AIAA 03-143

DESIGN OF A MULTI-MOON ORBITER

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

January 31, 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 recently issued a report calling on NASA to deploy a large mission every decade, one in which extended observation and experiments could be performed. 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. 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. A proposed mission to Europa, and perhaps also Ganymede and Callisto, would attempt to map these regions of liquid water for follow-on missions. A mission to tour the moons of Jupiter may be initiated in the near future.

Multi-Moon Orbiter. 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 jumps from an orbit around one jovian moon to an orbit around another. 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. The ΔV requirements for such a mission

[*]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

can be very low if the techniques of *low energy inter-moon transfer* and *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.

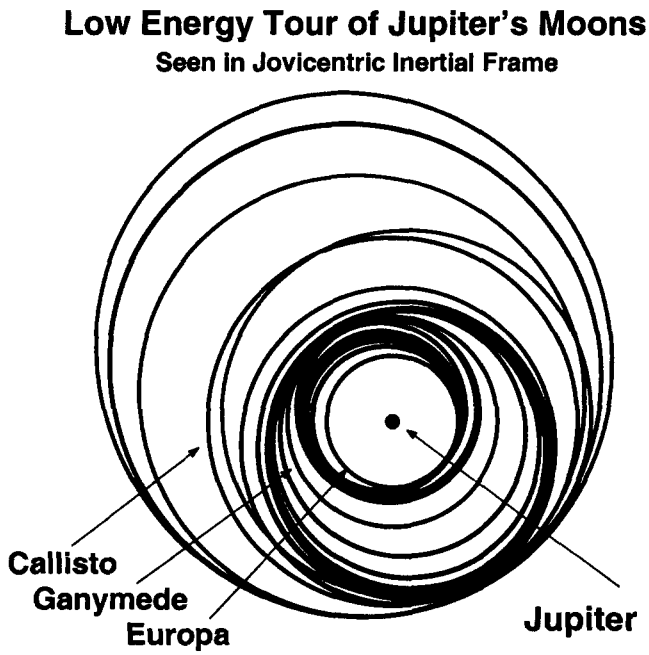


Figure 1: **The Multi-Moon Orbiter space mission concept for the jovian moons** involves long duration orbits of Callisto, Ganymede, and Europa, allowing for extensive observation. By utilizing resonant gravity assists with the moons, in addition to the tubes of orbits leading toward or away from temporary 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.

Mulit-Moon Orbiter: An Extended Petit Grand Tour. A tour of the moons of Jupiter of this type was introduced by Koon, Lo, Marsden, and Ross [1999], and further elaborated upon in Gómez, Koon, Lo, Marsden, Masdemont, and Ross [2001]. This trajectory concept,previously dubbed the *Petit Grand Tour*, grew out of a new method introduced in the foregoing papers; the use of *tubes of transit orbits* going toward or away from each moon. In this paper, we extend the

method significantly, introducing the use of *resonant gravity assists.* This method was inspired by the work of Sweetser and others who designed the first nominal trajectory for a Europa orbiter mission (see Sweetser *et al.* [1997]). By leap-frogging between the resonances of jovian moons, the ΔV required for the MMO can be significantly reduced.

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.[1] 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 i ΔV. Another constraint is a reasonable time of flight. We will leave discussion of this final constraint to the end.

The building blocks of such a trajectory are small impulsive burns, resonant gravity assists with the various Galilean moons,[2], and ballistic capture and escape trajectories. By "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. 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.

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.[3]

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 coupled planar circular restricted 3-body problem (PCR3BP) discussed in Koon, Lo, Marsden, and Ross [1999], which has been shown to be an excellent starting model for illuminating the transfer dynamics between two co-orbiting moons.

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-

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

[2]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.

[3]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.

body solutions (i.e., Jupiter-S/C-Europa and Jupiter-S/C-Ganymede) by picking the phase of the two moons appropriately.

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.[4] 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 (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 2.

