AAS 03-143

DESIGN OF A MULTI-MOON ORBITER*

S.D. Ross[†], W.S. Koon[‡], M.W. Lo[§], J.E. Marsden[¶]

February 7, 2003

Abstract

The Multi-Moon Orbiter concept is introduced, wherein a single spacecraft orbits several moons of Jupiter, allowing long duration observations. The ΔV requirements for this mission can be low if ballistic captures and resonant gravity assists by Jupiter's moons are used. For example, using only 22 m/s, a spacecraft initially injected in a jovian orbit can be directed into a capture orbit around Europa, orbiting both Callisto and Ganymede enroute. The time of flight for this preliminary trajectory is four years, but may be reduced by striking a compromise between fuel and time optimization during the inter-moon transfer phases.

INTRODUCTION

Mission to Europa is Strongly Recommended

The National Academy of Sciences (NAS) recently issued a report calling on NASA to deploy a large mission every decade, one in which extended observation and experiments could be performed.[2] In particular, the NAS report called on NASA to resurrect a mission to Jupiter's moon Europa—a project the space agency canceled earlier for budgetary reasons.[13] Europa is thought to be a place hospitable to life because of the vast, liquid oceans that may exist under its icy crust. Two other Jupiter moons, Ganymede and Callisto, are now also thought to have liquid water beneath their surfaces.[21, 14] A proposed mission to Europa, and perhaps also Ganymede and Callisto, would attempt to map these regions of liquid water for follow-on missions. The recent discovery of life in the ice of Lake Vostok, a lake deep beneath the Antarctic ice cap, lends impetus to a Europa mission with the suggestion that life may be possible on Europa.[7] A mission to tour the moons of Jupiter may likely be initiated in the near future.[3]

*This work is supported in part by the Caltech's President's Fund.

†Control and Dynamical Systems, California Institute of Technology, MC 107-81, Pasadena, California 91125, USA. Email: shane@cds.caltech.edu

‡Control and Dynamical Systems, California Institute of Technology, MC 107-81, Pasadena, California 91125, USA. Email: koon@cds.caltech.edu

§Navigation and Mission Design Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA. Email: Martin.Lo@jpl.nasa.gov

¶Control and Dynamical Systems, California Institute of Technology, MC 107-81, Pasadena, California 91125, USA. Email: marsden@cds.caltech.edu

Multi-Moon Orbiter: Orbiting Several of Jupiter's Moons with a Single Spacecraft

In response to the scientific interest in Jupiter's moons and the guidelines set forth by the NAS, a tour concept called the *Multi-Moon Orbiter* is herein introduced, wherein a single sophisticated spacecraft is capable of jumping from an orbit around one jovian moon to an orbit around another.[8, 9, 4] This would allow long duration observations of each moon, compared to brief flybys. The Multi-Moon Orbiter (MMO) embodies a radical departure from the past four decades of planetary exploration. Such a capability will allow close, detailed, and long-lerm studies to be made of many of the members of Jupiter's retinue of 40 (or more) moons. Furthermore, the ΔV requirements for such a mission can be very low if the technique of *low energy inter-moon transfer via resonant gravity assists* by jovian moons are used.

As an example, by using small impulsive thrusts totaling only 22 m/s, a spacecraft initially injected in a jovian orbit can be directed into an elliptical capture orbit around Europa. Enroute, the spacecraft orbits both Callisto and Ganymede for long duration using a ballistic capture and escape methodology developed previously. This example tour is shown in Figure 1. The MMO, constructed using a *patched three-body approach*, should work well with existing techniques, enhancing NASA's trajectory design capabilities.

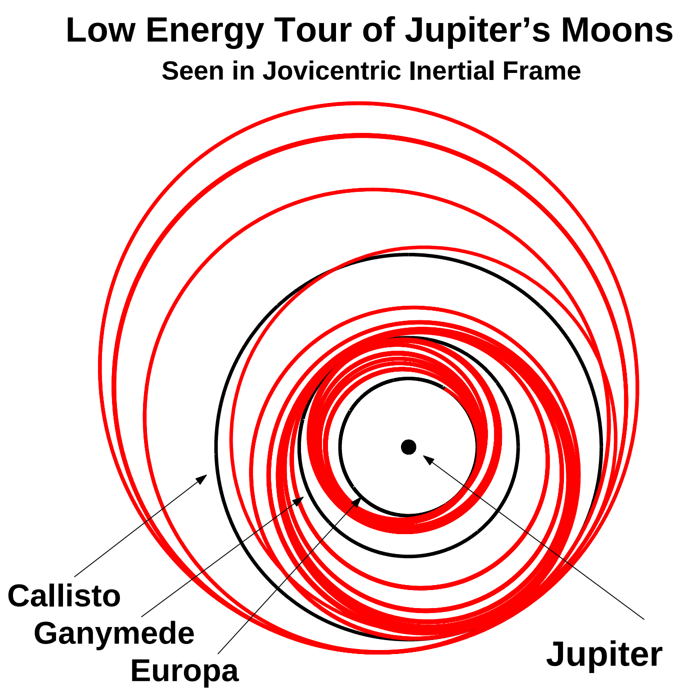


Figure 1: **The Multi-Moon Orbiter space mission concept for the jovian moons** involves long duration orbits of Callisto, Ganymede, and Europa, allowing for extensive observation. By utilizing resonant gravity assists with the moons, in addition to ballistic capture and escape orbits leading toward or away from temporary capture orbits about a moon, a tour can be constructed using very little fuel. The trajectory shown is a simulation of a restricted 5-body problem and requires a ΔV of only 22 m/s. The Multi-Moon Orbiter is a general concept applicable for any multi-moon system and is not limited to the specific example shown.

Europa and Beyond

The MMO concept meets the requirement laid down by the NAS of extended observation while staying within a reasonable ΔV budget. Furthermore, the techniques used to design a MMO are very general. The same techniques may be applied to a broad rnage of multi-body missions from the Earth's Neighborhood to other regions of the solar system.

