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# JOVIAN TOUR DESIGN FOR ORBITER AND LANDER MISSIONS TO EUROPA

**Stefano Campagnola,[*] Brent B. Buffington,[†] Anastassios E. Petropoulos,[‡]**

Europa is one of the most interesting targets for solar system exploration, as its ocean of liquid water could harbor life. Following the recommendation of the Planetary Decadal Survey, NASA commissioned a study for a flyby mission, an orbiter mission, and a lander mission. This paper presents the moon tours for the lander and orbiter concepts. The total $\Delta v$ and radiation dose would be reduced by exploiting multi-body dynamics and avoiding phasing loops in the Ganymede-to-Europa transfer. Tour 11-O3, 12-L1 and 12-L4 are presented in details and their performaces compared to other tours from previous Europa mission studies.

## INTRODUCTION

When in the late 1990s the Galileo spacecraft found compelling evidence of an ocean of liquid water beneath Europa's icy shell, the Galilean moon surged as one the most interesting bodies in the solar system, as it may possess all the ingredients for extraterrestrial life.[1–3] For this reason, over the last decade NASA and ESA have studied a variety of mission concepts dedicated to the exploration of Europa,[4–11] often finding that the estimated costs or risks where too high for the current technological and budgetary constraints. Following the recommendation in the Planetary Decadal Survey[12] however, NASA commissioned a new study to investigate new options for an Europa mission. A Science Definition Team (SDT) and a combined JPL and APL technical team soon determined that the key science questions about Europa's habitability could be addressed by three groups of investigations, to be carried independently by an Europa orbiter, an Europa lander, and a multiple-flyby mission.

An Europa orbiter would provide systematic geophysical measurements of gravity, topology, and magnetic field, to characterize the extent of the ocean and its relation to the deeper interior. An Europa lander would perform *in-situ* measurements to investigate the surface chemistry and mineralogy of the landing site and the nature of near-surface organics and salts. A flyby mission would focus on characterizing the ice shell, understand surface composition, and perform high-resolution targeted geological observations, and use the time between Europa flybys to transmit the high volume of data back to Earth when the spacecraft is outside the radiation belts[13].

Each spacecraft could be launched in 2021 and would reach Jupiter after a 6.37 year interplanetary cruise that would include one Venus and two Earth gravity assists. After the Jupiter arrival, the

[*]Department of Space Flight Systems, ISAS, JAXA, Yoshinodai 3-1-1, Chuo-ku, Sagamihara-shi, Kanagawa-ken 252-5210, JAPAN, stefano.campagnola@jaxa.jp

[†]Outer Planet Mission Analysis Group, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive , Pasadena, CA 91109, brent.buffington@jpl.nasa.gov

[‡]Outer Planet Mission Analysis Group, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive , Pasadena, CA 91109, anastassios.e.petropoulos@jpl.nasa.gov

trajectories of the orbiter, lander and flyby mission would target different science objectives. This paper presents the tour design of the orbiter and lander concepts, while the tour design of the flyby mission and the interplanetary trajectory were presented in a previous paper.[14] Additional details of the Europa Habitability Mission study are available in the May 2012 Final Study Report.[13]

The next section introduces the Europa orbiter mission and tour 11-O3, while section 3 introduces the Europa lander missions and tours 12-L1 and 12-L4. In both tours, the last part of the trajectory, called "courtship phase", is designed to minimize the $\Delta v$ costs and the total ionizing dose behind a 100-mil Aluminum spherical shield (TID), while satisfying the trajectory constraints. The $\Delta v$ is reduced with high-altitude flybys and Tisserand-leveraging transfers[15] that connect the high-energy part of the tour to the low-energy approach at Europa. The epoch of the Europa Orbit Insertion is selected to (1) minimize the TID by preventing phasing loops in the Ganymede-to-Europa transfer, (2) avoid any solar conjunction during any critical portion of the mission, and, (3) achieve the desired local solar time (LST) at the target science orbit.

The last section of the paper compares the $\Delta v$ and TID of tours 11-O3, 12-L1, and 12-L4, to those of other tours used in past Europa mission studies - in particular tour 99-35,[5] tour 08-008,[10] and the Banzai-Pipeline tour.[11] In general, a significant reduction of $\Delta v$ (or of radiation dose) is found with little or no penalty on the radiation dose (or $\Delta v$), suggesting such types of multi-body, low-radiation courtship phases be part of any future Europa orbiter or lander tour.

## EUROPA ORBITER

The Europa Orbiter Mission concept would deploy a highly capable, radiation-tolerant spacecraft into orbit around Europa to collect a global data set to map the moon's surface morphology, its tidal cycle through gravity fluctuations, and its ocean induction signature through investigation of Europa's interaction with the Jovian magnetosphere. These measurements would be performed from a 100 km, 2- to 4- PM LST, near-polar orbit over the course of a 30-day science mission. The model planning payload assumed for the Europa Orbiter Mission consists of a notional set of remote-sensing instruments (Laser Altimeter and Mapping Camera), *in-situ* instruments (Magnetometer and Langmuir Probe), and a telecommunications system that provides Doppler and range data for accurate orbit reconstruction in support of geophysical objectives.

The Orbiter Mission would start with the spacecraft launch on an Atlas V 551 that places it on a 6.537 year Venus–Earth–Earth Gravity Assist (VEEGA) interplanetary trajectory. At Jupiter arrival, a Ganymede flyby followed by a Jupiter Orbit Insertion maneuver (JOI) would put the spacecraft into a closed orbit around Jupiter; then a sequence of Ganymede, Callisto and Europa flybys would reduce the spacecraft energy with respect to Europa. The trajectory in the Jupiter system is typically referred to as Jovian tour. The 11-O3 tour is optimized for low $\Delta v$ and low TID, and it is described in details in the next section. Finally, the Europa Orbit Insertion (EOI) burn would place the spacecraft directly into a 100 km, circular, near-polar science orbit. After a short checkout period, science observations would be conducted for 30 days. This orbit and the mission duration were chosen to meet the science objectives for gravity science, laser altimetry, and mapping.

**Tour 11-O3**

At Jupiter arrival, a 500 km-altitude Ganymede flyby* (G0) and a $\sim$ 800 m/s JOI maneuver would put the spacecraft on a 230-day capture orbit. At the first apojove, a 122 m/s Perijove Raise maneuver (PJR) would increase the osculating perijove to about 15 $R_J$. Four Ganymede flybys (G1-G4) would then be used to decrease the energy and the inclination of the spacecraft orbit. The flybys are connected by orbits with a period commensurable to the period of Ganymede, starting from an 11:1 resonance orbit (spacecraft-to-Ganymede revolutions between flybys) , followed by a 8:1 resonance and a 5:1 resonance. A small orbit trim maneuvers (OTM) is included between G1 and G2. The last flyby (G4) would be used to target the first Callisto flyby (C5), which would pump up the perijove and target the next Ganymede flyby. To adjust the phasing for the last part of the tour, G9 would temporarily increase the spacecraft period to a 6:1 resonance, while G7 and G8 would decrease the period to a 3:1 and a 2:1 resonance. G9 would further reduce the orbit period and target the second Callisto flyby (C10), which would pump up the perijove beyond Ganymede orbit.

With the last Callisto flyby commences a critical part of any Europa orbiter or lander mission: the Europa "courtship phase". This phase generally includes impulsive maneuvers and flybys at Ganymede and Europa, and culminates with an Europa Orbit Insertion maneuver (EOI). With the exclusion of JOI, the majority of the TID and $\Delta v$ costs are accumulated in these last few months of the tour. The design of the courtship phase is complicated by the requirements on the science orbits (especially on its local solar time), and by operational constraints (no solar conjunction is allowed for 60 days before EOI and for 30 days after EOI).

