JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 39, No. 1, January–February 2002

Automated Design of the Europa Orbiter Tour

Andrew F. Heaton,* Nathan J. Strange,† and James M. Longuski‡
Purdue University, West Lafayette, Indiana 47907-1282
and
Eugene P. Bonfiglio§
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109-8099

Before the Europa Orbiter can be placed in orbit about Europa, it will be placed into a 200-day Jovian orbit and targeted for Ganymede. After a series of gravity-assist flybys of the Galilean satellites, the orbital energy is reduced to lower the arrival hyperbolic excess velocity at Europa. These energy-saving techniques reduce the propellant cost for Europa orbit insertion to a minimum. Key constraints during the tour include total time of flight and radiation dosage. Tours may employ 10 or more encounters with the Jovian satellites; hence, there is an enormous number of possible sequences of these satellites. A graphical method based on Tisserand's criterion is presented that greatly aids the design process. The Tisserand graph method facilitates the study of a wide range of arrival conditions, arrival dates, and satellite tours.

Nomenclature

P = period, days
R_J = Jovian radius, 71,492 km
r_p = periapsis, R_J
V_∞ = hyperbolic excess velocity, km/s
ΔV = change in orbital velocity, km/s

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. The spacecraft 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,[1] a lake deep beneath the Antarctic ice cap, lends impetus to Europa missions with the suggestion that life may be possible on Europa.

After arriving at Jupiter, the spacecraft does an initial flyby of Ganymede called the G0 flyby to lower the energy of the hyperbolic orbit and reduce the size of the insertion maneuver. This maneuver follows the G0 flyby and inserts the spacecraft into a 200-day Jovian orbit that again encounters Ganymede. This second Ganymede encounter is called the G1 flyby. Our tours start with variations of the G1 flyby.

The tour is a sequence of gravity-assist flybys of the Jovian satellites Callisto, Ganymede, and Europa. In the tour design process, we search for the best sequence of flybys to achieve the goal of reducing the arrival V_∞ at Europa as much as possible. Achieving this goal will substantially lower the propellant cost of Europa orbit insertion.

After the tour reduces the final arrival V_∞ at Europa, a phase called the endgame begins. The endgame is designed by the Jet Propulsion Laboratory (JPL) to use a combination of Europa flybys, small maneuvers, and three-body effects to reduce the energy of the orbit further before the orbit insertion maneuver. (For details of the endgame, see Johannesen and D'Amario.[2]) During the endgame, only Europa is used for flybys. The endgame requires certain arrival conditions for the final flyby of the tour.

The purpose of this paper is to describe how we designed tours for the Europa orbiter and to present the best tours designed so far. We describe how our method of designing tours matured, eventually resulting in the development of a new graphical method. We show how a simple graph, which we refer to as a Tisserand graph, greatly streamlines tour design.

Guidelines and Mission Constraints for Tour Design

The tour begins with a set of initial conditions at Ganymede. Typical initial conditions for a 2003 launch period appear in Table 1. In Table 1 the launch period ranges from 10 November to 25 November 2003, which corresponds to arrivals at Jupiter from 28 February to 4 December 2007. Thus, we refer to the conditions in Table 1 as the 2003 launch period. These dates are from an early design study. At present the precise launch and arrival dates for the Europa mission are unknown, although with the recent launch date slip it is expected that the launch will occur no sooner than 2006.

Starting from initial conditions such as those in Table 1, we design a tour that is subject to various mission goals, guidelines, and constraints. The most important goal is to have low V_∞ at Europa. Originally, JPL constrained the arrival V_∞ at Europa to a maximum of 3.5 km/s, but lower values are highly desirable. Based on the Hohmann transfer from Ganymede to Europa, the lowest ballistic V_∞ achievable is 1.49 km/s, and the values we achieve tend to be close to this limit.

Other important goals, guidelines, and constraints are as follows. The periapsis of any orbit in the tour should be greater than $8.8R_J$, to mitigate the effects of radiation exposure, which can damage the spacecraft. The flyby altitude at each satellite must be greater than 100 km in general, to avoid crashing into the surface due to navigational uncertainties. For the same reason, the initial flyby of any satellite is recommended to be greater than 200 km. While in transit between any two satellites, the spacecraft must not approach within 50,000 km of any third body, that is, a nontargeted flyby, to avoid perturbing the orbit too much. The total number of flybys should be kept to a minimum, because each flyby may require a slight correctional ΔV. No close flybys are allowed when Jupiter is in solar conjunction because the sun disrupts communication with the

Received 26 January 2001; revision received 21 June 2001; accepted for publication 23 June 2001.