After the spacecraft escapes from the outer moon, the outer moon's perturbation is only signifi-

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

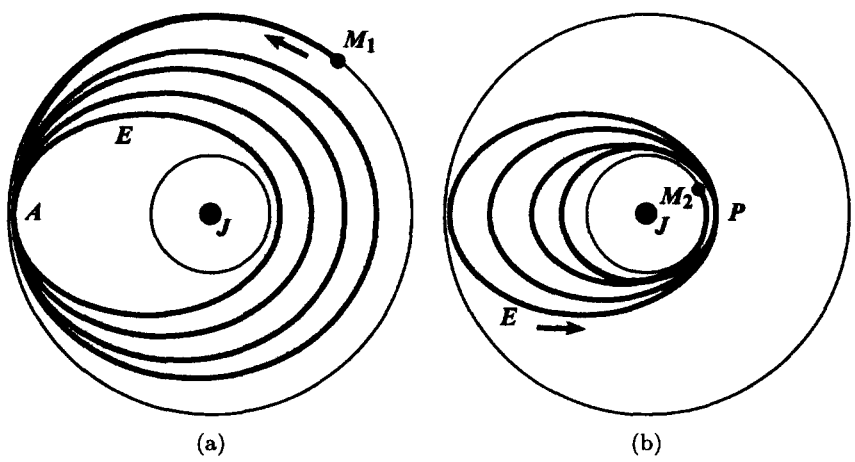


Figure 2: **Inter-moon transfer via resonant gravity assists.** (a) The orbits of two Jovian moons are shown as circles. Upon exiting the outer moon's sphere-of-influence at M_1, the spacecraft proceeds under three-body effects onto an elliptical orbit. The spacecraft gets a gravity assist from the outer 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.

cant 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 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. This is the near-resonance condition. As illustrated in Figure 2(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–which can be controlled through small on-board impulsive thrusts at perijove–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" 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). 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 2(b). When a particular resonance is reached, the spacecraft can then be ballistically captured by the inner moon at M_2. We note that a similar phenomenon has been observed in a study of low-thrust spacecraft trajectories to the Earth's Moon using lunar resonances (Schoenmaekers, Horas, and Pulido [2001]), and there is a theoretical foundation for its use in lunar missions (Schroer and Ott [1997]).

Small Impulsive Burns

Using several small impulsive burns, each less than or equal to some threshold[5], we desire to steer a ballistic trajectory which goes from the initial jovicentric orbit beyond Callisto to a capture orbit around Europa. To simplify the numerical procedure, we perform these burns when the spacecraft and a moon are in opposition when viewed from Jupiter, as in Figure 3. In this figure, we can

[5]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.

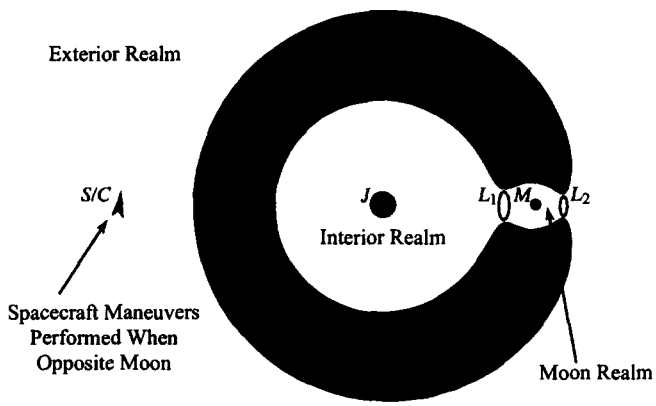


Figure 3: **Small impulsive maneuvers are performed** when the spacecraft (S/C) and a moon (M) are in opposition when viewed from Jupiter (J). Also shown here are the three realms through which the spacecraft can move as viewed in a rotating frame: an exterior realm external to the moon's orbit, a moon realm, and an interior realm around Jupiter and interior to the moon's orbit. Also shown are the 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.

imagine that we are viewing the motion of the spacecraft 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.

