Trajectory Design for the Europa Clipper Mission Concept

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Europa is one of the most scientifically intriguing targets in planetary science due to its potential suitability for extant life. As such, NASA has funded the California Institute of Technology Jet Propulsion Laboratory and the Johns Hopkins University Applied Physics Laboratory to jointly determine and develop the best mission concept to explore Europa in the near future. The result of nearly 4 years of work—the Europa Clipper mission concept—is a multiple Europa flyby mission that could efficiently execute a number of high caliber science investigations to meet Europa science priorities specified in the 2011 NRC Decadal Survey, and is capable of providing reconnaissance data to maximize the probability of both a safe landing and access to surface material of high scientific value for a future Europa lander. This paper will focus on the major enabling component for this mission concept—the trajectory. A representative trajectory, referred to as 13F7-A21, would obtain global-regional coverage of Europa via a complex network of 45 flybys over the course of 3.5 years while also mitigating the effects of the harsh Jovian radiation environment. In addition, 5 Ganymede and 9 Callisto flybys would be used to manipulate the trajectory relative to Europa. The tour would reach a maximum Jovicentric inclination of 20.1º, have a deterministic ΔV of 164 m/s (post periapsis raise maneuver), and a total ionizing dose of 2.8 Mrad (Si).

Nomenclature

IPR	=	Ice-penetrating radar
TI	=	Topographic imager
SWIRS	=	Short wave infrared spectrometer
(I)NMS	=	(Ion) Neutral mass spectrometer
MAG	=	Magnetometer (x2)
LP	=	Langmuir probe (x2)
RC	=	Reconnaissance camera
ThI	=	Thermal imager
V_∞	=	Hyperbolic excess velocity
C_3	=	Characteristic energy (V_∞^2)
ΔV	=	"delta-V" (i.e., change in velocity)
JOI	=	Jupiter orbit insertion
PRM	=	Periapsis raise maneuver
DSM	=	Deep space maneuver
DSN	=	Deep space network
SDT	=	Science Definition Team
AU	=	Astronomical unit
(E)VEEGA	=	(Earth) Venus-Earth-Earth gravity assist trajectory
NEPA	=	National Environmental Policy Act
SLS	=	Space Launch System
AO	=	Announcement of Opportunity
NRC	=	National Research Council
NLS	=	NASA Launch Services
LST	=	Local solar time
COT	=	Crank-over-the-top sequence
R_J	=	Jupiter equatorial radius (71,492 km)
SNR	=	Signal-to-noise ratio
i_{max}	=	Maximum inclination
TOF	=	Time-of-flight
FY	=	Fiscal year
CBE	=	Current best estimate
MEV	=	Maximum expected value
EELV	=	Evolved expendable launch vehicle
TID	=	Total ionizing dose (Si behind a 100 mil Al, spherical shell)

I. Introduction

DATA returned by NASA's Galileo spacecraft in the mid-1990's indicated the potential existence (but not definitive proof) of a global liquid water ocean beneath Europa's relatively thin ice shell.[1-5] While diminutive in sized compared to Earth, Europa—roughly the size of our moon—is believed to contain 2–3 times more liquid water than Earth.[6,7] This presumed global ocean is kept in a liquid state by the perpetual tidal flexing and heating associated with Europa's eccentric orbit around Jupiter, is believed to be in direct contact with a rocky mantle (potentially creating reductants via hydrothermal activity[8]), and is thought to have existed for the better part of the age of our solar system.[2,9] Furthermore, due to the harsh radiation environment Europa resides in, Europa's surface is continuously irradiated, a phenomenon known to create oxidants.[10,11] These postulates, coupled with a

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geodynamically active ice shell (as is evident from Europa's chaotic terrain void of many craters), could make Europa's ocean a rich source of chemical energy. Thus our current understanding of Europa points to it potentially possessing the three components (when simultaneously existing in a single environment) that define the necessary, but not sufficient, conditions required for life as we know it to exist: 1) a sustained liquid water environment, 2) a suite of biogenic elements (C, H, N, O, P, S), and, 3) energy sources that could be utilized by life. As such, Europa is arguably the most astrobiologically intriguing destination in our Solar System, and has been the focus of many mission concepts since the end of the Galileo mission.[12,13]

Many different architectures have been considered for further exploration of Europa, including impactors, flyby missions, sample return, orbiters with and without simple lander combinations, and sophisticated lander-only missions.[14-19] The vast majority of these mission studies have focused on the latter 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. While flyby-only missions (both single and multiple flybys) have been considered, they were quickly deemed insufficient due to the perceived deficiencies in accomplishing key Europa observations and measurements. However, in recent years (2011–present), a multiple flyby mission concept, referred to as Europa Clipper,[20,21] has been developed jointly by the Jet Propulsion Laboratory (JPL) and the Applied Physics Laboratory (APL) under NASA's Planetary Science Directorate sponsorship, and offers many advantages (cost, risk, and science value and volume) over the other aforementioned architectures.