In the 11-O3 tour, as in the others presented in this paper, the courtship phase is designed with a novel approach, where multi-body dynamics are exploited to minimize the total $\Delta v$ costs. At the same time, the epoch of EOI is chosen to enforce the mission constraints, and to avoid phasing loops in the Ganymede-to-Europa transfer, where up to 80 krad per orbit are accumulated. Once the courtship phase is designed, the first part of the tour is computed backward in time to patch the Jupiter arrival conditions.

Following C10, the courtship phase of tour 11-O3 would include two high-altitude flybys at Ganymede (G11 and G12) connected by a 3:2 resonance orbit, with the spacecraft osculating perijove always beyond Ganymede's orbit. G12 would place the spacecraft on a 1:1 resonance, and G13 would be followed by a 2.5-day, Hohmann-like transfer to Europa. Because of the high altitudes of G13 and E14, a single statistical maneuver would be sufficient during this short transfer. Note that using multi-body dynamics, the $v_\infty$ at G13 and the energy at Europa † is lower than in a regular Hohmann transfer. After E14, two maneuvers and a second high-altitude Europa flyby (E15) would further reduce the spacecraft energy relative to Europa. E14 and E15 are followed by 4:3 and 6:5 resonant orbits, respectively, both with their perijove beyond Europa orbit. In traditional tour design, this final part of the tour (called the "endgame"[4,16,17]) consists of low-altitude flybys and $v_\infty$-leveraging maneuvers[16,18–26] and is typically designed in the linked-conics model, where the spacecraft is subject to the gravity of Jupiter only, and flybys are modeled as instantaneous changes of velocities. The endgame of tour 99-35 was re-designed in the full model with a low-energy approach at Europa, yielding to some $\Delta v$ saving. The tours in this paper implement high-altitude

*The altitude $h$ of the flybys is constrained to be higher than 100 km, except for the altitude of G0 ($h > 500$ km), G1 ($h > 200$ km), and of the first Callisto flyby ($h > 200$ km) .

†$v_\infty$ for E14 is not defined because the spacecraft orbit does not intersect Europa's orbit, and because of the high-altitude of the closest approach.

flybys and Tisserand-leveraging maneuvers[15] (TLM, low-energy equivalent of the $v_\infty$- leveraging maneuvers) throughout the courtship phase, resulting in even larger$\Delta v$ savings *.

The complete tour is shown in Fig. 1(A) and (B) in the ecliptic reference frame J2000, centered at Jupiter ($xy$ projection and $xz$ projection). Fig. 1(C) shows a close-up plot of the courtship phase, while Fig. 1(D) shows the arrival at Europa and the first revolution of the science orbit, with solar local time of about 3:40 PM.

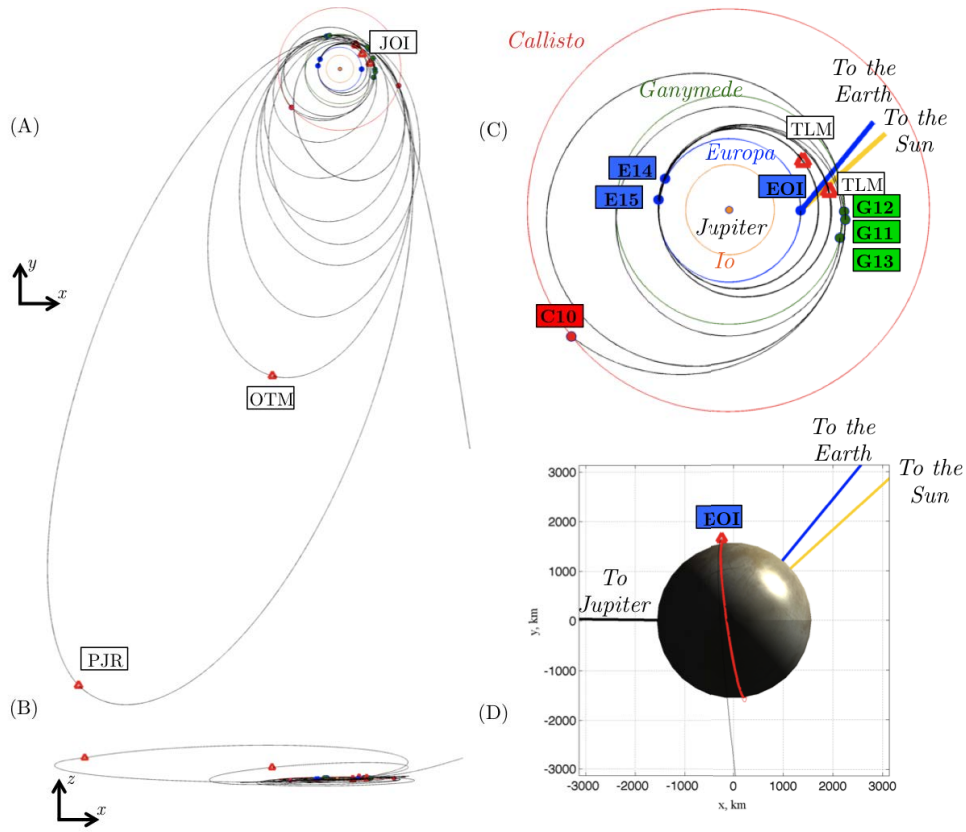


**Figure 1. Tour 11-O3 on the ecliptic reference frame J2000.**

Figure 2 shows the distance from Jupiter as function of the calendar date. The figure also shows the dates of the solar conjunction, i.e. when the Sun lays between the Earth and the spacecraft and communication with the ground station would be impeded. The first solar conjunction would occur early in the tour, while the second occurs two months before EOI, between the high-altitude flybys G11 and G12. The same plot also shows the TID time history . The majority of the radiation would be accumulated during the courtship phase (from C10 to EOI) . Table 1 lists all the significant events of the tour.

Figure 3 shows a discrete, two-dimensional representation of the tour on the Tisserand-Poincaré graph. The graph is a 2D projection of a Poincaré section of the trajectory with Tisserand level-sets. The spacecraft Tisserand parameter relative to a moon is an approximation of the Jacobi constant of the spacecraft-moon-Jupiter three-body problem, and can be defined as function of the osculating apojove and perijove. It is also a measure of the spacecraft $v_\infty$,[29,30] whenever the $v_\infty$ is defined, i.e.

* A similar design strategy was implemented for the JUICE mission to Ganymede.[15,27,28]