An Extension of the Petit Grand Tour

A tour of the moons of Jupiter of this type was introduced by Koon, Lo, Marsden, and Ross,[8] and further elaborated upon by Gómez, Koon, Lo, Marsden, Masdemont, and Ross.[4] The MMO tour, previously dubbed the *Petit Grand Tour*, grew out of a method introduced in the foregoing papers; navigation via phase space *tubes of ballistic capture (and escape) trajectories* going toward (or away) from each moon, respectively. An algorithm was designed for constructing orbits with any prescribed tour itinerary. Some initial results on a basic itinerary are illustrated in Figure 2.[4]

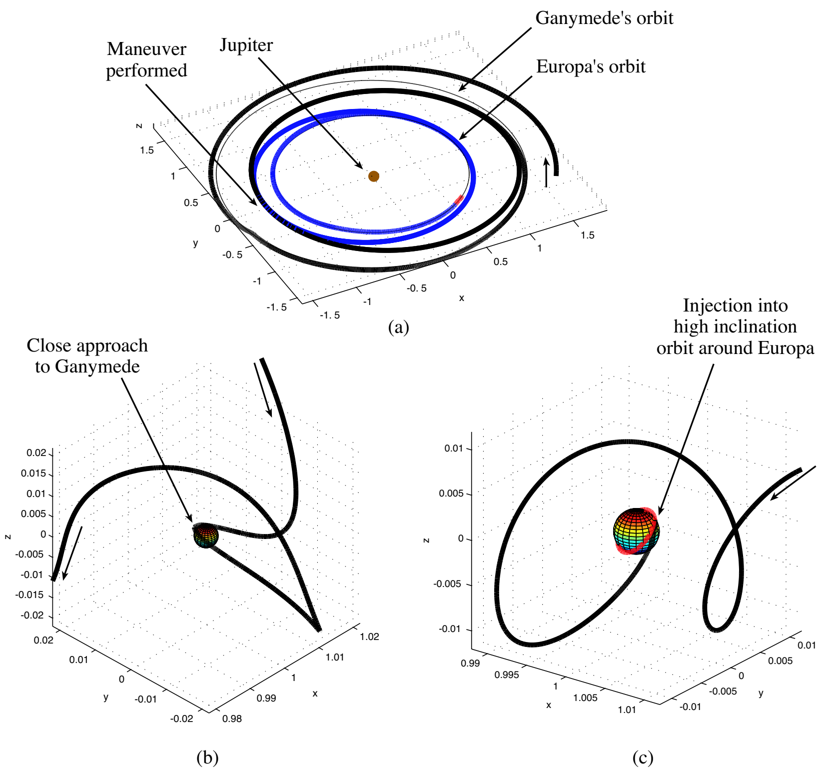


Figure 2: **The Petit Grand Tour of jovian moons, a precursor to the Multi-Moon Orbiter.**[4] (a) We show a spacecraft trajectory coming into the Jupiter system and transferring from Ganymede to Europa using a single impulsive maneuver, shown in a Jupiter-centered inertial frame. (b) The spacecraft performs one loop around Ganymede, using no propulsion at all, as shown here in the Jupiter-Ganymede rotating frame. (c) The spacecraft arrives in Europa's vicinity at the end of its journey and performs a final propulsion maneuver to get into a high inclination circular orbit around Europa, as shown here in the Jupiter-Europa rotating frame.

By approximating the dynamics of the Jupiter-Europa-Ganymede-spacecraft 4-body problem as two 3-body subproblems, we seek intersections between the channels of transit orbits enclosed by the stable and unstable manifold tubes of different moons. In the example shown in Figure 2, we show a low energy transfer trajectory from Ganymede to Europa that ends in a high inclination orbit around Europa.

In this paper, the previous method is extended significantly, introducing the use of *resonant gravity assists*. This method was inspired by the work of Sweetser and others at JPL who designed the first nominal trajectory for a Europa orbiter mission.[20, 12] By performing small maneuvers to achieve a particular moon/spacecraft geometry at close approach, the spacecraft can jump between mean motion resonances with the moon. The "jumping" provides an effective ΔV kick, and thereby the deterministic propulsive ΔV required for the MMO trajectory is very low.

TRAJECTORY CONSTRUCTION: THE BUILDING BLOCKS

The objective of the multi-moon tour design is to find a numerically integrated and continuous trajectory that starts in an initial jovian orbit and proceeds to get into orbits about Callisto, Ganymede, and Europa, successively. We assume that after a Jupiter orbit insertion maneuver, it is feasible to get into a jovian orbit with a period of several months and a perijove near the orbit of Callisto.[a] For our initial study, we assume our control is an impulsive propulsion system. For follow-on studies, we will incorporate low thrust propulsion. For the impulsive thrust case, *our main goal is to find a fuel efficient trajectory, i.e., one which minimizes the total deterministic* ΔV. Another constraint is a reasonable time of flight. We will leave discussion of this final constraint to the end.

The point of view adopted in this study is to initially approximate the n-body tour design problem as a series of 3-body problem solutions which will be patched together. The building blocks of the MMO tour are then (1) inter-moon transfers using resonant gravity assists with the various Galilean moons,[b] (2) ballistic capture and escape trajectories, and (3) small impulsive maneuvers to gently steer the space vehicle between these two types of trajectories.

By the term "ballistic capture and escape trajectories," we mean trajectory arcs in which the spacecraft, beginning on a jovian orbit, is captured, without using fuel, around a moon. The spacecraft orbits around the moon for several revolutions and then escapes from the moon, without using fuel, onto a jovian orbit once again. The number of revolutions around the moon can be controlled using very low ΔV controls. For the final ballistic capture into an operational orbit around Europa, we perform a Europa orbit insertion maneuver so that the spacecraft does not escape.

In the paragraphs that follow, the building blocks are presented within the framework of the patched three-body model, to be described shortly. In a subsequent section, we present a numerical example constructed using these building blocks.

---

[a]We assume this can be achieved via patched-conic methods.

[b]The Galilean moons, so named because of their discovery by Galileo Galilei in 1610, are Io, Europa, Ganymede, and Callisto, in the order of distance from Jupiter.

Patched Three-Body Model

Our goal is to construct a solution of a 5-body problem, i.e., a spacecraft moving in the gravitational field of Jupiter with three moons: Europa, Ganymede, and Callisto. We begin by approximating the real system as a restricted 5-body problem (R5BP), wherein the three moons of interest are in prescribed circular orbits about Jupiter within the same plane and do not gravitationally influence one another or Jupiter.[c]

The fifth body, the spacecraft, is assumed to be of negligible mass and moving under the influence of the four massive bodies, and we restrict its motion to be in the approximately common orbital plane of the three moons. In order to begin construction of a R5BP solution, we decompose the problem into several restricted 3-body problems. In particular, we use the patched planar circular restricted 3-body problem (PCR3BP), which has been shown to be an excellent starting model for illuminating the transfer dynamics between two co-orbiting moons.[8, 9, 4]

Within each restricted 3-body problem, we use phase space structures understood from earlier studies to find unpropelled trajectories with the desired characteristics. We then "patch" two 3-body solutions (i.e., Jupiter-S/C-Europa and Jupiter-S/C-Ganymede) by picking the phase of the two moons appropriately.[8]

Inter-Moon Transfer: Decreasing Jovian Orbit Energy Via Resonant Gravity Assists

As shown in Figure 1, we consider that the spacecraft begins its tour of the jovian moons in an elliptical orbit which grazes Callisto's orbit at perijove, with an apojove of several tens of R_J.[d] For this construction, it is important that the initial orbit have a perijove near the orbit of Callisto. Repeated flybys of Callisto when the spacecraft is at perijove (i.e., resonant gravity assists) are what decreases the jovicentric orbital energy and the apojove for this portion of the tour.