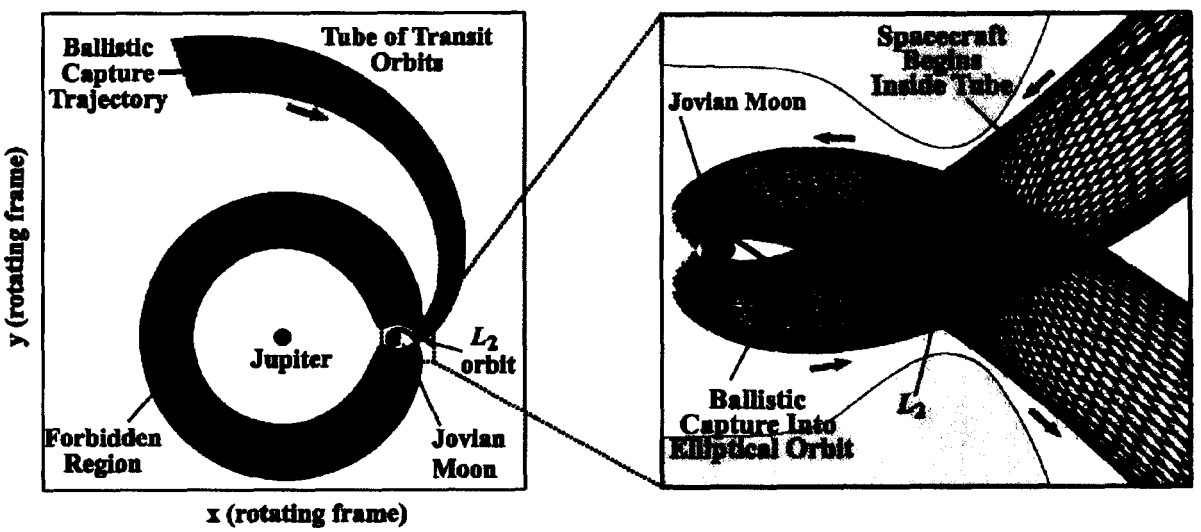
The problem of decreasing the semimajor axis of jovicentric orbit becomes one of performing appropriate small ΔV's at opposition such that the geometry of the subsequent encounter with the moon lowers the jovian energy of the spacecraft.

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 Koon, Lo, Marsden, and Ross [2000]). The tube exists in the phase space (positions *and* velocities), but when projected down to just position, as in Figure 4(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 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.1 After reaching the appropriate resonance, a small maneuver is performed at the apojove prior to the next encounter to



(a) (b)

Figure 4: **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.

provide the appropriate conditions for the ballistic capture into an elliptical orbit about the moon. The capture orbit achieved this way is unstable. Two 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, or (2) small station-keeping maneuvers can be performed periodically to keep the spacecraft's periapse from going below the moon's surface. Option (2) may be the more fuel efficient, but this needs to be studied.

We remark that unstable orbits have been used for operations in previous missions, for instance the *Genesis Discovery Mission.* 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 is the heart of the fuel-efficiency of the MMO.

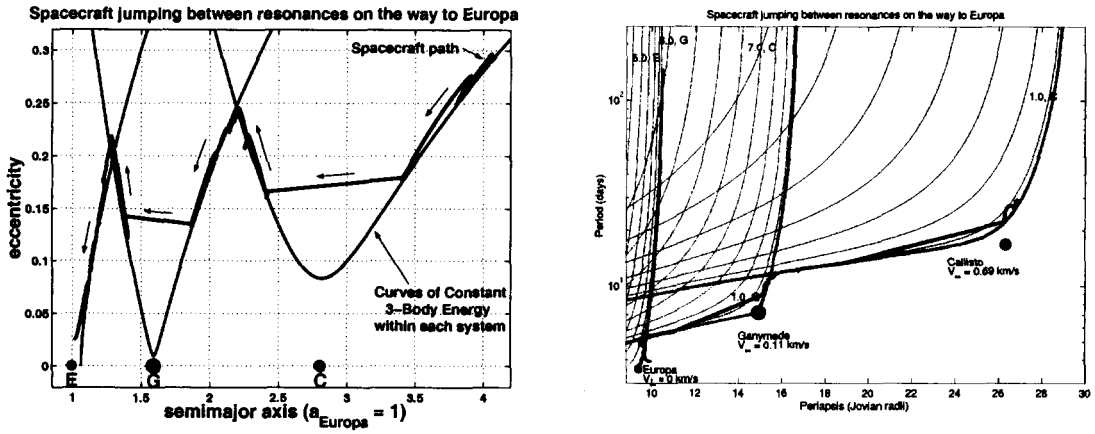
For option (1), one picks the trajectory from the incoming tube which has a close approach to the moon equal to the orbital distance of the desired operational orbit. A close up near L_2 is shown in Figure 4(b), where the black spacecraft trajectory, after a close approach of the moon, will be on an elliptical orbit around the moon if no maneuver is performed. For the trajectory shown in Figure 1, we can, for example, performed 450 m/s burn at a 100 km altitude close approach to Europa to put the spacecraft on a circular 100 km altitude orbit around Europa.

TRAJECTORY CONSTRUCTION: NUMERICAL RESULTS

The preliminary tour trajectory, generated using the above building block, is shown in Figure 1. 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 trajectory gets pumped down by Callisto, then passes by Callisto in a close encounter (~1400 km altitude), then changes "control" (in terms of which moon has the dominant effect) naturally from Callisto to Ganymede and gets pumped down by Ganymede. After a close encounter with Ganymede (~2100 km altitude), the trajectory is under the control of Europa, getting pumped down 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.