*M.S. Candidate, School of Aeronautics and Astronautics; currently Aerospace Engineer, Mission Planning Group, NASA Marshall Space Flight Center, Huntsville, AL 35812; andy.heaton@msfc.nasa.gov. Member AIAA.

†M.S. Candidate, School of Aeronautics and Astronautics; currently Member, Technical Staff, Navigation and Mission Design Section, Mail Stop 230-205, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109-8099; nathan.strange@jpl.nasa.gov. Member AIAA.

‡Professor, School of Aeronautics and Astronautics, 1282 Grissom Hall; longuski@ecn.purdue.edu. Associate Fellow AIAA.

§Member, Technical Staff, Navigation and Mission Design Section, Mail Stop 301-335, 4800 Oak Grove Drive; eugene.p.bonfiglio@jpl.nasa.gov. Member AIAA.

Table 1 Typical initial conditions at Ganymede

Launch date	Arrival date	V_∞, km/s	Perijove R_J	Period, days
10 Nov. 2003[a]	28 Feb. 2007	8.18	9.8	200.2
17 Nov. 2003[b]	21 July 2007	8.47	9.4	199.7
25 Nov. 2003[c]	4 Dec. 2007	8.14	9.8	191.4

[a]Beginning launch period. [b]Middle launch period. [c]Late launch period.

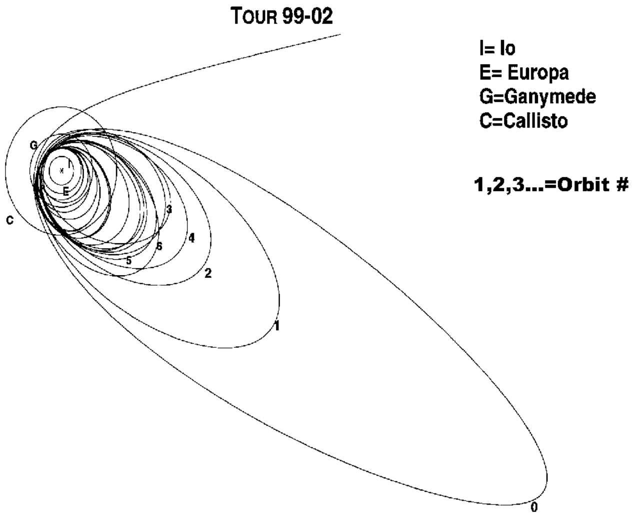

Fig. 1 Baseline tour for Europa orbiter.

spacecraft. Also, the tour should be completed while the spacecraft is within 5 astronomical units (AU) of the Earth to maintain a high data rate. The combination of the solar conjunction constraint and the 5-AU guideline limits the time of flight for the tour to a period that varies from roughly 280 to 500 days, depending on when the tour begins. Each leg of the tour must pass through apoapsis to allow for trajectory correction maneuvers. Finally, each tour must end in an orbit that has a 4:3 resonance (four spacecraft revolutions: three satellite revolutions) with Europa. JPL found this resonance to be highly desirable to use as a starting point for the endgame.

Solution Approach

The satellite tour design program (STOUR) is a software tool developed by JPL for the Galileo mission tour design.[3] The program has been enhanced and extended at Purdue University to perform automated design of gravity-assist tours of the solar system and of the satellite system of Jupiter.[4–7] STOUR uses the patched-conic method to calculate all gravity-assist trajectories meeting specified requirements.

We use STOUR as the principal tool for the design of Europa orbiter tours. From a starting condition at Ganymede, STOUR finds trajectories for a given path, that is, 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 designed[7] in 1999) uses 15 flybys of Europa, Ganymede, and Callisto and is depicted in Fig. 1. Even with the initial conditions specified at Ganymede, there are tens of millions of possible tours that follow a specified path due to the number of choices of time of flight between encounters. The calculation of these tours can take weeks for a single path. A typical tour might have 15 flybys, and at each flyby there are three satellites that can be targeted. However, the first and last flybys are always Ganymede and Europa, respectively, leaving 13 flybys to be targeted to one of the three satellites. Thus, for a typical tour there are 3^{13} (1.6 million) possible paths that begin at Ganymede and reach Europa in 15 encounters, making the problem of calculating all possible tours intractable with current computer technology. Clearly, we need to know what paths have the most promise to yield viable tour candidates before even beginning STOUR computations.