The several Callisto flybys which constitute this portion of the tour exhibit roughly the same spacecraft/Callisto geometry because the spacecraft orbit is in near-resonance with Callisto's orbital period and therefore must encounter Callisto at about the same point in its orbit each time. This portion of the trajectory is expected to take several months and culminates in a ballistic capture of the spacecraft by Callisto. The spacecraft then transfers between Callisto and Ganymede, orbits Ganymede for a time, and then transfers from Ganymede to Europa and finally orbits Europa.

During the inter-moon transfer–where one wants to leave a moon and transfer to another–the control problem becomes one of performing appropriate small ΔV's to decrease the jovicentric orbit energy by jumping between orbital resonances with a moon, i.e., performing resonant gravity assists. This is illustrated in the schematic spacecraft trajectory shown in Figure 3.

After the spacecraft escapes from the vicinity of the outer moon, the outer moon's perturbation is only significant over a small portion of the spacecraft trajectory near apojove (A). The effect of the moon is to impart an impulse to the spacecraft, equivalent to a

[c] The orbital planes of Europa, Ganymede and Callisto are within 0.3° of each other, being 0.467°, 0.172°, and 0.306° with respect to the local Laplace plane, respectively. Their orbital eccentricities are also very small, being 0.0002, 0.0011, and 0.0074, respectively.

[d] The initial apojove distance will be determined by the arrival trajectory coming from the Earth.

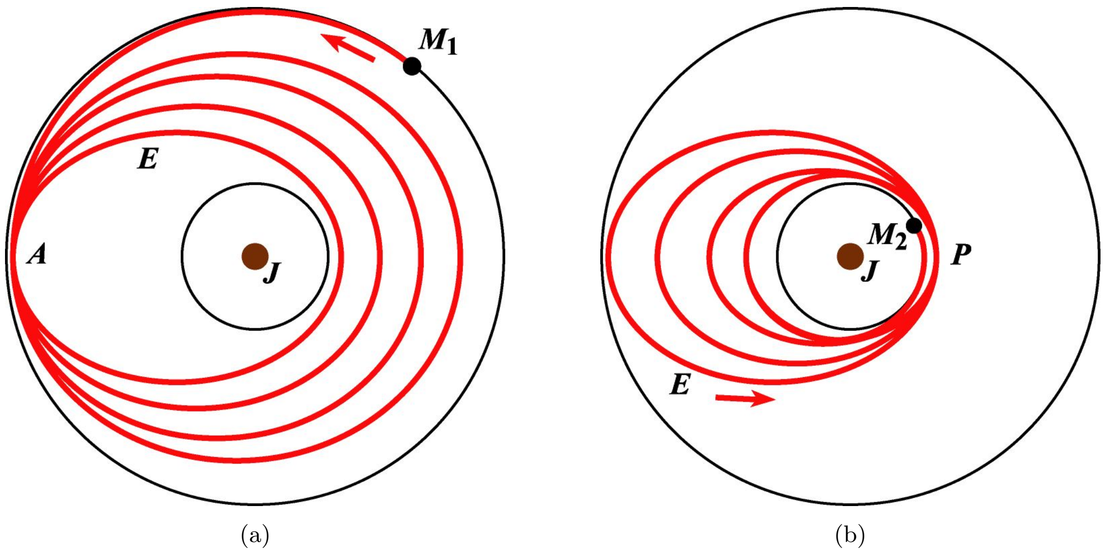


Figure 3: **Inter-moon transfer via resonant gravity assists.** (a) The orbits of two Jovian moons are shown as circles. Upon exiting the outer moon's sphere-of-influence at M_1, the spacecraft proceeds under third body effects onto an elliptical orbit. The spacecraft gets a gravity assist from the outer moon when it passes through apojove (denoted A). The several flybys exhibit roughly the same spacecraft/moon geometry because the spacecraft orbit is in near-resonance with the moon's orbital period and therefore must encounter the moon at about the same point in its orbit each time. Once the spacecraft orbit comes close to grazing the orbit of the inner moon, the inner moon takes "control." The spacecraft orbit where this occurs is denoted E. (b) The spacecraft now receives gravity assists from the inner moon at perijove (P), where the near-resonance condition also applies. The spacecraft is then ballistically captured by the inner moon at M_2.

ΔV in the absence of the moon. The strategy to achieve consecutive gravity assists is to maneuver the spacecraft to pass through apojove a little *behind* the moon. As illustrated in Figure 3(a), the result is a *decrease in the perijove* of the spacecraft's orbit, while the apojove remains (mostly) constant in inertial space due to the conservation of the Jacobi constant. As long as the spacecraft's trajectory repeatedly targets apojove a little behind the moon—the *near-resonance condition* which can be achieved through small on-board impulsive thrusts, to be discussed soon—it will decrease its perijove once more, and so on.

Once the spacecraft orbit comes close to grazing the orbit of the inner moon, the inner moon takes "control" (has the dominant effect) and the outer moon no longer has much effect. The spacecraft orbit where this occurs is denoted E. The spacecraft now gets gravity assists from the inner moon at perijove (P). Once again, we use small maneuvers to maintain the near-resonance condition, i.e., pass through perijove a little *ahead* of the moon. This causes the *apojove to decrease* at every close encounter with the inner moon, causing the spacecraft's orbit to get more and more circular, as in Figure 3(b). When a particular resonance is reached, the spacecraft can then be ballistically captured by the inner moon at M_2.[9] We note that a similar phenomenon has been observed in previous studies of Earth to lunar transfer trajectories.[17, 18]

Small Impulsive Maneuvers

Using several small impulsive maneuvers, each less than or equal to some threshold,[e] we desire to steer the spacecraft trajectory from the initial jovicentric orbit beyond Callisto to a capture orbit around Europa. To simplify the numerical procedure for this study, we perform these maneuvers when the spacecraft and the dominant moon are in opposition when viewed from Jupiter, as in Figure 4. In this figure, showing the motion of the spacecraft in the *rotating frame*, one can imagine that we are viewing the motion of the spacecraft

[e]We have chosen 2 m/s, an arbitrary figure. For an actual mission, the lower and upper bounds on this figure would be set by the capabilities of the engine used.