We can get a better understanding of what is going in the following way. As the spacecraft initially gets "pumped down" to smaller values of jovicentric semimajor axis, it will also have its eccentricity decreased (since it is in the exterior realm and the Tissrend parameter must remain constant). As the orbit gets more and more circular, converging upon the orbit of Ganymede, it will at some point get ballistically captured by Ganymede, and orbit Ganymede for a time. Small ΔV's can be used to steer the spacecraft such that it escapes Ganymede and goes into a jovicentric orbit to the inside of Ganyemde's orbit. The spacecraft will then continue to decrease its semimajor axis, but now eccentricity will climb (since it's in the interior realm). At some point, the spacecraft trajectory will intersect the case 3 energy of Ganymede. The projection of the trajectory onto (a, e) space and (r_p, P) space is shown in Figure 5.

At this point, the spacecraft can *switch control* to Ganymede, meaning that the restricted 3-body system best approximating the motion in the restricted 5-body simulation is given by the Jupiter-S/C-Ganymede system instead of the Jupiter-S/C-Callisto system. Physically, switching control occurs when the spacecraft's jovicentric periapse comes close to the orbit of Ganymede. In particular, when the spacecraft apoapse comes just *behind* the longitude of Ganymede, it will be "pumped up" (going backward in time) to an orbit with a larger periapse, and therefore will no longer be in the case 3 energy regime with respect to Europa, but will instead be in the case 1 energy regime, where the effect of the second primary in the restricted three-body problem is



(a) (b)

Figure 5: (a) The same trajectory as shown in Figure 1 is shown here, now plotting jovicentric semimajor axis (a) versus orbital eccentricity (e). The trajctory is shown in red, and jumps along the black curves of constant three-body energy, depending on which moon has "control" over the spacecraft. (b) We can also plot the trajectory in periapse (r_p) vs. period (P) following the convention of Heaton, Strange, Longuski, and Bonfiglio [2002]. Note that now curves of constant three-body energy are labeled with the V_∞ to which they correspond.

minimal.

The entire trajectory is shown with time histories of semimajor axis and jovicentric distance in Figure 6.

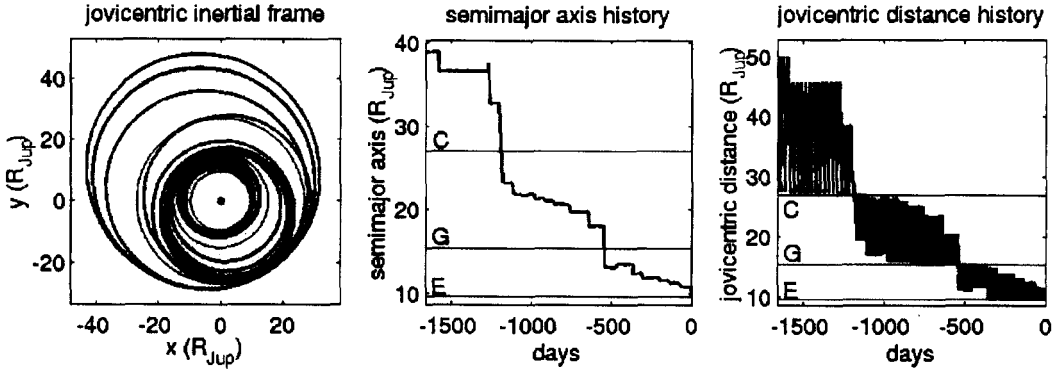
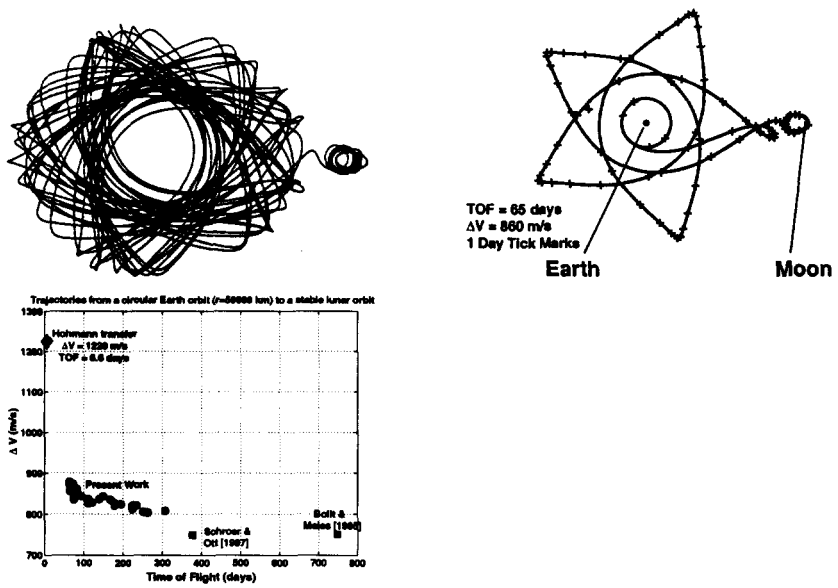


