

EUROPA MULTIPLE-FLYBY TRAJECTORY DESIGN

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As reinforced by the 2011 NRC Decadal Survey, Europa remains one of the most scientifically intriguing targets in planetary science due to its potential suitability for life. However, based on JEO cost estimates and current budgetary constraints, the Decadal Survey recommended—and later directed by NASA Headquarters—a more affordable pathway to Europa exploration be derived. In response, a flyby-only proof-of-concept trajectory has been developed to investigate Europa. The trajectory, enabled by employing a novel combination of new mission design techniques, successfully fulfills a set of Science Definition Team derived scientific objectives carried out by a notional payload including ice penetrating radar, topographic imaging, and short wavelength infrared observations, and ion neutral mass spectrometry *in-situ* measurements. The current baseline trajectory, referred to as 11-F5, consists of 34 Europa and 9 Ganymede flybys executed over the course of 2.4 years, reaches a maximum inclination of 15°, has a deterministic Δv of 157 m/s (post-PJR), and has a total ionizing dose of 2.06 Mrad (Si behind 100 mil Al, spherical shell). The 11-F5 trajectory—and more generally speaking, flyby-only trajectories—exhibit a number of potential advantages over an Europa orbiter mission.

Nomenclature

<i>IPR</i>	= Ice-penetrating radar	<i>AO</i>	= Announcement of Opportunity
<i>TI</i>	= Topographic imager	<i>EJSM</i>	= Europa Jupiter System Mission
<i>SWIRS</i>	= Short wavelength infrared spectrometer	<i>JEO</i>	= Jupiter Europa Orbiter
<i>INMS</i>	= Ion and neutral mass spectrometer	<i>JGO</i>	= Jupiter Ganymede Orbiter
<i>VEEGA</i>	= Venus-Earth-Earth gravity assist trajectory	<i>NRC</i>	= National Research Council
V_∞	= Hyperbolic excess velocity	<i>PSD</i>	= Planetary Science Division
C_3	= Characteristic energy (V_∞^2)	<i>NLS</i>	= NASA Launch Services
ΔV	= delta-V (i.e., change in velocity)	<i>ORT</i>	= Operation Readiness Test
<i>JOI</i>	= Jupiter orbit insertion	<i>LST</i>	= Local Solar Time
<i>PJR</i>	= Perijove raise maneuver	<i>COT</i>	= Crank-over-the-top
<i>DSM</i>	= Deep space maneuver	R_J	= Jupiter equatorial radius (71,492 km)
<i>DSN</i>	= Deep space network	<i>SNR</i>	= Signal-to-noise ratio
<i>SDT</i>	= Science Definition Team	i_{max}	= Maximum inclination
<i>NEPA</i>	= National Environmental Policy Act	<i>TOF</i>	= Time-of-flight
<i>HQ</i>	= Headquarters	<i>FY</i>	= Fiscal year
<i>TID</i>	= Total ionizing dose (Si behind a 100 mil Al, spherical shell)	<i>CBE</i>	= Current best estimate
		<i>MEV</i>	= Maximum estimated value

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I. Introduction

SINCE data returned by NASA's Galileo spacecraft in the mid-1990's first indicated the potential existence (but not definitive proof) of a liquid water ocean beneath Europa's relatively thin ice shell, Europa has been one of the most scientifically intriguing targets in our Solar System. Furthermore, scientists believe this potential liquid water ocean is in direct contact with a rocky mantle, and, due to Europa's slightly eccentric orbit, Jupiter's gravitational pull provides a perpetual energy source in the form of tidal heating¹⁻³. These three components, liquid water, chemistry, and energy—simultaneously existing in one place—defines the necessary, but not sufficient, conditions required for life as we know it to subsist. As such, Europa has been the focus of many mission concepts over the past decade and a half⁴.

Several different architectures have been considered for exploring Europa, including flyby missions, sub-satellites, orbiters with (and without) simple lander combinations, and sophisticated lander-only missions⁵⁻¹⁰. The vast majority of these mission studies have focused on the later two, under the premise that an orbiter and/or a lander were the platforms most conducive to performing the key Europa observations and measurements necessary to significantly advance our knowledge of Europa (i.e., answer key questions about Europa's habitability). While flyby-only missions (both single- and multiple-flybys) have been considered, they were quickly deemed insufficient due to the perceived deficiencies in accomplishing the aforementioned key Europa observations and measurements.

The most recent incarnation of a Europa mission, Jupiter Europa Orbiter (JEO), was part of a joint NASA-ESA Europa Jupiter System Mission (EJSM), whereby working in concert with ESA's Jupiter Ganymede Orbiter (JGO), would carry out a comprehensive investigation of the Jupiter System⁷. In 2008 the JEO project matured to a Pre-Phase A mission concept, and was further refined from 2009-2010. The JEO mission design¹⁰ entailed a launch in early 2020 followed by an approximately 6-year interplanetary cruise (VEEGA, Venus-Earth-Earth Gravity Assist), with a Jupiter arrival in December 2025. A 1000 km Io flyby would be used in combination with a Jupiter Orbit Insertion (JOI) maneuver of 677 m/s to capture JEO into a highly elliptical 210-day period orbit. Over the course of 2.5 years, 23 additional gravity assists (Io: 3, Europa: 5, Ganymede: 6, and Callisto: 9) would then be used to decrease the spacecraft's energy relative to Europa, thereby minimizing the 792 m/s Europa Orbit Insertion (EOI) maneuver needed to place JEO into an initial 200 km circular orbit about Europa (and eventually maneuvered into a 100 km circular orbit). Finally, a suite of 12 instruments would spend 9 months in Europa orbit collecting and downlinking data (in many instances concurrently) back to Earth.

The need to quickly collect and transmit data to Earth is an inherent requirement for any spacecraft continuously operating in the vicinity of Europa. This stems from Europa residing in a thick veil of high-energy particles, the result of Jupiter's very powerful magnetic field gathering and accelerating charged particles emanating from the Sun. As such, a spacecraft near Europa would be continually bombarded with high-energy particle (i.e., radiation), a detriment to onboard electronics and instrumentation. To counter this harsh environment, shielding—in the form of tantalum or other dense materials—must surround sensitive electronics. For a given launch vehicle, a finite delivery dry mass exists. Hence, the required shielding mass takes away from the scientific payload mass. Even with shielding though, the radiation would eventually render the spacecraft in-operable, and in the case of JEO, result in the spacecraft crashing into the surface of Europa. Over the course of the entire mission, JEO's TID[§] would be approximately 2.9 Mrad. The consequence of trying to perform many different scientific investigations under a very compressed time schedule due to a finite spacecraft operability lifetime significantly drove up JEO's complexity, and in turn, its total estimated cost. Cost estimates performed by the Jet Propulsion Laboratory (JPL) and an independent source (Aerospace Corp.) pegged the JEO mission at \$3.8 billion and \$4.7 billion^{**}, respectively.

II. Europa Mission Reset

Because of serious concerns over mission cost based on NASA's independent cost estimate, the 2011 NRC Planetary Decadal Survey¹¹ recommended that "NASA should immediately undertake an effort to find major cost reductions for JEO, with the goal of minimizing the size of the budget increase necessary to enable the mission". To that end, in April 2011, NASA's Planetary Science Division (PSD) directed the pre-project office to conduct a study to revise the JEO mission by examining a set of reduced-scope options for exploring Europa that met the NASA cost target of \$2.25B (\$FY15, excluding launch vehicle). These options were to include, but not limited to, a Europa orbiter that takes as its starting point the descope path in the 2008 JEO final report⁷ and a Jupiter orbiter with a large number of Europa flybys. NASA Headquarters (HQ) later (November 2011) directed a lander mission concept also

[§] Total ionizing dose Si behind a 100-mil Al, spherical shell.

^{**} Real year dollars. Also included cost of launch vehicle.

be investigated. Detailed results of all three mission concepts can be found in the Europa Study 2012 Report¹² delivered to NASA HQ and Congress in May 2012.

A. Revised Strategy

In response to the Decadal Survey's recommendations and the direction given by NASA HQ, a Science Definition Team (SDT) composed of 13 US scientists and a combined JPL and Applied Physics Laboratory (APL) technical team, reformulated a set of three Europa missions—using JEO as a basis of comparison—that would achieve compelling science but represented a descope from past studies¹².

Early in the re-formulation process, it became very clear that a division between key science investigations best conducted from Europa orbit and via multiple Europa flybys existed. The characterization of Europa's sub-surface ocean, to what extent it exists, and its relation to the deeper interior would be best accomplished through systematic geophysical measurements of gravity, topography, and magnetic field—measurements most compatible with an orbital platform. In addition, an orbital platform would permit uniform geological mapping. In contrast, observations to characterize the ice shell, understand the surface composition, and perform high-resolution targeted geological observations are quite data intensive and require high-mass, high-power instruments. This would best be carried out by a spacecraft that makes multiple flybys of Europa for a number of reasons. First, the large amount of time the spacecraft would spend away from Europa (in Jupiter orbit) would allow ample time to downlink the large amounts of data collected during each flyby without accumulating radiation dosage. Secondly, the “store and forward” approach (i.e., collect, store, and eventually downlink data) enables the use of higher power instruments in the vicinity of Europa since the spacecraft would never have to simultaneously operate the instruments with a high power telecom system. Thirdly, given the finite capability of a chosen launch vehicle, more mass is available for scientific instrumentation and electronic component shielding (effectively increasing the lifetime of the mission) by forgoing EOI (i.e., the large amount of propellant needed to dissipate the spacecraft's energy such that Europa orbit is reached). Both mission options would provide high caliber, compelling science that would change paradigms in our understanding of the nature and habitability of icy worlds.

Lastly, it must be noted a leading assumption in the process of separating JEO's investigations/instruments between platforms was, if an instrument was on one platform, it would not be included on the other platform. This paper will focus solely on the multiple-flyby mission platform.

B. Scientific Objectives: Multiple-Flyby Mission

The Europa multiple-flyby mission concept concentrates on remote sensing science via numerous close flybys of Europa. This includes exploring Europa's ice shell for evidence of liquid water within or beneath it, in order to understand the thickness of the ice shell and potential material pathways from the ocean to the surface and from the surface to the ocean. The mission concept also includes exploration of the surface and atmospheric composition of Europa, in order to address ocean composition and habitability. Detailed morphologic and topographic characterization of Europa's surface are included as well. The concept concentrates on the chemistry and energy themes, as related to habitability. It also addresses the water theme by probing for water within the ice shell and investigating the relationship of surface chemistry and geology to subsurface water¹².

The conceived model payload for a flyby-only Europa spacecraft contained an Ice-Penetrating Radar (IPR), Topographical Imager (TI), Shortwave Infrared Spectrometer (SWIRS), Ion and Neutral Mass Spectrometer (INMS), and. This notional payload is not meant to be exclusive of other measurements and instruments that might be able to meet the scientific objectives in other ways^{††}. Refer to the Europa 2012 Study Report¹² for the details mapping the specific instruments to their corresponding Europa investigation(s).

The following summarizes geometric constraints levied on the mission design in order to fulfill required scientific objectives for a compelling Europa multiple-flyby mission:

Ice Penetrating Radar (IPR)

- Closest approach (c/a) relative velocity: < 5 km/s
- c/a altitude: 100 km
- Coverage: Satisfy the following constraints in **11 of 14 panels** (see Figure 1 for panel definition)
 - Three 800 km groundtracks in anti-Jovian panels, and two 800 km groundtrack segments in each sub-Jovian panel (altitude \leq 400 km)
 - Each groundtrack must intersect another groundtrack (intersection may be outside the panel of interest) below 1,000 km (when altimetry mode begins)

^{††} NASA would ultimately select the payload through a formal Announcement of Opportunity (AO) process.