II. Europa Clipper Mission Concept

The Europa Clipper mission concept is predicated on the developed capability[22,23] to obtain global-regional coverage of Europa (i.e., data sets at the regional scale, distributed across Europa globally) via a complex network of flybys while in Jupiter orbit. The mission concept focuses strictly on investigating Europa; hence, the spacecraft would either be taking Europa data, downlinking Europa data, calibrating instruments to maintain/improve Europa data quality, or executing tasks to setup the next Europa flyby.

A. Science Objectives

The overarching goal of the Europa Clipper mission concept is to investigate the habitability of Europa. Per NASA's Astrobiological Roadmap, a habitable environment "must provide extended regions of liquid water, conditions favorable for the assembly of complex organic molecules, and energy sources to sustain metabolism."[24] A NASA-appointed Europa Science Definition Team (SDT) has derived a set of scientific objectives that include confirming the existence of an ocean, characterizing any water within and beneath Europa's ice shell, investigating the chemistry of the surface and ocean, and evaluating geological processes that might permit Europa's ocean to possess the chemical energy necessary for life. The SDT derived science objectives for Europa exploration, which flow from key science issues, are consistent with those objectives recommended by the 2011 Decadal Survey.[25] These science objectives are categorized in priority order as:

1. ***Ice Shell and Ocean:*** Characterize the ice shell and any subsurface water, including their heterogeneity, ocean properties, and the nature of surface-ice-ocean exchange.
2. ***Composition***: Understand the habitability of Europa's ocean through composition and chemistry.
3. ***Geology***: Understand the formation of surface features, including sites of recent or current activity, and characterize high science interest localities.

The Europa SDT emphasized the need for obtaining simultaneous complementary data sets at Europa in order to best address these driving goals and objectives, and the need to obtain global-regional data sets. Both requests drive the mission design, with the latter levying the requirement to accomplish regional-scale remote sensing measurements (with sufficient coverage and resolution) in at least 11 of the 14 roughly equal-area "panels" distributed across Europa's surface (Fig. 1).

B. Reconnaissance Objectives

In addition to performing high caliber science investigations at Europa, NASA also strongly desires that the next Europa mission enable a future lander mission. This desire stems from the likelihood of a landed mission being the next step in exploring Europa, and current data does not provide sufficient information to identify landing site hazards (in order to design a lander to maximize the probability of a safe landing), nor the ability to discern location(s) of the highest scientific value. Therefore, in consultation with the Europa Clipper study team and NASA,

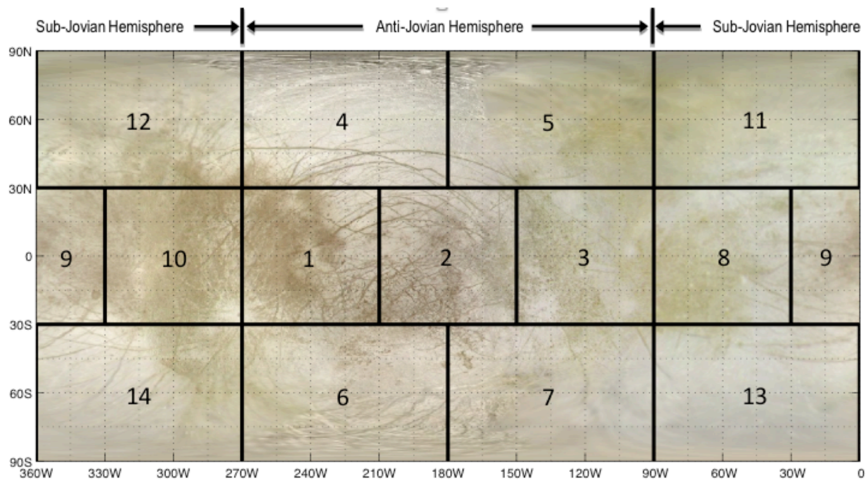

Figure 1. Europa cylindrical projection map of Europa, centered on the satellite's anti-Jupiter point. Europa is tidally locked, resulting in the same hemisphere always facing toward Jupiter (sub-Jupiter) and away from Jupiter (anti-Jupiter). The 14 numbered panels are those defined by the Europa Science Definition Team to assess "global-regional" coverage.

the Europa SDT developed two reconnaissance objectives emphasizing engineering and science, respectively:

1. ***Site Characterization***: Assess the distribution of surface hazards, the load-bearing capacity of the surface, the structure of the subsurface, and the regolith thickness.
2. ***Scientific Value***: Assess the composition of surface materials, the geologic context of the surface, the potential for geologic activity, the proximity of near-surface water, and the potential for active upwelling of ocean material.

C. Model Instrument Payload

An SDT-derived model payload was chosen as a best attempt to maximize the capability to efficiently achieve the required highest-priority science and reconnaissance objectives from a multiple flyby mission architecture. This model payload drives the mission characteristics and is necessary to quantify and analyze all engineering aspects of the mission concept and spacecraft design including scenarios associated with operating a spacecraft in the intense radiation environment at and around Europa. These measurements and notional instruments are in no way meant to be exclusive of different measurements and instruments that might be able to address the objectives and investigations in other ways, and which may impose somewhat different requirements. Ultimately, NASA would select the Europa Clipper mission instruments through a formal two-step instrument Announcement of Opportunity (AO) process.

