AIAA 2000-4034

AUTOMATED DESIGN OF THE EUROPA ORBITER TOUR

Andrew F. Heaton*, Nathan J. Strange†, James M. Longuski‡ and Eugene P. Bonfiglio§
School of Aeronautics and Astronautics, Purdue University,
West Lafayette, Indiana 47907-1282

Abstract

In this paper we investigate tours of the Jovian satellites Europa, Ganymede, and Callisto for the Europa Orbiter Mission. The principal goal of the tour design is to lower arrival V_∞ for the final Europa encounter while meeting all of the design constraints. Key constraints arise from considering the total time of the tour and the radiation dosage of a tour. These tours may employ 14 or more encounters with the Jovian satellites, hence there is an enormous number of possible sequences of these satellites to investigate. We develop a graphical method that greatly aids the design process.

Introduction

The Europa Orbiter Mission is currently scheduled to arrive at Jupiter by the end of the decade. The mission will investigate the possibility that liquid oceans may exist beneath the surface ice of Europa. It will attempt to map these regions of liquid water for follow-up missions to Europa. The recent discovery of life in the ice of Lake Vostok, a lake deep beneath the Antarctic ice cap, lends impetus to Europa missions with the suggestion that life may be possible on Europa.[1]

In order to place the spacecraft into orbit about Europa, the arrival V_∞ must be reduced as much as possible prior to orbit insertion. This paper investigates the problem of lowering the arrival V_∞ with a tour (i.e. a sequence of gravity assists) of the Jovian satellites, Europa, Ganymede, and Callisto.

This tour is only one phase of the Europa Orbiter mission. After arriving at Jupiter, a maneuver will be performed to capture the spacecraft about Jupiter in an orbit that encounters Ganymede. Our tours start with variations of this Ganymede encounter. After the tour reduces the final arrival V_∞ at Europa, the endgame begins. The endgame is designed by the Jet Propulsion Laboratory (JPL) to use a combination of Europa flybys, small maneuvers, and 3-body effects to reduce the energy of the orbit further prior to the orbit insertion maneuver (See Johannesen and D'Amario)[2].

Constraints for Tour Design

Table 1 Initial conditions at Ganymede

Launch Period	V_∞ (km/s)	Periapsis (R_J)	Period (days)
Early	8.18	9.8	200.2
Middle	8.47	9.4	199.7
Late	8.14	9.8	191.4

We start with a set of initial conditions at Ganymede, which vary depending on when the Orbiter is launched from Earth. JPL categorizes these conditions as "late," "middle," and "early" launch period. Typical initial conditions from each launch period are included in Table 1. In Table 1, launch period ranges from 11/10 to 11/25/2003, and results in arrivals at Jupiter from 2/28 to 12/05/2007. Starting from initial conditions such as those

*Graduate Student, Member AIAA
†Graduate Student, Member AIAA
‡Professor, Associate Fellow AIAA
§Engineering Staff, JPL, Member AIAA

in Table 1, we then proceed to design the tour subject to various constraints.

There are many constraints that must be met by the tour. Most important is to have as low a V_∞ at Europa as possible. Based on the Hohmann transfer from Ganymede to Europa the lowest ballistic V_∞ achievable is 1.49 km/sec. Periapsis of any orbit in the tour must be greater than 8.8 R_J (Jovian radii), to mitigate the effects of radiation exposure. Flyby altitude at each satellite must be greater than 100 km at each satellite in general, and must be greater than 200 km during the first flyby of any satellite, in order to avoid crashing into the surface due to navigational uncertainties. While in transit between any two satellites, the spacecraft must not approach within 50,000 km of any third body (i.e. a "non-targeted" flyby) in order to avoid perturbing the orbit too much. Another design constraint is to minimize the total number of flybys, since each flyby may require a slight correctional delta-V. No close flybys are allowed when Jupiter is in solar conjunction. It is highly desired that the tour should be completed while the spacecraft is within 5 AU of the Earth. The combination of the solar conjunction constraint and the 5 AU constraint limits the time of flight for the tour to a period that varies from roughly 280 to 500 days, depending on whether the tour is from the late, middle or early launch period. Each leg of the tour must pass through apoapsis to allow for trajectory correction maneuvers. Finally, each tour must end in a resonant orbit with Europa.