- Cover anti-Jupiter hemisphere first (preferred, not required)
- Requires *simultaneous* stereo imaging to provide topographic information necessary to process the IPR data

Topographic Imager (TI)

- c/a relative velocity: < 5 km/s
- c/a altitude: 100 km
- Solar phase: 50-70° (10-80° acceptable) when alt ≤ 400 km

Shortwave Infrared Spectrometer (SWIRS)

- c/a relative velocity: < 6 km/s
- c/a altitude: 100 km
- Local Solar Time: 9 am - 3 pm (the closer to noon the better)
- Solar phase angle: <45 degrees (preferred)
- Ability to target specific geologic features that are globally distributed (300 m/pixel, **11 of 14 panels**)
 ≥ 70% coverage at ≤ 10 km per pixel

Ion and Neutral Mass Spectrometer (INMS)

- c/a relative velocity: < 7 km/s
- c/a altitude: 25 km (or more generally, as close as navigationally possible)

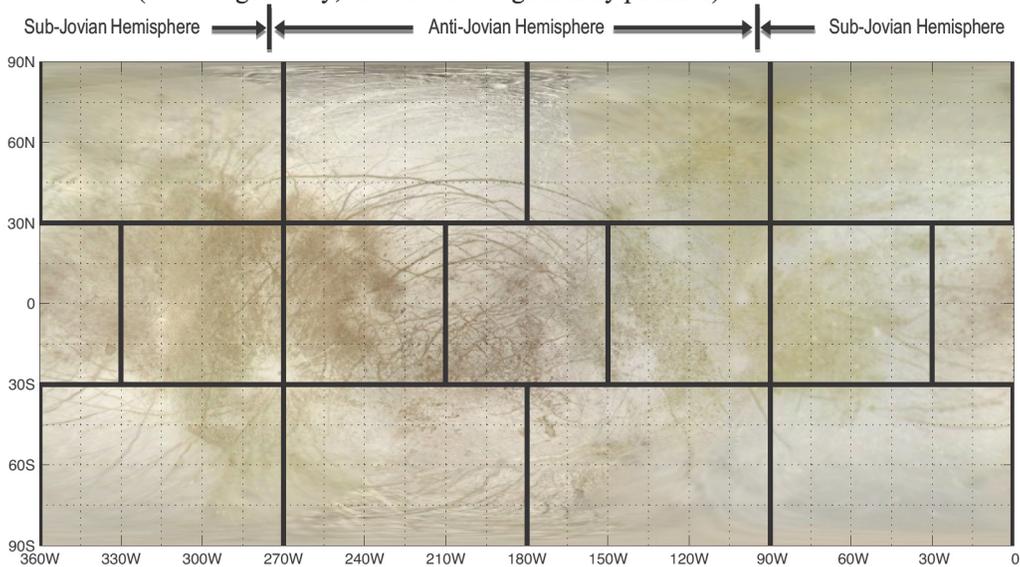


Figure 1. Europa Mercator projection map including the 14 sectors defined by the SDT used to assess global-regional coverage. Since Europa is tidally locked, the same hemispheres (and associated sectors) always face towards (sub-Jovian) or away from (anti-Jovian) Jupiter. As such, the terrain illuminated by the sun is simply a function of where Europa is encountered in its orbit.

III. Mission Design

The trajectory design goal for the Europa multiple-flyby mission study was to establish the existence and feasibility of a flyby-only Europa mission that meets the SDT observation and measurement requirements as outlined in Section II.B. The focus for this study was to maximize IPR, TI, SWIRS and INMS coverage while minimizing TID, mission duration (and hence operations costs), and ΔV.

The Europa multiple flyby mission flight system would be launched on an Atlas V 551 from Cape Canaveral Air Force Station on a Venus-Earth-Earth gravity assist (VEEGA) interplanetary trajectory. After a cruise of 6.37 years, the spacecraft would fly by Ganymede just prior to performing JOI via a large main engine maneuver. The spacecraft would then perform a perijove raise maneuver (PJR) and four additional Ganymede gravity assists over 11 months to lower its orbital energy with respect to Jupiter and set up the correct flyby conditions (lighting and relative velocity) at Europa. The spacecraft would then embark on a 18-month Europa science campaign. The first part of the science campaign would focus on Europa’s then day lit anti-Jovian hemisphere (Fig. 1). After the first phase, six Europa and three Ganymede flybys would be used to place the subsequent Europa flybys on the opposite

side of Jupiter where the sub-Jovian hemisphere of Europa would then be day lit. These Europa flybys, constituting the second phase of the science campaign, would focus on Europa’s sub-Jovian hemisphere. Finally, the mission would culminate with spacecraft disposal via Ganymede impact. Figure A.1 (Appendix) depicts a summary of the mission design.

A. Launch Vehicle and Launch Period

An Atlas V 551 would launch the spacecraft with a maximum C_3 of $15.0 \text{ km}^2/\text{s}^2$ during a 21-day launch period opening on November 15, 2021. The optimal launch date within the launch period is November 21, 2021 (Fig. 2). The date of Jupiter arrival is held fixed throughout the launch period, incurring only a negligible penalty while simplifying the design of the tour in the Jovian system. The launch vehicle and launch period parameters are shown in the Appendix. The launch vehicle performance is taken as that specified in the NASA Launch Services (NLS)-II Contract, which includes, in particular, a performance degradation of 15.2 kg/yr. for launches occurring after 2015. The spacecraft propellant tanks would be loaded up to the launch vehicle capability. The flight system is designed to launch on any given day in the launch period without reconfiguration or modification.

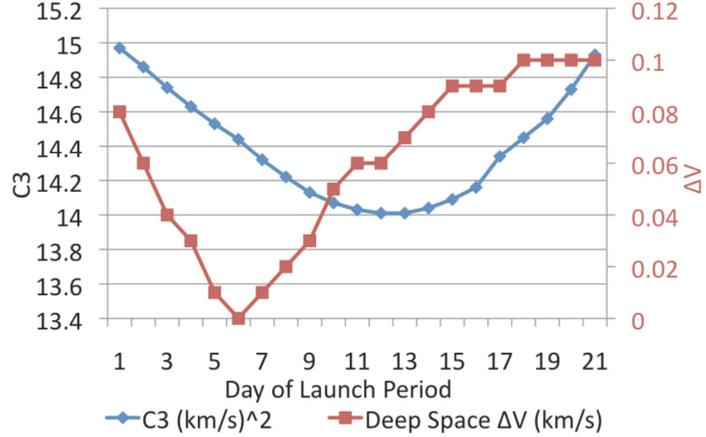


Figure 2. Baseline interplanetary launch period.

The date of Jupiter arrival is held fixed throughout the launch period, incurring only a negligible penalty while simplifying the design of the tour in the Jovian system. The launch vehicle and launch period parameters are shown in the Appendix. The launch vehicle performance is taken as that specified in the NASA Launch Services (NLS)-II Contract, which includes, in particular, a performance degradation of 15.2 kg/yr. for launches occurring after 2015. The spacecraft propellant tanks would be loaded up to the launch vehicle capability. The flight system is designed to launch on any given day in the launch period without reconfiguration or modification.

B. Interplanetary Trajectory

The baseline trajectory used for the Europa multiple-flyby mission is a VEEGA (Appendix and Table 1). Cruise navigation would use Doppler and range observations from the Deep Space Network (DSN). The deep-space maneuver (DSM) ΔV required on the optimal day of the launch period is zero, but is about 80 m/s at the start of the launch period and reaches its highest level of 100 m/s on the last day. The DSM occurs on the Earth-Venus leg of the trajectory. The interplanetary trajectory design would comply with all required National Environmental Policy Act (NEPA) assessment and safety analysis by implementing an aim-point-biasing strategy for both Earth flybys. The nominal flyby altitudes of Venus and Earth do not vary significantly over the launch period and are relatively high, as seen in Table 1. For comparison, Cassini flew by Earth at an altitude of 1166 km , and Galileo at altitudes of 960 and 304 km .

A 500-km Ganymede flyby would be performed approximately 12 hours before JOI, thereby saving about 400 m/s of ΔV (compared to the case of no Ganymede flyby). The JOI maneuver would last about 2 hours and occur at perijove at a range of 12.8 R_J (i.e., in the less intense outer regions of the radiation belts). Gravity losses are negligible due to the small angle subtended by the burn-arc.

Table 1. Baseline VEEGA interplanetary trajectory (for optimal launch date).

Event	Date	V_∞ (km/s)	ΔV (m/s)	Flyby Alt. (km)
Launch	21-Nov-2021	3.77	-	-
DSM	Mar-2021*	-	0-100	-
Venus	14-May-2022	6.62	-	3184
Earth	24-Oct-2023	12.07	-	11764
Earth	20-Oct-2025	12.05	-	3336
G0	03-Apr-2028	7.37	-	500
JOI	04-Apr-2028	-	858	12.8 R_J

*Date varies across launch window

C. Backup Interplanetary Trajectories

Many backup interplanetary trajectory options are available, offering a launch opportunity every calendar year. The results of a comprehensive search of all 1-, 2-, 3-, and 4-gravity assist trajectories are shown in Figure 3. The best candidates from the search are shown in Table 2, which includes launch period effects. The table shows, for each trajectory, the optimal launch date of the launch period, the flight time to Jupiter, the expected maximum C_3

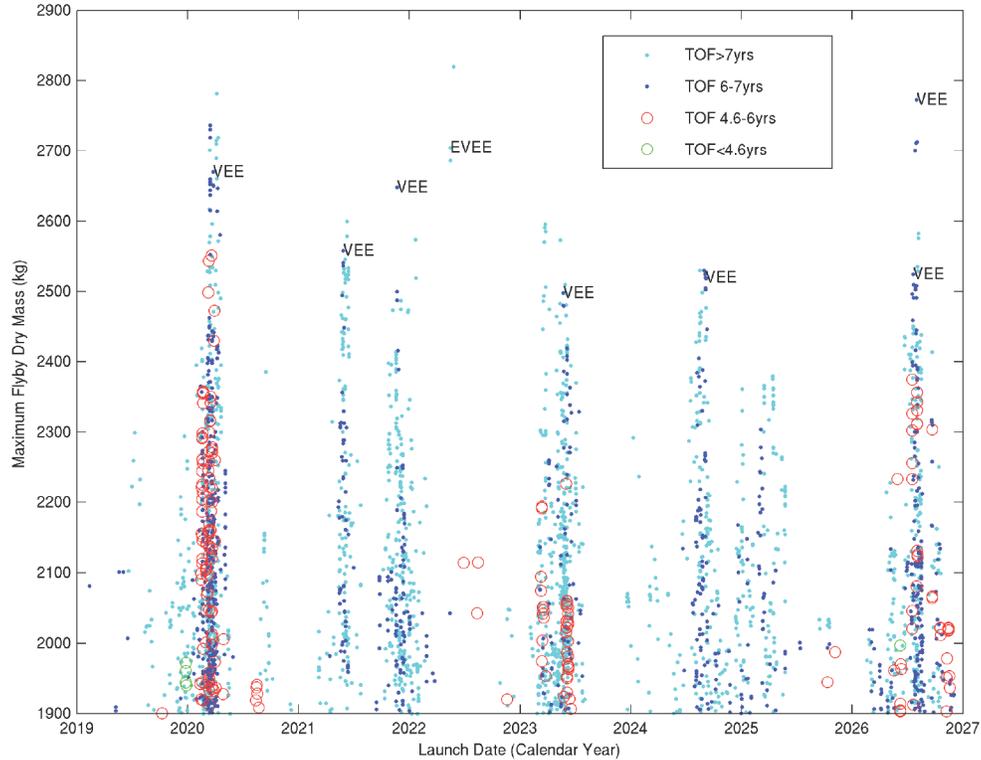


Figure 3. Interplanetary trajectory options. All 1-, 2-, 3-, and 4-gravity assist trajectories to Jupiter with launch dates between 2019 and 2027 color coded based on time-of-flight (TOF).

over the launch period, the launch vehicle capability at maximum C_3 for the indicated launch year (NLS-II contract), the propellant required for flying the mission (assuming the full launch vehicle capability is used), the maximum dry mass (i.e., the difference between the two preceding numbers), and the propellant required to fly the mission assuming the CBE value for the dry mass. In all cases, the MEV ΔV from Table 5 is used.