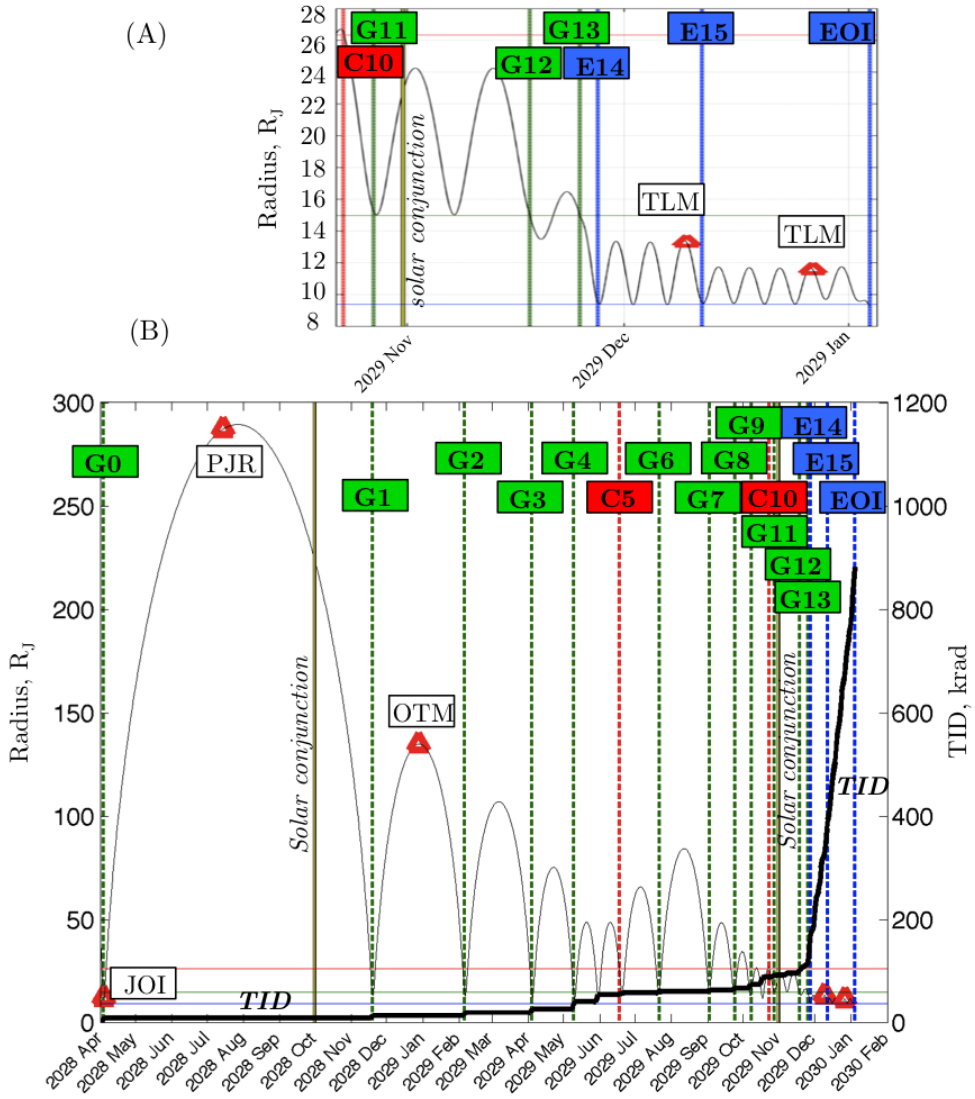


**Figure 2. Radius vs. date and TID vs. date for the orbiter tour 11-O3**

very close to the flyby-body, or far from it, if the spacecraft osculating orbit intersects the flyby-body orbit. When the spacecraft crosses the Poincaré section (typically some section of the flow far from any moon), its osculating perijove and apojove are recorded on the graph. If a flyby occurs between two consecutive section crossing, the spacecraft coordinates moves on the graph, remaining on the same the Tisserand level-set. For example, at the beginning of the tour the spacecraft osculating apojove and perijove jump between the resonant lines 32:1, 11:1, 8:1 and 5:1 after the flybys G1-G4.

Impulsive maneuvers are also represented on the graph: prior to G1, the PJR maneuver is shown as a jump between two points with the same apojove. The effect of the Sun perturbation, which lowers the osculating perijove during the first orbit, is also visible before and after PJR. Finally, for each moon the graph shows boxed regions representing the linked-conics domain, i.e. the set of orbits intersecting the orbit of the moon, and for which the linked-conic model can be used. When

**Table 1. Events of the orbiter tour 11-O3**

| EVENT | DATE (ET Calendar) | MANEUVER $\Delta$v (km/s) | FLYBY v$\infty$ (km/s) | Alt. (km) | In /Out |
|---|---|---|---|---|---|
| *Earth escape* | *2021 NOV 22 00:01:13* | *3.852* | *3.77* | *200* | |
| *Venus* | *2022 MAY 14 09:30:43* | | *6.62* | *300* | *In* |
| *Earth* | *2023 OCT 24 22:41:49* | | *12.07* | *11761* | *In* |
| *Earth* | *2025 OCT 24 09:06:48* | | *12.05* | *3330* | *In* |
| Ganymede 0 | 2028 APR 03 11:53:40 | | 7.99 | 500 | In |
| JOI | 2028 APR 03 22:53:35 | 0.812 | | | |
| PJR | 2028 JUL 14 13:40:14 | 0.122 | | | |
| Ganymede 1 | 2028 NOV 18 20:22:49 | | 5.61 | 629 | In |
| OTM | 2028 DEC 28 04:45:07 | 0.005 | | | |
| Ganymede 2 | 2029 FEB 05 12:34:23 | | 5.68 | 100 | In |
| Ganymede 3 | 2029 APR 03 17:20:35 | | 5.8 | 3370 | In |
| Ganymede 4 | 2029 MAY 09 11:45:33 | | 5.79 | 643 | In |
| Callisto 5 | 2029 JUN 17 12:40:13 | | 5.48 | 221 | In |
| Ganymede 6 | 2029 JUL 21 13:57:07 | | 3.87 | 6645 | Out |
| Ganymede 7 | 2029 SEP 02 10:32:53 | | 3.79 | 268 | Out |
| Ganymede 8 | 2029 SEP 23 21:08:34 | | 3.77 | 2009 | Out |
| Ganymede 9 | 2029 OCT 08 04:05:01 | | 3.76 | 2730 | Out |
| Callisto 10 | 2029 OCT 23 05:10:28 | | 1.77 | 2124 | In |
| Ganymede 11 | 2029 OCT 27 09:33:56 | | N/A | 23667 | N/A |
| Ganymede 12 | 2029 NOV 17 22:51:09 | | N/A | 4900 | N/A |
| Ganymede 13 | 2029 NOV 24 20:15:57 | | 1.19 | 1185 | In |
| Europa 14 | 2029 NOV 27 08:10:12 | | N/A | 6681 | N/A |
| TLM | 2029 DEC 09 15:08:29 | 0.054 | | | |
| Europa 15 | 2029 DEC 11 17:16:32 | | N/A | 6563 | N/A |
| TLM | 2029 DEC 27 01:25:06 | 0.097 | | | |
| EOI | 2030 JAN 03 21:29:49 | 0.477 | N/A | 100 | |

limited to the linked-conic domain, the Tisserand-Poincaré graph is equivalent to the well-known Tisserand graph.[31,32]

Figure 3B is a close-up of the Tisserand-Poincaré graph, which shows that the courtship phase occurs mostly outside the linked-conics domain. Navigating the low-energy "wings" outside the linked-conics domain has two advantages: first, the spacecraft can transfer between moons at lower energy levels than required by a linked-conics Hohmann transfer; second, impulsive maneuvers are more efficient in changing the spacecraft energy because the Tisserand (energy) curves are more dense. For a more detailed discussion on the Tisserand-Poincaré graph and its use in for low-energy transfers, we refer the interested reader to Campagnola et al.[17,33,34]

## EUROPA LANDER

The lander mission would be composed by two elements, a Carrier and a soft Lander. The Lander would analyze the localized chemistry and composition of the surface and of the near-surface. It