The Europa Clipper model payload consists of eight instruments, plus a gravity science investigation that would utilize the spacecraft's telecommunications hardware. Specifically, the model payload includes: Ice-Penetrating Radar (IPR), Short Wave Infrared Spectrometer (SWIRS), Topographical Imager (TI), Neutral Mass Spectrometer (NMS), two magnetometers (MAG), two Langmuir probes (LP), Reconnaissance Camera (RC), and Thermal Imager (ThI).

Given the model payload, Table 1 summarizes the geometric constraints levied on the mission design. Refer to the science and reconnaissance traceability matrices[26] for a complete mapping of the scientific objectives to the model payload.

D. Key Design Strategy

Europa orbits Jupiter in a region of intense radiation, the result of Jupiter's strong magnetosphere collecting and accelerating charged particles. As such, spacecraft near Europa would be continually bombarded by radiation, a detriment to onboard electronics and instrumentation. To counter this harsh environment, shielding—in the form of aluminum, titanium, tantalum or other metals—would need to surround sensitive electronics. For a given launch vehicle, this shielding mass takes away from mass that could be used for scientific instrumentation. For a Europa orbiter architecture, available payload mass would be further decremented due to the large amount of propellant required to dissipate the spacecraft's energy necessary to reach Europa orbit.

The key design strategy of a multiple Europa flyby mission is, while in orbit around Jupiter, 1) quickly dip into the harsh radiation environment to collect a large volume of Europa data (remote observations and *in situ*

Table 1. SDT-derived science objectives that drive mission design.

	Instrument		Velocity (km/s)	Altitude (km)	Viewing Geometry	Coverage
Floor	IPR	Deep	< 6	≤ 1000	Groundtrack lengths ≥ 1600 km	Distributed in 11 of 14 panels with ≥ 3 groundtracks in each anti-Jupiter panel and ≥ 2 groundtracks in each sub-Jupiter panel. Each groundtrack must intersect another below 1000 km (intersection may lie outside panel of interest)
		Shallow		≤ 400	Groundtrack lengths ≥ 800 km	
	SWIRS		< 6	≤ 66,000	Local solar time between 9:00 and 15:00	≥ 70% of Europa at better than 10 km/pixel ~100 representative landforms at better than 300 m/pixel distributed across 11 of 14 panels All reconnaissance sites at better than 300 m/pixel
	Topographical Imager			≤ 4000	Required: Incidence angles in the range of 20° to 80° and solar phase angle ≤135° Desired: Incidence angles in the range of 45° to 70° and solar phase angle ≤135°	Stereo imaging spanning radar ground tracks ≥ 70% of Europa at better than 1 km/pixel ≥ 25% of Europa at better than 250 m/pixel
	NMS		< 7	≤ 200 (lower is better)	Ideally within ~8° of spacecraft ram direction	Global distribution
Baseline	Magnetometer			< 1561	N/A	Flybys distributed across a range of orbital phases and System III longitudes (better than each 45° of longitude)
	Langmuir Probe			< 1561	N/A	Same as MAG
	Gravity Science			≤ 100	Highest value: Repeat equatorial flybys along the Jupiter-Earth line. Spacecraft must not be occulted ± 18 Europa radii from closest approach. Avoid flybys near solar conjunction.	Flybys distributed across a range of orbital phases, especially near Europa's periapsis and apoapsis
Recon.	Reconnaissance Camera			≤ 50	Required: Incidence angles in the range of 20 to 80° Desired: Incidence angles in the range of 45° to 70°	Required: At least 15 2x10 km images at better than 0.5 m/pixel Desired: At least 15 5x10 km images at at better than 0.5 m/pixel
	Thermal Imager			≤ 1000	10:00 to 15:00 local solar time	All reconnaissance sites at better than 250 km/pixel
				≤ 60,000	3:00 to 6:00 and 10:00 to 15:00 local solar time	Selected reconnaissance sites at better than 15 km/pixel

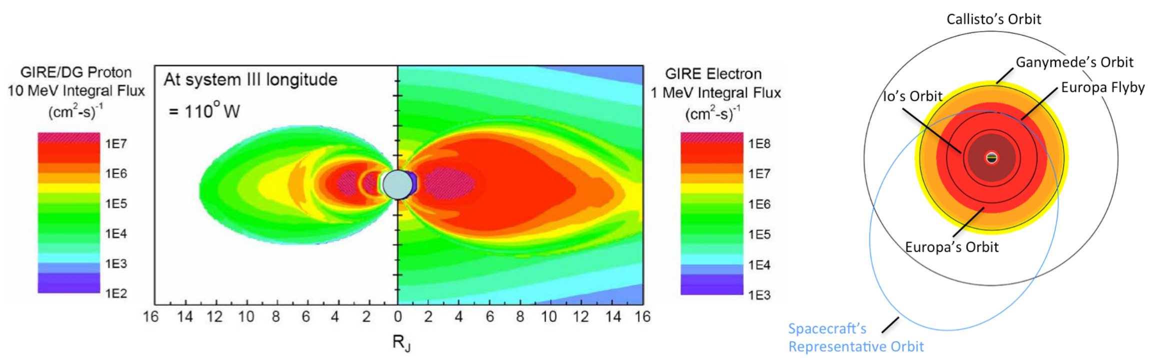

Figure 2. Radiation Environment and Overall Mission Design Strategy. Representative orbit with a 14.2-day period. Approximately 70% of the orbit is spent outside the harsh radiation environment (~10 days).