We began tackling this problem by choosing paths by trial and error, tempered with engineering judgment. For instance, we could lower the spacecraft's period with a flyby to decrease the total energy relative to Jupiter in an attempt to reduce the final arrival V_∞ at Europa. A series of these energy pump downs with Ganymede would accomplish this quickly, but would also lower the periapsis into the hazardous radiation environment (which would damage the spacecraft). Thus, we cannot use Ganymede alone for period reduction. We found that although Europa has less mass, it is able to reduce period more than Ganymede for the same decrease in periapsis height. We also noticed that Callisto is useful for raising periapsis because it can do so with the lowest increase in orbit period. If we combine these satellites in the right order (e.g. Ganymede–Callisto or Ganymede–Europa–Callisto), we can reduce period (by reducing orbital energy with Ganymede or Europa) while maintaining a high enough periapsis at the end of a sequence of satellite flybys (by increasing orbital energy with Callisto). The identification of useful path segments such as these took months of experience to design.

To improve over this trial-and-error method, we 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 that had 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 set of five flybys will lead to a good tour. One figure of merit is the V_∞ at the fifth flyby, but it is difficult to draw comparisons between the final V_∞ of path segments ending at different satellites. For example, how do we rate $V_\infty = 3$ km/s at Ganymede 5 compared to $V_\infty = 4$ km/s at Europa 5?

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

This observation suggests the P–r_p plot (Fig. 2). This analytical tool is a plot of period vs perijove for orbits with less than 200-day periods that meet the perijove guideline ($r_p \geq 8.8 R_J$). Each point on the plot represents a static orbit about Jupiter that is coplanar with the Galilean satellites.

Figure 2 shows contours of constant V_∞ for each satellite, assuming circular, coplanar satellite orbits. The V_∞ of the spacecraft with respect to a given satellite is calculated in the usual way as the vector subtraction of the satellite velocity from the spacecraft velocity. During a flyby, energy is conserved with respect to the satellite, so that the incoming V_∞ and outgoing V_∞ of the spacecraft are identical. Thus, the effect of the flyby is to rotate the direction of the V_∞ vector. In Fig. 2, the rotation of the V_∞ vector corresponds to movement along a contour of constant V_∞. With the value of the V_∞ at a particular satellite and Fig. 2, we instantly know the range of spacecraft orbits that correspond to that V_∞. The first point on the left side of a V_∞ contour represents a spacecraft orbit that has just enough energy to encounter the satellite with that particular period and periapsis. The right side of the contour approaches escape velocity as period is increased, but cannot have a periapsis that exceeds the satellite's orbital radius. (In the case of Europa this is $9.4 R_J$.)

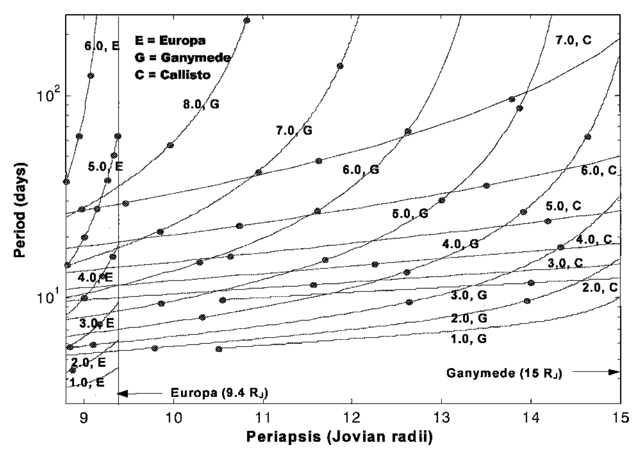

Fig. 2 P–r_p plot: a single point represents the shape of an orbit around Jupiter.

If the flybys are constrained 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 constraint is represented on the plot by tick marks (dots). 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 judge how far one flyby can move up or down a contour even when not starting from a tick mark.)