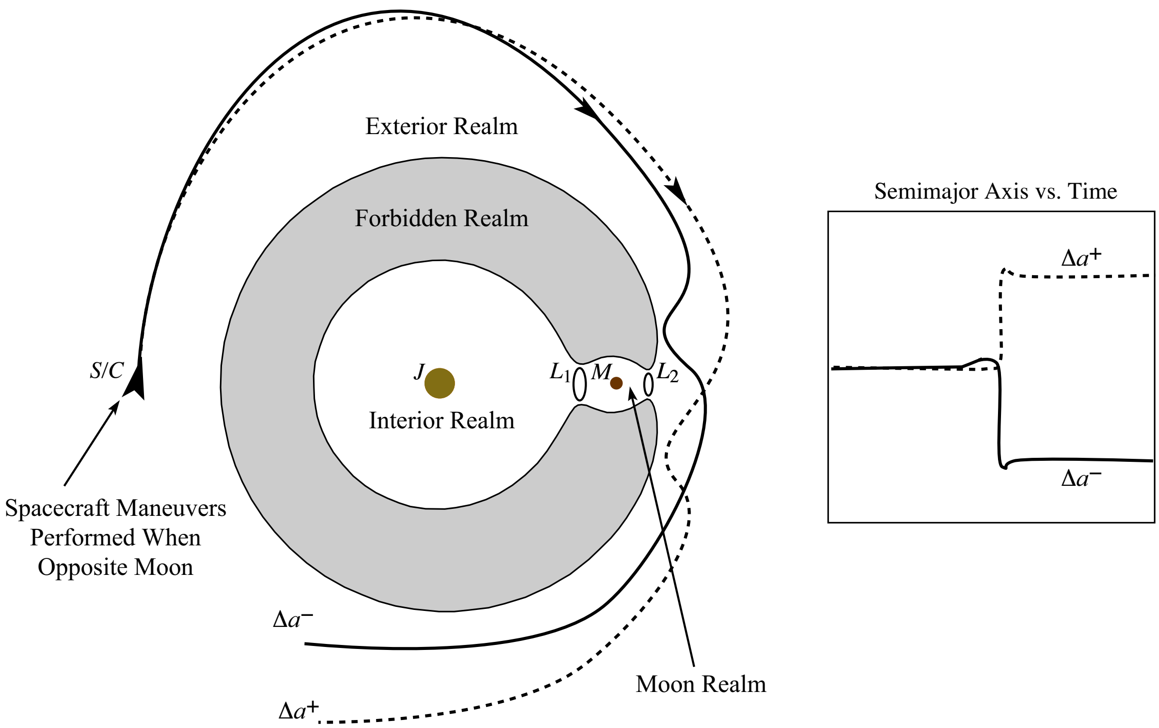


Figure 4: **Small impulsive maneuvers are performed** when the spacecraft (S/C) and a moon (M) are in opposition when viewed from Jupiter (J). We schematically show example effects of small ΔV's performed at this location in the rotating frame. The uncontrolled dashed trajectory reaches perijove just behind the moon, and thus increases in semimajor axis as shown in the time history. But by performing a small ΔV, the spacecraft can travel along the solid trajectory, reach perijove just ahead of the moon, and subsequently decrease in semimajor axis. Also shown here are the three realms through which the spacecraft can move as viewed in a rotating frame: an exterior realm external to the moon's orbit, a moon realm, and an interior realm around Jupiter and interior to the moon's orbit. For a range of values of the Jacobi constant, there are bottlenecks around L_1 and L_2, through which orbits passing between realms must pass. There are special periodic orbits inside the bottlenecks which generate the tubes of transit orbits between realms, as shown in Figure 5. Not all trajectories, such as the ones shown here, enter the moon realm upon closely approaching the bottlenecks. Only those trajectories inside a phase space tube of capture orbits can get captured, as described in the text.

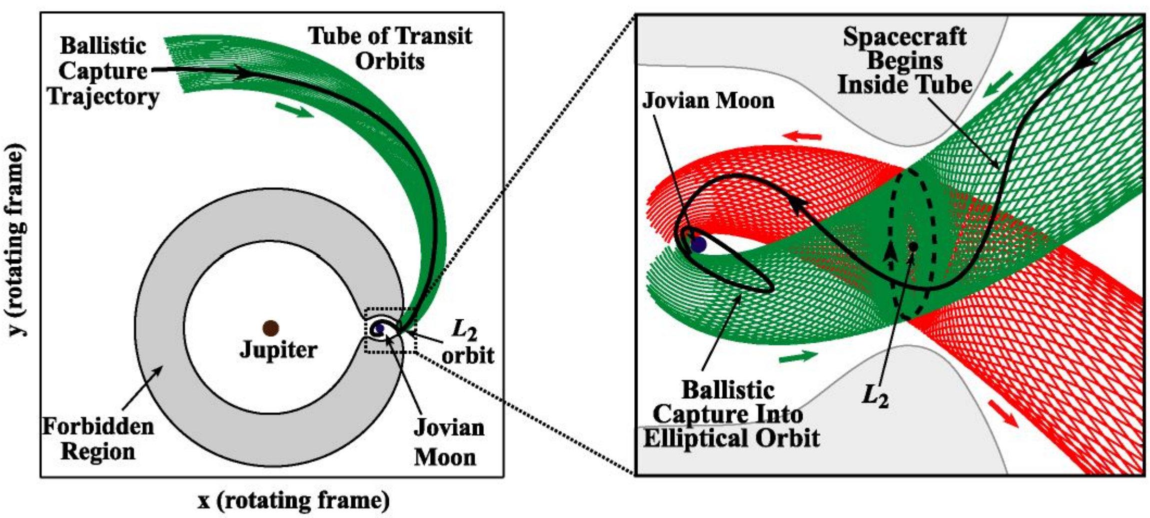
from a camera which is above the orbital plane of the moon and co-orbiting with it in a counter-clockwise direction, such that the moon appears stationary. The familiar elliptical orbits of the inertial frame are replaced by winding curves in the rotating frame due to the Coriolis effect. Although at first unfamiliar, using the rotating frame simplifies the calculation.