It is worth noting that two types of commonly considered trajectories¹³ do not appear in the short list of interplanetary trajectories because of their relatively poor mass performance. The first type is the ΔV -Earth gravity assist (ΔV -EGA), which is a V_∞ leveraging type of trajectory involving a large maneuver near aphelion before the Earth flyby. For the ΔV -EGA, the maximum dry mass that can be delivered in the years 2019–2027 is about 1650 kg (about 1000 kg less than the “Max Dry Mass” numbers in the short list, Table 2). The required C_3 is in the range 25–30 km^2/s^2 , and the flight time is typically 4–5 years, corresponding to a 2:1 ΔV -EGA (4.5 years for the maximum-dry-mass case). The second type is the Venus-Earth Gravity Assist (VEGA), involving a large maneuver after the Venus flyby. For flight times of around 4.4 yrs., the maximum dry mass for the VEGA is about 1740 kg. For flight times around 5.4 yrs., approaching the VEEGA flight times, the maximum dry mass becomes about 2190 kg. Thus, these two trajectory types significantly underperform in terms of delivered mass compared to the typical VEEGA trajectory. To save some flight time, these trajectory types may be considered in later phases of the mission design, once the vehicle mass is better characterized, assuming it does not grow significantly from current levels.

Table 2. Short list of interplanetary trajectories. Launch period effects are included. Baseline trajectory is in bold; subsequent trajectories represent viable backup opportunities.

Launch Date	Flyby Path	TOF to JOI (yrs.)	C_3 (km^2/s^2)	Atlas V 551 Capability (kg)	Max Prop Mass (kg)	Max Dry Mass (kg)	Prop for CBE Dry Mass (kg)
25-Mar-2020	VEE	6.03	15.6	4456	1739	2717	864
27-May-2021	VEE	6.87	14.5	4541	1938	2603	1005
21-Nov-2021	VEE	6.37	15	4494	1846	2648	898
15-May-2022	EVEE	7.22	10.2	4935	2182	2753	1070
23-May-2023	VEE	6.18	16.4	4339	1797	2542	955

D. Jovian Tour (11-F5 Trajectory)

The current baseline Jupiter tour for the Europa Flyby Mission is a fully integrated trajectory (i.e., flight-level fidelity, no approximations made), and one of many tours developed for this study. The Jovian portion of the baseline trajectory, referred to as 11-F5, begins after JOI and consists of 34 Europa and 9 Ganymede flybys over the course of 2.4 years, reaches a maximum Jovicentric inclination of 14.9°, has a deterministic ΔV of 157 m/s (post-PJR), and has a TID of 2.0 Mrad. This proof-of-concept trajectory employs a novel combination of mission design techniques to successfully fulfill a set of SDT-defined scientific objectives including global-regional IPR, TI, and SWIRS observations, and INMS *in situ* measurements. The entire 11-F5 trajectory can be broken into six distinct phases, each detailed in Tables 3 & 4 and depicted in Figure A.1.

Table 3. 11-F5 mission phase definitions and descriptions.

Phase	Sub-Phase	Activity	Start/End
Interplanetary	Launch and Early Ops	Begins with the launch countdown, launch, initial acquisition by the DSN, checkout and deployment of all major flight-system subsystems and a moderate maneuver to clean-up trajectory errors from launch vehicle injection.	Nov./Dec. 2021 + 30 days
	Cruise	Science instrument calibrations, Venus and Earth (2) gravity assist flyby operations, annual spacecraft health checks, trajectory correction maneuvers (including a potential DSM), and operations readiness tests (ORTs).	Jan. 2021–Oct. 2027
	Jupiter Approach	Training, and ORTs for all mission elements in preparation for JOI and Jovian tour. This phase includes the inbound Ganymede (G0) flyby just a couple of hours before JOI and ends with completion of JOI.	Oct. 2027–Apr. 2028
Pump Down		PJR execution near apojove of initial 206-day period orbit to counter solar perturbations and target G1. Four outbound Ganymede gravity assists (G1–G4) are used to reduce energy relative to Jupiter and set up the encounter geometry for the first Europa science phase such that an acceptable relative velocity to Europa would be achieved and Europa's anti-Jupiter hemisphere would be well illuminated.	Apr. 2028–Feb. 2029 (11 months)
Europa Anti-Jupiter Hemisphere Coverage	COT-1	Seven Europa flyby crank over the top sequence (COT) used to systematically cover Europa's anti-Jupiter hemisphere. Places groundtrack in all seven anti-Jupiter hemisphere sectors. All Europa flybys occur at the ascending node. COT-1 changes the flybys from outbound to inbound.	Feb. 2029–Jul. 2029 (4.7 months)
	Non-Resonant Transfer	Inbound to outbound Europa non-resonant transfer to get back to outbound flybys such that another COT sequence can be implemented to cover the anti-Jupiter hemisphere.	Jul. 2029–Aug. 2029 (0.5 months)
	COT-2	Six Europa flyby COT sequence to systematically cross all seven COT-1 groundtracks to fulfill the IPR/topographic imager requirements for <i>all</i> anti-Jupiter hemisphere sectors. All flybys occur at the descending node. COT-2 changes the flybys from outbound to inbound.	Aug. 2029–Nov. 2029 (3.2 months)
Change Lighting Conditions	Pump Down, Crank up	Reduces spacecraft orbit period and increases inclination to set up correct geometry for Europa-to-Ganymede pi-transfer.	Nov. 2029–Jan. 2030 (2.7 months)
	Switch-flip	Includes a Europa-to-Ganymede pi-transfer, a Ganymede pi-transfer (placing periapsis on the opposite side of Jupiter), and finally a Ganymede-to-Europa pi-transfer which places the subsequent Europa flybys approximately 180° from the location of the Europa flybys in COT-2.	Jan. 2030–Feb. 2030 (0.6 months)
Europa Sub-Jupiter Hemisphere Coverage	COT-3	Eight Europa flybys used to increase spacecraft orbit period while also cranking over the top to cover the sub-Jupiter hemisphere. All Europa flybys occur at the descending node. Sequence changes the flybys from inbound to outbound.	Feb. 2030–Jun. 2030 (3.7 months)
	Non-Resonant Transfer	Outbound to inbound Europa non-resonant transfer to get back to inbound flybys such that another COT sequence can be implemented to cover the sub-Jupiter hemisphere.	Jun. 2030 (0.3 months)
	COT-4	Six Europa flyby COT sequence to systematically cross the COT-3 groundtracks to fulfill the IPR/topographic imager requirements for 6 of the 7 sub-Jupiter hemisphere sectors. All flybys occur at the ascending node.	Jun. 2030–Aug. 2030 (2.4 months)
Spacecraft Disposal		Baseline strategy: Ganymede impactor (although many options exist, see Section III.O).	Aug. 2030

Table 4. Detailed 11-F5 flyby and maneuver summary.

Phase	Flyby/ Maneuver	In/ Out	Date	Altitude (km)	B-Plane Ang (deg)	V-Infinity (km/s)	Inc. (deg)	Peri. (RJ)	Apo. (RJ)	m	n	Period (days)	TOF (days)	Total TOF (months)
Jupiter Approach	Ganymede0	I	03-Apr-2028 14:56:45	500	0.1	7.382	5.17	12.96	-	N	R	-	202.1	0.00
	<i>JOI</i>		<i>04-Apr-2028 03:30:08</i>	$\Delta v = 857 \text{ m/s}$			<i>4.97</i>	<i>12.78</i>	<i>268.5</i>	-	-	<i>205.7</i>	<i>0.5</i>	
Pump Down	<i>PJR</i>		<i>13-Jul-2028 14:52:13</i>	$\Delta v = 114 \text{ m/s}$			<i>4.95</i>	<i>13.6</i>	<i>264.5</i>	-	-	<i>202.6</i>	<i>100.5</i>	
	Ganymede1	O	22-Oct-2028 16:52:57	100	-171.1	6.34	4.6	11.99	97.73	7	1	50.09	50.1	6.74
	<i>CU-Man-G1</i>		<i>25-Oct-2028 17:51:55</i>	$\Delta v = 0 \text{ m/s}$									<i>3.0</i>	
	<i>Apo-Man-G1</i>		<i>16-Nov-2028 02:26:26</i>	$\Delta v = 0.427 \text{ m/s}$									<i>21.4</i>	
	Ganymede2	O	11-Dec-2028 19:05:43	100	-136.4	6.42	1.54	11.16	64.37	4	1	28.61	28.6	8.41
	<i>Apo-Man-G2</i>		<i>25-Dec-2028 08:31:15</i>	$\Delta v = 4.821 \text{ m/s}$									<i>13.6</i>	
	Ganymede3	O	09-Jan-2029 09:42:57	3496.3	-175.5	6.37	1.37	10.63	51.74	3	1	21.46	21.5	9.36
	<i>CU-Man-G3</i>		<i>12-Jan-2029 11:40:03</i>	$\Delta v = 0 \text{ m/s}$									<i>3.1</i>	
	<i>Apo-Man-G3</i>		<i>19-Jan-2029 07:59:00</i>	$\Delta v = 0 \text{ m/s}$									<i>6.8</i>	
	Ganymede4	O	30-Jan-2029 20:52:12	172.9	191.1	6.40	0.45	9.33	36.18	N	R	13.37	25.9	10.07
<i>CU-Man-G4</i>		<i>02-Feb-2029 22:47:42</i>	$\Delta v = 0 \text{ m/s}$									<i>3.1</i>		
<i>Apo-Man-G4</i>		<i>05-Feb-2029 15:05:55</i>	$\Delta v = 0 \text{ m/s}$									<i>2.7</i>		
Europa Anti-Jovian Hemisphere Coverage	Europa5	O	25-Feb-2029 17:45:14	724.3	104.6	3.84	2.32	9.27	34.04	7	2	12.43	24.9	10.94
	<i>CU-Man-E5</i>		<i>10-Mar-2029 02:14:25</i>	$\Delta v = 0 \text{ m/s}$									<i>12.4</i>	
	<i>Apo-Man-E5</i>		<i>16-Mar-2029 06:24:12</i>	$\Delta v = 7.375 \text{ m/s}$									<i>6.2</i>	
	Europa6	O	22-Mar-2029 14:52:04	100	25	3.92	3.33	9.42	37.93	4	1	14.20	14.2	11.77
	<i>CU-Man-E6</i>		<i>25-Mar-2029 14:59:58</i>	$\Delta v = 9.125 \text{ m/s}$									<i>3.0</i>	
	<i>Apo-Man-E6</i>		<i>29-Mar-2029 15:26:54</i>	$\Delta v = 0 \text{ m/s}$									<i>4.0</i>	
	Europa7	O	05-Apr-2029 19:35:07	100	73.6	3.92	5.98	9.45	33.89	7	2	12.43	24.9	12.24
	<i>CU-Man-E7</i>		<i>18-Apr-2029 04:34:59</i>	$\Delta v = 0 \text{ m/s}$									<i>12.4</i>	
	<i>Apo-Man-E7</i>		<i>24-Apr-2029 09:45:13</i>	$\Delta v = 1.216 \text{ m/s}$									<i>6.2</i>	
	Europa8	O	30-Apr-2029 16:28:04	100	-18.1	3.94	5.01	9.50	37.86	4	1	14.20	14.2	13.07
	<i>CU-Man-E8</i>		<i>03-May-2029 16:38:07</i>	$\Delta v = 0 \text{ m/s}$									<i>3.0</i>	
	<i>Apo-Man-E8</i>		<i>07-May-2029 18:50:08</i>	$\Delta v = 2.201 \text{ m/s}$									<i>4.1</i>	
	Europa9	I	14-May-2029 20:58:09	100	24.1	3.93	6.03	9.48	33.86	7	2	12.43	24.9	13.54
	<i>CU-Man-E9</i>		<i>27-May-2029 08:55:17</i>	$\Delta v = 0 \text{ m/s}$									<i>12.5</i>	
	<i>Apo-Man-E9</i>		<i>02-Jun-2029 14:05:16</i>	$\Delta v = 1.951 \text{ m/s}$									<i>6.2</i>	
	Europa10	I	08-Jun-2029 17:51:49	25	-72.3	3.92	3.27	9.42	37.92	4	1	14.20	14.2	14.37
	<i>CU-Man-E10</i>		<i>11-Jun-2029 18:15:35</i>	$\Delta v = 1.439 \text{ m/s}$									<i>3.0</i>	
	<i>Apo-Man-E10</i>		<i>15-Jun-2029 22:22:27</i>	$\Delta v = 0 \text{ m/s}$									<i>4.2</i>	
	Europa11	I	22-Jun-2029 22:24:10	100	-25	3.93	2.05	9.29	33.94	7	2	12.43	24.9	14.84
	<i>CU-Man-E11</i>		<i>25-Jun-2029 23:12:45</i>	$\Delta v = 0 \text{ m/s}$									<i>3.0</i>	
<i>Apo-Man-E11</i>		<i>11-Jul-2029 17:51:19</i>	$\Delta v = 11.635 \text{ m/s}$									<i>15.8</i>		
Non-Res	Europa12	I	17-Jul-2029 19:10:35	100	-124.6	3.90	0.34	9.34	38.12	N	R	14.25	14.4	15.67
	<i>CU-Man-E12</i>		<i>20-Jul-2029 19:24:29</i>	$\Delta v = 0 \text{ m/s}$									<i>3.0</i>	
	<i>Apo-Man-E12</i>		<i>25-Jul-2029 01:26:55</i>	$\Delta v = 3.976 \text{ m/s}$									<i>4.3</i>	
COT-2	Europa13	O	01-Aug-2029 05:25:51	100	-74.2	3.81	3.11	9.39	37.98	4	1	14.20	14.2	16.15
	<i>CU-Man-E13</i>		<i>04-Aug-2029 06:49:40</i>	$\Delta v = 0 \text{ m/s}$									<i>3.1</i>	
	<i>Apo-Man-E13</i>		<i>08-Aug-2029 07:27:23</i>	$\Delta v = 2.142 \text{ m/s}$									<i>4.0</i>	
	Europa14	O	15-Aug-2029 10:30:01	100	-36.1	3.82	4.72	9.42	37.96	4	1	14.20	14.2	16.63
	<i>CU-Man-E14</i>		<i>18-Aug-2029 11:44:29</i>	$\Delta v = 0 \text{ m/s}$									<i>3.1</i>	
	<i>Apo-Man-E14</i>		<i>22-Aug-2029 13:31:02</i>	$\Delta v = 2.498 \text{ m/s}$									<i>4.1</i>	
	Europa15	I	29-Aug-2029 15:32:40	100	1.4	3.82	4.55	9.37	38	4	1	14.20	14.2	17.10
	<i>CU-Man-E15</i>		<i>01-Sep-2029 16:39:17</i>	$\Delta v = 0 \text{ m/s}$									<i>3.0</i>	
	<i>Apo-Man-E15</i>		<i>05-Sep-2029 19:49:51</i>	$\Delta v = 1.045 \text{ m/s}$									<i>4.1</i>	
	Europa16	I	12-Sep-2029 20:33:20	25	40.9	3.81	2.58	9.31	38.07	4	1	14.20	14.2	17.57
<i>CU-Man-E16</i>		<i>15-Sep-2029 21:32:51</i>	$\Delta v = 0 \text{ m/s}$									<i>3.0</i>		
<i>Apo-Man-E16</i>		<i>20-Sep-2029 01:53:29</i>	$\Delta v = 4.581 \text{ m/s}$									<i>4.2</i>		
Europa17	I	27-Sep-2029 01:34:33	25	82.1	3.80	0.72	9.27	38.09	4	1	14.20	14.2	18.05	
<i>CU-Man-E17</i>		<i>30-Sep-2029 01:29:00</i>	$\Delta v = 0 \text{ m/s}$									<i>3.0</i>		
<i>Apo-Man-E17</i>		<i>04-Oct-2029 06:05:15</i>	$\Delta v = 2.908 \text{ m/s}$									<i>4.2</i>		
Europa18	I	11-Oct-2029 06:13:06	100	74.2	3.82	3.36	9.22	34.12	7	2	12.43	24.8	18.52	