Where contours from two satellites intersect, there exists a potential transfer between those satellites. These contours give the values of V_∞ at each satellite for this transfer arc and also provide a method for comparing the V_∞ at different bodies. For a more detailed discussion of the graphical construction and its application to solar system missions see Strange and Longuski.[8]

By studying the P–r_p plot in Fig. 2, we can quickly deduce design concepts that previously took months to learn. Remembering that the goal of 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 sharp upward slope of its V_∞ contours. However, due to the greater distance between the tick marks, Ganymede is much more effective in lowering period with a single flyby. The shallow slope of Callisto's contours show that Callisto is the best choice for raising periapsis because it costs the least in terms of increased period to do so.

With one of these plots 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 that comet orbits perturbed by Jupiter's gravity satisfy Jacobi's integral.[9] Each V_∞ contour in the P–r_p plots obeys Tisserand's criterion; thus, we refer to these graphs as Tisserand graphs, in honor of the astronomer.

Figure 3 shows the Ganymede–Europa Hohmann transfer, which represents the lowest possible arrival V_∞ at Europa from Ganymede. From Fig. 3, we can also see that the value of this arrival V_∞ at Europa is 1.49 km/s. A more detailed plot, similar to Fig. 2, reveals that the Ganymede V_∞ contour that represents a Hohmann transfer between Europa and Ganymede cannot be reached from Callisto. Thus, to achieve the Hohmann transfer between Ganymede and Europa, we must use multiple Ganymede–Europa transfers, which is typically how our tours end.

After considerable experience with our graphical technique,[10] which we have found to be of great benefit in our tour design work for the Europa orbiter, we learned of a similar technique described in the excellent book by Labunsky et al.[11] They describe their approach as the graphical-analytic method. They make the same assumptions regarding circular, coplanar orbits and patched conics for the orbits of the satellites. In their version, they plot periapsis on the vertical axis and period on the horizontal axis. Besides plotting periapsis vs period, they also plot periapsis vs such parameters as inclination and argument of periapsis. In general, we can say that the methods outlined by Labunsky et al. are a survey of what is possible with their approach. In essence, the two methods are mathematically equivalent.

Results

Altogether, we designed 35 tours in 1999 and 35 in 2000. Tour 99-02 (Fig. 1) is currently being used as a baseline by JPL. The details of tour 99-02 are presented in Table 2.

Tour 99-02 is one of our earlier tour designs, where we relied primarily on trial and error to design and link promising path segments. A good example of such a segment is the first five flybys of tour 99-02. We start out with three Ganymede resonances, followed by a Europa–Callisto combination. This pattern of multiple Ganymede flybys followed by a Europa–Callisto pairing accounts for the majority (19) of the tours we designed for the beginning launch period.

For low-radiation tours, we would like the periapsis to remain as high as possible. An orbit with a periapsis above $12R_J$ essentially does not contribute to the radiation hazard. The periapses in tour 99-02 never exceed $12R_J$, and are rarely greater than $10R_J$, because when we designed tour 99-02 total radiation dose was neither modeled nor constrained. The Ganymede 3 flyby violated the periapsis guideline by having a lower periapsis than $8.8R_J$ ($8.6R_J$). This violation was waived by JPL. The flybys of Europa on events 8 and 9 appreciably increase the radiation dosage of tour 99-02. Because Europa has a semimajor axis of approximately $9.4R_J$, any flyby of Europa will have significant radiation dosage. For this reason, in later tour designs we avoid encountering Europa until the end of the tour. However, the early flybys of Europa in tour 99-02 do serve a purpose. A glance at Fig. 2 will confirm that Europa can efficiently reduce the orbital period with only a slight lowering of the periapsis. Tour 99-02 achieves a final V_∞ of 3.28 km/s, which meets the constraint ($V_\infty \leq 3.50$ km/s) imposed by JPL. Later tour designs achieve much lower V_∞, but at a cost in time of flight.

We used the Tisserand graph method to design tour 99-35. First, a promising path for the tour was selected from the Tisserand graph and evaluated interactively (in STOUR) to test its effectiveness. We used this simulation in conjunction with the Tisserand graph to adjust the selected path as necessary. Finally, the path was used as the basis of an automated search in STOUR. A summary of tour 99-35 is provided in Table 3.

With tour 99-35, we limited the number of flybys and maintained a high periapsis for low radiation because radiation dose is a function of periapsis. For the purposes of tour design, we use an approximation for the radiation dose that varies inversely with the value of periapsis, increasing as periapsis is decreased. The dose is normalized so that the value is unity at a periapsis corresponding to the orbital radius of Europa. This method allows the relative dose of each tour to be compared on a consistent basis and compares favorably with the full radiation model used at JPL.