The problem of decreasing the semimajor axis of the jovicentric orbit becomes one of performing appropriate small ΔV's at opposition such that the geometry of the subsequent encounter with the moon lowers the jovian energy of the spacecraft. For example, consider the dashed trajectory in Figure 4. Let us presume this is the uncontrolled trajectory, and under the natural dynamics reaches perijove just behind the moon. The result will be an increases in semimajor axis as shown in the time history. The solid trajectory, on the other hand, was altered by performing a small ΔV at opposition. It reaches perijove just ahead of the moon, and subsequently decrease in semimajor axis. By repeating this procedure, one can construct the types of orbits shown schematically in inertial space in Figure 3.

Orbiting Each Moon: Ballistic Capture and Escape

To effect a *ballistic capture* of the spacecraft by a jovian moon, one finds the tube of transit orbits which are heading toward that moon (the procedure is described in Refs. [9] and [11]). The tube exists in the phase space (positions *and* velocities), but when projected down to just position, as in Figure 5(a), it appears as a winding strip of variable width.

From the set of trajectories inside this tube, all of which will be ballistically captured by the moon, one picks the trajectory with the most desirable properties. Most trajectories come in from the exterior realm, experience a close approach of the moon, and will be on



(a) (b)

Figure 5: **Construction of a spacecraft trajectory captured by a jovian moon.** (a) The tube going to the region around the moon from outside the moon's orbit is shown schematically. (b) A close-up near the moon shows the complex of tubes going toward or away from the moon's L_2 neighborhood.

an elliptical orbit around the moon if no maneuver is performed. The orbit may linger over particular regions of the moon which are desirable to study for a scientific mission. Subsequent *escape* from the moon either toward the interior or exterior realm is easily achieved using a very small ΔV, and is simply the time-reversed process of ballistic capture. For the mission we have in mind, the spacecraft will proceed from the exterior realm to the moon realm to the interior realm, and thence onto the next moon.

Ballistic capture and escape trajectories are linked to particular resonances.[9, 10] After reaching the appropriate resonance, a small maneuver is performed at opposition prior to the next encounter (as in Figure 4) to provide the appropriate conditions for the ballistic capture into an elliptical orbit about the moon. The capture orbit achieved this way is unstable, in the sense that it may collide with the surface of the moon or naturally escape after some time, both of these fates being due to third body effects of Jupiter. Three approaches can be considered to resolve this: (1) an energy reducing maneuver can be performed at the closest approach to the moon to place the spacecraft in a stable orbit about the moon, (2) a maneuver can be performed to place the spacecraft on a stable precessing ellipse around the moon,[1, 17] or (2) small station-keeping maneuvers can be performed periodically to keep the spacecraft's periapse from going below the moon's surface. Options (2) and (3) may be the more fuel efficient, but this needs to be studied.[15] Furthermore, option (3) may require sophisticated on-board autonomous navigation and control.

We remark that unstable orbits have been used for operations in previous missions, for instance the *Genesis Discovery Mission*.[6, 22] Using appropriate station-keeping maneuvers, the instability of such orbits need not be detrimental to a mission. Quite the contrary. "Unstable" orbits are easy to escape from, but are also easy to enter. This lies at the heart of the fuel efficiency of missions such as the MMO and *Genesis*, which theoretically required no deterministic maneuvers, 0 m/s, in the optimal case.[19]

Supposing one chose option (1), one picks the trajectory from the incoming tube in Figure 5 which has a close approach to the moon equal to the orbital distance of the desired operational orbit. A close up near L_2 is shown in Figure 5(b), where the black spacecraft trajectory, after a close approach of the moon, will be on an elliptical orbit around the moon if no maneuver is performed. For the trajectory shown in Figure 1, one can, for example, perform a 450 m/s maneuver at a 100 km altitude close approach to Europa to put the spacecraft on a stable circular 100 km altitude orbit around Europa, as is shown in a close-up around Europa in Figure 2(c).

TRAJECTORY CONSTRUCTION: NUMERICAL RESULTS

The preliminary tour trajectory, generated using the above building blocks, is shown in Figure 1. The entire trajectory is shown with time histories of semimajor axis and jovicentric distance in Figure 6. Assuming that the spacercaft enters the jovian system in an elliptical jovian orbit which grazes Callisto's orbit at perijove, the spacecraft has its jovicentric semimajor axis decreased by resonant gravity assists with the moons in sequence. First the spacecraft trajectory gets its energy reduced by Callisto, then temporarily orbits Callisto (closest approach $\sim$1400 km altitude) before escaping inward of Callisto's orbit, getting its energy further reduced by Callisto. The spacecraft then changes control naturally from Callisto to Ganymede and gets its energy reduced by Ganymede. After temporarily orbiting Ganymede (closest approach $\sim$2100 km altitude), and passing to the control of Europa, the

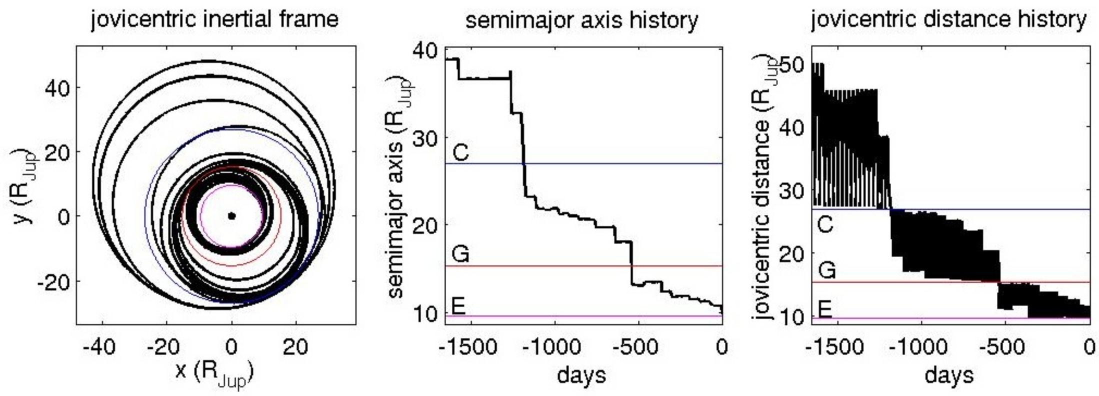
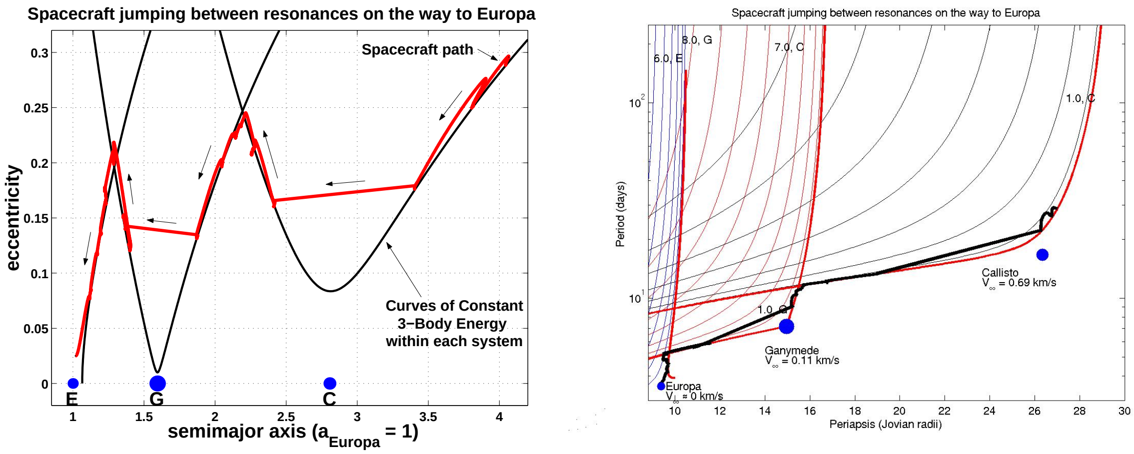