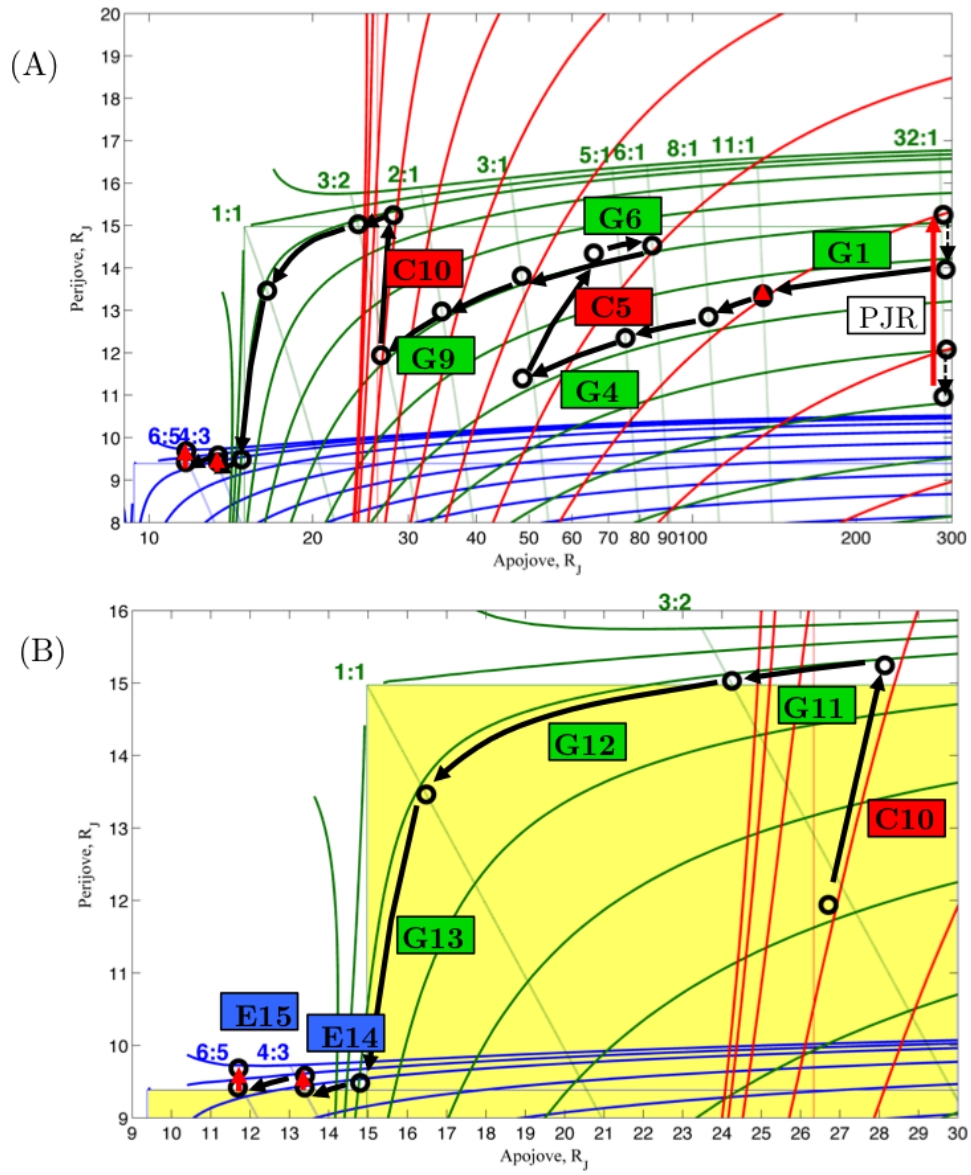


**Figure 3. Tisserand-Poincaré graph of the orbiter tour 11-O3**

would perform sample morphology and high resolution imagery of landing site, and conduct a seismological and magnetic study of the local and regional ice and ocean thickness and dynamics. The Lander payload would consist of a Mass Spectrometer, a Raman Spectrometer, a Magnetometer, a Multiband Seismometer Package, a Site Imaging System, and a Microscopic Imager. The Carrier payload would consist only of Reconnaissance Camera to aid landing site selection, but would also have a high-gain antenna enabling bent pipe lander-to-Earth data relay.

The lander and the carrier would be launched as a single spacecraft with a Delta IV Heavy on the same VEEGA interplanetary trajectory of the orbiter and flyby missions. After Jupiter arrival and over the course of 1.5 years, the spacecraft would fly the Jovian tour 12-L1, which is described in detail in the next section. Another tour option was also considered and is presented in this paper (12-

L4), which requires less propellant but more shielding mass. At the end of the tour, the spacecraft would be placed into a near-polar, near-circular 200-km-altitude orbit. The solar local time was initially constrained within the interval 7-9 AM, and later in the study was fixed to 7:30 AM. After 30 days in this site-certification orbit, periapsis would be lowered to 5 km, where the Lander would be released to perform its 1.4 km/s de-orbit burn and landing sequence. After separation, the Carrier would return to the 200-km circular orbit to perform data-relay functions and to take images of the Lander. The Carrier would remain in orbit for a nominal mission of 30 days, after which, if left uncontrolled, would impact Europa due to natural orbit periapsis decay over the course of two to three months.

**Jovian tour 12-L1**

It is desired to keep the TID as low as possible during the Jovian tour so to avoid having to carry extra shielding mass for the Lander (landed mass affects both the Lander wet mass and the Carrier wet mass); To meet this low-TID goal, the Jovian pump-down tour would use gravity assists of only Ganymede and Callisto, which are just outside the main radiation belts, and it would maintain periapsis as high as possible, near Ganymede's orbit, before approaching Europa. EOI would be performed after a Hohmann-type transfer from Ganymede. To reduce EOI below the two-body Hohmann value, multi-body gravitational effects would be used in the final Ganymede gravity assist sequence—the spacecraft's orbit essentially would skirt Ganymede's and Europa's, rather than intersecting them. Jupiter cruise would have a TID of 125 krad up to EOI.

After JOI and a perijove raise maneuver (PJR), the Jovian cruise would start with three resonant Ganymede flybys which would greatly reduce the orbital period and energy. The first Callisto flyby, C4, would raise periapsis while not greatly affecting orbital energy. Three more Ganymede flybys would be again used for energy reduction, followed by C8 for periapsis raising. There would follow the last three flybys of the tour, G9 through G11, involving resonances of 3:2 and 1:1 . The 3:2 resonance would have a small deterministic $\Delta$V of 14 m/s at apojove of the second spacecraft revolution. The G10 flyby would set up a 1:1 resonance leading to G11, which then puts the spacecraft on a transfer to Europa. The transfer is Hohmann-like, but has even lower $v_\infty$ at Europa than a traditional Hohmann because multi-body effects are exploited.

Figure 4 (A) and (B) show the lander tour 12-L1 in the ecliptic reference frame; Fig. 4 (C) shows a close-up of the courtship phase and Fig. 4 (D) shows the final Europa approach. The LST of the science orbit would be about 9 AM, which satisfies the early requirement set by the mission team, but not the final one. A modified version of the 12-L1 tour can be designed with limited or no penalties in $\Delta v$ and TID to obtain the desired 7:30 AM LST.

Figure 5 shows the time evolution of the distance from Jupiter and of the accumulated radiation dose. One solar conjunction would appear in the early part of the trajectory; since no endgame is included in this tour, the EOI epoch is chosen months before the November 2029 solar conjunction shown in Fig. 2. Table 2 lists the main events of the tour. The Tisserand-Poincaré graph in Fig. 6 shows that large part of the courtship phase lays outside the linked-conics domain.

**Jovian tour 12-L4**

Later in the study, a second tour option was proposed with a low-energy endgame to reduce the $\Delta v$ at the expenses of the TID. For a fast design, a trajectory similar to tour 11-O3 is used until the last Europa flybys. To change the SLT from 3:40 PM to 7:30 AM without re-designing large portion