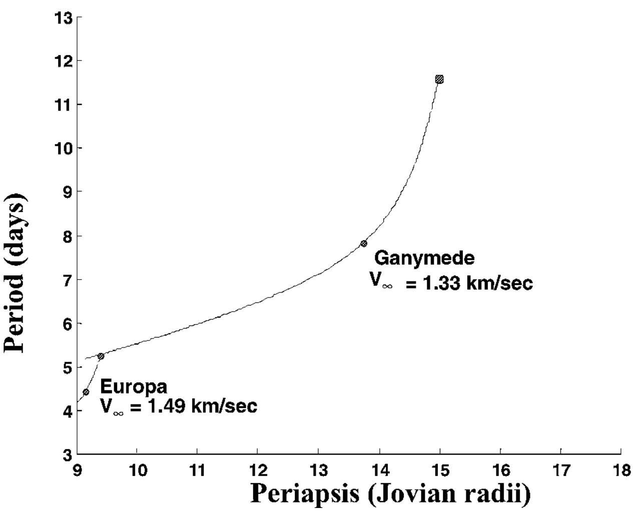

Fig. 3 Hohmann transfer between Ganymede and Europa.

Table 2 Tour 99-02 summary

Event number/ satellite	V_∞, km/s	Period, days	Perijove 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[a]	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

[a]Guideline violation ($r_p \geq 8.8R_J$) waived by JPL.

Table 3 Tour 99-35 summary

Event number/ 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	9.3	253
13/Europa	1.62	——	——	267

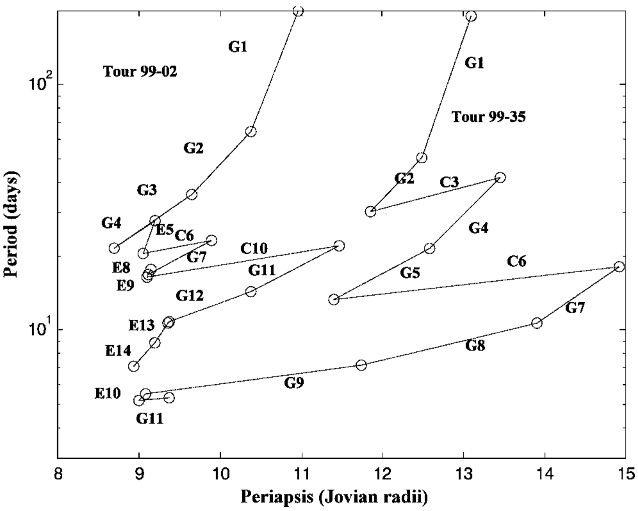

Fig. 4 Tisserand graph comparison of tours 99-02 and 99-35.

Because a high periapsis is desirable for low radiation dose, we started tour 99-35 with the highest periapsis possible. The highest available periapsis has a value of $13.2R_J$ for an initial condition from the late launch period. The use of the Tisserand graph paid off nicely because tour 99-35 has a final arrival V_∞ of 1.62 km/s (which is fairly close to the Hohmann limit of 1.49 km/s) and has the lowest time of flight of any tour we designed in 1999. The radiation dosage during tour 99-35 is minimal through event 10, and if we had ended the tour on event 10, tour 99-35 would have an exceptionally low-radiation dosage. However, we chose to append an additional Ganymede–Europa sequence to lower the final arrival V_∞ from 2.45 to 1.62 km/s (a considerable improvement). Consequently, we have a significant increase in radiation dose on events 11 and 12.

The respective paths of tours 99-02 and 99-35 appear in the Tisserand graph in Fig. 4. A comparison of these tours demonstrates the efficacy of the Tisserand graph. From the point of view of path selection, we can see a clear inefficiency in tour 99-02 for events G3 and G4. The Ganymede 3 flyby reduces the periapsis to 8.6 (which is a slight violation of the r_p guideline), and then G4 increases energy and periapsis for 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 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 on the Tisserand graph. 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, Tisserand graphs not only aid in designing a tour, they also provide a means of critiquing a final tour design.

