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TRAJECTORY DESIGN FOR A EUROPA ORBITER MISSION: A PLETHORA OF ASTRODYNAMIC CHALLENGES

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The icy moon of Europa is a hot topic in planetary exploration. This paper discusses the trajectory design of a Europa orbiter mission intended to find out if Europa is a possible habitat for extraterrestrial life. Getting into orbit at Europa is difficult; the simplest trajectory design (a direct Hohmann-type transfer to Jupiter followed by an immediate insertion into orbit at Europa) requires more than 5.5 km/s of velocity change capability by the spacecraft. This paper describes a number of trajectory design techniques which can reduce this AV requirement step by step down to around 2.5 km/s. The variety of trajectory "tricks" involved make this mission a showcase of modern trajectory design.

INTRODUCTION

The icy moon of Europa is a hot topic in planetary exploration. Beneath Europa's icy crust it may actually be hot; if it's hot then maybe there is a liquid water ocean underneath; if there is liquid water then maybe there's life there, extraterrestrial life, that is. The first step in examining whether life is possible on Europa is a mission to determine whether the conjectured liquid water ocean exists under the smooth ice surface. An orbiter mission would provide three kinds of evidence concerning such an ocean:

radar sounding data measuring the thickness of the ice over liquid water;

precise measurement of the gravity field of Europa using precision radiometric navigation from Earth to see how much the shape of Europa changes with time;

direct measurement of changes in the shape of Europa using precise orbit determination and laser altimetry.

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A number of requirements on the mission orbit follow from the nature of the above data measurements. In order to obtain clear radar sounding data without excessive power requirements, the periapse of the spacecraft orbit at Europa should be less than 200 km. Also the orbit must allow us to measure the gravity field and radius at the sub-Jovian point when Europa is near periapse and apoapse in its jovicentric orbit. This would allow us to calculate the change in Europa's radius at that point which could be as much as 30 m between the two extremes of distance from Jupiter (alternatively or additionally, the change could be measured at the anti-Jovian point).

Another mission goal is internally derived from the desire to maximize data return. This goal is that the operations phase of the mission occur as close to Earth as reasonably possible, i.e. within two months of Jupiter opposition.

MISSION OVERVIEW

The simplest mission would begin with a direct transfer to Jupiter with an arrival tangent to Europa's orbit so that the spacecraft would insert directly into an orbit around Europa. This however requires an orbit insertion maneuver of almost 5500 m/s, far exceeding reasonable spacecraft capability. Fortunately there are a number of ways to change the trajectory and reduce the required AV. These trajectory "tricks" are summarized here and will be discussed in more detail in the rest of the paper.

The first step is to use a more efficient means of reducing our arrival energy at Europa by inserting into an initial orbit about Jupiter. Since kinetic energy is proportional to velocity squared, a given velocity change will result in a larger energy change when the velocity is higher. So the closer to Jupiter we can do our Jupiter orbit insertion (JOI) the better. Once we are in orbit at Jupiter, we need to raise perijove to tangency with Europa's orbit to minimize the arrival velocity at Europa; this is best done at apojove, and the further from Jupiter the better. Ideally we would use a parabola as an intermediate orbit and raise perijove at zero cost when the spacecraft is "at infinity," but this would take infinite time and also takes us out of Jupiter's sphere of influence. So instead an intermediate ellipse replaces the ideal parabola. A further improvement in the arrival sequence can be found by doing a gravity assist at one of the Galilean satellites to reduce the jovicentric velocity. We have now rediscovered the arrival strategy of the Galileo mission to Jupiter.

The next step is to reduce the AV needed to insert into orbit at Europa. There are several ways to do so. Since the spacecraft is in a larger orbit than the body it is going to we can use a technique first proposed by Chen-Wan Yen for a Mercury mission[1], the reversed AV-gravity-assist. With this technique a series of Europa flybys to shrink the jovicentric orbit are alternated with apojove maneuvers to raise the spacecraft's perijove. Also, since the spacecraft orbit crosses the orbits of Ganymede and Callisto (at least in the initial orbits), flybys of those bodies can be used to raise perijove and thus replace the initial apojove maneuvers. Once the spacecraft orbit has been shrunk down to a 6:5 resonance with Europa, the reversed ΔV-Europa gravity assist (ΔV-EuGA) technique is less efficient than a straightforward periapse maneuver at Europa, but there is one more trick in the trajectory design kit: it is possible to do the final approach to Europa along a trajectory on the Weak Stability Boundary of Europa with respect to Jupiter. This leads to a free ballistic "capture" at Europa, just as Belbruno and Miller found for transfers to the Moon[2].

Our baseline mission, then, begins with a direct transfer to Jupiter. An example of such a transfer is shown in Figure 1, which also shows the initial large ellipse around Jupiter. At arrival, an incoming Io or Ganymede flyby is used to reduce the spacecraft energy as much as possible. The trajectory after the flyby is aimed as close to Jupiter as possible to minimize the AV needed for capture at Jupiter. A Jupiter Orbit Insertion burn (JOI) is performed to put the spacecraft into a 200 day orbit and at the apoapse of that orbit a Perijove Raise maneuver (PJR) is done. The next perijove of this capture ellipse commences a tour of the Galilean satellites which ballistically (i.e., with no deterministic AV) reduces the energy of the spacecraft orbit until the spacecraft orbit is almost inside Ganymede's orbit. Then reversed ΔV-Europa-gravity-assists are used to further reduce the energy of the spacecraft orbit with minimal AV costs. When the spacecraft orbit is down to a 6:5 resonance with Europa's orbit, the spacecraft targets for a weak stability capture at an altitude of 100 km. At the Europa periapse, a Europa orbit insertion (EOI) is done into a circular orbit. The spacecraft stays in this orbit for one month to do radar sounding, gravity field determination, and laser altimetry and then the mission ends.

