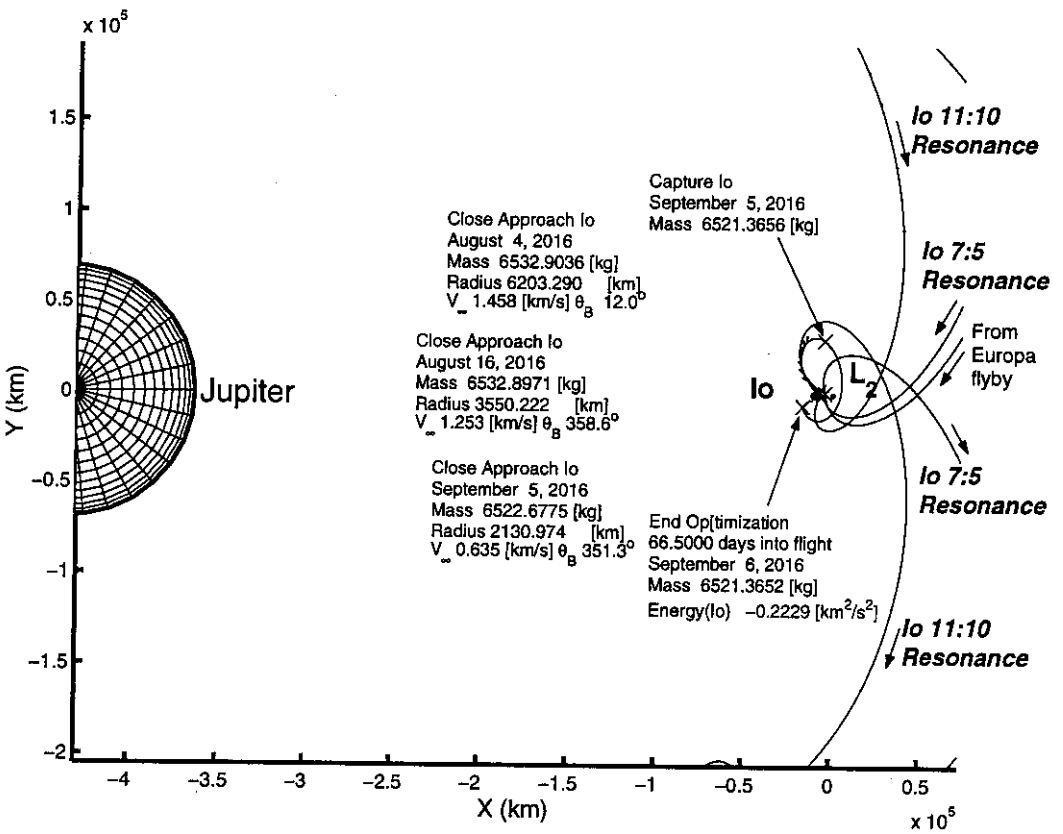

Figure 16: Part of the optimal trajectory for the Europa retrograde orbit to Io retrograde orbit transfer is illustrated in a Jupiter-Io rotating frame centered on L_2. Three Io flybys and a DRO type capture is used to enter into Io orbit.