measurements), 2) escape the intense radiation environment such that the majority of the transfer time to the next Europa flyby would be available to downlink data sans radiation dose accumulation and with large downlink margins (Fig. 2), and 3) repeat steps 1 and 2 to systematically build-up a network of Europa flybys to obtain global-regional coverage of Europa. This "store and forward" approach (i.e., collect, store, and eventually downlink data) would enable the use of higher power instruments in the vicinity of Europa since the spacecraft would never have to simultaneously operate the instruments and a high power telecom system. In addition, the time away from the harsh radiation environment (and the subsequent Europa flyby) provides margin to react to anomalies and discoveries. These benefits are not available with a Europa orbiter architecture. A Europa orbiter would need to perform many different scientific investigations under a very compressed time schedule—due to a short spacecraft operability lifetime—driving up complexity, risk, and cost, and would have little opportunity to react to anomalies and discoveries without further driving up those attributes.

III. Interplanetary Trajectory

A. Launch Vehicle Options

The Europa Clipper spacecraft would launch from Kennedy Space Center, Cape Canaveral, Florida, USA, on a NASA selected and supplied launch vehicle. The mission concept is compatible with both the Space Launch System (SLS) and the Evolved Expendable Launch Vehicle (EELV) class (Atlas V 551, Delta IV Heavy, and Falcon Heavy) launch vehicles.

B. Interplanetary Trajectory Options

Due to the SLS and EELV launch vehicles offering a widely varying range of performance, and to make best use of each vehicle, the pre-Project has developed two interplanetary trajectory scenarios which could deliver the flight system from Earth to Jupiter. Specifically, an EELV would require a VEEGA trajectory to deliver the required mass to the Jupiter System for the Europa Clipper concept (Fig. 3), whereas the SLS is capable of delivering roughly the same mass on an Earth-Jupiter direct transfer (Fig. 4). The 13F7-A21 trajectory† assumes the use of an Atlas V 551 EELV, and hence, would utilize a Venus-Earth-Earth gravity assist (VEEGA) interplanetary trajectory[27] that would reach Jupiter in April of 2028. The maximum C_3 over a 21-day launch period (Nov. 15 – Dec. 5, 2021) is 15 km^2/s^2. The optimal launch date within the launch period is November 24, 2021 (Fig. 3). 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 Jupiter system (i.e., a single tour is compatible with any launch within the launch period). The launch vehicle and launch period parameters are shown in the Appendix. The spacecraft propellant tanks would be loaded up to the launch vehicle capability and the flight system would be designed to launch on any given day in the launch period without reconfiguration or modification.

The Europa Clipper interplanetary trajectory design would comply with all required National Environmental Policy Act (NEPA) assessment and safety analysis by implementing an Earth aimpoint-biasing strategy. The nominal flyby altitudes of Venus and Earth do not vary significantly over the launch period and are relatively high, as seen in Table 2. For comparison, Cassini flew by Earth at an altitude of 1166 km, and Galileo at altitudes of 960 and 304 km. Lastly, the minimum distance to the Sun would be 0.67 AU, occurring between launch and the Venus flyby.

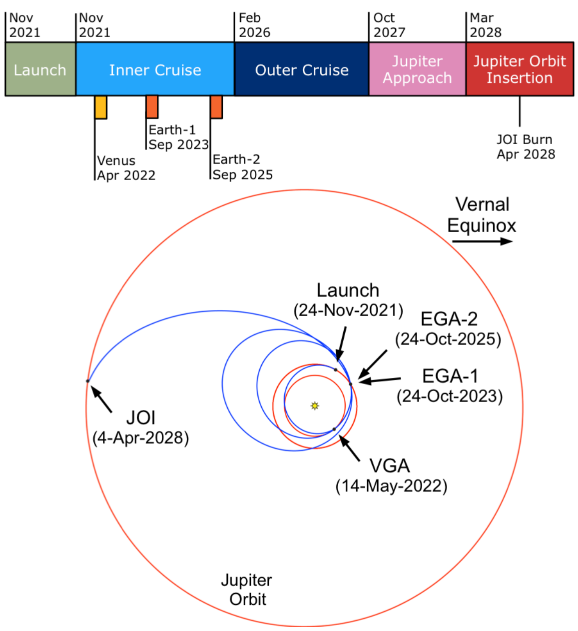

Figure 3. 2021 VEEGA Interplanetary Trajectory. Timeline with 21-day launch period opening in Nov. 2021 and interplanetary trajectory with optimal Nov. 24, 2021 launch date.