Table 2 Maximum V_∞ for a given resonance[3]

Resonance	V_∞ (km/s)
3:1	3.2
5:2	3.6
2:1	3.0
5:3	3.1
4:3	1.8
6:5	1.2

The endgame follows the tour. The endgame consists of a series of Europa flybys combined with a maneuver at apojove[2]. The maneuvers raise perijove and lower V_∞, while the flybys reduce the period. There is a maximum V_∞ desired for a given final resonance achieved by the tour[3], as shown in Table 2. For example, for a 4:3 resonance (4 spacecraft revs : 3 Europa revs) the arrival V_∞ at Europa should not exceed 1.8 km/sec. On the other hand, a 6:5 resonance requires a V_∞ of less than 1.2 km/sec, which is not achievable ballistically. Since it is possible to achieve less than 1.8 km/sec at Europa for the 4:3 resonance, most tours end with a 4:3 resonance.

Solution Approach

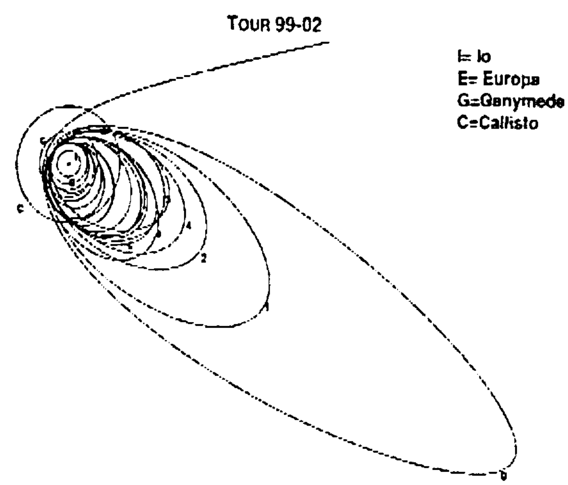

Figure 1 Baseline tour form Europa orbiter

STOUR (Satellite Tour Design Program) is a software tool that was developed by JPL for the Galileo mission tour design[4]. It has been enhanced and extended at Purdue to enable the automated design of gravity-assist tours in the Solar System as well as the satellite system of Jupiter[5-8]. STOUR uses the patched-conic method to calculate all gravity-assist trajectories meeting specified requirements.

We use STOUR as our principal tool for the design of Europa Orbiter tours. From a starting condition at Ganymede, STOUR finds trajectories for a given path, i.e. a sequence of gravity-assist bodies. The massive number of trajectories produced by STOUR must be sifted through to find viable tour candidates.

Tour 99-02 (the second tour we discovered in 1999) uses 15 flybys of Europa, Ganymede, and Callisto (Figure 1)[8,9]. Even with the initial position and velocity specified, there are tens of thousands of possible tours that follow a specified path. The calculation of these can take weeks for a single path. When we consider that there are 3^{13} (1.6 million) possible paths that begin at Ganymede and reach Europa in 15 flybys, we see that the problem of calculating all possible tours is intractable with current computer technology. Clearly, we need to know what paths have the most promise to yield viable tour candidates before even beginning an STOUR run.

We began tackling this problem by choosing paths by trial and error tempered with engineering judgement. For instance, we could lower the spacecraft's period and thus decrease the total energy relative to Jupiter in an attempt to reduce the final arrival V_∞ at Europa. A series of pump-downs with Ganymede would accomplish this quickly, but would also quickly lower the periapsis into the hazardous radiation environment (i.e. fry the spacecraft). We could then modify this path to include Europa and Callisto. Following such logic, we found that although Europa has less gravity to assist us, it is able to reduce period more than Ganymede for the same decrease in periapsis height. We also noticed that Callisto is very handy for raising periapsis, as it can do so with the lowest cost in increased orbit period. If we combine these satellites in the right order (e.g. Ganymede-Callisto or Ganymede-Europa-Callisto), we could reduce period and periapsis at the end of a sequence of satellite flybys. The identification of useful path segments such as these took months of experience with the problem.