This baseline trajectory naturally falls into several phases: Earth/Jupiter transfer, Jupiter capture, tour, Europa orbit insertion, and Europa operations. These phases are described separately in more detail below along with options to the baseline for selected phases.

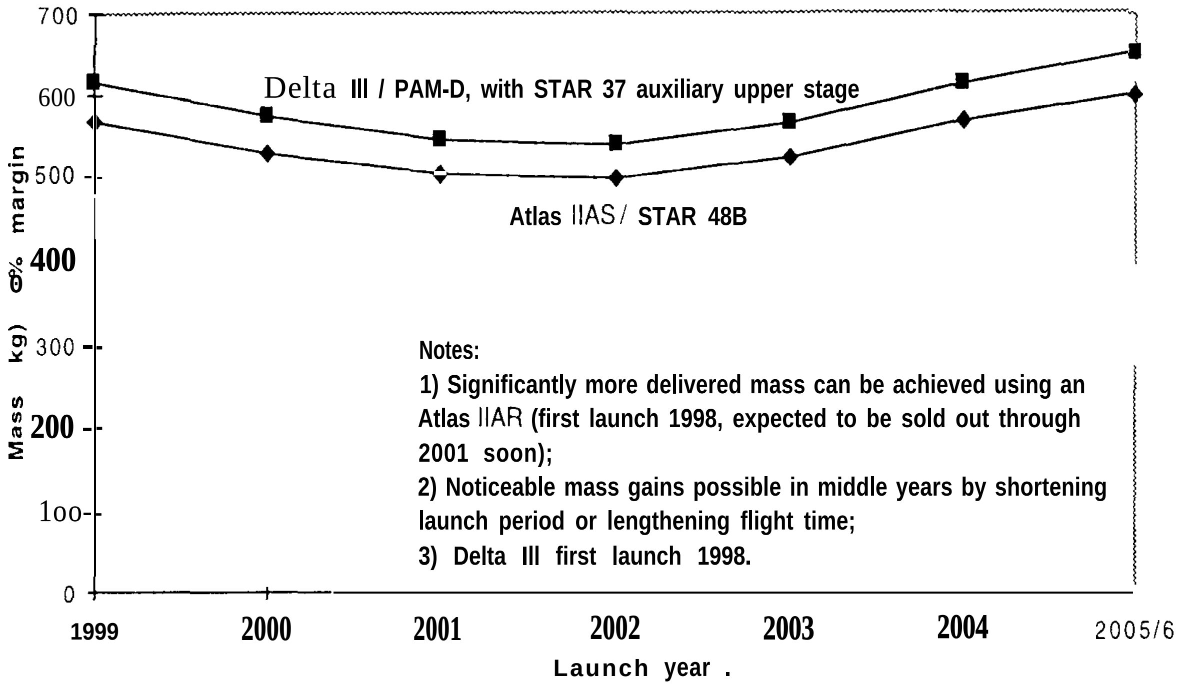
EARTH/JUPITER TRANSFER PHASE

Type I direct transfers take about two and one-half years from Earth to Jupiter. By the geometry of the transfer an opposition occurs 3.6 years after launch, which allows one year for the tour before operations begins. Direct transfers were examined for the years 1999 through 2006 (opportunities occur every 13 months) where the launch period was 15 days and the arrival was restricted to occur no later than one year before the opposition 3.6 years after launch. In every year after 1999 the performance requirements are minimized for launch and post-launch ΔV if a broken-plane maneuver is performed on the way to Jupiter. The results are summarized in Table 1, where the value in each column is the extreme over the launch period:

Table 1. Direct Earth/Jupiter Transfer Characteristics

Opportunity	Launch open	C3 (km2/s2)	DLA (degrees)	ΔV (m/s)	V-infinity (km/s)	DAP (degrees)
1999	Jul 1	81.76	8.1	0	5.651	-5.2
2000	Aug 2	83.00	24.1	240	5.739	-6.6
2001	Sep 4	83.72	31.1	411	5.519	-4.5
2002	Oct 4	82.53	30.1	450	5.607	1.9
2003	Nov 4	81.32	24.0	360	5.719	4.0
2004	Dec 4	79.83	13.1	170	5.802	5.3
2006	Jan 5	77.74	-13.6	44	6.099	6.6

In order to compare these transfers, delivered wet mass in Jupiter orbit serves as a performance index which reflects the different launch energies and post-launch AVS required. In order to calculate this we allocate an additional 100 m/s for trajectory correction maneuvers *en* route to Jupiter and assume an Isp of 325 s to calculate the propellant mass needed. We also assume that an additional hardware mass equal to 10% of propellant mass is needed for increases in the propulsion subsystem dry mass. We subtract the propellant mass and additional hardware mass from the injected mass to arrive at a delivered wet mass. (Thus the “delivered wet mass” does not include the mass of the additional tankage, etc., needed for propellant used for maneuvers from Earth departure through Jupiter Orbit Insertion (JOI), even though this additional hardware mass is actually delivered as well). The results are given in Figure 2 for two intermediate expendable launch vehicles. (These results use planning estimates of the launch vehicle performances, so the values obtained and especially the difference between the launch vehicles should be taken as very preliminary; the year-to-year change, however, should be reasonably accurate.)



Notes:
1) Significantly more delivered mass can be achieved using an Atlas IIAR (first launch 1998, expected to be sold out through 2001 soon);
2) Noticeable mass gains possible in middle years by shortening launch period or lengthening flight time;
3) Delta III first launch 1998.

Figure 2. Delivered wet mass in a 200 day orbit at Jupiter for direct transfers taking 2.5 years from Earth.