B-plane = B-plane angle relative to the satellite's mean equator of epoch; V-infinity = Hyperbolic excess velocity; In/Out = inbound (I) or outbound (O) flyby; Inc., Peri., Apo., and Period = Spacecraft central body mean equator inclination, perijove, apojoove, and period after the encounter; m = Integer number of gravity assist body orbits; n = Integer number of spacecraft orbits (NR=non-resonant transfer); TOF = time-of-flight; CU-Man = Post-flyby cleanup maneuver; Apo-Man = Orbit shaping maneuver typically done near apojoove; e = Flyby in eclipse.

Phase	Flyby/ Maneuver	In/ Out	Date	Altitude (km)	B-Plane Ang (deg)	V-Infinity (km/s)	Inc. (deg)	Peri. (RJ)	Apo. (RJ)	m	n	Period (days)	TOF (days)	Total TOF (months)
Pump Down, Crank Up	CU-Man-E18		14-Oct-2029 06:21:55	$\Delta v = 0$ m/s									3.0	
	Apo-Man-E18		30-Oct-2029 00:14:13	$\Delta v = 5.847$ m/s									15.7	
	Europa19	I	05-Nov-2029 02:34:07	100	92.4	3.85	6.17	9.17	29.92	3	1	10.65	10.6	19.35
	CU-Man-E19		08-Nov-2029 03:53:46	$\Delta v = 2.465$ m/s									3.1	
	Apo-Man-E19		10-Nov-2029 13:54:09	$\Delta v = 0$ m/s									2.4	
	Europa20	I	15-Nov-2029 18:02:04	100	97.7	3.85	8.73	9.22	25.39	5	2	8.88	17.7	19.70
	CU-Man-E20		18-Nov-2029 19:32:54	$\Delta v = 0$ m/s									3.1	
	Apo-Man-E20		28-Nov-2029 13:38:02	$\Delta v = 6.345$ m/s									9.8	
	Europa21	I	03-Dec-2029 11:56:44	100	92.9	3.87	11.09	9.23	20.6	2	1	7.10	7.1	20.30
	Apo-Man-E21		05-Dec-2029 16:04:02	$\Delta v = 2.68$ m/s									2.2	
	Europa22	I	10-Dec-2029 14:14:08	100	109.1	3.88	12.87	9.28	17.15	5	3	5.92	17.7	20.53
	CU-Man-E22		22-Dec-2029 11:06:26	$\Delta v = 0$ m/s									11.9	
	Apo-Man-E22		25-Dec-2029 10:07:17	$\Delta v = 2.082$ m/s									3.0	
Europa23	I	28-Dec-2029 08:03:48	805.1	117.6	3.89	13.87	8.27	14.03	N	R	5.22	28.7	21.12	
Switch-flip	CU-Man-E23		07-Jan-2030 20:29:36	$\Delta v = 0$ m/s									10.5	
	Apo-Man-E23		10-Jan-2030 11:09:44	$\Delta v = 0$ m/s									2.6	
	Ganymede24	O	26-Jan-2030 00:58:15	1346.7	-88.3	2.78	14.86	13.91	13.99	pi-tran		7.15	3.5	22.08
	CU-Man-G24		27-Jan-2030 13:36:44	$\Delta v = 0$ m/s									1.5	
	Ganymede25	O	29-Jan-2030 13:39:45	123.1	-2.7	2.79	11.93	12.64	17.3	1	1	7.11	7.1	22.20
	Apo-Man-G25		31-Jan-2030 14:18:35	$\Delta v = 0$ m/s									2.0	
Ganymede26	O	05-Feb-2030 16:18:38	1584.7	-157.6	2.75	10.2	9.06	15.75	N	R	5.39	8.5	22.44	
Apo-Man-G26		06-Feb-2030 11:27:15	$\Delta v = 0$ m/s									0.8		
Europa Sub-Iovian Hemisphere Coverage	Europa27 (e)	I	14-Feb-2030 04:41:04	100	-144.6	3.51	10.81	9.35	17.07	5	3	5.92	17.7	22.72
	CU-Man-E27		20-Feb-2030 08:02:04	$\Delta v = 0$ m/s									6.1	
	Apo-Man-E27		01-Mar-2030 05:07:30	$\Delta v = 2.338$ m/s									8.9	
	Europa28 (e)	I	03-Mar-2030 22:40:57	100	166.1	3.50	9.63	9.43	20.41	2	1	7.10	7.1	23.31
	CU-Man-E28		07-Mar-2030 00:20:31	$\Delta v = 1.92$ m/s									3.1	
	Apo-Man-E28		08-Mar-2030 01:48:52	$\Delta v = 0$ m/s									1.1	
	Europa29 (e)	I	11-Mar-2030 01:00:39	100	122.8	3.50	7.26	9.45	25.18	5	2	8.88	17.7	23.55
	CU-Man-E29		19-Mar-2030 22:37:34	$\Delta v = 0$ m/s									8.9	
	Apo-Man-E29		23-Mar-2030 19:59:29	$\Delta v = 9.779$ m/s									3.9	
	Europa30 (e)	I	28-Mar-2030 18:58:34	100	112.4	3.50	4.52	9.42	29.67	3	1	10.65	10.6	24.14
	CU-Man-E30		31-Mar-2030 19:59:29	$\Delta v = 0$ m/s									3.0	
	Apo-Man-E30		03-Apr-2030 03:11:29	$\Delta v = 1.912$ m/s									2.3	
	Europa31	O	08-Apr-2030 09:47:49	100	-135.6	3.48	6.56	9.39	25.25	5	2	8.88	17.8	24.49
	CU-Man-E31		17-Apr-2030 06:36:22	$\Delta v = 0$ m/s									8.9	
	Apo-Man-E31		21-Apr-2030 05:49:06	$\Delta v = 5.931$ m/s									4.0	
	Europa32	O	26-Apr-2030 04:12:11	100	89	3.50	3.51	9.38	29.71	3	1	10.65	10.6	25.09
	CU-Man-E32		29-Apr-2030 05:49:06	$\Delta v = 7.373$ m/s									3.1	
	Apo-Man-E32		01-May-2030 12:25:55	$\Delta v = 0$ m/s									2.3	
	Europa33	O	06-May-2030 19:02:35	25	-162.5	3.44	4.4	9.28	25.36	5	2	8.88	17.8	25.44
	CU-Man-E33		15-May-2030 15:19:14	$\Delta v = 0$ m/s									8.8	
Apo-Man-E33		19-May-2030 15:38:43	$\Delta v = 11.098$ m/s									4.0		
Europa34	O	24-May-2030 13:26:26	601.8	45	3.47	2.52	9.34	29.78	3	1	10.65	10.6	26.03	
CU-Man-E34		27-May-2030 14:22:34	$\Delta v = 0$ m/s									3.0		
Apo-Man-E34		29-May-2030 19:18:54	$\Delta v = 10.07$ m/s									2.2		
Non-Res	Europa35	O	04-Jun-2030 04:55:10	100	113.6	3.49	0.47	9.32	29.66	N	R	10.58	10.3	26.39
	CU-Man-E35		07-Jun-2030 06:03:39	$\Delta v = 0$ m/s									3.0	
	Apo-Man-E35		09-Jun-2030 10:10:59	$\Delta v = 13.642$ m/s									2.2	
COT-4	Europa36	I	14-Jun-2030 13:13:38	100	111.6	3.48	3.47	9.31	29.79	3	1	10.65	10.7	26.73
	CU-Man-E36		17-Jun-2030 13:50:22	$\Delta v = 0$ m/s									3.0	
	Apo-Man-E36		20-Jun-2030 00:31:43	$\Delta v = 3.714$ m/s									2.4	
	Europa37	I	25-Jun-2030 04:56:31	100	144	3.46	5.2	9.37	29.74	3	1	10.65	10.6	27.09
	CU-Man-E37		28-Jun-2030 05:31:29	$\Delta v = 0$ m/s									3.0	
	Apo-Man-E37		30-Jun-2030 14:47:53	$\Delta v = 9.232$ m/s									2.4	
	Europa38	I	05-Jul-2030 20:10:39	100	175.1	3.49	5.26	9.36	29.75	3	1	10.65	10.7	27.44
	CU-Man-E38		08-Jul-2030 21:12:34	$\Delta v = 0$ m/s									3.0	
	Apo-Man-E38		11-Jul-2030 04:40:04	$\Delta v = 2.909$ m/s									2.3	
	Europa39	O	16-Jul-2030 11:54:32	100	-147.6	3.49	3.52	9.33	29.76	3	1	10.65	10.6	27.80
	CU-Man-E39		19-Jul-2030 12:53:40	$\Delta v = 0$ m/s									3.0	
	Apo-Man-E39		21-Jul-2030 18:49:52	$\Delta v = 0.656$ m/s									2.2	
	Europa40	O	27-Jul-2030 02:56:52	25	-113.3	3.42	0.43	9.29	29.77	3	1	10.65	10.6	28.15
	CU-Man-E40		30-Jul-2030 04:33:56	$\Delta v = 0$ m/s									3.1	
Apo-Man-E40		01-Aug-2030 09:55:21	$\Delta v = 0$ m/s									2.2		
Europa41	O	06-Aug-2030 16:56:23	2661.5	-157.5	3.31	0.19	9.12	28.08	N	R	9.89	18.6	28.50	
CU-Man-E41		09-Aug-2030 20:13:52	$\Delta v = 0$ m/s									3.1		
Apo-Man-E41		11-Aug-2030 16:26:24	$\Delta v = 0$ m/s									1.8		
Impact	Ganymede42	I	25-Aug-2030 06:48:55	100	17.8	5.77	-	-	-	-	-	-	-	29.12