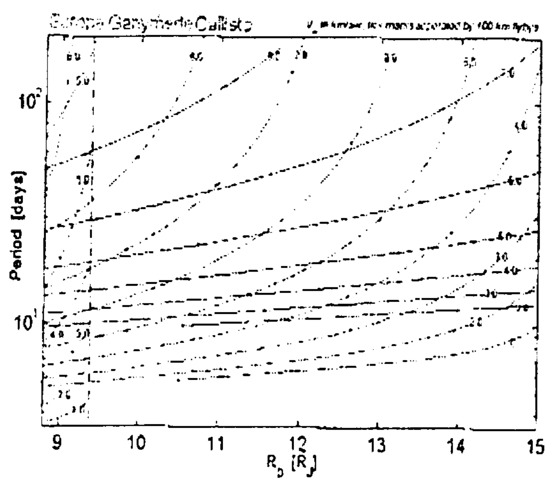

Figure 2 P-r_p plot

To improve this trial and error method, we next conducted exhaustive searches through all possible five-body path segments for the beginning of the tour. Even limiting the paths to five bodies left us with a computationally intensive and time consuming process which needed to be repeated for each different initial condition at the first Ganymede encounter. Moreover, the results of this endeavor were hard to interpret. A key question is how to characterize what will end up being a good tour after only five flybys. One figure of merit is the V_∞ at the fifth flyby, but it is difficult to draw comparisons between the final V_∞'s of path segments ending at different satellites.

During the initial process we found that tracking both period and periapsis could often identify interesting path segments. Since the satellites we are working with are in almost circular orbits about Jupiter, period and periapsis prescribe both the spacecraft's orbit about Jupiter and the V_∞ at each satellite.

This observation suggests the "P-r_p" plot (Figure 2). This is a plot of period versus perijove for orbits with less than 200 day periods that meet the perijove constraint (> 8.8 R_J). The plot shows contours of constant V_∞ for each satellite, assuming circular, coplanar orbits. A gravity assist rotates the V_∞ vector of the spacecraft along one of these contours modifying the orbit about Jupiter. Where contours from different satellites intersect, there exists a transfer between those satellites. These contours give the values of V_∞ at each satellite for this transfer arc. This provides a method for comparing the V_∞ at different bodies.

If we constrain the flybys to have a minimum altitude of 100 km above the surface of the satellite, we are limited in how far we can travel along a contour in one flyby. This is illustrated on the plot by tick marks. From one tick mark on a contour we may move a maximum of the distance to the next tick mark up or down that contour. The tick marks also can help us judge how far one flyby can move up or down a contour even when not starting from a tick mark.

We can now see on the plot in a few minutes what before took months. Remembering that our goal with the tours is to decrease the spacecraft's period but still keep the periapsis high, we can see that Europa is most effective in lowering period with a minimal cost in periapsis height by the slope of its V_∞ contours. However, due to the distance between the tick marks, Ganymede is much more effective in lowering period with a single flyby. The slope of Callisto's contours show that it is the best choice for raising periapsis as it costs the least in terms of increased period to do so.

With one of these charts and a pencil, a tour designer can quickly sketch out a promising path for analysis in STOUR. Also, known tours can be plotted and examined for possible improvements.

The P-r_p plots can be derived from Tisserand's criterion. Tisserand showed in the 19th century[10] that comet orbits perturbed by Jupiter's gravity will satisfy Jacobi's integral. The resulting equations can be solved and plotted on a P-r_p plot. We used Tisserand's criterion to verify our P-r_p plots.