As noted in Figure 2 the delivered mass can be increased by allowing a longer flight time. In particular, Figure 1 shows a trajectory with a 3.6 year flight time which is optimal for a launch in 2001; it has a launch C_3 of 83.1 km^2/s^2, a deep-space AV requirement of 210 m/s, and an arrival V_∞ of about 5.9 km/s. In comparison with the data in Figure 2, the trajectory which is shown in Figure 1 has a delivered wet mass of a little over 530 kg for the Atlas IIAS/STAR 48 launch vehicle and the same assumptions as used before. The longer flight time can be accommodated operationally since Jupiter oppositions occur every 1.1 years so the arrival is one year before the opposition which occurs about 4.7 years after launch. (Recall that we would like to conduct Europa orbit operations near an opposition).

As an alternative to direct transfers, gravity assist trajectories can be used to increase the mass delivered to Jupiter or perhaps allow selection of a smaller, less expensive launch vehicle for the same mass. For example, a AV-Earth gravity assist (ΔV-EGA) transfer as first introduced by G.R. Hollenbeck[3] is a viable method for improving delivery mass capability. For this mission, the delivered wet mass into Jupiter orbit increases to well over 1000 kg for the above launch vehicles even after the additional deep-space AV is accounted for. This type of transfer takes four and one-half years (because of the two year Earth-return loop added at the beginning of the transfer).

Total mission flight time is thus significantly longer than for direct transfers. Another disadvantage to an Earth gravity assist is that having one on the transfer trajectory would make it very difficult to get approval for use of a radioisotope power source, which is desirable for this mission because of Jupiter's distance from the Sun and Earth.

Another example of a gravity assist trajectory is one using multiple Venus gravity assists, avoiding the approval problems of an Earth gravity assist. A very nice triple Venus gravity assist transfer trajectory has been found for a March 2001 launch and is shown in Figure 3. This transfer has a launch C_3 of 16.3 km^2/s^2, a deep-space AV requirement of 354 m/s, and an arrival V_∞ of 6.7 km/s. Although the deep-space and JOI AV requirements combined are somewhat higher than in the direct cases for that year, the greatly reduced C_3 allows a much higher injected mass. With the assumptions above (except for a higher navigation allowance of 300 m/s because of the additional flybys of Venus) the net delivered mass is over 1300 kg. The performance improvement might even be enough to allow the use of a Delta II launch vehicle for this mission. Such performance improvement is not without other costs, though — the flight time for this trajectory is 6.7 years, almost twice what even the longer direct transfer requires. Also, triple Venus flyby transfer opportunities do not occur every year, nor are they all quite this good. Double Venus flyby transfers are more frequent and have a shorter flight time of 4.5 years to 5 years, but often require around 1500 m/s for deep space maneuvers (including a powered flyby at Venus). They offer performance (in terms of delivered wet mass) between direct and triple Venus transfers and would need larger propellant tanks than either.

A very different alternative would be to use large solar arrays to power a solar electric propulsion module which would be jettisoned before JOI.

JUPITER CAPTURE PHASE

Given the objective of being captured with a perijove at Europa's orbit, the optimal two-body maneuver sequence is to go as deep into Jupiter's gravity well as possible, capture into the largest possible ellipse, and raise perijove to Europa's orbit radius of 9.4 R_J (Jupiter radii) by a maneuver at apojove of the capture ellipse. As mentioned above the optimal capture orbit would actually be a parabola (an ellipse to infinity) if we consider Jupiter's system alone. In the presence of solar perturbations, Galileo mission design experience was that the total AV required for JOI and PJR tended to level off for capture orbit periods between 150 and 250 days. We have selected an initial capture ellipse period of 200 days to balance between the needs to minimize AV and to complete the tour by Jupiter opposition; this ellipse period leaves us close to the minimum AV.

Conic analyses gave AV requirements for JOI burns done without flybys, with a Ganymede flyby, and with an Io flyby, all for JOI done at 1.02 R_J, an incoming V_∞ of 5.65 km/s, and with satellite flyby altitudes of 500 km. The two satellite flyby cases came out with essentially the same total AV, Ganymede being a couple of meters per second better, and they were about 50 m/s better than when no flyby occurs. The AV for JOI is then about 315 m/s, for PJR is about 435 m/s to raise perijove from 1.02 R_J to 9.4 R_J, and the total is about 750 m/s.

In the real world additional considerations cause the actual Capture Phase AV to be higher: there will be small gravity losses at JOI, Jupiter's oblateness will raise the perijove velocity noticeably, the incoming arrival is some degrees out of the plane of the Galilean satellite orbits, and the solar perturbations during the initial capture ellipse increase the PJR maneuver needed for the same effective perijove raise. The inclination of the incoming trajectory can probably be removed by the first flybys, before JOI and at the beginning of the tour. When the direct transfer case shown in Figure 1 is integrated through the capture phase using an Io flyby and impulsive maneuvers, the AV for JOI comes out to be 340 m/s and for PJR comes out to be 540 m/s. This transfer has an incoming V_∞ of 5.9 km/s rather than 5.65 km/s which was used in the conic analysis, which explains the increase in the JOI AV; the increase in the PJR AV is greater than expected from Galileo experience and is not entirely understood. This latter increase over the value from conic analysis still appears to be due to solar perturbations; the greater magnitude of the increase (compared to Galileo) may be due to a different geometry at Jupiter arrival. The Io flyby was chosen over the Ganymede flyby for science reasons. This capture phase trajectory is shown in Figure 4 and a close-up of it around Jupiter in Figure 5.

TOUR PHASE

From the 200-day jovicentric ellipse, a tangent approach to Europa's orbit leaves a V_∞ with respect to Europa of 5.36 km/s, so that a periapse maneuver of 4.32 km/s is needed to insert into a 100 km altitude circular orbit. As mentioned before, it is more effective when coming from a larger orbit into insertion at a secondary body to do an alternating series of gravity assists which lower the period and the perijove radius and deep-space maneuvers which primarily raise perijove.