Figure 6: Starting in an elliptical jovian orbit with perijove near Callisto's orbit, the spacecraft trajectory gets successively reduced in jovicentric energy by resonant gravity assists with the various moons, effectively jumping to lower resonances at each close approach. The trajectory has its jovicentric energy reduced by Callisto, Ganymede, and Europa. As the orbit converges upon the orbit of Europa, it will get ballistically captured by Europa. At that point, a ΔV of approximately 450 m/s is needed to get into a 100 km altitude orbit about Europa.

final stage of the trajectory begins. The spacecraft has its jovicentric energy further reduced until it gets ballistically captured by Europa. At that point, a ΔV of approximately 450 m/s is needed to get into a 100 km altitude orbit about Europa.

One can gain a better physical understanding of what is going on by considering the following. The spacecraft trajectory can be shown in eccentricity (e) vs. semimajor axis (a), as in Figure 7(a) along with lines of constant Jacobi constant (approximated as the Tisserand parameter[9]). The spacecraft begins the jovian tour at the top right corner of Figure 7(a). As it has its a reduced via resonant gravity assists, it will also have its e decreased (since it is in the exterior realm and the Tisserand parameter must remain roughly constant). As the orbit gets more and more circular, converging upon the orbit of Callisto, it will at some point get ballistically captured by Callisto, and orbit Callisto for a time. Small ΔV's can be used to steer the spacecraft such that it escapes Callisto and goes into a jovicentric orbit inside the orbit of Callisto. Like the schematic trajectory shown in Figure 3(a), the spacecraft will continue to decrease in a, but now e will climb (since it's in the interior realm).

When the spacecraft reaches the orbit labeled E in Figure 3, the spacecraft will switch control to Ganymede. Physically, switching control occurs when the spacecraft's jovicentric periapse comes close to the orbit of Ganymede. The right side of the V shaped curve above Ganymede (G) in Figure 7(a) is approximately the line of all orbits whcih graze the orbit of Ganymede. This is a property of Tisserand parameters (and Jacobi constants) with values close to those of L_1 and L_2, like the values we have used for this numerical example. We note that one can also plot the spacecraft trajectory in jovicentric orbital period (P) vs. periapse (r_p), shown in Figure 7(b). This follows the convention of Heaton, Strange, Longuski, and Bonfiglio.[5] Contours of the Tisserand parameter are here shown as contours of hyperbolic excess velocity (V_∞) with respect to the moon to which they correspond.



(a) (b)

Figure 7: (a) The same trajectory as shown in Figures 1 and 6 is shown here, now plotting eccentricity (e) vs. jovicentric semimajor axis (a). The trajectory is the thick line, and jumps along curves of constant three-body energy (or the Jacobi constant, also approximated as the Tisserand parameter), depending on which moon has the dominant third body effect on the spacecraft. (b) One can also plot the trajectory in jovicentric orbital period (P) vs. perijove (r_p), following the convention of Heaton, Strange, Longuski, and Bonfiglio.[5] Note that now contours of the Jacobi constant are labeled with the V_∞ (in km/s) and the moon to which they correspond. The actual V_∞ of the spacecraft trajectory at each moon is also shown.

Trade-Off Between Fuel and Time Optimization

A few small ΔV's adding up to 22 m/s are used throughout the tour. The dramatically low ΔV is achieved at the expense of time—the present trajectory has a time of flight (TOF) of about four years, mostly spent in the inter-moon transfer phase. This is likely too long to be acceptable for an actual mission. With refinement, we believe the method could be applied to an actual mission, maintaining both a low ΔV for the tour and low accumulated radiation dose (a concern for an actual mission in the jovian system).[f]

We conjecture that for slightly larger ΔV, a reasonable time of flight of several months can be achieved. This conjecture is based upon evidence in a similar astrodynamics problem using the planar, circular, restricted three-body problem as the model; a time and fuel optimized trajectory from an Earth orbit to a lunar orbit. Bollt and Meiss[1] considered the transfer from a circular Earth orbit of radius 59669 km to a quasi-periodically precessing ellipse around the moon, with a perilune of 13970 km. Their method takes advantage of the fact that long trajectories in a compact phase space are recurrent. Starting with a long unperturbed chaotic trajectory that eventually reaches the target, the use small well chosen ΔV's to cur recurrent loops from the trajectory, shortening it whenever possible. They find a transfer (see Figure 8(a)) that achieves ballistic capture requiring 749.6 m/s, 38% less total velocity boost than a comparable Hohmann transfer, but requiring a transfer time of 748 days. Later, Schroer and Ott[17] considered this problem with the same initial and

[f]The current trajectory spends about 260 days inside of 12 R_J (never lower than 10 R_J) before Europa orbit insertion.

