Trajectory Design for a Europa Orbiter Mission: A Plethora of Astrodynamic Challenges

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by

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The first step in examining possible life on Europa is an mission to determine whether a 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 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.

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 near both apsides to measure the change at that point (alternatively or additionally, the change could be measured at the anti-Jovian point).

Another mission requirement is internally derived from the need to maximize data return. This requirement 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 ΔV.

Our baseline mission begins with a direct transfer to Jupiter to get there as quickly as reasonably possible. At arrival, an incoming 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 ΔV needed for capture at Jupiter. A Jupiter Orbit Insertion burn (JOI) is performed to put the spacecraft into an 200 day orbit and a Perijove Raise maneuver (PJR) is done at the apoapse of that orbit. The next perijove of this capture ellipse commences a tour of the outer Galilean satellites which ballistically (i.e., with no deterministic ΔV) reduces the energy of the spacecraft orbit until the spacecraft orbit is entirely inside Ganymede's orbit. Then reversed ΔV-Europa-gravity-assists are used to further reduce the energy of the spacecraft orbit with minimal ΔV costs. When the spacecraft orbit is down to a 6:5 resonance with Europa's orbit, the spacecraft targets for a polar flyby and performs a Europa Orbit Insertion burn (EOI) to end up in a polar circular orbit around Europa at an altitude of 100 km. 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 arc described separately in more detail below along with options to the baseline for selected phases.

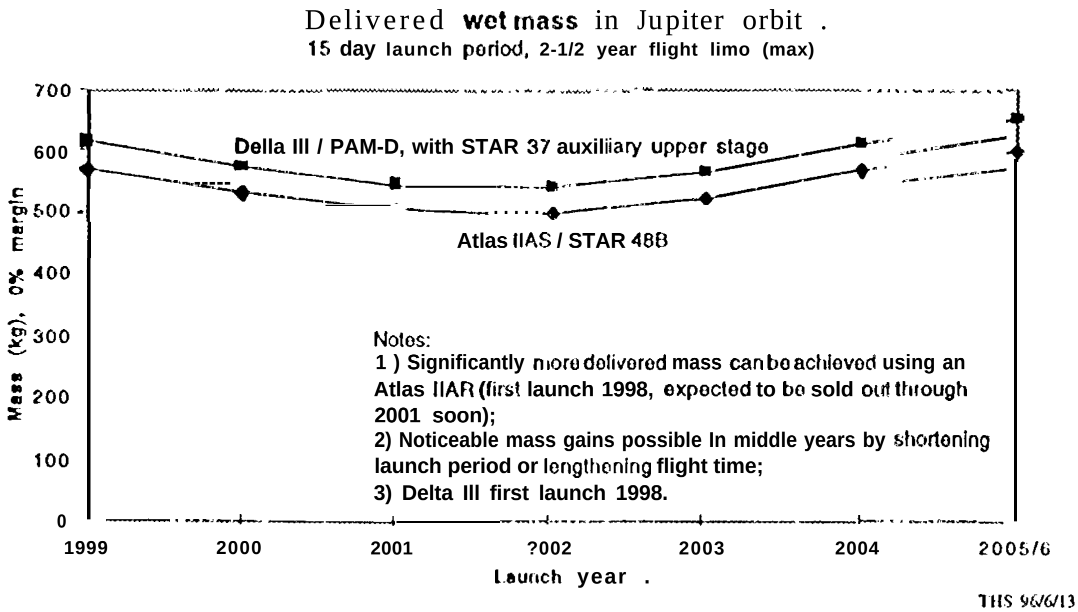
Earth/Jupiter Transfer I'base

Type 1 direct transfers take about two and one-half yews from Earth to Jupiter and by the geometry of the transfer an opposition occurs 3.6 years after launch, allowing 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 the first the performance requirements are minimized for launch and post-launch AV if a broken-plane maneuver is performed on the way to Jupiter. The results are summarized in the following table, where the value in each column is the extreme over the launch period:

Direct Earth/Jupiter Transfer Characteristics

opportunity	Launch open	C3 (km2/s2)	DLA (degrees)	AV (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 wc allocate an additional 100 m/s for trajectory correction maneuvers *en route* to Jupiter and assume an Isp of 325 s with an addition equal to 10'% of propellant mass needed for increases in the propulsion subsystem dry mass (so the delivered wet mass is without the additional tankage, etc., needed for additional AV through Jupiter Orbit Insertion (JOI) even though this additional mass is actually delivered as well). The results are given in the figure for two intermediate expendable launch vehicles.



As an alternative to direct transfers, gravity assist trajectories can be used to increase the mass delivered to Jupiter. For example, an Earth gravity assist is a viable method for improving delivery mass capability. 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), so total mission time is significantly longer than for direct transfers, but the delivered wet mass into Jupiter orbit increases to well over 1000 kg for the above launch vehicles. Another example of a gravity assist trajectory could be a multiple Venus gravity assist trajectory taking five or six years. A very different alternative would be to use large solar arrays to power a solar electric propulsion module which would be jet tisoned before J()].

Jupiter Capture Phase

Given the objective of being captured with a perijove at Ganymede'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 pei ijove at apojove of the capture ellipse. in the presence of solar perturbations, however, Galileo mission design experience was that the total AV requir cd tended to level off between 150 and 250 days. We have selected an initial capture ellipse period of 200 days to balance between the need to minimize AV and 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 RJ (Jupiter radii) and with satellite flyby altitudes of 500 km. The two satellite flybys came out with the same ΔV, Ganymede being a couple of meters per second better, and they were about 75 m/s better than no flyby. The total for JOI and PJR then is about 750 m/s plus small gravity losses at JOI.

In the real world two additional considerations will cause the actual Capture Phase ΔV to be higher: the incoming arrival is some degrees out of the plane of the Galilean satellite orbits and the solar perturbations during the initial capture ellipse will increase the PJR maneuver needed (by perhaps more than 50 m/s). The inclination of the incoming trajectory can probably be removed by the first flybys, before JOI and at the beginning of the tour.

Tour Phase

We continue to search for satellite tours which satisfy our mission constraints. 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 600 m/s over a series of ΔV-Europa gravity assist orbits (and kilometers/second over a direct rendezvous). Unfortunately it takes about two months longer than available before opposition. We believe that it should be possible to reduce the tour duration by another month to meet the operations constraint.

Galileo mission design experience is that each flyby requires about 10 m/s for trajectory correction and navigation. Additionally, a ΔV-Europa gravity assist tour done with conic orbits for a previous study showed that about 300 m/s is needed to complete the tour when the spacecraft orbit is inside Ganymede's orbit, where completion is defined as achievement of a 6:5 resonance with Europa's orbit.

Europa Orbit Insertion Phase

From a jovicentric spacecraft orbit in 6:5 resonance with Europa's orbit, the spacecraft v-infinity coming in tangent to Europa's orbit is about 770 m/s. With this hyperbolic incoming velocity, capture into a circular orbit at 100 km altitude requires 720 m/s plus some gravity loss.

The tremendous third-body effects of Jupiter can be significant in the Europa orbit insertion. We have found that 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. Thus if we were extremely fortunate in our geometry at the end of the Tour Phase we could save as much as 200 m/s in the orbit insertion due to Jupiter effects.

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 be stable. It is polar to maximize mapping coverage for the radar. 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 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 radar mapping of Titan. An example tour has been designed which gave about 30 flybys of Europa with only navigation ΔV needed, but the flyby altitudes were not constrained to be below 200 km. Further work is being carried out in this regard. One expected result is that flybys will be restricted to be either near the equator or near two particular longitude meridians.

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