Tour 99-35 also benefits from having a better initial condition. When we designed tour 99-35, the goal was a lower radiation dosage, and so we selected the highest initial r_p available. Sample initial con-

Table 4 Typical 2006 launch period initial conditions

Arrival date	V_∞, km/s	Perijove R_J	Period, days
5 Dec. 2008	7.32	10.9	200.5
12 Dec. 2008	6.83	11.5	200.2
19 Dec. 2008	6.41	12.0	200.0

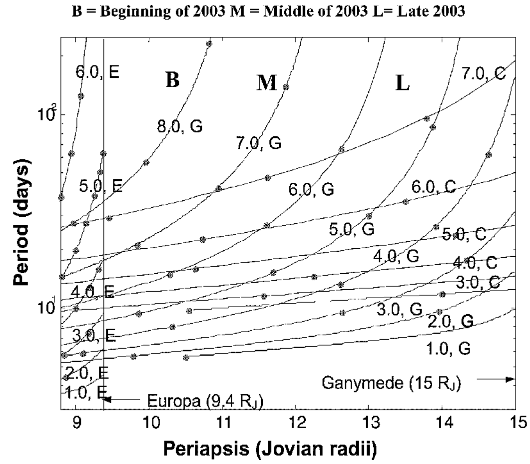

Fig. 5 Tisserand graph of sample initial conditions.

ditions for tour design are plotted in the Tisserand graph in Fig. 5 for the case of a 2003 launch. 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 Tisserand graph of the beginning, middle, and late launch periods, we can see that the initial Ganymede–Ganymede–Europa–Callisto sequence for the B tours makes sense. Given the low periapsis, we need to reduce energy quickly to get to one of the shallow Callisto V_∞ curves, which are efficient at increasing periapsis while not increasing period too much. We can also see that, because the M and L tours 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 ΔV cost associated with starting the tour at a higher periapsis. Also, the time of flight for the L and M tours will be generally lower because they start with a lower V_∞ value. Clearly, the initial conditions greatly affect our tour design strategy.

Given the combination of V_∞ and low-radiation constraints, we almost always want the last Callisto–Ganymede transfer orbit to have a periapsis as close to Ganymede's semimajor axis ($14.97R_J$) as possible (because 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 final Ganymede–Europa transfer. In fact, the final sequence of flybys is much more of a limiting factor than any other portion of the tour, that is, in the middle of the tour, many transfer orbits for a given flyby are available, but at the end, only a few.

Since April 2000, the initial conditions for the Europa Orbiter mission have changed, due to a launch date slip to 2006. Typical new launch conditions are listed in Table 4. The trades for these launch conditions are fairly straightforward. Just as for the 2003 launch period, there is a trade between the later arrival time (which implies shorter time of flight) and the lower V_∞ (which implies a higher ΔV). Thus, the situation is similar to that for the 2003 launch conditions, but there are some differences. First, the range of arrival dates is much tighter. Second, the time of flight is now limited to 278 days for the earliest arrival date. For the 2003 launch conditions, we could take as long as 550 days for a tour by jumping over a solar conjunction period. That is, a solar conjunction violation could be avoided by choosing a tour that has a flyby before and after, but not during, the solar conjunction forbidden period (about two weeks in length). Obviously, meeting the solar conjunction constraint in this fashion complicates the tour design, but allows much longer times of flight. However, the timing of the guideline to complete the tour while the spacecraft is within 5 AU of the Earth precludes us from designing the 550-day tours for the 2006 launch period. On the other hand, flybys during solar conjunction are not an issue. (Many of the earliest tours designed for the 2003 launch date had to be discarded after JPL imposed the solar conjunction constraint.) The solar conjunction for the 2006 launch period occurs in January 2009. Because the spacecraft arrives at the first Ganymede flyby (G1) of the tour in December 2008, and the post-G1 orbit is typically an 8:1 resonance with Ganymede (which corresponds to a period of 57 days), the solar conjunction constraint is usually not a problem because it is physically impossible to violate it for all but the 5 December arrival date. Not having to worry about the solar conjunction simplifies the tour design problem, but the complications caused by a shorter time of flight greatly outweigh that advantage. In summary, tour design for the 2006 launch period is more challenging than for the 2003 launch period, due to the lower time of flight constraint.