It may seem counter-intuitive that one can reduce the orbit energy more efficiently by doing maneuvers at apoapse when the velocity is lowest, especially when the maneuvers themselves add energy. This has been discussed in an earlier paper by Ted Sweetser[4], and has to do with the fact that in a restricted three-body system the energy of the spacecraft (which depends in part on its inertial velocity) is not constant — instead Jacobi's integral (which depends in part on the velocity in the rotating system instead of the inertial velocity) is conserved along the trajectory. In the Jupiter/Europa system, on ellipses which are tangent to Europa's orbit and have a period greater than about 6/5 of Europa's period, the velocity at apojove in the rotating system is greater than the velocity at periapse of a Europa flyby. Thus for these orbits maneuvers at apojove are more effective than powered flybys.

A couple of years ago, Chen-Wan Yen[5] found a Europa gravity assist sequence which reduced the jovicentric orbit from 200 days to a 6:5 resonance and which required about 1100 m/s in deterministic maneuvers. Given that final orbit and assuming that Europa's orbit is circular, a conic analysis shows that the V_∞ approaching Europa is 0.77 km/s and that EOI into a circular orbit would require about 720 m/s. Thus this technique cuts the Europa arrival ΔV by more than a half. Once again the cost is flight time — this tour takes on the order of a year.

Further AV reduction is possible by taking advantage of the fact that the initial tour orbits cross the orbits of Ganymede and Callisto. These orbit crossings make it possible to replace some of the apojove maneuvers with gravity assists. Indeed, one tour has been found which required no maneuvers to reduce the spacecraft orbit below Ganymede's orbit using 13 flybys of Ganymede, Callisto, and Europa, thus saving about 700 m/s over the series of AV-Europa gravity assist (ΔV-EuGA) orbits. This multisatellite tour begins with a perijove near Ganymede in 2002, consistent with a fast direct transfer launching in 1999. A plot of this tour is shown in Figure 6 and characteristics are given in Table 2 [TBD]. Galileo mission design experience is that each flyby requires about 10 m/s for trajectory correction and navigation. Additionally, the final orbits of the conicly-defined ΔV-EuGA tour need about 400 m/s to achieve a 6:5 resonance with Europa's orbit. Figure 7 shows an example of the final, ΔV-EuGA portion of the tour; characteristics of this tour are given in Table 3 [TBD]. The tour depicted begins with a 3:1 resonance with Europa's orbit and takes just a bit over 300 m/s up to the last maneuver in the 6:5 resonant orbit which sets up the arrival at Europa. Conic analysis tells us this last maneuver should be just under 70 m/s. The maneuvers between the 3:1 resonant orbit and the 2:1 resonant orbit total just over 90 m/s, which it should be possible to reduce or even remove with Ganymede flybys depending on the geometry at the transition between the types of tour.

Unfortunately the combined multisatellite and ΔV-EuGA tour takes about two months longer than available before opposition. We continue to search for satellite tours which satisfy our mission constraints. We believe that it should be possible to reduce the duration of the multi-satellite portion of the tour by another month to meet the operations constraint.

EUROPA ORBIT INSERTION PHASE

As stated above conic analysis shows that from a jovicentric spacecraft orbit in 6:5 resonance with Europa's orbit, capture into a circular orbit at 100 km altitude above Europa's surface requires 720 m/s plus some additional ΔV for gravity loss. But it is possible to do better than this by using three-body dynamics, in particular the Weak Stability Boundary around Europa with respect to Jupiter.

The tremendous third-body effects of Jupiter can be significant in the Europa orbit insertion. Integrating the state with both Jupiter's and Europa's gravity included in the acceleration models, it is possible to start from an altitude of 100 km in an ellipse around Europa with 0.9 eccentricity and, with no maneuver, escape into a jovicentric orbit in 6:5 resonance with Europa's orbit. This would save as much as 200 m/s in the orbit insertion if a capture using these three-body effects with the same characteristics could be found.

Because a near-polar orbit at Europa is needed to make global mapping possible, an attempt was made to find a free ballistic capture into a polar orbit. This attempt has been unsuccessful to date, apparently because the excursions out of Europa's orbit plane necessary to arrive over a pole make it difficult to come from an encounter at a different point on Europa's orbit.

More recently scientists[6] have advised us that an orbit with inclination as low as 45 deg would be acceptable for determining the shape variations of Europa as its distance from Jupiter changes. Using a multistep, multiconic propagator a periapse state on a **45** deg inclined ellipse with 100 km periapse altitude and 0.9 eccentricity was propagated backwards to apojove; the longitude of the ascending node and the argument of periapse were varied until the apojove radius matched that on the 6:5 resonant ellipse of the ΔV-EuGA tour above and the date of arrival and eccentricity were then varied also until the apojove longitude and time approximately matched as well.

The resulting elliptical periapse state at Europa was then added to the initial conditions of the AV-EUGA tour, an additional maneuver time was set for one day after the apojove maneuver on the 6:5 resonant orbit, and an optimizing integrator was used to generate a continuous reduced-AV trajectory ending in ballistic "capture". The total AV for this tour completion was 520 m/s including just under 220 m/s in the two maneuvers on the final orbit before arrival and just over 90 m/s in the maneuvers on the first two orbits, which overlap with the final orbits of the multisatellite tour. Circularization from the final periapse state requires another 520 m/s plus small additional AV for gravity losses (which can be controlled by doing smaller partial periapse burns on successive orbits). The trajectory for this final approach to Europa is shown in Figure 8, starting four days (almost one orbit) before the final apojove maneuver.