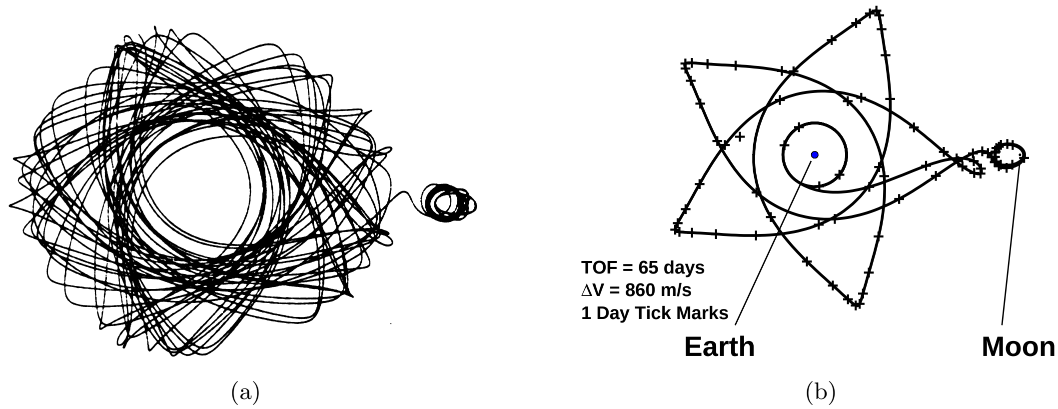


Figure 8: **Much lower time-of-flight achieved using only slightly more fuel.** (a) The transfer from a circular earth orbit of radius 59669 km to precessing lunar orbit of perilune 13970 km found by Bollt and Meiss[1] is shown in the rotating frame. The ΔV is 749.6 m/s and the time of flight is 748 days. (b) A transfer between the same initial and final orbits, using a ΔV of 860.1 m/s, but requiring a flight time of 65 days.

final orbits, but found a transfer requiring about half the flight time, 377.5 days, but using roughly the same total ΔV, 748.9 m/s, suggesting that this is near the minimum required for a transfer between these two orbits.

In the present work, we seek transfer trajectories that provide a compromise between time and fuel optimization. Using the method of Schroer and Ott[17], together with methods for achieving ballistic capture [9, 10], we find a transfer, shown in Figure 8(b), with a flight time of 65 days which uses a total ΔV of 860.1 m/s. Thus the trajectory takeis one-tenth of the time as the Bollt and Meiss[1] trajectory using only about 100 m/s more fuel. The previously described trajectories are shown in Figure 9 compared with other trajectories produced using this method.

The method of determining the ΔV vs. TOF trade-off has been applied to only one three-body system thus far.[15] In the future, we would like to adapt the method to missions combining several restricted three-body systems, such as the MMO, in order to seek more reasonable flight times. As has been proposed, the time of flight may be drastically reduced by using only slightly more fuel during the inter-moon transfer phases.

FUTURE WORK

In addition to exploring the important compromise between time and fuel optimization, future studies will investigate the following.

- *The use of low-thrust continuous propulsion and optimal control:* The maturity of current ion engine technology has brought low thrust controls into the practical world of mission design in industry and in NASA (cf. the *Deep Space 1 mission*). Similar work is being done at the European Space Agency as well. Therefore, low thrust trajectory control is of great interest to current mission design. Our current work on the MMO considers several small impulsive burns. But an actual mission may

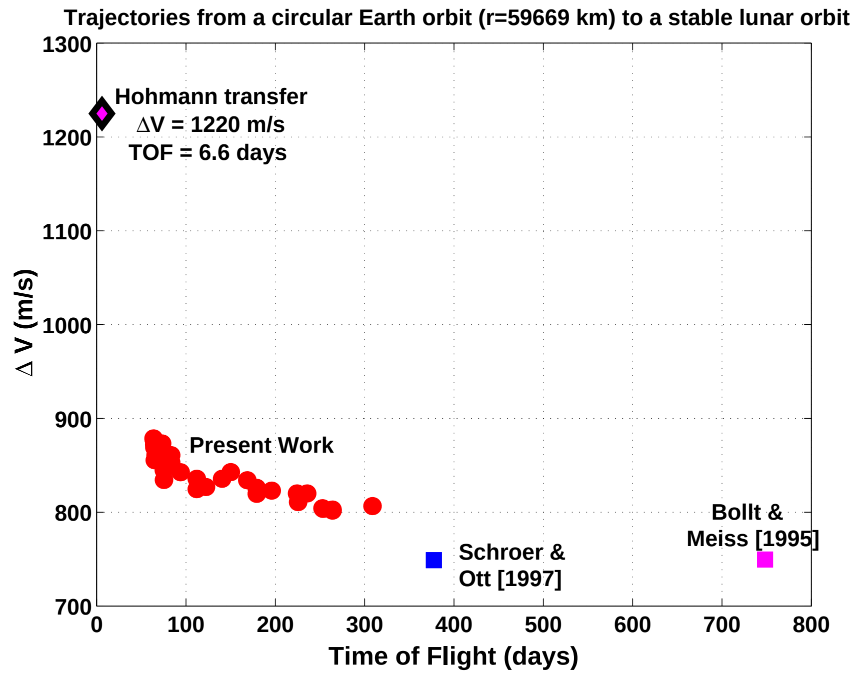


Figure 9: **Trade-off between fuel and time optimization.** The ΔV vs. time of flight plot for several transfer trajectories to the moon which use nonlinear third-body effects, compared with the Hohmann transfer. As can be seen, a trajectory of one-fifth to one-tenth of the flight-time of some previous fuel optimized trajectories can be achieved using only about 100 m/s more ΔV.

want to save on spacecraft weight by using low thrust propulsion. How could our method be modified to incorporate low-thrust? Theoretically, one of the most favored approaches is to use optimal control in generating low thrust trajectories. We have found that a good first guess is often vital for numerical optimization algorithms, especially for an n-body problem, which is numerically very sensitive. Dynamical systems theory can provide geometrical insight into the structure of the problem and even good approximate solutions, as we found in an earlier paper.[19] There is evidence that optimal trajectories using multiple low thrust burns are "geometrically similar" to impulsive solutions.[18, 23] Thus, multiple burn impulsive trajectories that we construct for the MMO can be good first guesses for an optimization scheme which uses low thrust propulsion to produce a fuel efficient mission.

- *Radiation effects:* The current model does not include radiation effects. Evidence suggests it is desirable to keep the spacecraft outside of a 12 R_J from Jupiter, in which the radiation may destroy sensitive electronics on board the spacecraft. The orbit of Europa is located at 10 R_J, so the transfer between Ganymede and Europa must minimize the time spent near its perijove for the final resonant gravity assists that lead to a capture by Europa.[g] One needs to determine what is the best way to minimize radiation effects and still achieve a very low thrust transfer. On the

[g]The perijove for this portion of the tour is just outside the radial distance of Europa's L_2 point, which is located slightly within 12 R_J.

other hand, the strong magnetic field of Jupiter may make the use of tethers a viable propulsion or power generation option.