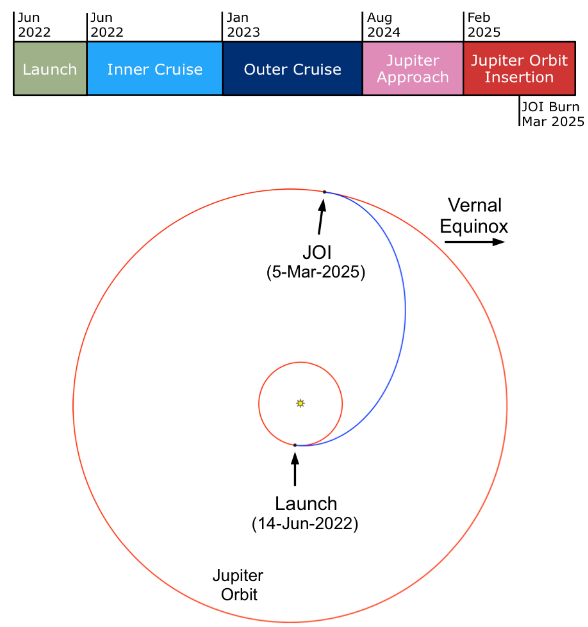

Figure 4. 2022 Earth-Jupiter Direct Interplanetary Trajectory. Timeline with 21-day launch period opening in June 2022 and interplanetary trajectory with optimal June 14, 2022 launch date.

Table 2. 2021 VEEGA Interplanetary Trajectory.

Event	Date	V_∞ (km/s)	ΔV (m/s)	Flyby Alt. (km)
Launch	21-Nov-2021	3.77	-	-
DSM	Mar-2022*	-	0-100	-
Venus	14-May-2022	6.62	-	318
Earth-1	24-Oct-2023	12.07	-	11764
Earth-2	24-Oct-2025	12.05	-	3336
G0	03-Apr-2028	7.37	-	500
JOI	04-Apr-2028	-	858	11.1 Rj

*Date varies across launch period

† A Jupiter tour stemming from the 2022 Earth-Jupiter direct trajectory is currently being developed.

IV. Jupiter Tour

The 13F7-A21 trajectory is numerically integrated in a high-fidelity *n*-body full force model, begins at Earth launch, and ends after the nominal mission is complete. The tour design objective is to balance the model payload coverage of Europa with Total Ionizing Dose (TID) [‡], ΔV, and mission complexity and duration (the latter affecting operations costs). The trajectory naming convention is as such: the first two digits refer to the year the trajectory was designed, the ‘F’ refers to the trajectory being a multiple Europa flyby mission (as opposed to a Europa orbiter or lander mission), the next digit is the sequential number of trajectory developed for a Europa mission, the ‘A’ denotes the assumed use of an Atlas V 551 launch vehicle, and the last two digits the launch year.

The Jupiter tour portion of 13F7-A21 would consist of 45 Europa, 5 Ganymede, and 9 Callisto flybys over the course of 3.5 years (Fig. 5 and Table 3), reaching a maximum Jovicentric inclination of 20.1°, having a deterministic ΔV of 164 m/s (post–periapsis raise maneuver), and a TID of 2.8 Mrad (Si). The entire tour can be broken into five distinct phases (Fig. 6), each detailed in subsequent sections.