EUROPA OPERATIONS PHASE

The operational orbit at Europa has been chosen to be circular at 100 km altitude, both to maximize science return and because it is necessary for the orbit to have a fairly low altitude in order for it to be stable. An orbit at this altitude was integrated with the effects of Jupiter's gravity and a presumed non-spherical gravity field at Europa; the propagation showed that the periapse altitude varied by only a couple of kilometers over the course of a month-long trajectory. Another orbit with the same periapse altitude but an apoapse altitude of 1000 km was found to drop its periapse altitude to a minimum of 83 km and then raise it again (at 90 deg inclination) or to intersect the surface (generally undesirable) within about a day (at 89 deg inclination).

The altitude and other parameters of the operations orbit are still objects of discussion among scientists and mission designers. It should be at least 45 deg inclined to maximize mapping coverage for the radar and minimize errors in determining changes in Europa's shape as it orbits Jupiter. For navigation purposes we need this orbit to be at least 20 degrees from being either edge on or face on to Earth. We also need it to be aligned so that its line of nodes is within 30 degrees of the line of apsides of Europa's orbit. Since we have a four month period around opposition for our one month of operations to occur in and the line of apsides precesses by about 18 degrees per month, it should be possible to meet all these constraints in any launch year.

The spacecraft will experience eclipses and occultations each orbit ranging from very short (if it is nearly 20 degrees from face on) to about 46 minutes (at 20 degrees from edge on). The orbit period itself is about 126 minutes. Also there will be an eclipse/occultation by Jupiter lasting 3 hours on every Europa orbit, i.e., every 3.55 days. It is possible that these eclipses could string together to make a maximum total eclipse of about 5 hours unless the operations orbit is synchronized with Europa's orbit.

FALLBACK FLYBY MISSION

If it should prove impossible to deliver the required mass to Europa for the mission described above, one possible fallback mission would be to do a series of very close flybys of Europa and do radar sounding only, not unlike the Cassini mission's radar mapping of Titan. An example tour has been designed which gave about 30 flybys of Europa with only 60 m/s AV needed, but the flyby altitudes were not constrained to be below 200 km. When the periapse altitude of flybys was constrained to a maximum of 200 km then the tour required a bit over 360 m/s. Since this constrained tour contains most of its AV requirement on only a half-dozen orbits it should be possible to come close to the AV found for the unconstrained case by relaxing the altitude constraint on only a few of the flybys. One limitation of this flyby strategy is that most of the flybys are over only a few points on Europa's equator, near 30, 140, 22o, and 340 west longitude, followed by a series of flybys at various latitudes along the prime meridian. The main exceptions were two flybys around 210 west longitude at 40 north and 45 south latitude, and one flyby very near the north pole of Europa. Both tours were preceded by a number of Ganymede flybys to bring the orbit down from the initial large post-JOI ellipse and both were constrained to a minimum altitude of 50 km. A plot of the Europa flyby orbits for the constrained case is given in Figure 9, which shows that the flybys occur over a variety of lighting conditions as the jovicentric orbits rotate considerably relative to the line toward the Sun.

CONCLUSION

A number of trajectory design techniques have been discussed. These techniques can be used to greatly reduce the AV required to perform a difficult mission such as a Europa orbiter, but generally AV reduction is achieved by increasing the complexity and flight time of the trajectory. Table 4 shows how the introduction of each trick of the trade reduces the AV needed to a value almost 600/0 less than that needed for the simplest trajectory.

Table 4

AV REQUIREMENTS AT JUPITER FOR V.AR1OUS TRAJECTORY OPTIONS.

Conic analysis results, where each column adds an element of the strategy. The last column, which includes integrated analysis, gives an improved estimate.

(All AVS are in meters per second.)

	Direct	Low JOI	IGA	ΔV-EuGa	GGA CGA	WSB	Final
JOI	·	3s0	320	320	320	320	340
Grav loss	·	10	10	10	10	10	10
PJR	—	430	430	430	430	430	540
Solar perb.	—	50	50	50	50	50	—
Tour **AV**	—	—	—	1100	400	500	430
Tour nav	—	·	—	50	150	150	150
EOI	5400	4330	4330	720	720	520	520
Grav loss	500	400	400	20	20	15	15
Margin	200	300	300	300	300	300	200
Total	6100	5900	5840	3000	2400	2295	2205

cronyms: JOI -- Jupiter Orbit Insertion	ΔV-EuGA - ΔV-Europa Gravity Assist
PJR – Perijove Raise Maneuver	GGA -- Ganymede Gravity Assist
EOI - Europa Orbit Insertion	CGA - Callisto Gravity Assist

WSB – Weak Stability Boundary capture

Table 4 includes estimates for gravity losses of 9% for very large maneuvers and 3’% for other periapse maneuvers; navigation allowances are roughly 10 m/s per flyby for the multisatellite portion of the tour and a few m/s per resonance for the ∆V-EuGA portion of the tour (since that portion akeady includes apojove maneuvers). Margins were based on the size of the maneuvers in the first three columns and on the complexity of the trajectory and the limitations of conic analysis in the second three columns. Note that the “Final” trajectory numbers are based on a mixture of conic and integrated analyses of each phase and that these phases were not entirely consistent with each other (e. g., the JOI and PJR numbers are based on a different launch year than the tour numbers), hence the continued inclusion of margin.

FUTURE WORK

There is still clearly a lot of work to be done in the design of an actual Europa orbiter mission. Tour design and finding the best sequence of satellite flybys is a major area of needed effort. Even just defining what is “best” requires attention; note that we have said very little about the radiation environment around Jupiter, which is a major concern and will affect design decisions. We also have to avoid Jupiter’s rings, so our ring plane crossings need to be considered in the tour design.