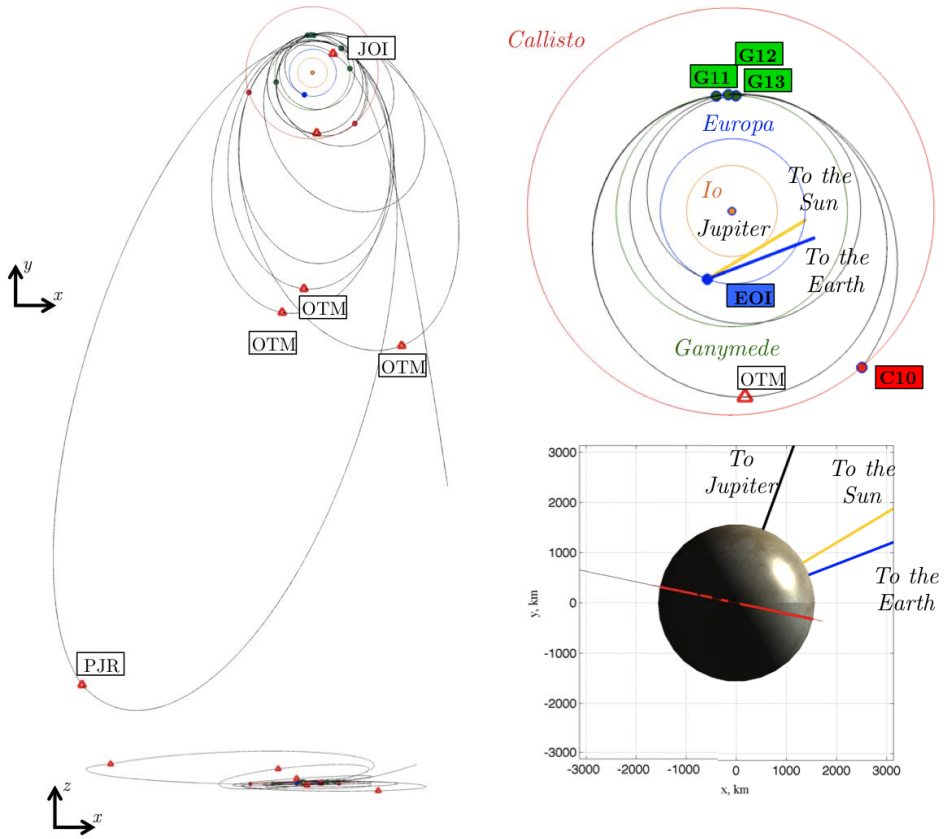


**Figure 4. Tour 11-O3 on the ecliptic reference frame J2000.**

of the tour, or incurring in high $\Delta v$ penalties, the final approach of 11-O3 is modified so that the spacecraft would be gravitationally captured in a one-day closed-orbit around Europa. The capture is ballistic, i.e. no maneuver would be required until the next pericenter passage, where the EOI would eventually put the spacecraft on its target science orbit.

Figure 3 (A) shows the gravitational capture trajectory as seen from the Earth. The figure also shows the projection on the ecliptic plane of the courtship phase (B) and of the gravitational capture (C). During the gravitational capture orbit, the Jupiter-gravity perturbation would change the plane of the spacecraft orbit around Europa so that the final approach is near-polar, with a 7:30 AM descending node.

Table 3 lists the tour events, which clearly shadow the events of tour 11-O3 in Table 1 until E15. Finally, Figure 3 shows the arrival trajectory in a rotating frame centered at Europa that keeps Jupiter on the negative x-axis. The gravitational capture (A) of tour 12-L4 is compared to the low-energy approach (B) of the orbiter tour 11-O3. Both trajectories would pass near the libration point L2 during their approach to Europa.

## COMPARISON OF ORBITER AND LANDER TOURS

An accurate comparison of the orbiter and lander tours which can be found in literature with the new tours presented in this paper should take into account the different Jupiter arrival conditions, and the specific assumptions and priorities in each tour design. Such analysis is beyond the scope

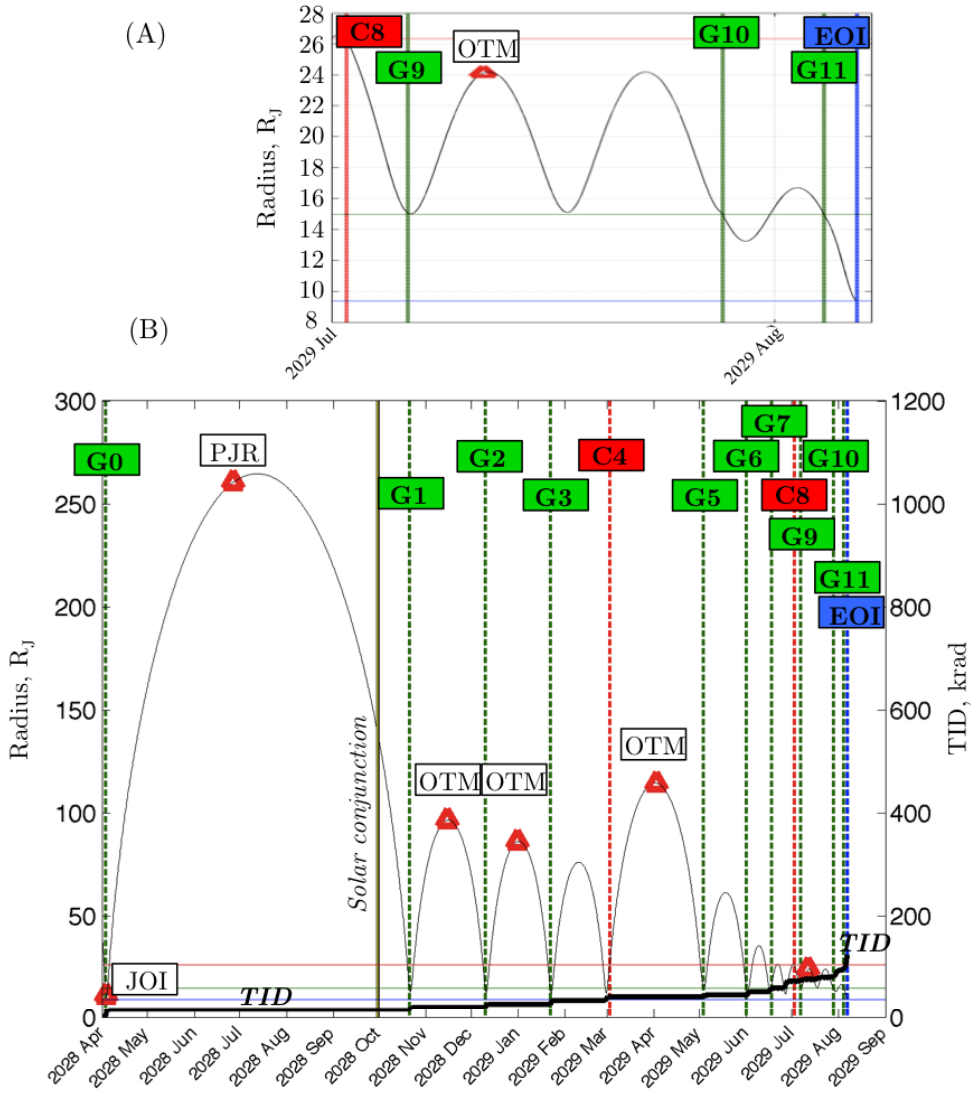


**Figure 5. Radius vs. date and TID vs. date for the lander tour 12-L1**

of this work; instead, the purpose of this section is to demonstrate the benefits of the low-energy, low-radiation courtship phase by showing the $\Delta v$, TID, and time of flight of both the courtship phase and of the total trajectory for the main Europa Orbiter and Lander tours.