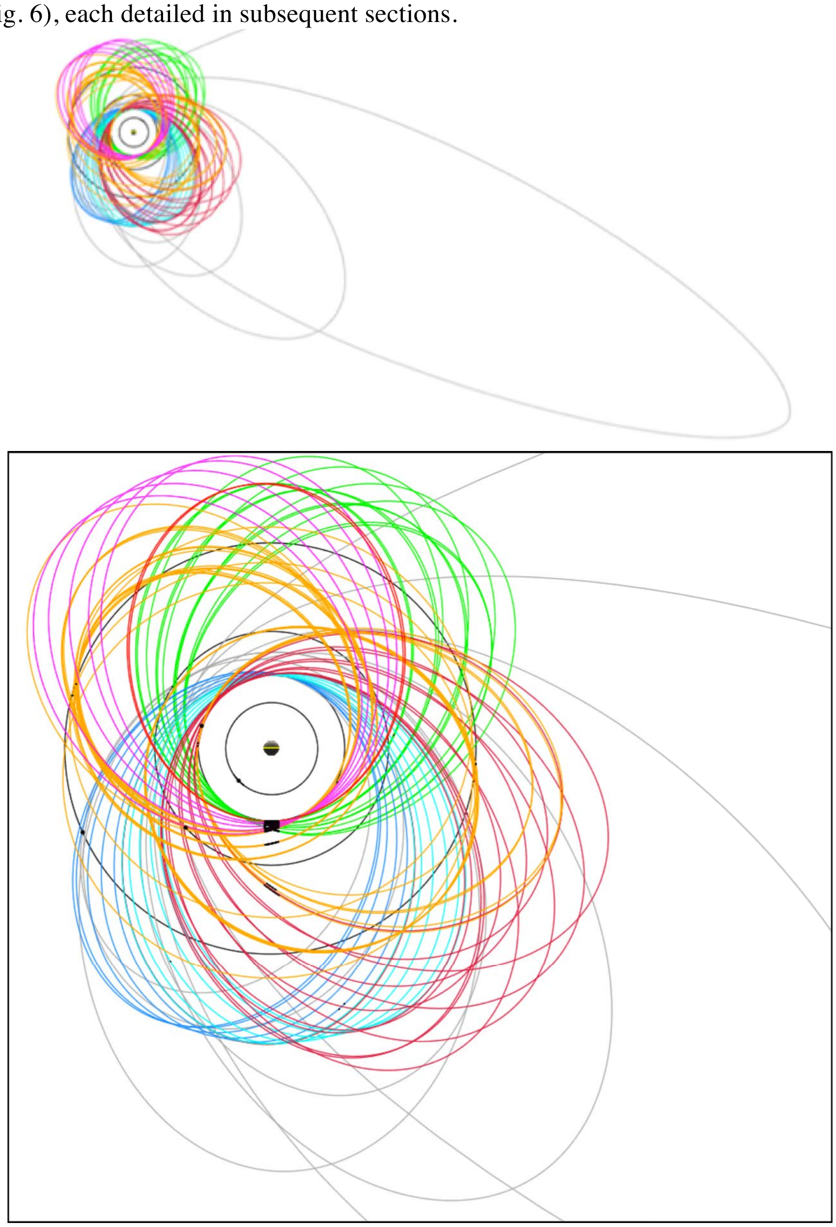

Figure 5. Europa Science Tour Trajectory Petal Plot. View from Jupiter’s north pole, Sun-fixed towards top of page. Gray: pump-down; blue: COT-1; cyan: COT-2; maroon: petal rotation; orange: Europa illuminated hemisphere transition; magenta: COT-3; green COT-4; black: orbits of the four Galilean satellites. Spacecraft’s trajectory shaded black when in Jupiter’s shadow.

[‡] Total ionizing dose Si behind a 100-mil Al, spherical shell (GIRE2 radiation model)

Table 3. 13F7-A21 Targeted Flybys. Closest approach and post-flyby Jupiter-centered orbital parameters.