Another major area of needed effort is understanding the behavior of orbits around Europa as their semi-major axes and eccentricity grow from the values we assumed. How eccentric can the orbit be before it becomes unstable or changes undesirably? This area of study could lead to further reductions in the required EOI AV.

One of the biggest problems we face is the absence of any tool to aid the design of the end of the tour including the WSB capture at the final satellite. Conic analysis is entirely inappropriate for this analysis and the integrating optimizer requires good initial conditions because the problem is so non-linear. Some kind of multiconic or integrating propagator with heuristic design aids and interactive operation with graphics is needed.

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REFERENCES

1. C.-W. L. Yen, “Ballistic Mercury Orbiter Mission via Venus and Mercury Gravity Assists,” AAS Paper 85-346, presented at the AAS/AIAA Astrodynamics Specialist Conference, Vail, Colorado, 12-15 August 1985.

2. Belbruno and Miller

3. G. R. Hollenbeck, “New Flight Techniques for Outer Planet Missions, ” AAS Paper 75-087, presented at the 1975 AAS/AIAA Astrodynamics Specialist Conference, Nassau, Bahamas, 28-30 July 1975.

4. T. H. Sweetser, “Jacobi’s Integral and ΔV-Earth-Gravity-Assist(ΔV-EGA) Trajectories,” AAS Paper 93-635, presented at the AAS/ AIAA Astrodynamics Specialist Conference, Victoria, Canada, 16-19 August 1993.

5. Chen-Wan Yen, personal communication.

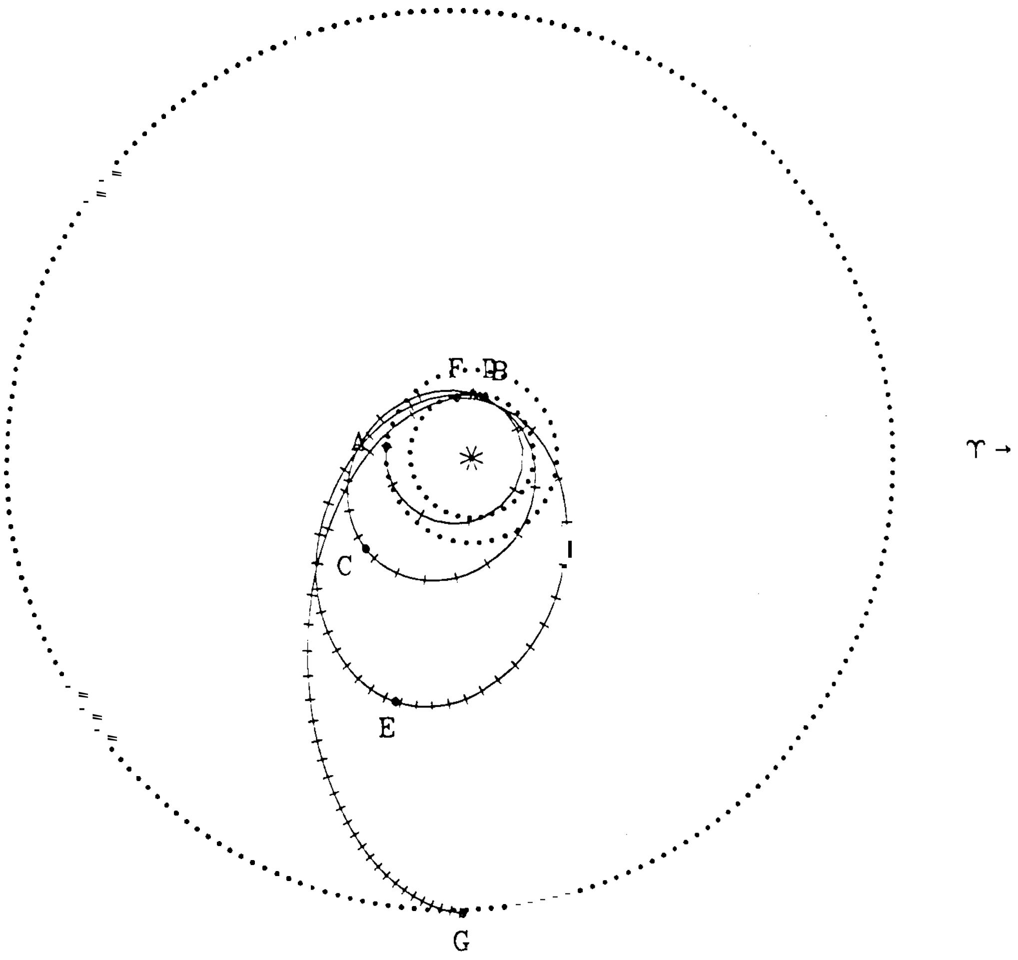
6. Charles Yoder, personal communication.

7. K. Kiedron and T. H. Sweetser, “A Comparison Between Onestep and Other Multiconic Trajectory Propagation Methods”, Paper AIAA 88-4286, in *AIAA/AAS Astrodynamics Conference (Proceedings),* pp. 532-544, AIAA, Washington, 1988.