Figure 6: Starting in an elliptical orbit which grazes Callisto's orbit at perijove, the trajectory gets successively "pumped down" in energy by repeated distant encounters with the various moons, effectively jumping to lower resonances at each distant encounter. First the trajectory gets pumped down by Callisto, then passes by Callisto in a close encounter (~1400 km altitude), then changes "control" (in terms of which moon has the dominant effect) naturally from Callisto to Ganymede and gets pumped down by Ganymede. After a close encounter with Ganymede (~2100 km altitude), the trajectory is under the control of Europa, getting pumped down 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.

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, most 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).[6]

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 the Earth's moon. Bollt and Meiss [1995] 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 7(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. Schroer and Ott [1997] also considered this

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



(a) (b) (c)

Figure 7: **Compromise between fuel and time optimization.** (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 [1995] 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. (c) The ΔV vs. time of flight plot for several "chaotic" trajectories to the moon, 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.

problem with the same initial and 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 [1997], together with methods for achieving ballistic capture (Koon, Lo, Marsden, and Ross [2000,2001]), we find a transfer, shown in Figure 7(b), with a flight time of 65 days which uses a total ΔV of 860.1 m/s. Thus we take one-tenth of the time as the Bollt and Meiss [1995] trajectory using only about 100 m/s more fuel. See Figure 7(c).

This "compromise" method has been applied to only one three-body system thus far. In the future, we wish to adapt the method to missions combining several restricted three-body systems, such as the MMO, in order to seek more reasonable flight times.

Future Work

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

1. **The effects of three-dimensionality:** The current work considers only the planar 5-body problem. What about the case when the moons are not coplanar?

2. **The use of low-thrust continuous propulsion:** 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 Multi-Moon Orbiter considers several small impulsive burns. But an actual mission may want to save on spacecraft weight by using low thrust propulsion. The current work considers several small, specifically placed impulsive burns. An actual mission may want to save on spacecraft weight by using low-thrust propulsion. How could our method be modified to incorporate low-thrust? For instance, the impulsive trajectory may be a good initial guess for an optimization scheme which uses low-thrust propulsion.

3. **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 resonance "pump down" to enter a Europa orbit (the perijove for this portion of the tour is just outside the radial distance of Europa's L_2 point, which is within 12 R_J). One needs to determine what is the best way to minimize radiation effects and still achieve a very low thrust transfer.

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

Acknowledgement

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. This work was also supported by the Caltech President's Fund.

References

1. G´omez, G., W.S. Koon, M.W. Lo, J.E. Marsden, J. Masdemont, and S.D. Ross [2001] In-variant manifolds, the spatial three-body problem and space mission design, AAS/AIAA Astrodynamics Specialist Conference, Quebec City, Canada, Aug. 2001.
2. 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.
3. Koon, W.S., M.W. Lo, J.E. Marsden and S.D. Ross [1999] Constructing a Low Energy Transfer between Jovian Moons, Celestial Mechanics : dedicated to Donald Saari for his 60th birthday: proceedings of an international conference on celestial mechanics, December 15-19, 1999, Northwestern University, Evanston, Illinois, published in Contemporary Mathematics, 292 [2002] (Eds. Alain Chenciner, Richard Cushman, Clark Robinson, and Zhihong Jeff Xia), 129–145.
4. 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.
5. Schoenmaekers, J., D. Horas, and J.A. Pulido [2001] SMART-1: With Solar Electric Propul-sion to the Moon, 16th International Symposium on Space Flight Dynamics, Pasadena, CA, Dec. 2001.
6. Sweetser, T., R. Maddock, J. Johannesen, J. Bell, P. Penzo, A. Wolf, S. Williams, S. Ma-tousek, and S. Weinstein [1997] Trajectory Design for a Europa Orbiter Mission: A Plethora of Astrodynamic Challenges, AAS Paper 97-174, presented at AAS/AIAA Space Flight Me-chanics Meeting, Huntsville, AL, Feb. 1997.