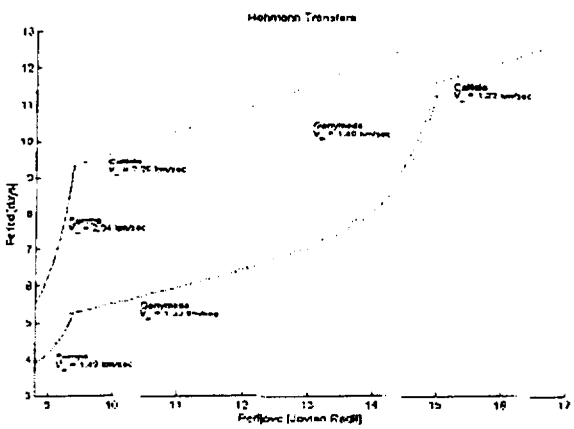

Figure 3 Hohmann transfers

Figure 3 shows the Ganymede-Europa, Callisto-Ganymede, and Callisto-Europa Hohmann transfers. These orbits provide a lower bound of 1.49 km/sec for arrival V_∞ at Europa. The chart shows this can only be achieved via multiple Ganymede-Europa arcs at the end of a tour as opposed to directly after a Callisto flyby.

We are currently extending this method to search for the fastest possible path to Europa as well as low radiation paths to Europa. This involves developing software to automatically traverse the P-r_p plots to find possible paths and calculate a cost for those paths.

Results

Altogether, we discovered 35 tours in 1999. Tour 99-02 (see Figure 1) is currently being used as a baseline by JPL. The details of Tour 99-02 are in Table 3.

Tour 99-02 is one of our earlier tour designs, where we relied primarily on trial and error to discover and link promising path segments. A good example of such a segment is the first 5 flybys of Tour 99-02. We start out with 3 Ganymede resonances, followed by a Europa-Callisto combination. This pattern of multiple Ganymede flybys followed by a Europa-Callisto pairing accounts for the great majority (19) of tours we discovered for the early launch period initial conditions. For low radiation tours, we would like the periapsis to remain as high as possible.

Table 3 Tour 99-02 summary

Event #/ Satellite	V_∞ (km/s)	Period (days)	r_p (R_J)	Time (days)
1/Ganymede	7.85	64.3	10.3	0
2/Ganymede	7.85	35.7	9.6	64
3/Ganymede	7.86	21.4	8.6	100
4/Ganymede	7.86	27.8	9.1	122
5/Europa	5.11	20.4	9.0	151
6/Callisto	6.39	23.1	9.8	169
7/Ganymede	7.10	16.7	9.1	193
8/Europa	4.74	17.7	9.1	211
9/Europa	4.73	16.5	9.1	229
10/Callisto	5.75	22.0	11.4	247
11/Ganymede	5.85	14.3	10.3	268
12/Ganymede	5.85	10.8	9.3	282
13/Europa	3.34	10.6	9.3	303
14/Europa	3.31	8.8	9.1	313
15/Europa	3.29	7.1	8.9	331
16/Europa	3.28			338

An orbit with a periapsis above 12 R_J essentially does not contribute to the radiation hazard[3]. The periapses in Tour 99-02 never exceed 12 R_J, and are rarely greater than 10 R_J, because when we designed Tour 99-02 radiation was not an official constraint. The flybys of Europa on events 8 and 9 appreciably increase the radiation dosage of Tour 99-02. Since Europa has a semi-major axis of approximately 9.4 RJ, any flyby of Europa will have a significant radiation dosage. For this reason, our later tours avoid going to Europa until the end of the tour. However, the early flybys of Europa in Tour 99-02 do serve a purpose. A glance at the P-Rp plot (Figure 2) will confirm that Europa can efficiently pump down the orbital period with only a slight lowering of the periapsis. Tour 99-02 achieves a final V_∞ of 3.28 km/sec, which meets the maximum constraint of 3.50 km/sec imposed by JPL. Later tour efforts achieve lower V_∞, but at a cost in time of flight.

Table 4 Tour 99-35 summary

Event #/ Satellite	V_∞ (km/s)	Period (days)	Perijove (R_J)	Time (days)
1/Ganymede	5.99	50.1	12.5	0
2/Ganymede	5.99	30.5	11.9	50
3/Callisto	6.31	41.9	13.5	84
4/Ganymede	4.93	21.5	12.6	124
5/Ganymede	4.93	13.3	11.4	145
6/Callisto	3.93	18.0	14.9	155
7/Ganymede	2.37	10.7	13.9	194
8/Ganymede	2.37	7.2	11.7	215
9/Ganymede	2.37	5.5	9.1	222
10/Europa	2.45	5.2	9.0	232
11/Ganymede	1.59	5.3	9.4	245
12/Europa	1.64	4.7	9.33	253
13/Europa	1.62			267

We used P-r_p plots to discover Tour 99-35. First, a promising path for the tour was selected from the P-Rp plot and evaluated interactively (in STOUR) to test its effectiveness. We used this run in conjunction with the P-R_p plot to adjust our selected path as necessary. Finally, the selected path was used as the basis of an automated search in STOUR. Tour 99-35 is listed in Table 4.