Figure 3

2001 EUROPA VVV

30 day tics on s/c



Earth
Jupiter
Venus
——— Spacecraft

Event Times

A	Mar 11, 2001
B	Aug 31, 2001
C	Mar 22, 2002
D	Nov 27, 2002
E	Feb 14, 2004
F	May 27, 2005
G	Nov 16, 2007

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Figure 5

Jupiter arrival and first orbit

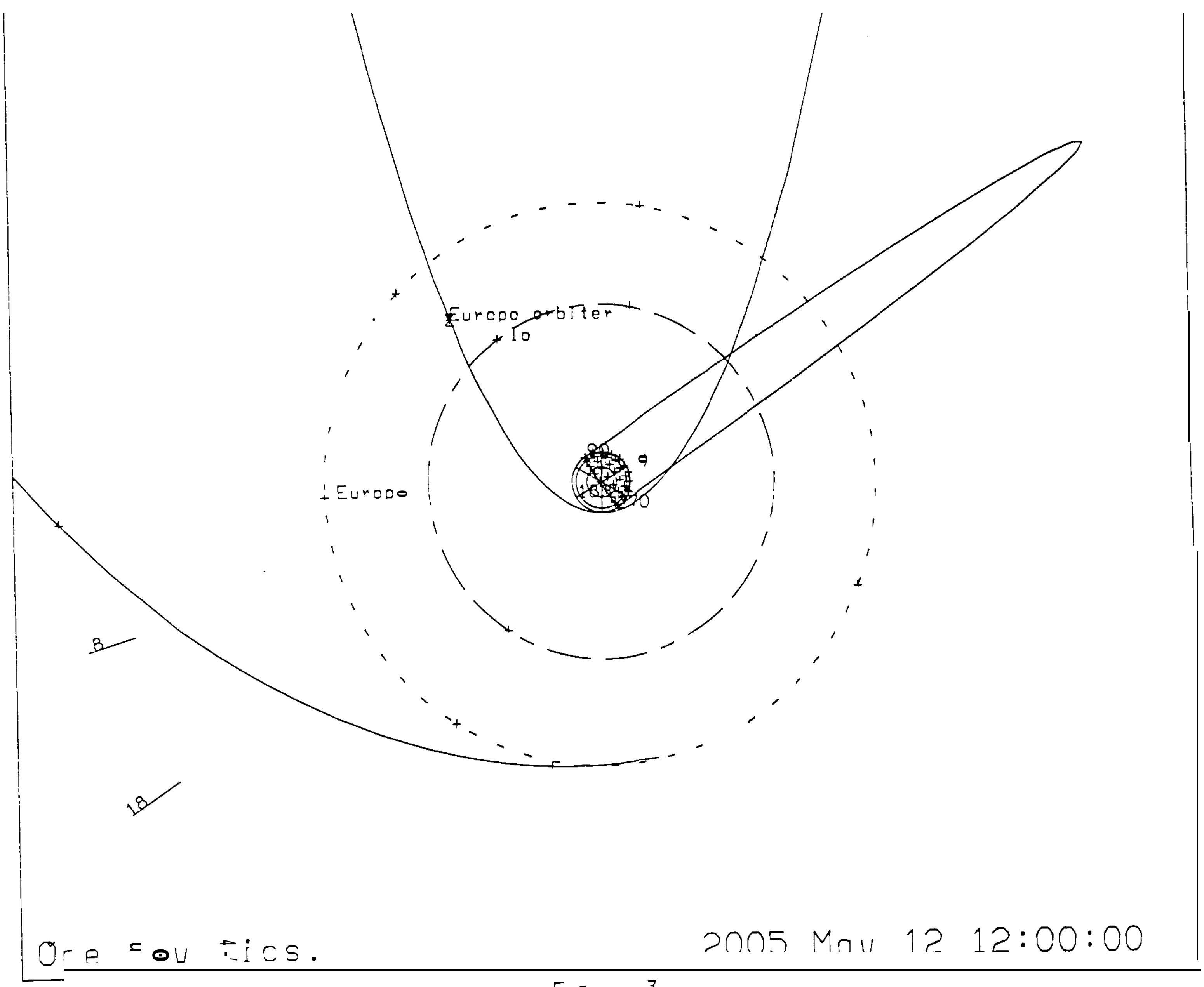

Fig 3