Mission Phase		Flyby		In/ Out	Date (ET)	V_∞ (km/s)	θ (deg)	Closet Approach						Post Flyby Jupiter-Centered Quanties						
								Altitude (km)	Velocity (km/s)	Lat. (deg)	Lon. (deg)	SEP (deg)	T.A (deg)	Inc. (deg.)	Peri (R_J)	Apo (R_J)	m	n	Period (days)	TOF (months)
Jupiter Approach		Ganymede0	0G0	I	03-Apr-2028 11:58:20	7.98	0.1	500	8.36	-2.2	250.5	156	31	5.4	12.96	265.1	N	R	200	0.0
Transition to Europa Science		Ganymede1	1G1	O	22-Oct-2028 17:14:58	6.39	-152.7	100	6.93	27.6	297.5	17	129	3.7	12.00	107.8	8	1	57.2	6.7
		Ganymede2	2G2	O	18-Dec-2028 23:07:28	6.44	-147.9	100	6.98	32.3	287.2	64	117	1.3	11.09	64.4	5	1	28.6	8.6
		Ganymede3	3G3	O	16-Jan-2029 13:49:12	6.43	188.0	1035.4	6.84	8.2	277.1	90	97	0.8	10.20	45.9	N	R	18.3	9.5
		Callisto1	4C1	I	31-Jan-2029 12:30:02	5.54	156.2	911.6	5.92	-23.7	103.9	105	259	1.61	12.33	55.0	N	R	24.11	10.1
		Ganymede4	5G4	O	27-Feb-2029 18:42:50	5.24	163.5	523.6	5.81	-16.7	282.6	133	70	0.2	11.17	37.0	N	R	14.6	10.9
		Callisto2	6C2	I	16-Mar-2029 06:22:29	4.35	178.3	2635.9	4.67	-1.7	246.6	150	117	0.2	9.22	33.9	N	R	12.4	11.4
Europa Anti-Jupiter Hemisphere Coverage	COT-1	Europa1	7E1	O	25-Mar-2029 22:26:47	4.00	-36.2	752.7	4.34	36.2	148.0	161	120	1.4	9.29	38.0	4	1	14.2	11.8
		Europa2	8E2	O	09-Apr-2029 02:40:15	3.93	-71.1	250	4.36	68.8	182.3	176	127	3.84	9.37	37.9	4	1	14.2	12.3
		Europa3	9E3	O	23-Apr-2029 07:42:56	3.96	-44.3	100	4.42	40.1	179.6	168	138	5.7	9.44	37.9	4	1	14.2	12.8
		Europa4	10E4	O	07-May-2029 12:42:33	3.97	-15.9	100	4.43	12.0	178.9	152	149	6.3	9.48	37.8	4	1	14.2	13.3
		Europa5	11E5	I	21-May-2029 17:42:13	3.97	14.7	50	4.44	-16.0	178.3	137	160	5.5	9.47	37.8	4	1	14.2	13.7
		Europa6	12E6	I	04-Jun-2029 22:42:16	3.96	46.7	25	4.44	-45.5	177.3	123	172	3.33	9.40	37.9	4	1	14.21	14.2
	Non-Res (I/O)	Europa7	13E7	I	19-Jun-2029 03:44:29	3.93	78.0	100	4.40	-76.6	172.2	109	183	0.5	9.38	38.1	4	1+	14.3	14.7
	COT-2	Europa8	14E8	O	03-Jul-2029 15:16:07	3.97	80.8	100	4.43	-78.9	188.2	96	224	2.5	9.38	37.9	4	1	14.2	15.2
		Europa9	15E9	O	17-Jul-2029 20:14:28	3.99	53.0	25	4.47	-48.7	179.4	84	235	4.7	9.41	37.9	4	1	14.2	15.6
		Europa10	16E10	O	01-Aug-2029 01:15:16	4.00	27.3	50	4.47	-22.3	178.7	72	246	5.79	9.45	37.9	4	1	14.21	16.1
		Europa11	17E11	I	15-Aug-2029 06:11:34	4.00	-2.5	25	4.48	5.3	177.9	60	256	5.5	9.42	37.9	4	1	14.2	16.6
		Europa12	18E12	I	29-Aug-2029 11:07:50	4.00	-34.1	50	4.47	33.2	177.0	49	267	4.0	9.31	38.0	4	1	14.2	17.1
		Europa13	19E13	I	12-Sep-2029 16:00:58	3.98	-63.0	25	4.46	60.9	175.9	38	277	1.4	9.25	38.1	4	1	14.2	17.5
	Petal Rotation	Europa14	20E14	I	26-Sep-2029 21:15:22	3.92	-88.7	565.2	4.29	87.2	137.6	26	289	0.95	9.25	38.2	4	1+	14.28	18.0
		Europa15	21E15	O	11-Oct-2029 09:12:54	3.96	21.6	1872.2	4.19	-21.7	152.6	15	329	0.6	9.29	41.9	9	2–	16.0	18.5
		Europa16	23E16	I	12-Nov-2029 01:39:23	4.08	10.7	2710.3	4.26	-10.7	208.1	10	324	0.4	9.16	38.3	4	1+	14.3	19.0
		Europa17	24E17	O	26-Nov-2029 14:57:34	4.02	-1.9	50	4.48	2.0	155.7	21	11	0.4	9.28	45.5	5	1–	17.7	19.5
		Europa18	25E18	I	14-Dec-2029 04:40:32	4.01	-0.3	50	4.48	0.3	201.5	35	5	0.45	9.18	38.3	4	1+	14.28	20.1
		Europa19	26E19	O	28-Dec-2029 17:40:00	4.04	0.1	81.4	4.49	-0.2	155.4	47	50	0.5	9.30	45.5	5	1–	17.7	20.6
		Europa20	27E20	I	15-Jan-2030 07:07:06	4.04	0.5	50	4.51	-0.1	202.5	62	44	0.5	9.19	38.3	4	1+	14.3	21.1
		Europa21	28E21	O	29-Jan-2030 20:00:01	4.04	0.1	100	4.49	-0.1	156.4	75	87	0.5	9.37	45.4	5	1–	17.7	21.6
		Europa22	29E22	I	16-Feb-2030 09:40:09	4.04	0.2	50	4.51	-0.2	202.2	91	80	0.45	9.27	38.2	4	1+	14.29	22.2
		Europa23	30E23	O	02-Mar-2030 22:49:08	4.08	-0.8	50	4.54	0.8	155.1	105	125	0.4	9.39	45.4	5	1–	17.7	22.7
		Europa24	31E24	I	20-Mar-2030 12:05:36	4.08	-4.9	100	4.53	4.9	203.0	122	119	0.5	9.29	38.2	4	1+	14.3	23.3