B-plane = B-plane angle relative to the satellite's mean equator of epoch; V-infinity = Hyperbolic excess velocity; In/Out = inbound (I) or outbound (O) flyby; Inc., Peri., Apo., and Period = Spacecraft central body mean equator inclination, perijove, apojove, and period after the encounter; m = Integer number of gravity assist body orbits; n = Integer number of spacecraft orbits (NR=non-resonant transfer); TOF = time-of-flight; CU-Man = Post-flyby cleanup maneuver; Apo-Man = Orbit shaping maneuver typically done near apojove; e = Flyby in eclipse.

E. Jupiter Orbit Insertion and Pump-down

The purpose of the first mission phase is threefold: 1) insert into orbit around Jupiter, 2) reduce the spacecraft’s energy relative to Jupiter, and 3) orient the spacecraft orbit such that the first set of Europa flybys has near-optimal relative velocity and lighting conditions for IPR, TI, and SWIRS observations (Fig. 4).

On the initial approach to Jupiter, the spacecraft would execute an inbound^{‡‡} Ganymede gravity assist just prior to JOI. JOI, an 857-m/s maneuver, straddles the 12.8-Jovian-radii (R_j) perijove and puts the spacecraft into a 206-day period orbit. Near apojoive of this first orbit, another large maneuver (PJR) would be necessary to counter solar perturbations induced as a result of the spacecraft’s large distance from Jupiter which suppress periapsis and to target an outbound^{§§} Ganymede flyby. Four additional Ganymede flybys would then be used to further pump-down the spacecraft’s energy relative to Jupiter in order to reach the required hyperbolic excess velocity (V_∞) for the first Europa science campaign.

Lastly, since Europa is tidally locked (i.e., the prime meridian always faces towards Jupiter), the terrain illuminated by the Sun is simply a function of where Europa is in its orbit. By implementing a nonresonant G0–G1 transfer followed by three outbound resonant transfers, we can rotate the spacecraft’s line of nodes clockwise such that the first set of Europa flybys would occur very near the Sun–Jupiter line, and hence, Europa’s anti-Jovian hemisphere is well lit. This is necessary since visible wavelength stereo imaging must be done in unison with IPR measurements as outlined in Section II.B.

F. Crank-over-the-Top

The mission design technique used to systematically cover a specific hemisphere of Europa is referred to as a crank-over-the-top (COT) sequence. This technique entails starting from an equatorial orbit, cranking the inclination up to the maximum^{***} (i_{max}) and then returning it to the equatorial plane via a set of resonant transfers. When starting from an inbound flyby, the COT sequence changes the flybys to outbound (transition occurs after i_{max} is reached, hence the term “over the top”), and vice versa when starting with outbound flybys. COT sequences starting from inbound flybys render coverage of the sub-Jovian hemisphere; COT sequences starting from outbound flybys cover the anti-Jovian hemisphere. The number of flybys—hence the density of groundtracks—for a given COT sequence is a function of spacecraft orbit period and its V_∞ relative to the gravity assist body. Specifically,

- For a given period: The number of flybys increases/decreases as V_∞ increases/decreases.
- For a given V_∞ : The number of flybys increases/decreases as the spacecraft period decreases/increases.

Lastly, if the same period resonant transfers are used throughout a COT sequence (i.e., only cranking, no pumping), all closest approaches would lie very near the prime or 180° meridians (i.e., longitudinally 90° away from gravity assist body’s velocity vector). If different period resonant transfers are used during a COT sequence (i.e., cranking and pumping), the closest approach can be placed away from the prime or 180° meridians.

G. Europa Science Campaign, Part I: Europa Anti-Jovian Hemisphere Coverage

The first Europa science campaign would focus on Europa’s anti-Jovian hemisphere. This would be done since it is more efficient (time, TID, and ΔV) to reach the proper lighting conditions—required by TI and SWIRS observations—on the anti-Jovian hemisphere given the Jupiter arrival conditions of the interplanetary trajectory. This

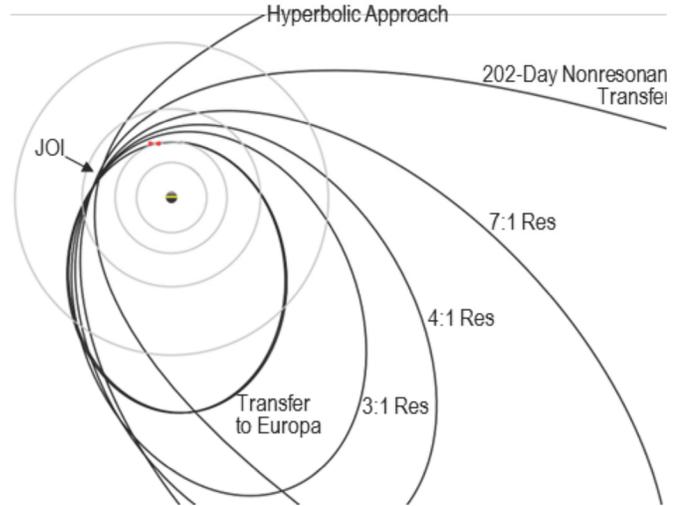


Figure 4. Energy Pump-down phase. View from Jupiter’s north pole (Sun-fixed, towards top) of the pump-down phase of the 11-F5 trajectory. Black: spacecraft orbit; Gray: orbits of the four Galilean satellites.

^{‡‡} Inbound flyby: Flyby that occurs prior to Jupiter perijove ($180^\circ < \text{spacecraft true anomaly} < 360^\circ$)

^{§§} Outbound flyby: Flyby that occurs after Jupiter perijove ($0^\circ < \text{spacecraft true anomaly} < 180^\circ$)

^{***} i_{max} is a function of spacecraft period and the V_∞ relative to the gravity assist body. When the spacecraft period is greater than the gravity assist body period, i_{max} occurs when the gravity assist body is at the spacecraft’s periapsis.

strategy was also preferred by the SDT since IPR measurements performed on Europa's anti-Jovian hemisphere yield a much higher SNR^{†††}.

To meet the science coverage requirements, but also minimize the number of Europa flybys (and hence minimize TID), the first COT sequence (COT-1) would use a combination of 4:1 ($T=14.3$ days) and 7:2 ($T=12.4$ days) resonant transfers with a V_∞ of approximately^{†††} 3.9 km/s. While alternating between the two resonances takes more time and leads to a higher TID (7:2 resonance has two perijove passages between Europa flybys) as opposed to using only 4:1 resonant transfers, it would result in the closest approaches being pulled away from the 180° meridian far enough to place a large portion of the groundtrack in the equatorial leading and trailing sectors of the anti-Jovian hemisphere (Fig. 6).

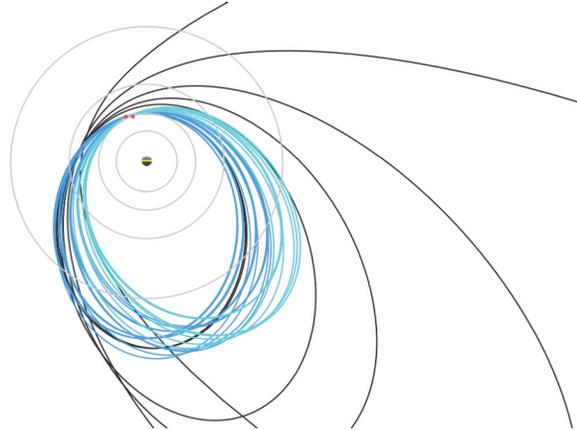


Figure 5. COT-1 and COT-2 Petal Plot. View from Jupiter's north pole (Sun-fixed, towards top) of the anti-Jovian hemisphere coverage mission phase. Black: pump-down; blue: COT-1; cyan: COT-2; gray: orbits of the four Galilean satellites.

Once COT-1 is complete (which would change the Europa flybys from outbound to inbound), a nonresonant Europa transfer would be used to get back to an outbound flyby such that another COT sequence could be implemented to cover the anti-Jovian hemisphere of Europa again. This nonresonant transfer would also change the local solar time (LST) of the Europa flybys.

All flybys in COT-1 occur at the ascending node. COT-2 (using strictly 4:1 resonant transfers) instead cranks in the opposite direction, placing the flybys at the descending node. This results in the COT-2 groundtracks intersecting the COT-1 sequence groundtracks (instead of running nearly parallel), hence fulfilling the IPR requirements in all seven anti-Jovian hemisphere sectors to have groundtracks with intersections (Fig. 7).

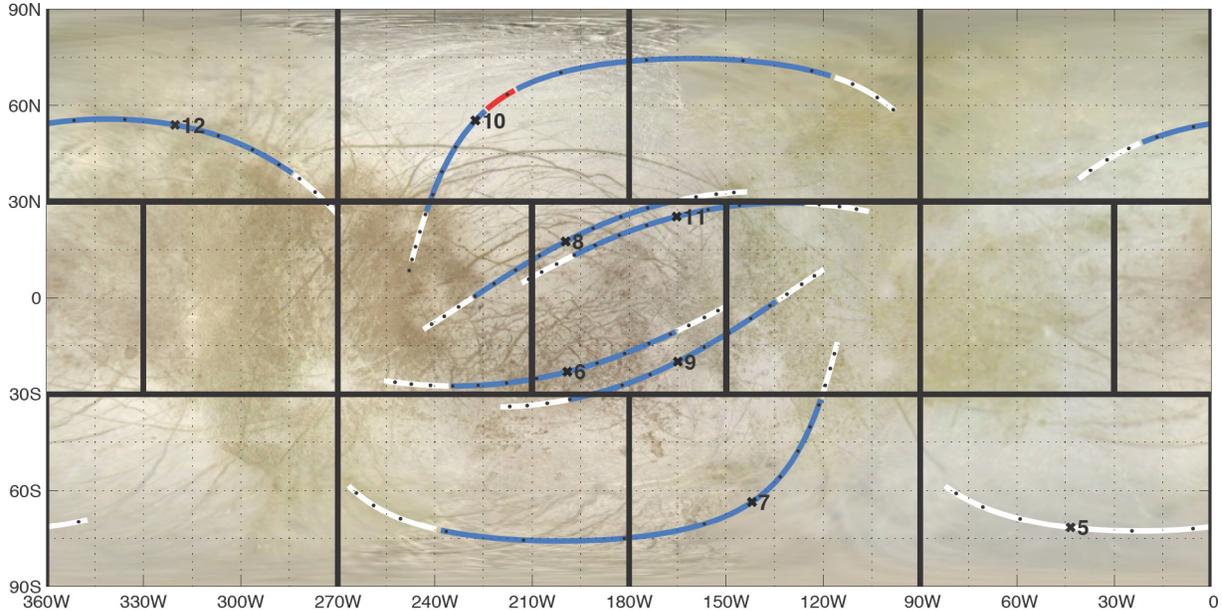


Figure 6. Europa COT-1 nadir groundtracks. Europa nadir groundtrack for COT-1. Closest approach is marked with an "x" and numbered in accordance with Table 4. Red: $0 < alt \leq 25$ km; blue: $25 < alt < 400$ km; white: $400 < alt < 1,000$ km.