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Figure 7

Jupiter tour end and Europa rendezvous

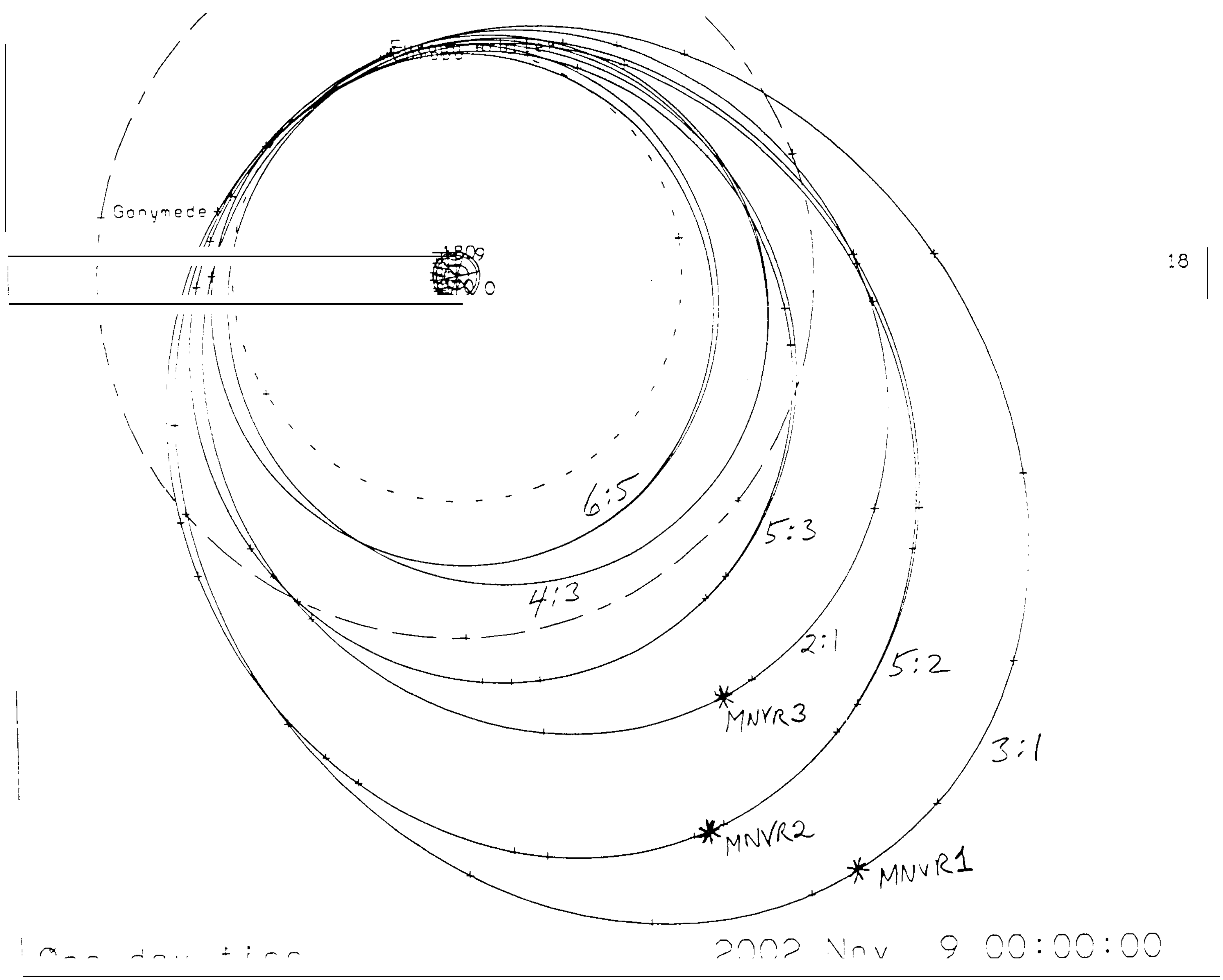

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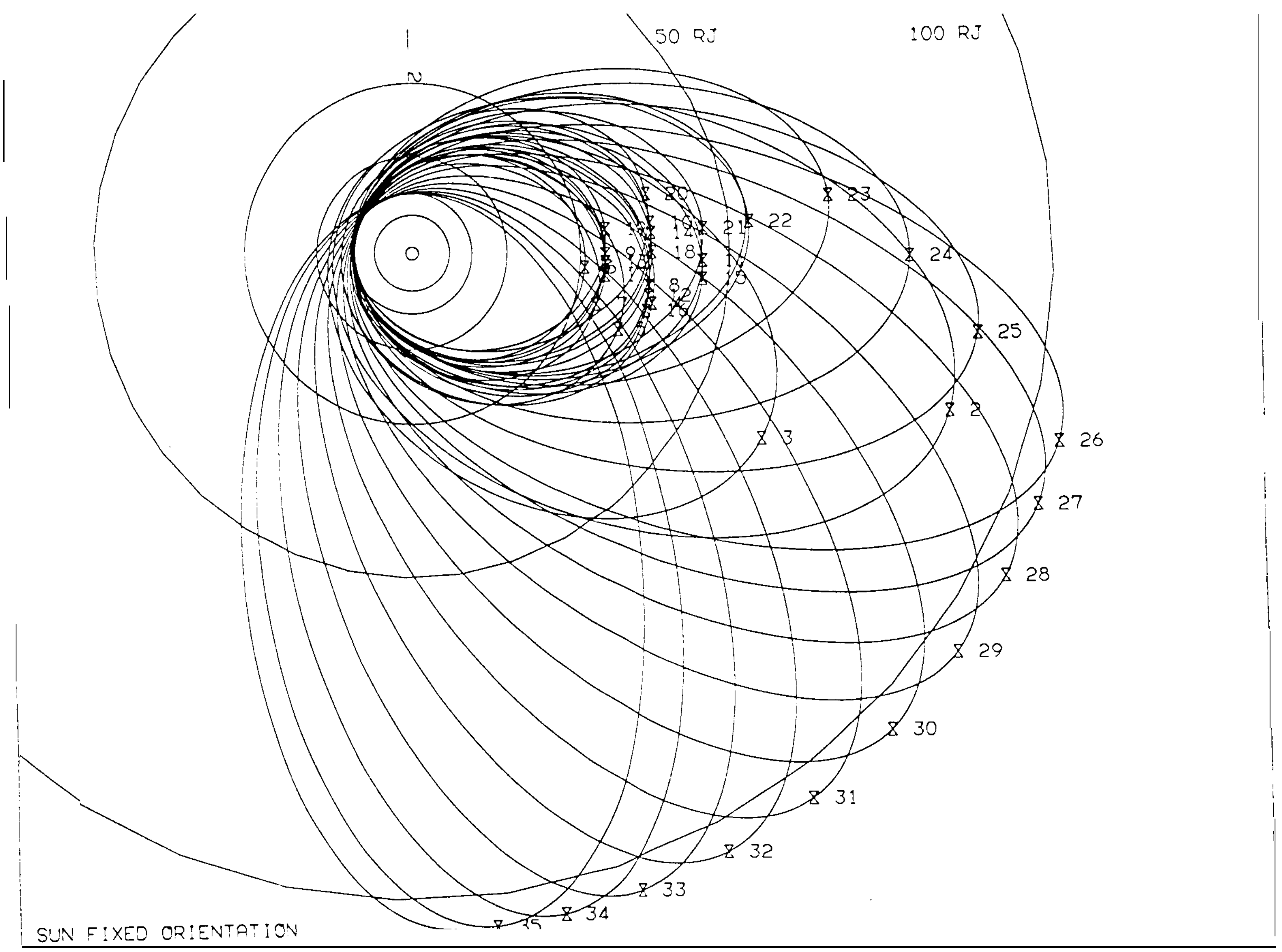
Figure 9

PETAL PLOT FOR EUROPA ORBITER MISSION WITH CONSTRAINED ALTITUDES



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