With Tour 99-35, we were trying to limit the number of flybys and maintain a high periapsis for low radiation. Consequently, we started Tour 99-35 with the highest periapsis possible. This turned out to be a periapsis of 13.2 R_J for an initial condition from the late launch period. The use of the P-r_p plot paid off nicely, as Tour 99-35 has the lowest time of flight of any tour we discovered. Tour 99-35 also has a final arrival V_∞ of 1.62 km/sec, which is about as close to the Hohmann limit of 1.49 km/sec as we have been able to achieve. The radiation environment during Tour 99-35 is excellent through event 10, and if we had stayed at Europa on event 10, Tour 99-35 would have an exceptionally low radiation dosage. However, we chose to tack on an additional Ganymede-Europa sequence to lower the final arrival V_∞ from 2.45 km/sec to 1.62 km/sec (a considerable improvement). Consequently, we take a hit in radiation dosage on events 11 and 12.

The respective paths of Tours 99-02 and 99-35 appear in the P- r_p in Figure 4. A comparison of these tours demonstrates the efficacy of the P-r_p plot. The path of Tour 99-35 is represented by dashed lines; that of 99-02 by solid lines. From the point of view of path selection, we can see a clear inefficiency in Tour 99-02 for events G3 and G4. G3 pumps all the way down to a periapsis of 8.7 (which is a slight violation of the r_p constraint), and then G4 pumps up to a transfer to Europa (E5). Instead of this roundabout method of reaching E5, in retrospect we could have simply used the G3 transfer to reach Europa, thus saving a flyby and reducing the radiation dose. A similar inefficiency for Tour 99-02 occurs with the E8

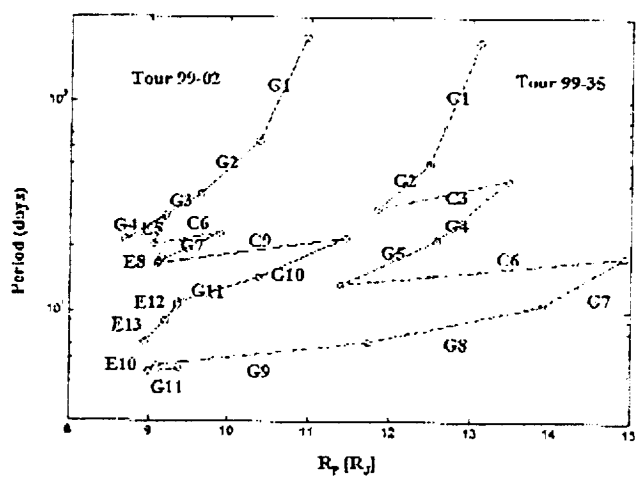

Figure 4 P-r_p comparison of Tours 99-02 and 99-35

and E9 flybys. On the other hand, Tour 99-35 proceeds smoothly from initial condition to final arrival. There is very little "wasted movement" or meandering about the P-r_p plot. Furthermore, in general each flyby in Tour 99-35 moves farther along a V_∞ curve than the flybys of Tour 99-02, implying more efficient use of each flyby. Thus, the use of the P-r_p plot helps us in two particular ways. First, we can always select the next best event in a path. Second, since we have a good way of selecting a path, each flyby can be more effective (move farther along a V_∞ curve). In addition, the P-r_p plot can also be used to