^{†††} Jupiter is a radio source in the operating spectrum of the IPR instrument. Hence, IPR measurements done on the hemisphere of Europa shielded from Jupiter render a higher signal-to-noise ratio (SNR).

^{††††} Variations in V_∞ occur due to Europa's eccentricity and apsidal precession.

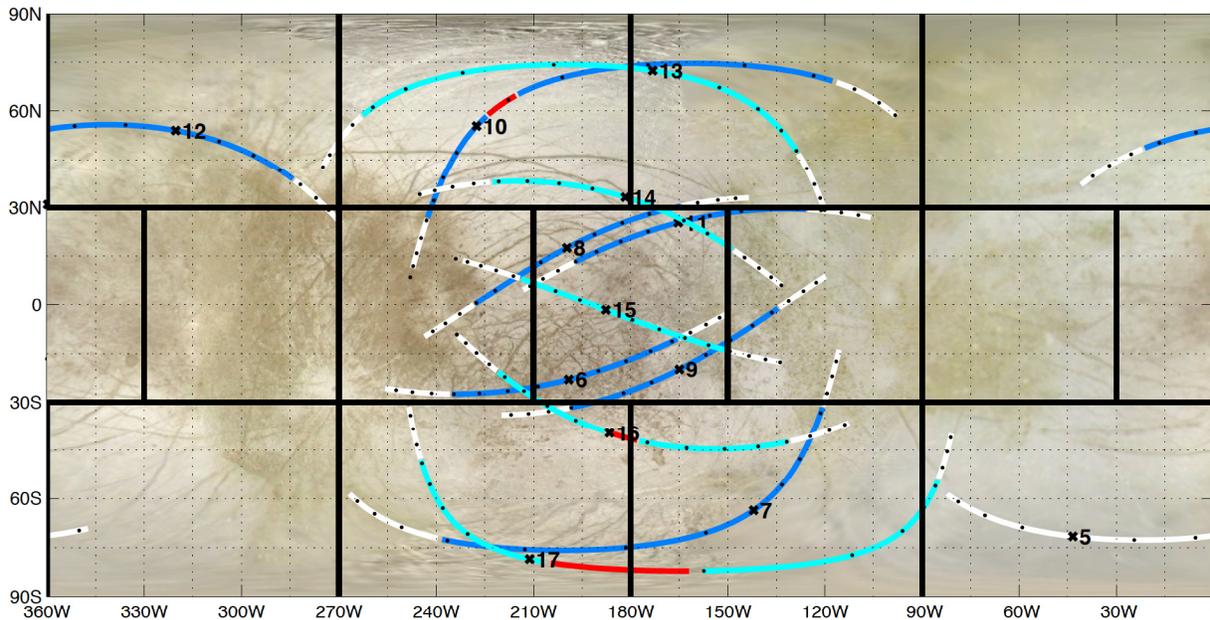


Figure 7. Europa COT-1 and COT-2 nadir groundtracks. Europa nadir groundtrack plot with COT-1 and COT-2. Green check marks indicate IPR requirements are met in specified sector. Closest approach is marked with an “x” and numbered in accordance with Table 4. Red: $0 < alt \leq 25$ km; blue (COT-1) and cyan (COT-2): $25 < alt < 400$ km; white: $400 < alt < 1000$ km.

H. Lighting Condition Change

Again, since visible wavelength stereo imaging must be done in unison with IPR measurements, it’s necessary to change the observation lighting conditions by 180° prior to taking IPR data on Europa’s sub-Jovian hemisphere. That is, the location of the Europa flybys needs to be moved to the opposite side of Jupiter so that Europa’s sub-Jovian hemisphere is well lit. Three different strategies can be implemented to accomplish this, using:

1. Primarily nonresonant Callisto and/or Ganymede transfers
2. Only nonresonant Europa transfers
3. A “switch-flip” (Europa-to-Ganymede pi-transfer^{§§§} \rightarrow Ganymede pi-transfer \rightarrow Ganymede-to-Europa pi-transfer)

Each strategy has its advantages. Option 1 would have the longest time of flight (TOF) but the lowest TID since perijove would be above Europa’s orbit radius the majority of the time. Option 2 would have the highest TID but would stay at Europa the entire time providing opportunities for continuous Europa observations over a wide range of geometries. Option 3 provides by far the fastest way to get from one side of Jupiter to the other, but does have a fairly high TID (although not as high as Option 2).

For this study, the switch-flip option was employed due to its time efficiency (Fig. 8). The detailed sequence of events includes first cranking up the inclination and pumping down the orbit period with Europa flybys to set up the correct geometry for a Europa-to-Ganymede transfer (Table 4). Once at Ganymede, a Ganymede pi-transfer is executed (3.5-day TOF), followed by a 1:1 resonant Ganymede transfer that cranks down the inclination and sets up the Ganymede-to-Europa pi-transfer. The result: All subsequent Europa flybys are located $\sim 180^\circ$ away from the last Europa flyby in COT-2.

It should be noted that either Option 1 or 2 could instead be seamlessly added to the end of the 11-F5 COT-2 sequence; however, everything downstream would need to be re-designed.

^{§§§} A nonresonant transfer, typically inclined, in which two successive flybys are separated by n *pi-radians (where n is an odd integer) in true anomaly (i.e., flybys occur on the opposite sides of Jupiter).

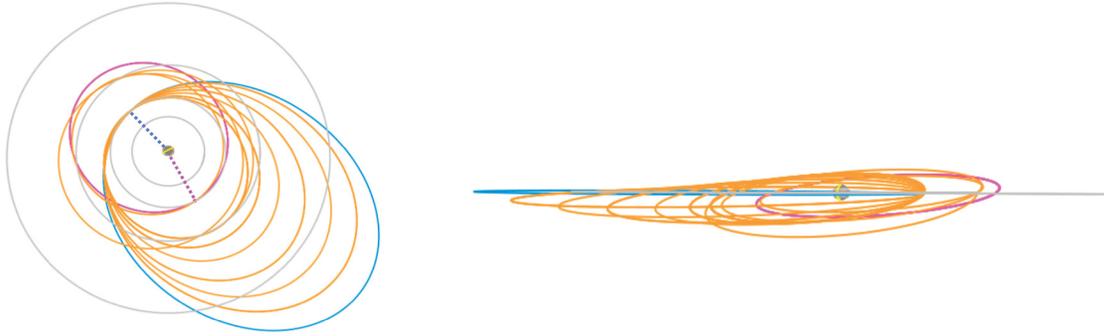


Figure 8. “Switch-flip” method used to change the Europa lighting conditions by $\sim 180^\circ$. Dashed lines indicate locations of the Europa flybys before (blue) and after (magenta) the switch-flip. Blue: Last COT-2 orbit; orange: switch-flip sequence; magenta: first COT-3 orbit. Left: View from Jupiter’s north pole (Sun-fixed, towards top). Right: View from Jupiter’s equatorial plane, north pole towards top of the page.

I. Europa Science Campaign, Part II: Europa Sub-Jovian Hemisphere Coverage

The second Europa science campaign would focus on Europa’s sub-Jovian hemisphere. Immediately following the Ganymede-to-Europa transfer, Europa flybys would be used to pump-up the orbit and crank-over-the-top. Like COT-1, the goal of COT-3 is to minimize the number of flybys while still providing adequate coverage for science. However, since the V_∞ is ~ 3.5 km/s (instead of 3.9 km/s in COT-1), the COT-3 sequence would need to instead alternate between 3:1 ($T=10.7$ days) and 5:2 ($T=8.8$ days) resonant transfers to accomplish this. Lastly the first four Europa flybys in COT-3 (Europa27 [E27] to Europa30 [E30]), would be in Jupiter’s shadow; hence no stereo imaging can be performed in unison with IPR measurement (see Fig. 10).

Once COT-3 is complete, a nonresonant Europa transfer would be used to get back to an inbound flyby such that another COT sequence can be implemented to cover Europa’s sub-Jovian hemisphere. This nonresonant transfer also changes the LST of the Europa flybys, as is shown in Figure 9.

Finally, COT-4 cranks in the opposite direction from COT-3 (i.e., switches the node at the Europa flybys from descending to ascending) with 3:1 resonant transfers to intersect the COT-3 sequence groundtracks, fulfilling the IPR requirements in six of the seven sub-Jovian hemisphere sectors (Fig. 11).

At the conclusion of COT-4, 13 of the 14 sectors have been covered sufficiently to meet the observational and measurement requirements of all four instruments on board as defined by the SDT.

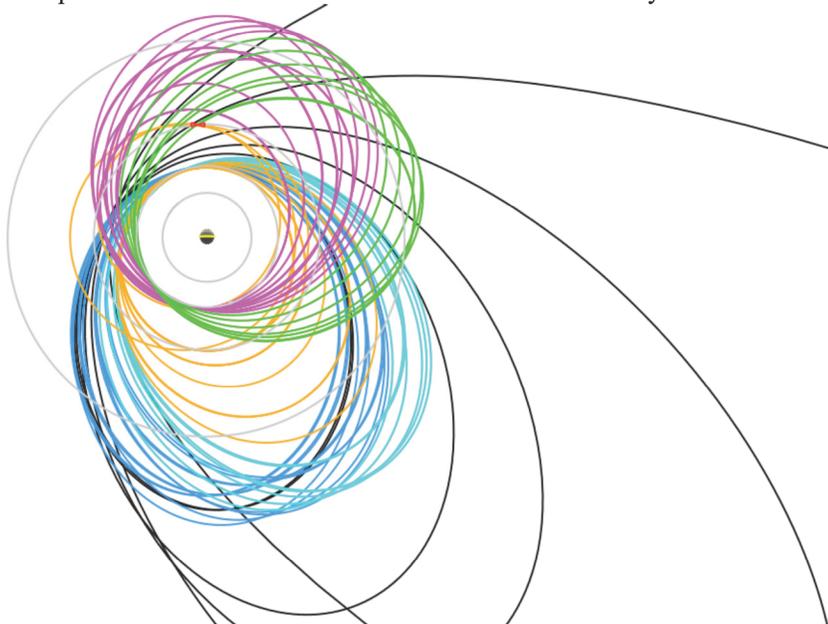


Figure 9. 11-F5 Petal Plot. View from Jupiter’s north pole (Sun-fixed, towards top) of the 11-F5 baseline trajectory. Black: pump-down; blue: COT-1; cyan: COT-2; orange: switch-flip; magenta: COT-3; green COT-4; gray: orbits of the four Galilean satellites.