Tour 99-35 was designed for NASA's Europa mission study in the 90s, with launch in 2003. The tour was computed in a linked-conics model,[35] then in a high-fidelity, full-ephemeris model; eventually a low-energy approach at Europa was included by Bonfiglio and Finlayson. Tour 08-008 was designed in the linked-conics model for the Jupiter Europa Orbiter study, with launch in 2020. The tour includes the Io campaign, an initial sequence of Io flybys that saves ~300 m/s from the JOI and PJR, for about one additional Mrad of TID and about two additional years of time-of-flight. Although the propellant mass saved is larger than the additional required shielding mass, the Io campaign is not included in the EHM study to mitigate the mission risks. Since tour 99-35 and 08-008 both include an Europa endgame with 4:3 and 6:4 resonances, two new fictional tours are

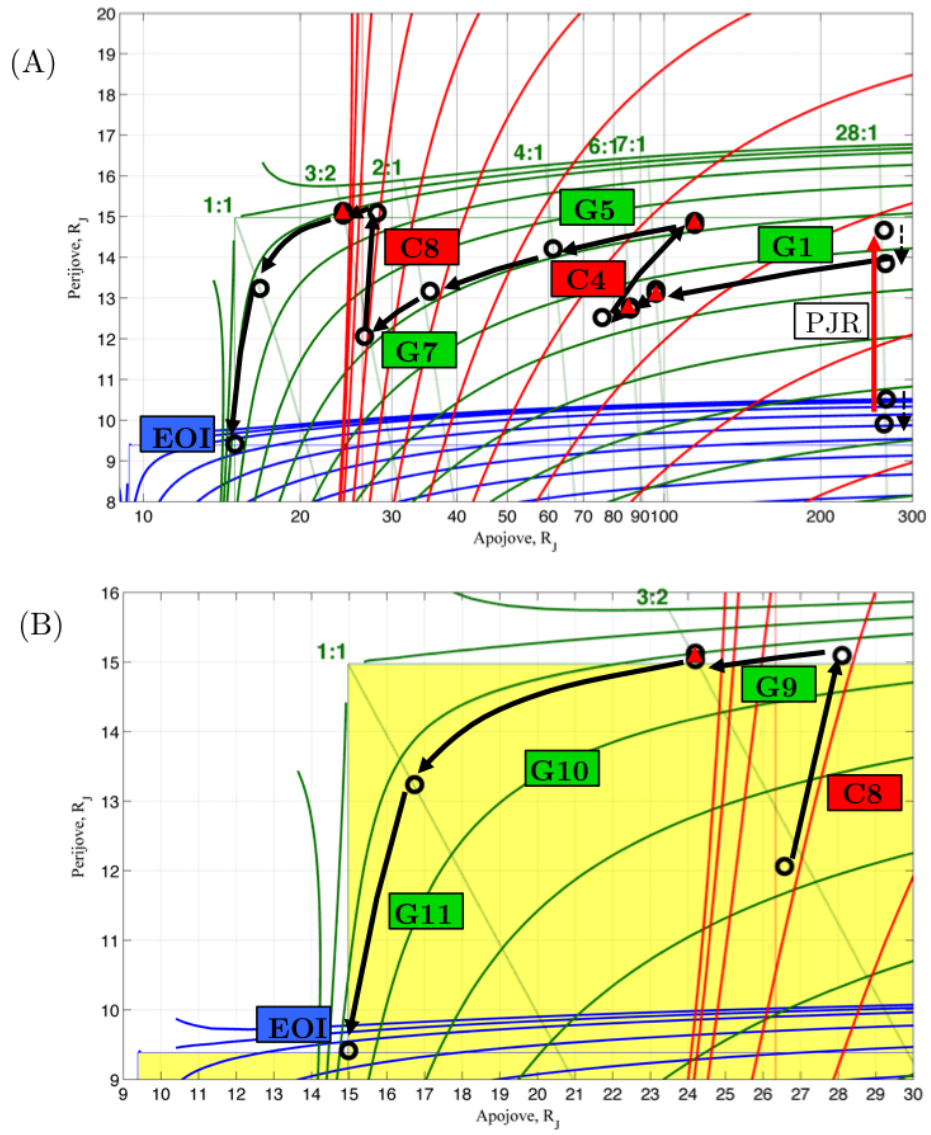


**Figure 6. Tisserand-Poincaré graph of the lander tour 12-L1**

considered ( "99-35 short" and "08-008 short") assuming a direct EOI in place of the first Europa flyby. A more recent Europa tour is the "Banzai-Pipeline", designed in 2012 for a feasibility study lead by Casani at JPL. To decrease the costs and risks, a lander spacecraft was designed with a very short science phase (<1 day); the tour minimizes the TID while containing the total $\Delta v$ with an unique courtship phase entirely composed by $\pi$-transfers[11] .

Table 4 , Table 5 , and Table 6 compare the partial and total $\Delta v$ , TID, and time of flight of the different tours. Since the tours have different assumptions on the altitude of the G0/I0 and G1/I1 flybys * and of the science target orbit†, the $\Delta v$ of JOI and EOI are adjusted for 500-km altitude

*Tour 99-35 : 350 km for G0, 150 km for G1. Tour 08-008: 1000 km for I0, 300 km for I1. Banzai-Pipeline tour: 100 km for G0, 100 km for G1.

†Tour 99-35 and tour 08-008: 200 km science orbit. Banzai-Pipeline tour: 50 km science orbit.

**Table 2. Events of the lander tour 12-L1**

| EVENT | DATE (ET Calendar) | MANEUVER $\Delta$v (km/s) | FLYBY v$\infty$ (km/s) | Alt. (km) | In /Out |
|---|---|---|---|---|---|
| *Earth escape* | *2021 NOV 22 01:11:28* | *3.852* | *3.77* | *200* | |
| *Venus* | *2022 MAY 14 10:01:53* | | *6.62* | *303* | *In* |
| *Earth* | *2023 OCT 24 23:06:01* | | *12.07* | *11760* | *In* |
| *Earth* | *2025 OCT 24 09:31:27* | | *12.06* | *3328* | *In* |
| Ganymede 0 | 2028 APR 03 06:23:43 | | 9.21 | 500 | In |
| JOI | 2028 APR 03 16:49:29 | 0.839 | | | |
| PJR | 2028 JUN 26 17:48:57 | 0.162 | | | |
| Ganymede 1 | 2028 OCT 21 06:21:39 | | 5.7 | 293 | In |
| OTM | 2028 NOV 15 07:26:23 | 0.007 | | | |
| Ganymede 2 | 2028 DEC 10 08:31:35 | | 5.63 | 176 | In |
| OTM | 2028 DEC 31 19:42:17 | 0.004 | | | |
| Ganymede 3 | 2029 JAN 22 06:46:42 | | 5.6 | 120 | In |
| Callisto 4 | 2029 MAR 02 13:48:18 | | 6.31 | 200 | Out |
| OTM | 2029 APR 02 14:11:42 | 0.005 | | | |
| Ganymede 5 | 2029 MAY 03 11:40:25 | | 3.8 | 202 | In |
| Ganymede 6 | 2029 JUN 01 01:58:54 | | 3.81 | 559 | In |
| Ganymede 7 | 2029 JUN 17 10:31:51 | | 3.71 | 2171 | Out |
| Callisto 8 | 2029 JUL 02 15:21:32 | | 1.82 | 2883 | In |
| Ganymede 9 | 2029 JUL 06 20:17:43 | | N/A | 15847 | N/A |
| OTM | 2029 JUL 12 00:13:08 | 0.014 | | | |
| Ganymede 10 | 2029 JUL 28 10:31:38 | | N/A | 552 | N/A |
| Ganymede 11 | 2029 AUG 04 09:28:08 | | 1.39 | 3995 | In |
| EOI | 2029 AUG 06 15:36:32 | 1.067 | 1.48 | 200 | |

G0/I0, a 200-km altitude G1/I1, and a 200 km altitude EOI. In particular, the JOI $\Delta v$ adjustment are estimated using table 2 in Kloster and Petropoulos;[10] the EOI adjustment is computed using linked-conics formulae for the Banzai Pipeline ( $v_\infty = 1.7$ km/s), and by re-optimizing the low-energy approach for tour 11-O3.

For each tour, Figure 9 plots the $\Delta v$ against the TID for the entire trajectory (A) and for the courtship phase only (B). Among the short tours, tour 08-008 short involves the lowest $\Delta v$ (1.84 km/s), but also the largest TID (1.1 Mrad). Instead the Banzai Pipeline only absorbs 89 krad, but the $\Delta v$ is 2.35 km/s . Tour 12-L1 represents a good compromise, with a total $\Delta v$ of 2.10 km/s, and a TID just 35 krad higher than for the Banzai Pipeline. Among the long tours, tour 11-O3 and 12-L4 improves on tour 99-35 on both TID and $\Delta v$ , but not on the time of flight. However, the duration of the tour depends on the launch year, since the EOI epoch must be postponed for several months if a solar conjunction occurs at the end of the mission. Compared to 08-008, tours 11-O3 and 12-L4 half the TID for a small $\Delta v$ penalty ($\sim 70/80$ m/s).