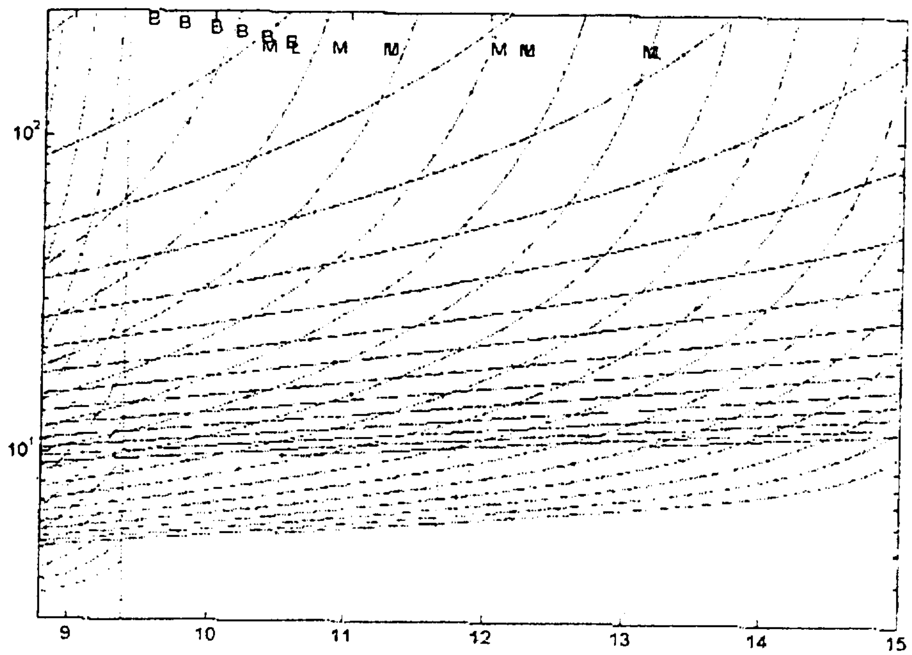

Figure 5 P-r_P plot of initial conditions

evaluate the efficacy of an existing tour at a glance. The result, as can clearly be seen in Figure 4, is a shorter, more efficient tour.

Tour 99-35 also benefits from having a better initial condition. When we designed Tour 99-35, our goal was a lower radiation dosage, so we selected the highest initial r_p that we had available. All the initial conditions that we used for tour design are plotted in the P-r_p plot in Figure 5. The beginning launch period initial conditions are marked with a "B", the middle launch period initial conditions with an "M", and the late launch period initial conditions with an "L". By comparing the positions on the P-r_p plot of the beginning, middle, and late launch periods, we can see that the initial GGEC sequence for most of our beginning launch period tours intuitively makes sense. Given the low periapsis, we need to pump down quickly to get to one of the flatter Callisto V_∞ curves, which are efficient at increasing periapsis while not increasing period too much. We can also see that since many of the middle and late launch periods start with higher r_p values, we can reduce period somewhat more at the beginning of the tour without lowering the periapsis too much (and thus our radiation dosage is much lower). (Of course, there is a delta-V cost associated with starting the tour at a lower periapsis). Also, the time of flight for the late and middle launch periods is generally lower, because they start with a lower V_∞ value. Clearly, the initial conditions greatly affect our tour design strategy.

Table 5 lists the best tours for arrival V_∞, time of flight, radiation dose, and number of flybys for each launch period. The table does not include tours that had better performance but violated either the flyby altitude, non-targeted, or solar conjunction constraints One issue that has not been addressed in detail is phasing (ie, timing between the jovian satellites and the spacecraft orbit). Phasing can significantly affect the performance of a tour. The P-r_p plot does not address phasing or timing issues at all. Hence, while a path may look promising on the P-r_p path, STOUR may not be able to find viable tours. Phasing tends to become more of an issue towards the end of the tour, when the energy of the spacecraft orbit is low and fewer transfer arcs between satellites are possible.

Given the combination of V_∞ and low radiation constraints, we almost always want our last Callisto-Ganymede transfer orbit to have a periapsis as close to

Ganymede's semi-major axis (14.971 R_J) as possible (since we are trying to achieve a Hohmann transfer between Callisto and Ganymede). In practice, due to phasing, the ideal transfer between Ganymede and Callisto proves elusive, as does the later final Ganymede-Europa transfer. In fact, our experience is that the final sequence of flybys is much more of a limiting factor than any other portion of the tour (ie. in the middle of the tour, many transfer orbits for a given flyby are available, at the end, only a few).