The change in launch date to 2006 allows us to demonstrate the power of tour design with Tisserand graphs. With the original tour design methods of hunt and peck or brute force, a change to a new set of initial conditions for tour design could be a major undertaking. Our experience with the change to 2006 initial conditions was an easy transition. Finding a viable tour for the 2003 launch period was a process that took weeks. Finding a viable tour with the Tisserand graph approach for the 2006 launch period took a few days. Although some of the ease in adjustment was due to experience with the problem, the Tisserand graph approach simplified the task considerably. By analogy, a Tisserand graph is like a map for a trip by car. Without a map, a driver may wander around aimlessly before reaching the destination, whereas with the map the best route can be selected ahead of time. The same is true for tour design. The Tisserand graph helps select the best path in advance. The map can also help in the event of an unexpected detour, just as with the adjustment to the 2006 launch period, the Tisserand graph proved invaluable.

Key events of tour 00-14 are listed in Table 5. The launch date for tour 00-14 is 3 January 2006. Tours beginning with 00 are sequentially numbered according to the order they were discovered in 2000. Tours 00-10 and higher are all from the 2006 launch period (tours 00-01–00-09 are from the 2003 launch period). Thus, tour 00-14 is one of the earliest tours designed for the 2006 launch period. Tour 00-14 meets all constraints, achieves a final V_∞ of 1.80 km/s, and has a radiation dosage of 7.3, which is one of the lowest doses of any tour, including the 2003 launch period tours.

Figure 6 is a Tisserand graph of tour 00-14. Tour 00-14 possesses many of the same positive characteristics of tour 99-35 (Fig. 4). Tour 00-14 flows smoothly from initial condition to arrival at Europa. There is an inefficiency in tour 00-14, however, which may not be obvious at a glance. On the plot, there is no line for the G4 event (it remains a point), because it is a distant (85,000 km) flyby and hardly affects the orbit of the spacecraft. In fact, the G4 flyby could almost be considered a phasing orbit. Flyby G4 is considered less than desirable by JPL from a navigational standpoint, but distant flybys are allowed. Given the other outstanding characteristics of tour 00-14, the distant flyby is acceptable. Tour 00-14 also reaches Europa without any earlier flyby of Europa, which is a significant factor in achieving a low radiation dose (unlike tour 99-35, which ended with a Ganymede–Europa–Ganymede–Europa sequence). Tour 00-14 was discovered about three weeks into the tour design process for the 2006 launch period, whereas tour 99-35 was discovered six months into tour design for the 2003 launch period. The design concepts developed in this paper have dramatically improved tour design for the Europa orbiter mission.

Table 5 Tour 00-14 summary

Event number/ satellite	V_∞, km/s	Period, days	r_p (R_J)	Time, days
1/Ganymede	5.57	57.2	13.0	0
2/Ganymede	5.57	28.6	12.3	57
3/Ganymede	5.57	15.4	11.0	86
4/Ganymede	5.57	15.4	11.0	103
5/Callisto	4.79	20.3	13.6	120
6/Ganymede	3.95	13.7	12.7	139
7/Ganymede	3.96	10.3	11.7	151
8/Callisto	1.90	11.7	14.1	157
9/Ganymede	2.42	7.2	11.7	174
10/Ganymede	2.42	5.6	9.2	181
11/Europa	1.81	4.7	13.0	207
12/Europa	1.80	——	——	221

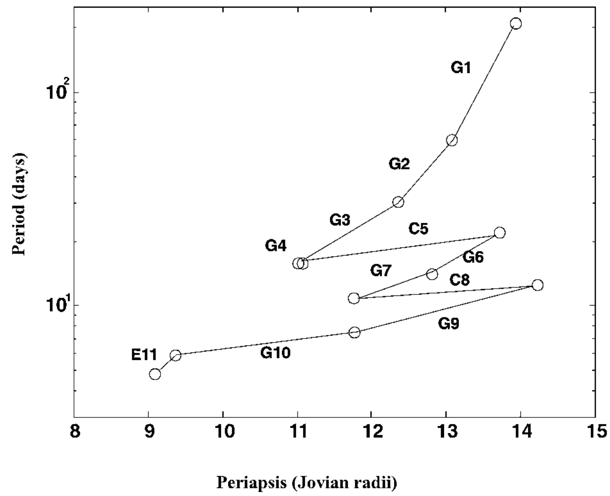

Fig. 6 Tisserand graph of tour 00-14 for a launch on 3 Jan. 2006.