- *More control over operational orbits for scientific observation:* For a mission to Europa and the other moons, some control strategy is necessary to maximize desirable scientific observation and avoid collisions with the moon surface or escape from the moon's vicinity. Exotic strategies might be considered. For instance, what is the optimal thrusting strategy during the ballistic capture approach in order to achieve an operational orbit which maximizes observation time over an interesting portion of a moon's surface? Also, what is the optimal station-keeping strategy for elliptical operational orbits? In the short term, it may be desirable to target particular stable operational orbits, but still save fuel using third body effects.[4, 16]

- *Autonomous on-board navigation and control:* A trajectory of this type, which is sensitive to ΔV errors and modeling errors, will need to have the capability of autonomous on-board navigation and control. The first step toward this which one can look at is the trajectory correction maneuver problem, in which errors are modeled and a control algorithm corrects for those errors.[19]

ACKNOWLEDGEMENTS

This work was carried out in part at the Jet Propulsion Laboratory and California Institute of Technology under a contract with the National Aeronautics and Space Administration.

REFERENCES

[1] Bollt, E.M. and J.D. Meiss [1995], Targeting chaotic orbits to the Moon through recurrence. *Physics Letters A* **204**, 373–378.

[2] Burris, J. and C. Arberg [2002], "Missions to Kuiper Belt Now, Europa Within the Decade Are Key to Space Discoveries," National Academy of Sciences press release, July 11, 2002. (http://www4.nas.edu/news.nsf/isbn/0309084954?OpenDocument)

[3] Cowing, K. [2003], "NASA Set to Unveil 'Jupiter Tour' Mission," January 29, 2003. (http://www.spaceref.com/news/viewnews.html?id=714)

[4] Gómez, G., W.S. Koon, M.W. Lo, J.E. Marsden, J. Masdemont, and S.D. Ross [2001], Invariant manifolds, the spatial three-body problem and space mission design, *Paper No. AAS 01-301*, presented at *AAS/AIAA Astrodynamics Specialist Conference, Quebec City, Canada, Aug. 2001.*

[5] Heaton, A.F., N.J. Strange, J.M. Longuski, and E.P. Bonfiglio [2002], Automated Design of the Europa Orbiter Tour, *Journal of Spacecraft and Rockets* **39**(1), 17–22.

[6] Howell, C., B. Barden and M. Lo [1997], Application of dynamical systems theory to trajectory design for a libration point mission. *The Journal of the Astronautical Sciences* **45**(2), 161–178.

[7] Karl, D.M., D.F. Bird, K. Bjorkman, T. Houlihan, R. Shackelford, and L. Tupas [1999], Microorganisms in the Accreted Ice of Lake Vostok, Antarctica. *Science* **286**, 2144–2147.

[8] Koon, W.S., M.W. Lo, J.E. Marsden and S.D. Ross [1999], Constructing a Low Energy Transfer between Jovian Moons, presented at *Celestial Mechanics : an international conference on celestial mechanics,* Evanston, IL, Dec. 1999. Published in *Contemporary Mathematics* **292** [2002], 129–145.

[9] Koon, W.S., M.W. Lo, J.E. Marsden, and S.D. Ross [2000] Heteroclinic Connections between Periodic Orbits and Resonance Transitions in Celestial Mechanics, *Chaos* **10**(2), 427–469.

[10] Koon, W.S., M.W. Lo, J.E. Marsden, and S.D. Ross [2001], Resonance and capture of Jupiter comets. *Celest. Mech. Dyn. Astron.* **81**(1-2), 27–38.

[11] Koon, W.S., M.W. Lo, J.E. Marsden, and S.D. Ross [2001a], Low energy transfer to the Moon, *Celest. Mech. Dyn. Astron.* **81**(1-2), 63–73.

[12] Ludwinski, J., M. Guman, J. Johannesen, R. Mitchell and R. Staehle [1998], The Europa Orbiter Mission Design, *Paper No. 98-4.2.02*, presented at the *49th International Astronautic al Congress*, Melbourne, Australia, Sep. 28 - Oct. 2, 1998.

[13] McFarling, U.L. [2002] "Astronomers See Pluto, Jupiter as Top Missions," *Los Angeles Times*, July 12, 2002.

[14] Platt, J. [1998], "Jupiter's moon Callisto may hide salty ocean," NASA press release 98-192, October 21, 1998. (http://www.jpl.nasa.gov/releases/98/glcallistoocean.html)

[15] Ross, S.D. [2003], Trade-Off Between Fuel and Time Optimization, presented at *New Trends in Astrodynamics and Applications, College Park, MD, Jan. 2003.*

[16] Scheeres, D.J., M.D. Guman, and B. Villac [2001], Stability analysis of planetary satellite orbiters: Application to the Europa Orbiter. *J. of Guidance, Control, and Dynamics* **24**(4), 778–787.

[17] Schroer, C.G. and E. Ott [1997], Targeting in Hamiltonian systems that have mixed regular/chaotic phase spaces. *Chaos* **7**(4), 512–519.

[18] Schoenmaekers, J., D. Horas, and J.A. Pulido [2001] SMART-1: With Solar Electric Propulsion to the Moon, *16th International Symposium on Space Flight Dynamics, Pasadena, CA, Dec. 2001.*

[19] Serban, R., W.S. Koon, M.W. Lo, J.E. Marsden, L.R. Petzold, S.D. Ross and R.S. Wilson [2002], Halo orbit correction maneuvers using optimal control. *Automatica* **38**(4), 571–583.

[20] Sweetser, T., R. Maddock, J. Johannesen, J. Bell, P. Penzo, A. Wolf, S. Williams, S. Matousek, and S. Weinstein [1997] Trajectory Design for a Europa Orbiter Mission: A Plethora of Astrodynamic Challenges, *Paper No. AAS 97-174*, presented at *AAS/AIAA Space Flight Mechanics Meeting, Huntsville, AL, Feb. 1997.*

[21] Webster, G. [2000], "Solar system's largest moon likely has a hidden ocean," JPL press release, December 16, 2000. (http://www.jpl.nasa.gov/releases/2000/aguganymederoundup.html)

[22] Yamato, H., and D.B. Spencer [2002], Trajectory Design of Spacecraft Using Invariant Manifolds, *ISTS 2002-s-16*, presented at *International Symposium on Space Technology and Science, Matsue, Japan, May 2002.*

[23] Zondervan, K.P., L.J. Wood, and T.K. Caughy [1984], Optimal Low-Thrust, Three-Burn Transfers with Large Plane Changes. *The Journal of the Astronautical Sciences* **32**, 407–427.