Table 5 Details of Best Tours

Parameter	Early	Middle	Late
1.Arrival Date	99-02 (2/01/08)	99-23 (7/27/08)	99-35 (8/13/08)
2. Lowest V_∞	99-33 (1.59)	99-25 (1.71)	99-35 (1.62)
3. Lowest Dose	99-18 (9.2)	99-26 (8.3)	99-35 (7.2)
4. Fewest Flybys	99-04 (14)	99-32 (13)	99-35 (12)

Conclusions

The process of designing tours for the Europa Orbiter mission has been considerably streamlined via the use of the P-r_p plots. Delta V savings exceeded expectations. The V_∞ improved from 3.5 km/sec for the initial tour to 1.6 km/sec for the best case. Radiation dosage for the later tours was reduced up to 70% from the earlier numbers, and exceeded the expectations of the radiation group at JPL[11]. P- r_p plots help tremendously with path selection and insight, and have proven a useful tool in other gravity assist missions. In the process of designing and improving the Europa Orbiter mission, we found something with a general applicability.

Acknowledgements

This research has been supported in part by the Jet Propulsion Laboratory, California Institute of Technology under Contract Number _____. The National Aeronautics and Space Administration also supported this work through a NASA fellowship. We are extremely grateful to Jennie Johanessen, Lou D'Amario, Jan M. Ludwinski, and Dennis Byrnes (Technical Manager) for assistance with initial conditions, technical questions and overall guidance of the project. We thank Anastassios Petropaulos, a graduate student in the School of Aeronautics and Astronautics at Purdue University for his assistance and suggestions. Also, we thank Pat Avery of NASA for her kind assistance in making the fellowship available.

References

[1] D. M. Karl, D. F. Bird, K. Björkman, T. Houlihan, R. Shackelford, and L. Tupas, "Microorganisms in the Accreted Ice of Lake Vostok, Antarctica," *Science*, Dec 10 1999: 2144-2147.

[2] Johannesen, J. R., and D'Amario, L. A., "Europa Orbiter Mission Trajectory Design", AAS 99 360, AAS/AIAA Astrodynamics Specialists Conference, Girdwood, AK, August 1999.

[3] Johannesen, J. R., Jet Propulsion Lab, Pasadena, Ca., personal communication, July 1999.

[4] Rinderle, E. A., "Galileo User's Guide, Mission Design System, Satellite Tour Analysis and Design Subsystem," Jet Propulsion Laboratory, Pasadena, CA, JPL Internal Document D-263, 1986.

[5] Williams, S. N., "Automated Design of Multiple Encounter Gravity-Assist Trajectories," Master's Thesis, School of Aeronautics and Astronautics, Purdue University, 1990.

[6] Longuski, J. M. and Williams, S. N., "Automated Design of Gravity-Assist Trajectories to Mars and the Outer Planets," *Celestial Mechanics and Dynamical Astronomy*, Vol. 52, No. 3, 1991, pp. 207-220.

[7] Patel, M. R., "Automated Design of Delta-V Gravity-Assist Trajectories for Solar System Exploration," Master's Thesis, School of Aeronautics and Astronautics, Purdue University, 1993.

[8] Bonfiglio, E. P., "Automated Design of Gravity-Assist and Aerogravity-Assist Trajectories" Master's Thesis, School of Aeronautics and Astronautics, Purdue University, 1999.

[9] Bonfiglio, E. P., Strange, N. J., Heaton, A. F., Longuski, J. M., "Low-Thrust and Gravity-Assist Trajectory Design for Planetary

Missions," Progress Report #9: Europa Orbiter Tour Design, JPL Contract # 961211, Purdue University, September 1999.

[10] Roy, A. E., Orbital Motion, Adam Hilger Co., 1982, 129-130.

[11] Johannesen, J. R., Jet Propulsion Lab, Pasadena, Ca., personal communication, March 20