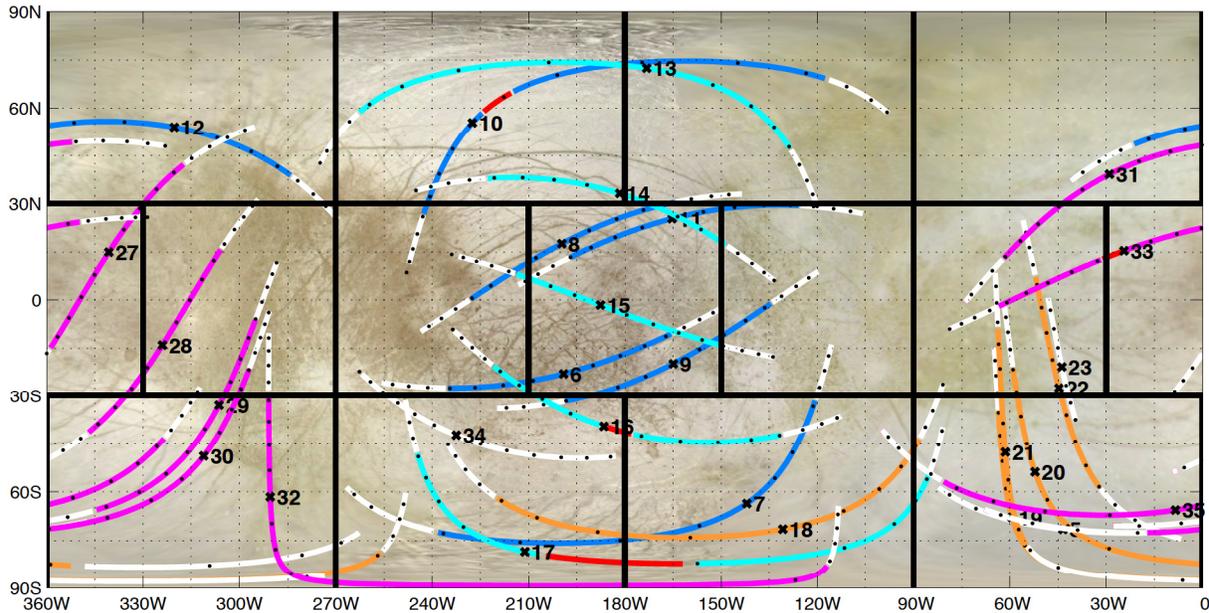


Figure 10. Europa COT-1-COT-3 nadir groundtracks. Europa nadir groundtrack plot for COT-1 through COT-3. Green check marks indicate IPR requirements are met in specified sector. Red circles with “e” indicate flybys in eclipse. Closest approach is marked with an “x” and numbered in accordance with Table 4. Red: $0 < alt \leq 25$ km; blue (COT-1), cyan (COT-2), orange (change lighting), and magenta (COT-3): $25 < alt < 400$ km; white: $400 < alt < 1000$ km.

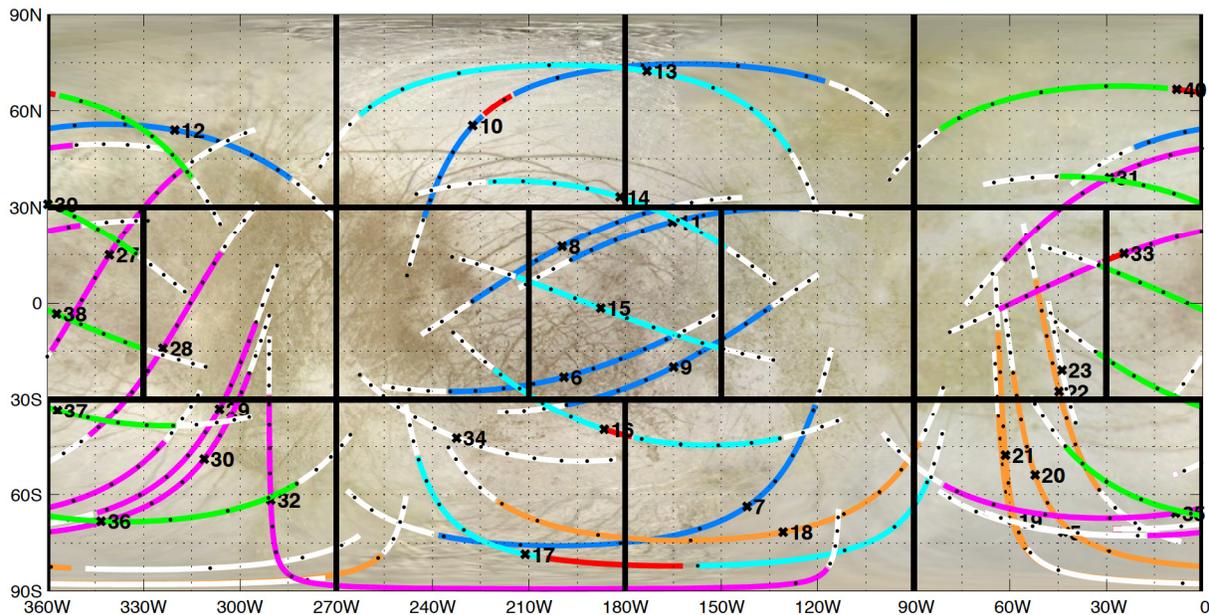


Figure 11. Europa COT-1-COT-4 nadir groundtracks. Europa nadir groundtrack plot for entire 11-F5 baseline trajectory. Green check marks indicate IPR requirements are met in specified sector. Red circles with “e” indicate flybys in eclipse. Closest approach is marked with an “x” and numbered in accordance with Table 4. Red: $0 < alt \leq 25$ km; blue (COT-1), cyan (COT-2), orange (switch-flip), magenta (COT-3), and green (COT-4): $25 < alt < 400$ km; white: $400 < alt < 1000$ km.

J. Navigational Feasibility

A sufficient amount of time is required between successive targeted flybys to accurately determine the spacecraft's orbit after the first flyby, as well as design, uplink, and perform a series of maneuvers to target the subsequent flyby. This places a lower bound on the TOF between targeted encounters.

The delivery accuracy for a given targeted flyby is primarily a function of the spacecraft trajectory uncertainties, as well as the ephemeris uncertainties of the bodies in the system the spacecraft resides in (especially the targeted flyby body). The delivery accuracy for a given flyby directly affects the ΔV costs (i.e., how much propellant is required to clean up flyby misses) and the minimum allowable flyby altitude of a body (probability of impact must be nil after the last maneuver to target the flyby has been executed). As the spacecraft and system uncertainties decrease—as knowledge of the system is gained via tracking data—so too does the minimum TOF between targeted flybys and the minimum flyby altitude. As such, the 11-F5 trajectory adheres to a two-prong strategy to maintain navigation feasibility:

- 1) Temporally ratchet down minimum flyby altitudes, paying particular attention to the first encounter of each body
- 2) Slowly decrease the average TOF between flybys

The first portion of the strategy would be implemented by targeting the first Ganymede and Europa flybys to the relatively high altitudes^{****} of 500 and 724 km, respectively (Table 4). Subsequent flybys of each body decrease uncertainties, and hence allow lower flybys to be carried out. Notice that all 25 km Europa flybys (done to maximize the quality of INMS measurements) would be performed at the end of COT sequences, where numerous 100 km flybys would have been completed and Europa's ephemeris would have become well known (at the particular LST the COT sequence occurs at). Lastly, it should be noted that since Ganymede and Europa are in a 1:2 orbital resonance, the first five Ganymede flybys (G0-G4) would provide knowledge of Europa's dynamics, thereby decreasing Europa's ephemeris uncertainties prior to the first Europa flyby.

The second portion of the strategy would be implemented by beginning with alternating 4:1 (TOF=14.2 days) and 7:2 (TOF=24.88 day) resonant transfers in the first COT sequence (COT-1). This oscillation in resonant transfers lessens the navigation intensity by interleaving longer TOF multi-revolution resonant transfers between each shorter 4:1 resonant transfer, and results in a mean TOF per encounter equal to 19.5 days.

With decreased Europa ephemeris uncertainties, a 14.4-day non-resonant transfer would be followed by COT-2, consisting of five back-to-back 4:1 resonant transfers, translating to a mean TOF per encounter of 14.2 days.

The pump-down and pi-transfer phases of the tour continue the downward average TOF per encounter trend, namely a decrease to 14 days. Of notable interest is the 3.5-day Ganymede-to-Ganymede pi-transfer. This transfer was implemented to minimize total tour TOF, and is believed to be navigationally feasible based on the ballistic nature of the transfer (i.e., no deterministic maneuvers) and the high altitude of the first Ganymede flyby (G24, 1346.7 km), which would decrease the ΔV sensitivity of a flyby miss. The later characteristic would minimize the magnitude of the G24 cleanup maneuver, which is important since there would only be time for a single maneuver. For comparison, Cassini successfully executed an 8-day Titan pi-transfer in 2009. This transfer was also designed to be ballistic; in operations a single statistical maneuver was executed with a magnitude of 0.75 m/s. If however the current baseline 3.5-day Ganymede pi-transfer is ultimately deemed too aggressive, a 3-, 5-, or 7-pi-transfer (i.e., TOFs of 10.5, 14, or 17.5 days, respectively) could be utilized instead.

COT-3 and COT-4 would proceed to further reduce the average TOF per encounter, with values of 13.75 and 11.95, respectively. The former would use the same alternating resonance strategy as COT-1 (only this time with 3:1 [TOF=10.65 days] and 5:2 [TOF=25.44 days] resonances), and the latter would implement five back-to-back 3:1 resonant transfers.

As a reference, Cassini performed nine back-to-back 1:1 resonant transfers with Titan (15.9-day TOF) under much more dynamic conditions (12–63° inclination and much closer central body periapses) and higher ΔV loads^{††††}.

K. Maneuvers

Throughout a mission's lifetime, numerous deterministic maneuvers are required to shape the trajectory, and statistical maneuvers are necessary to correct trajectory errors due to a number of sources. In the case of the 11-F5 trajectory, maneuver locations were generally placed 3 days after each flyby to clean up any flyby errors, and near apojoive to target the subsequent flyby (where timing permitted). Due to time constraints associated with the study for which the 11-F5 trajectory was developed, the maneuvers have not yet been placed for optimal navigation

^{****} When compared to minimum flyby altitudes executed by Galileo.

^{††††} Cassini's average ΔV budget was ~100 m/s per year during the Prime and Equinox missions.

robustness (i.e., provide time for apojoive backup maneuver locations prior to the targeted flyby). However, all transfers in the 11-F5 trajectory have, at most, only one maneuver with a deterministic component. In addition, the trajectory has very comfortable ΔV margins. These facts make future adjustments to maneuver locations of no foreseeable concern (based on extensive design experience on Cassini’s prime and two extended missions).

L. Overall Flexibility

The proposed 11-F5-like trajectory would push the envelope of navigational complexity, but would do so in a very strategic manner. However, if future analysis reveals any portion of the trajectory is navigationally infeasible, many trajectory design options exist. As previously mentioned, phasing orbits can be inserted to lengthen the 3.5-day-TOF transfer, and other “lighting condition change” options can be implemented, whether it’s the alternate options detailed in Section III.H or a different switch-flip sequence to obtain a higher V_{∞} at Europa, so the COT-3 and COT-4 sequences maintain a high average TOF between flybys.

M. ΔV Budget

Table 5 summarizes both the estimated current best estimate (CBE) and maximum estimated value (MEV) for the total ΔV needed to execute the Europa flyby-only mission. The two totals are comprised of both computed values (DSM, JOI, PRM and the tour’s deterministic ΔV) and estimated values (launch injection cleanup, Earth bias ΔV , interplanetary statistical ΔV and tour’s statistical ΔV).

Table 5. 11-F5 ΔV Summary.