More Europa orbiter tours can be found in literature but are not included in this analysis, because of their higher $\Delta v$ and TID costs. The 99-02 tour[5] was the early baseline for the Europa Orbiter, which was designed to tolerate 4 Mrad of TID (behind a 100-mil Aluminum spherical shell). It

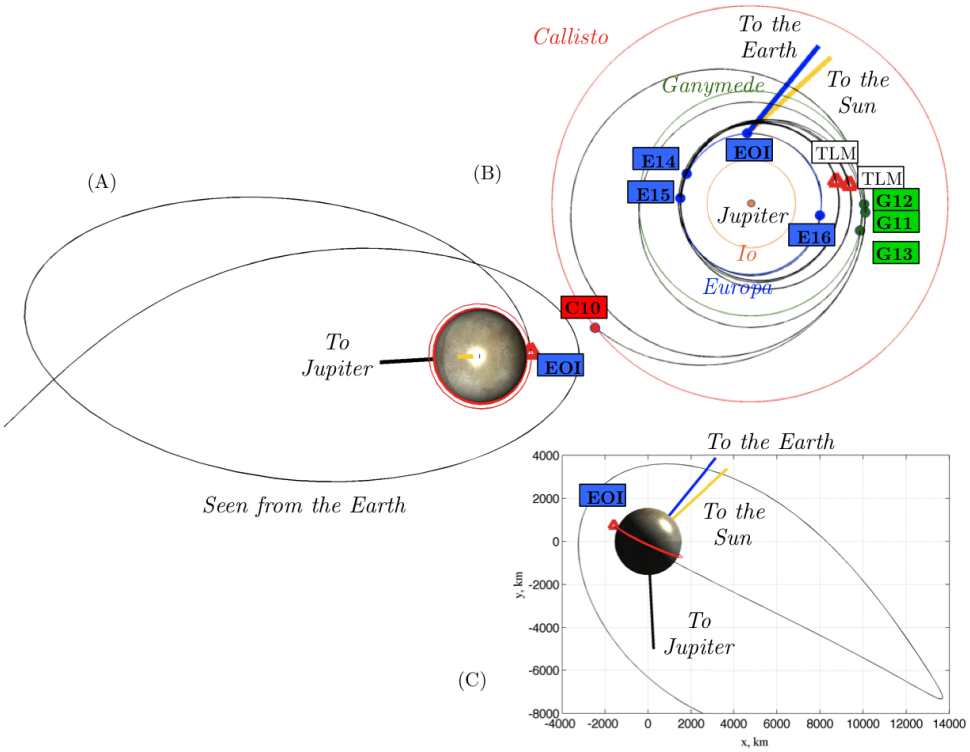


**Figure 7. Tour 12-L4 on the ecliptic reference frame J2000.**

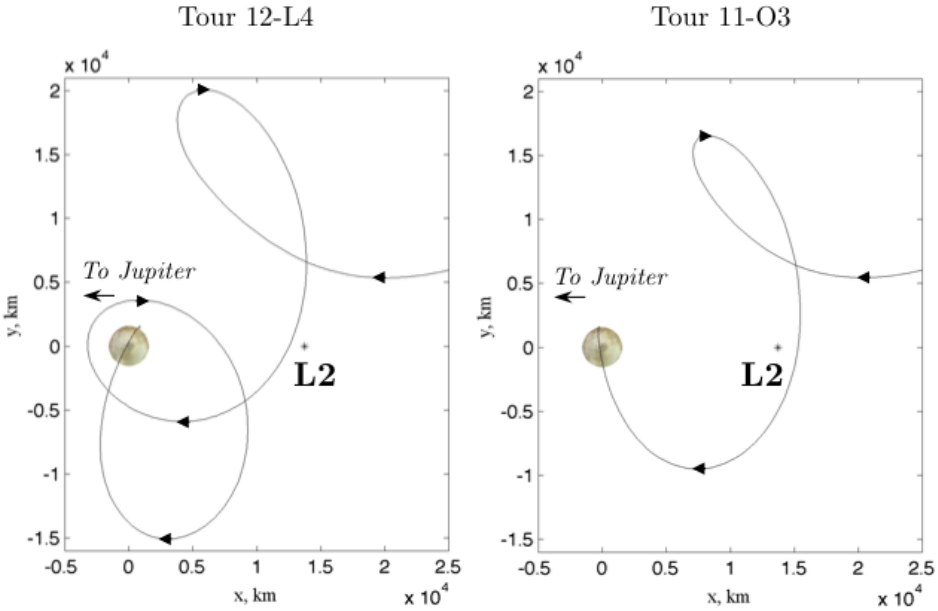


**Figure 8. Europa arrivals in the rotating frame**

included few endgame options with a low-energy approach at Europa.[4] The 08-007 tour[10] was computed for the Jupiter Europa Orbiter, with a slightly larger TID than the 08-008 tour. Two more

**Table 3. Events of the lander tour 12-L4**

| EVENT | DATE (ET Calendar) | MANEUVER $\Delta$v (km/s) | FLYBY v$\infty$ (km/s) | Alt. (km) | In /Out |
|---|---|---|---|---|---|
| *Earth escape* | *2021 NOV 22 00:00:51* | *3.852* | *3.77* | *200* | |
| *Venus* | *2022 MAY 14 09:30:36* | | *6.62* | *300* | *In* |
| *Earth* | *2023 OCT 24 22:41:39* | | *12.07* | *11761* | *In* |
| *Earth* | *2025 OCT 24 09:06:38* | | *12.05* | *3330* | *In* |
| Ganymede 0 | 2028 APR 03 11:56:14 | | 7.98 | 500 | In |
| JOI | 2028 APR 03 22:53:46 | 0.812 | | | |
| PJR | 2028 JUL 14 13:46:24 | 0.122 | | | |
| Ganymede 1 | 2028 NOV 18 20:26:14 | | 5.6 | 536 | In |
| OTM | 2028 DEC 28 04:48:15 | 0.005 | | | |
| Ganymede 2 | 2029 FEB 05 12:37:12 | | 5.67 | 100 | In |
| Ganymede 3 | 2029 APR 03 17:23:27 | | 5.8 | 3356 | In |
| Ganymede 4 | 2029 MAY 09 11:47:32 | | 5.79 | 698 | In |
| Callisto 5 | 2029 JUN 17 12:44:06 | | 5.48 | 222 | In |
| Ganymede 6 | 2029 JUL 21 13:57:01 | | 3.86 | 6636 | Out |
| Ganymede 7 | 2029 SEP 02 10:32:29 | | 3.78 | 265 | Out |
| Ganymede 8 | 2029 SEP 23 21:08:06 | | 3.77 | 2010 | Out |
| Ganymede 9 | 2029 OCT 08 04:04:29 | | 3.76 | 2735 | Out |
| Callisto 10 | 2029 OCT 23 05:10:17 | | 1.76 | 2120 | In |
| Ganymede 11 | 2029 OCT 27 09:43:44 | | N/A | 23483 | N/A |
| Ganymede 12 | 2029 NOV 17 23:02:20 | | N/A | 4891 | N/A |
| Ganymede 13 | 2029 NOV 24 20:22:00 | | 1.18 | 1250 | In |
| Europa 14 | 2029 NOV 27 08:23:30 | | N/A | 6471 | N/A |
| TLM | 2029 DEC 09 15:20:25 | 0.051 | | | |
| Europa 15 | 2029 DEC 11 18:13:08 | | N/A | 5182 | N/A |
| TLM | 2029 DEC 26 18:48:27 | 0.084 | | | |
| Europa 16 | 2030 JAN 03 19:20:05 | | N/A | 1751 | N/A |
| EOI | 2030 JAN 04 19:18:22 | 0.484 | N/A | 200 | |

Jovian tours[36] were designed by ESA for the Jovian Minisat Explorer: the first tour was to be flown by the radiation-hardened Jovian Europa Orbiter, and included several Europa flyby; at the same time, the second tour was to be flown by the solar-array powered Jovian Relay Spacecraft, stationed in a radiation-safe orbit between Ganymede and Callisto orbits. Low-thrust tours are also excluded from this analysis, since a meaningful comparison could only be performed at system level. Among such tours are the baseline for the JIMO spacecraft,[9] and for some solar-electric-propulsion mission study.[37,38] Finally the Multi-Moon orbiter[39] , which has inspired much of the research on low-energy tours, was not included for the expected high TID costs.