Conclusions

The Europa orbiter mission presents new challenges in mission design because of the enormous number of possible tours. The automated gravity-assist design technique developed in earlier work proved ineffective (by itself) against this computationally gigantic task. Experience through trial and error, and the identification of some rules of thumb, provided inroads into the problem and resulted in a baseline, flyable tour. A breakthrough came with the discovery of a graphical method based on Tisserand's criterion. The graphical method led to great improvements in the V_∞ of arrival at Europa (which was reduced from 3.3 km/s to less than 2 km/s) and in the total radiation dosage (which was reduced by 70%). These results exceeded the expectations of mission designers at JPL. Now we have a theory that will guide all future tour design and that will have clear applications in future gravity-assist missions in the solar system.

The Tisserand graph approach has streamlined tour design for the Europa orbiter mission so that new tours with particular characteristics (such as flight time, low-radiation dose, and fewest flybys) can be quickly designed. The ability to adjust to changing requirements is critical because the launch date for the Europa orbiter mission has been slipped to 2006. Without a theory, such a slip could be devastating to mission designers. Yet we welcome the opportunity to demonstrate the power of this tool to design new Europa orbiter tours and to design new missions for the exploration for the solar system.

Acknowledgments

This research has been supported in part by the Jet Propulsion Laboratory, California Institute of Technology, under Contract Number 1211514 (G. T. Rosalia, Contract Administrator, and Dennis V. Byrnes, Technical Manager). NASA also supported this work through a NASA fellowship. We are particularly grateful to Louis A. D'Amario, Dennis V. Byrnes, Jennie R. Johannesen, and Jan M. Ludwinski, for their generous support, enthusiastic collaboration, and expert guidance. We thank Anastassios E. Petropoulos, a doctoral student in the School of Aeronautics and Astronautics at Purdue University, for his contribution to the development of the Tisserand graph. The first author thanks the NASA Marshall Space Flight Center for granting a Full Time Study fellowship, and specifically Patricia E. Avery and Irene E. Taylor for providing educational leave.

References

[1]Karl, D. M., Bird, D. F., Björkman K., Houlihan T., Shackelford R., and Tupas, L., "Microorganisms in the Accreted Ice of Lake Vostok, Antarctica," *Science*, Vol. 286, No. 5447, 1999, pp. 2144–2147.

[2]Johannesen, J. R., and D'Amario, L. A., "Europa Orbiter Mission Trajectory Design," American Astronautical Society, AAS Paper 99-360, Aug. 1999.

[3]Rinderle, E. A., "Galileo User's Guide, Mission Design System, Satellite Tour Analysis and Design Subsystem," Jet Propulsion Lab., JPL Internal Document D-263, California Inst. of Technology, Pasadena, CA, July 1986.

[4]Williams, S. N., "Automated Design of Multiple Encounter Gravity-Assist Trajectories," M.S. Thesis, School of Aeronautics and Astronautics, Purdue Univ., West Lafayette, IN, Aug. 1990.

[5]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.

[6]Patel, M. R., "Automated Design of Delta-V Gravity-Assist Trajectories for Solar System Exploration," M.S. Thesis, School of Aeronautics and Astronautics, Purdue Univ., West Lafayette, IN, Aug. 1993.

[7]Bonfiglio, E. P., "Automated Design of Gravity-Assist and Aerogravity-Assist Trajectories" M.S. Thesis, School of Aeronautics and Astronautics, Purdue Univ., West Lafayette, IN, Aug. 1999.

[8]Strange, N. J., and Longuski, J. M., "Graphical Method for Gravity-Assist Trajectory Design," *Journal of Spacecraft and Rockets*, Vol 39, No. 1, 2002, pp. 9–16; also AIAA Paper 2000-4030, Aug. 2000.

[9]Roy, A. E., *Orbital Motion*, 2nd ed., Adam Hilger, Bristol, England, U.K., 1982, pp. 129, 130.

[10]Heaton, A. F., "A Systematic Method for Gravity-Assist Mission Design," M.S. Thesis, School of Aeronautics and Astronautics, Purdue Univ., West Lafayette, IN, Dec. 2000.

[11]Labunsky, A. V., Papkov, O. V., Sukhanov, K. G., *Multiple Gravity Assist Interplanetary Trajectories*, 1st ed., Gordon and Breach Science Publishers, Amsterdam, 1998, pp. 101–197.

C. A. Kluever
Associate Editor