Activity	CBE ΔV (m/s)	MEV ΔV (m/s)	Comments
Launch Injection Cleanup	20	20	Estimate to correct injection errors from launch vehicle.
Earth Bias ΔV	50	50	Needed for final correction of deliberate aim-point bias away from the Earth. ~25 m/s per Earth flyby. May be performed separately or integrated with other TCMs.
Deep Space Maneuver (DSM)	0–100	150	Maneuver on Earth-Venus leg near aphelion. Baseline launch period variation goes from 0 m/s up to 100 m/s.
Interplanetary Statistical & ΔV Cleanup	50	50	Multiple small maneuvers.
JOI at 12.8 Rj, 500-km G0 Flyby	857	900	200-day initial orbit.
Perijove Raise Maneuver	114	135	Counteracts solar perturbations, targets G1 flyby.
Tour Deterministic ΔV	157	200	Used primarily for targeting many resonant transfers.
Tour Statistical ΔV	63	170	~5 m/s per flyby for first 20 flybys, then 3 m/s for last 22 flybys (conservative). Rounded up. Expected average per-flyby values: 1.5 m/s per flyby
TOTALS	1311*	1675	*Assumes maximum DSM value

N. Potential Extended Mission(s)

Given a healthy spacecraft at the end of the baseline mission and support from NASA HQ, a variety of different extended missions are possible. They include, but are not limited to:

- Additional IPR and TI campaigns to fill in gaps, significantly advancing the baseline data set (not just incremental improvements)
- Dedicated new Europa campaigns
 - Gravity/tides investigation
 - Regional mapping of leading and/or trailing hemisphere(s) with TI and SWIRS
- Similar intricate Callisto and/or Ganymede flyby campaigns
- Ganymede or Callisto orbit (if sufficient propellant is available)
- Jupiter science campaigns

O. Spacecraft Disposal

Planetary protection may require that before control of the spacecraft is lost, action must be taken to minimize the probability of biological contamination of Jupiter’s moon Europa resulting from spacecraft impact. To preclude Europa impact, the study team chose Ganymede impact as the baseline spacecraft disposal scenario. This disposal

scenario was chosen simply because it was the transfer with the lowest TOF (post Europa-41) that resulted in impact. Many additional potential spacecraft disposal options exist, including (but not limited to) the following:

- Jovian system impacting trajectories:
 - Jupiter (via short- or long-period orbits, the latter using solar perturbations)
 - Io, Ganymede, or Callisto
- Long-term Jupiter-centered orbits:
 - Circular orbit between Ganymede and Callisto
 - Eccentric orbit outside of Callisto
- Jupiter system escape:
 - Heliocentric orbit
 - Saturn flyby, impactor, or potentially even capture
 - Icy-giant flyby or impactor
 - Trojan asteroid flyby or impactor

While theoretically all of these options are possible, numerical verification would need to be carried out to prove the existence (particularly the gas- and icy-giant flyby/impact trajectories) and quantify the TOF and associated ΔV costs of each.

IV. Potential Multiple-Flyby Trajectory Advantages

A variety of scientific investigations are required to address and answer key questions about Europa's habitability. As previously discussed, specific investigations naturally map to specific platforms based on their required geometries, the frequency of observations, data intensity, and instrument mass and power consumption.

The orbiter mission concept would concentrate on the water theme, as related to habitability, while addressing chemistry and energy themes as well. The conceived model payload for the Europa orbiter concept in the Europa 2012 Study Report would consist of a mapping camera, laser altimeter, magnetometer and Langmuir probe, and would focus on confirming the existence of an ocean and characterizing that ocean through geophysical measurements of Europa's gravitational tides and magnetic induction response. It also includes mapping of the global morphology and topography of the satellite, to reveal its geological evolution¹².

Based on the current configurations of the flyby and orbiter platforms¹², a multiple-flyby mission exhibits many potential advantages over an orbiting spacecraft.

- Much higher total data return
- While per unit time Europa science is more radiation expensive, much more data can be gathered per unit time at Europa. Ample time away from Europa (and the harsh radiation environment) is then available to downlink the data (Fig. 12)
- Data return is less susceptible to spacecraft or DSN anomalies due to much less compressed/stressed operations at Europa
- The ability to operate more massive and higher power instruments in the vicinity of Europa (for a given launch vehicle)
- The ability to shield to higher TID
- A simpler operations strategy
- The ability to perform extended (and even new) science campaigns at Europa to add significantly to the baseline data set (not just incremental improvements or redundancy)
- Since spacecraft is not constrained to permanently residing in Europa's gravity well, new Jupiter system campaigns could be executed (as outlined in Section III.N) once the spacecraft expected TID limits are reached
- Most likely—although certainly not a forgone conclusion—a lander mission would be the next step in exploring Europa if either a Europa multiple-flyby or orbiter mission concluded the probability of Europa habitability to be high. Given the many advantages (technically and scientifically) of a carrier/relay spacecraft accompanying a lander, it is reasonable to believe the low mass, low power investigations that are currently being considered for the orbiter mission (i.e., not currently part of the multiple-flyby notional payload) could be accommodated on the carrier/relay spacecraft

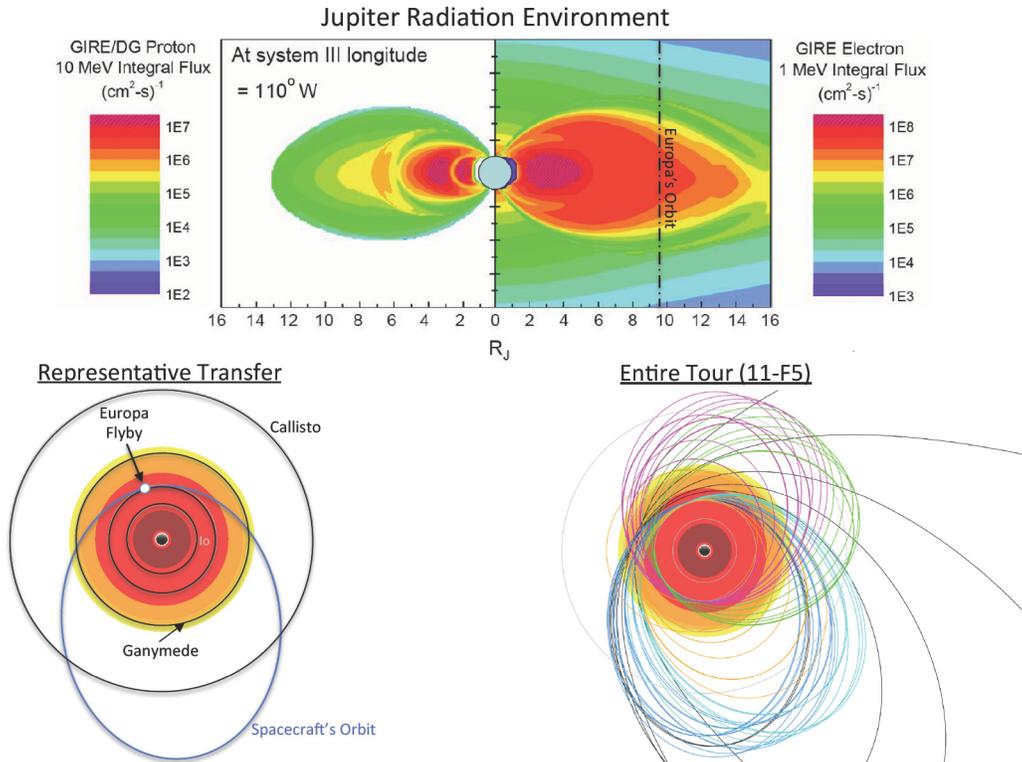


Figure 12. Jupiter’s Harsh Radiation Environment: *The uppermost figure shows a crosscut of Jupiter’s donut shaped radiation environment (Jupiter’s north pole pointing toward top of the page). The hotter the color, the more intense the radiation is. The bottom figures (looking down Jupiter’s north pole) exhibit how only a small portion of the flyby mission’s orbits traverse the most intense areas of radiation.*

V. Conclusion

A multiple-flyby mission architecture to efficiently investigate Europa—previously thought infeasible—has not only been developed, but is now the preferred path (given fiscal constraints and the quality and quantity of science return) by the scientific community to explore Europa in the near future. This complex network of flybys, would make possible the execution of a set of SDT-derived science investigations that would provide high caliber, compelling science, and would significantly change paradigms in our understanding of Europa. The enabling factor that made this mission architecture possible was the derivation of new mission design techniques, specifically, the crank-over-the-top sequence and switch-flip. The development of numerous multiple-flyby trajectories (culminating with 11-F5) have uncovered that a multiple-flyby mission architecture exhibits a number of potential advantages over an orbiter mission including: much higher total data return, data return less susceptible to spacecraft or DSN anomalies, the ability to operate more massive and higher power instruments in the vicinity of Europa (for a given launch vehicle), the ability to shield to a higher TID, a simpler operations strategy, the ability to perform extended (and even new) science campaigns at Europa to add significantly to the baseline data set (not just incremental improvements), and the potential to execute a plethora of Jupiter system science and intricate Callisto and/or Ganymede flyby campaigns once the spacecraft expected TID limits are reached.

Appendix

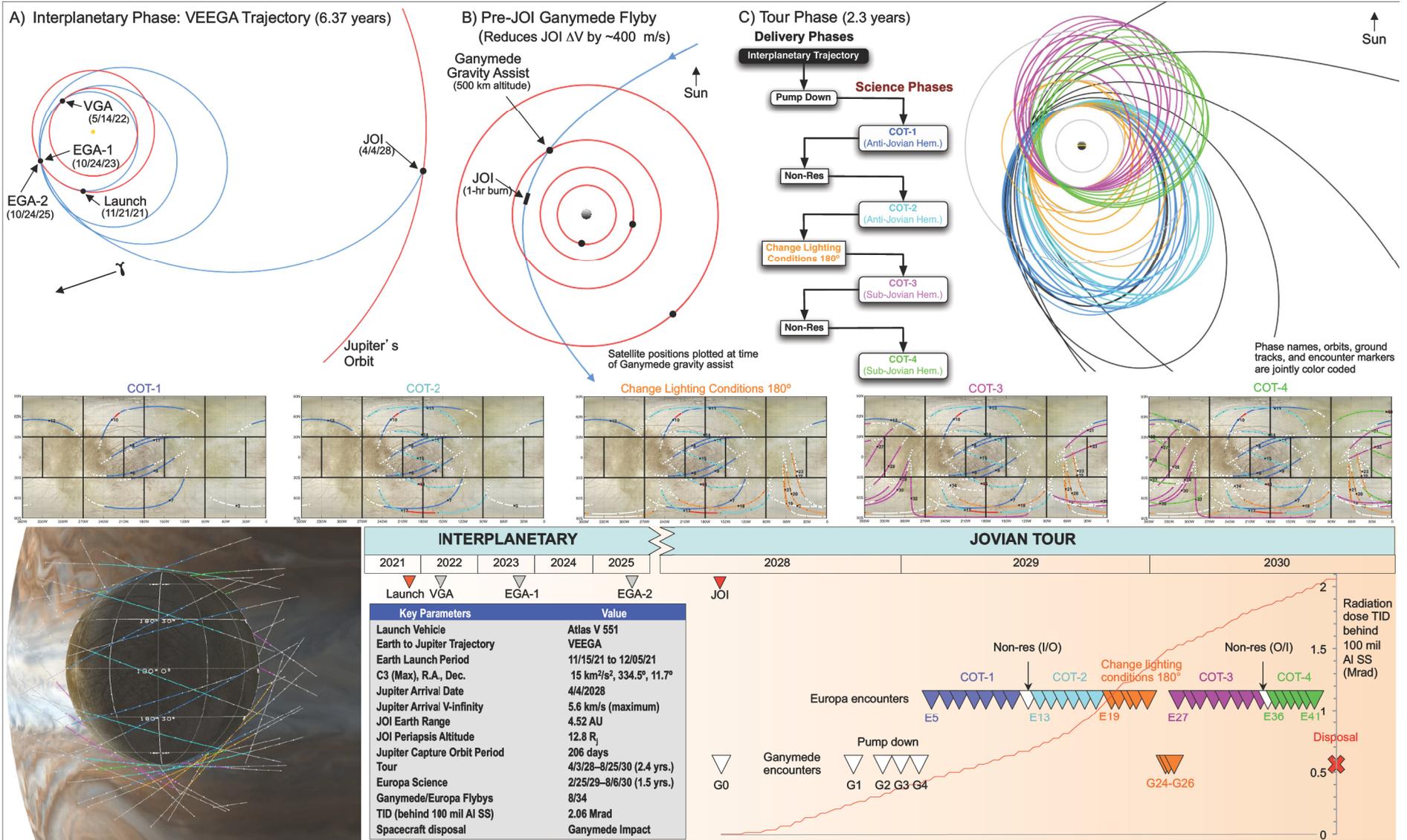


Figure A.1. Europa Multiple-Flyby Mission Design. Multiple-flyby approach to explore Europa and investigate its habitability.

Acknowledgments

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