## CONCLUSIONS

This work presents the tour design of the orbiter and lander mission options of the Europa Habitability Mission study. Compared to other tours used in previous Europa mission studies, the orbiter

**Table 4. Tour comparison: $\Delta v$ table.**

| PHASE | SHORT-TOUR $\Delta v$ (km/s) | | | | LONG-TOUR $\Delta v$ (km/s) | | | |
|---|---|---|---|---|---|---|---|---|
| | 99-35 *short* | 08-008 *short* | Banzai Pipeline | 12-L1 | 99-35 | 08-008 | 11-O3 | 12-L4 |
| JOI | 0.98 | 0.60 | 0.81 | **0.84** | 0.98 | 0.60 | **0.81** | **0.81** |
| JOI adjustment | +0.01 | -0.04 | +0.05 | - | +0.01 | -0.04 | - | - |
| PJR | 0.08 | 0.08 | 0.11 | **0.16** | 0.08 | 0.08 | **0.12** | **0.12** |
| *Total G0/I0→G1/I1* | *1.07* | *0.64* | *0.97* | ***1.00*** | *1.07* | *0.64* | ***0.93*** | ***0.93*** |
| *Total G1/I1→lastC* | *0.00* | *0.00* | *0.22* | ***0.02*** | *0.00* | *0.00* | ***0.00*** | ***0.01*** |
| Endgame TLM1 | - | - | - | **-** | 0.12 | 0.07 | **0.05** | **0.05** |
| Endgame TLM2 | - | - | - | **-** | 0.07 | 0.07 | **0.10** | **0.08** |
| EOI | 1.17 | 1.16 | 1.21* | **1.07** | 0.45 | 0.71 | **0.48** | **0.48** |
| EOI adjustment | - | - | -0.004 | - | - | - | -0.02 | - |
| *Total lastC→EOI* | *1.17* | *1.16* | *1.21* | ***1.08*** | *0.64* | *0.85* | ***0.61*** | ***0.62*** |
| *Tour total* | *2.24* | *1.80* | *2.39* | ***2.10*** | *1.71* | *1.48* | ***1.55*** | ***1.56*** |

**Table 5. Tour comparison: TID table**

| PHASE | SHORT-TOUR TID (krad) | | | | LONG-TOUR TID (krad) | | | |
|---|---|---|---|---|---|---|---|---|
| | 99-35 *short* | 08-008 *short* | Banzai Pipeline | 12-L1 | 99-35 | 08-008 | 11-O3 | 12-L4 |
| G0/I0→lastC | 53 | 880 | 42 | **73** | 53 | 880 | **89** | **88** |
| lastC→EOI | 384 | 230 | 48 | **52** | 1047 | 880 | **792** | **832** |
| *Tour total* | *438* | *1110* | *89* | ***124*** | *1100* | *1760* | ***881*** | ***920*** |

**Table 6. Tour comparison: Time-of-flight table**

| PHASE | SHORT-TOUR TIME OF FLIGHT (months) | | | | LONG-TOUR TIME OF FLIGHT (months) | | | |
|---|---|---|---|---|---|---|---|---|
| | 99-35 *short* | 08-008 *short* | Banzai Pipeline | 12-L1 | 99-35 | 08-008 | 11-O3 | 12-L4 |
| G0/I0→lastC | 11.5 | 28.5 | 19.5 | **15** | 11.5 | 28.5 | **18.5** | **18.5** |
| lastC→EOI | 3 | 1 | 0.5 | **1** | 4.5 | 2 | **2.5** | **2.5** |
| *Tour total* | *14.5* | *29* | *20* | ***16*** | *16* | *30.5* | ***21*** | ***21*** |

tour 11-O3 would reduce the TID of 15-50% with almost no $\Delta v$ penalty (compared to 08-008) or significant $\Delta v$ savings (compared to tour 99-35). The TID of the lander tour 12-L1 would be only 124 krad (ten times lower than typical orbiter tours), just 35 krad more then the Banzai Pipeline, for a total $\Delta v$ of 2.10 km/s ($\sim$ 250 m/s less than the Banzai Pipeline, and $\sim$ 500 m/s more than typical orbiter tours). Finally, tour 12-L4 shows how a gravitational capture at Europa could be implemented in actual missions to target different science orbits and possibly to reduce mission risks.

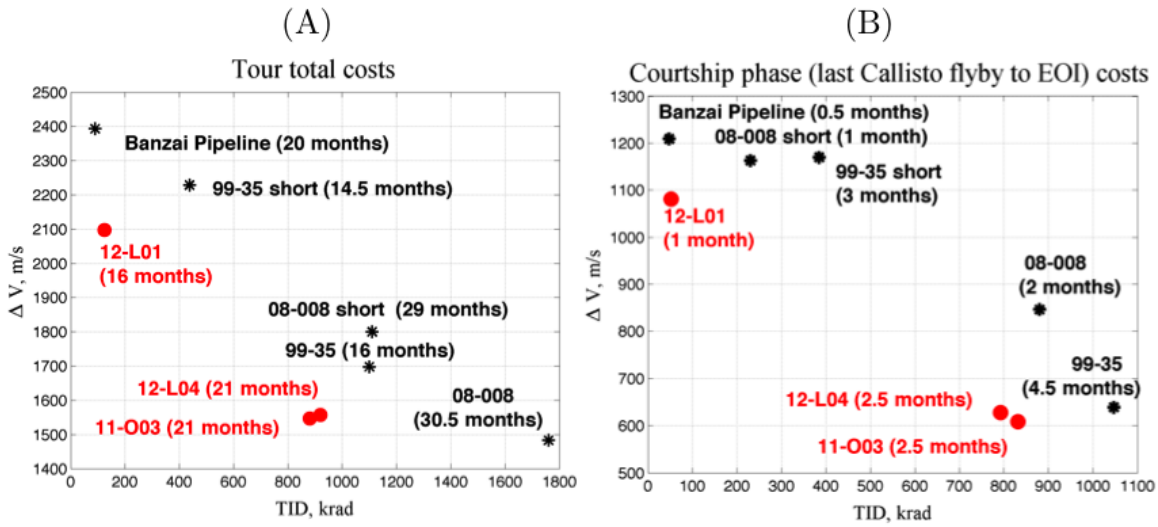


**Figure 9. Comparison between Europa lander and orbiter tours**

The $\Delta v$ and TID savings of tours 11-O3, 12-L1, 12-L4 over previous tours come largely from an efficient design of the Europa "courtship phase", the final part of the tour from the last Callisto flyby to the Europa Orbit Insertion. Multi-body dynamics and Tisserand-leveraging transfers are used to reduce the $\Delta v$ costs. A proper selection of the Europa Orbit Insertion epoch enforces the missions constrains and allows a direct Ganymede-to-Europa transfer, without radiation-costly phasing loops. For these reasons, we envision such types of courtship phase be part of any future Europa lander or orbiter mission study.

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