Europa Illum. Hemisphere Transition	Crank Up Pump Down	Europa25	32E25	O	04-Apr-2030 01:17:20	4.10	84.8	50	4.56	-82.8	193.2	137	165	3.0	9.31	38.0	4	1	14.2	23.8
		Europa26	33E26	O	18-Apr-2030 06:13:37	4.12	63.1	50	4.58	-58.3	180.8	153	176	5.42	9.40	37.9	4	1	14.21	24.2
		Europa27	34E27	O	02-May-2030 11:03:14	4.13	74.2	50	4.58	-58.4	214.9	168	186	7.9	9.45	33.9	7	2	12.4	24.7
	Switch-Flip	Europa28	36E28	O	27-May-2030 07:36:51	4.14	109.5	25	4.61	-46.8	278.9	165	203	10.4	9.36	26.9	N	R	9.5	25.1
		Callisto3	37C3	I	01-Jun-2030 20:43:21	2.84	-138.0	466.5	3.62	31.0	120.6	159	307	14.5	14.77	28.7	3	4	12.5	25.4
		Callisto4	41C4	I	21-Jul-2030 21:11:52	2.84	-98.8	100	3.71	36.2	48.7	109	307	19	23.05	28.7	1	1	16.68	25.8
		Callisto5	42C5	I	07-Aug-2030 12:47:16	2.84	-64.1	1828.3	3.39	10.2	0.8	94	306	20.1	26.11	29.6	pi-trans		16.7	26.4
		Callisto6	43C6	O	15-Aug-2030 18:43:55	2.81	-177.6	100	3.69	15.5	180.8	86	125	17.4	21.84	26.5	1	1	16.7	27.0
		Callisto7	44C7	I	01-Sep-2030 10:18:27	2.83	-40.7	50	3.72	34.5	262.8	72	119	13.6	12.47	30.8	2	3	11.1	27.5
		Callisto8	47C8	I	04-Oct-2030 17:52:49	2.80	-106.3	25	3.71	67.7	183.8	45	120	1.07	11.15	27.8	2	3	11	27.9
		Callisto9	50C9	I	07-Nov-2030 06:37:46	2.97	-4.4	3673.1	3.34	4.6	314.7	18	122	0.5	9.01	29.2	N	R	9.7	28.3
Europa Sub-Jupiter Hemisphere Coverage	Pump Up, Avoid Sol. Conj.	Europa29	53E29	I	09-Dec-2030 22:16:03	3.99	173.6	546.7	4.35	-6.4	38.9	7	117	0.4	9.18	27.9	#	3+	11.8	28.6
		Europa30	56E30	O	14-Jan-2031 21:03:56	4.05	-8.7	1008.9	4.35	8.7	144.5	36	191	0.7	9.34	32.8	4	1–	14.1	29.0
	COT-3	Europa31	57E31	I	28-Jan-2031 18:06:22	3.99	-108.7	100	4.45	70.0	4.1	48	167	3.06	9.36	37.8	4	1	14.2	29.4
		Europa32	58E32	I	11-Feb-2031 23:08:17	3.97	-135.8	100	4.43	40.7	359.6	60	179	4.9	9.42	37.9	4	1	14.2	29.9
		Europa33	59E33	I	26-Feb-2031 04:12:05	3.95	-169.8	50	4.43	7.1	358.5	72	191	5.3	9.46	37.9	4	1	14.2	30.4
		Europa34	60E34	O	12-Mar-2031 09:13:50	3.96	152.7	50	4.43	-27.6	357.9	84	203	3.9	9.39	37.9	4	1	14.2	30.9
		Europa35	61E35	O	26-Mar-2031 14:15:57	3.97	118.4	25	4.45	-60.4	356.1	97	214	1.3	9.35	37.9	4	1	14.2	31.3
	Non-Res (O/I)	Europa36	62E36	O	09-Apr-2031 18:29:46	3.91	151.8	303.4	4.33	-28.5	334.0	111	222	0.3	9.28	37.9	7	2–	12.4	31.8
	COT-4	Europa37	64E37	I	04-May-2031 06:22:11	3.89	105.1	50	4.37	-73.4	3.4	135	204	3.11	9.33	33.9	7	2	12.44	32.2
		Europa38	66E38	I	29-May-2031 03:37:25	3.78	187.1	25	4.28	8.6	14.6	161	225	2.6	9.40	34.0	4	1	14.2	32.6
		Europa39	67E39	I	12-Jun-2031 07:37:05	3.81	96.5	50	4.30	-70.9	302.1	177	231	5.5	9.41	37.9	7	2	12.4	33.1
		Europa40	69E40	I	07-Jul-2031 04:32:16	3.79	-139.5	25	4.29	39.5	18.8	157	252	3.5	9.38	33.9	4	1	14.2	33.5
		Europa41	70E41	I	21-Jul-2031 08:16:20	3.80	124.8	50	4.29	-48.8	333.5	142	257	5.87	9.41	37.9	7	2	12.45	34.0
		Europa42	72E42	O	15-Aug-2031 05:17:45	3.80	-112.9	50	4.29	60.7	28.8	117	275	3.1	9.38	33.9	4	1	14.2	34.4
		Europa43	73E43	O	29-Aug-2031 08:56:30	3.76	-210.5	25	4.26	-27.4	339.6	104	280	4.6	9.35	37.9	7	2	12.5	34.9
		Europa44	75E44	O	23-Sep-2031 05:37:43	3.74	-82.1	50	4.24	74.3	101.7	81	298	1.7	9.34	33.8	4	1	14.2	35.3
		Europa45	76E45	O	07-Oct-2031 08:47:55	3.68	-177.6	25	4.19	3.2	350.0	69	301	1.5	9.28	37.9	7	2	12.5	42.7

In/Out = inbound (I) or outbound (O) flyby; V_∞ =V-infinity; **θ** = B-plane angle; SEP = Sun-Earth-Probe angle; Inc., T.A. = Europa true anomaly; Peri., Apo., and Period = Spacecraft central body mean equator inclination, periapsis, apoapsis, and period after the encounter; m = Integer number of gravity assist body orbits; n = Integer number of spacecraft orbits (NR = non-resonant transfer, pi-trans = pi-transfer); TOF = time-of-flight

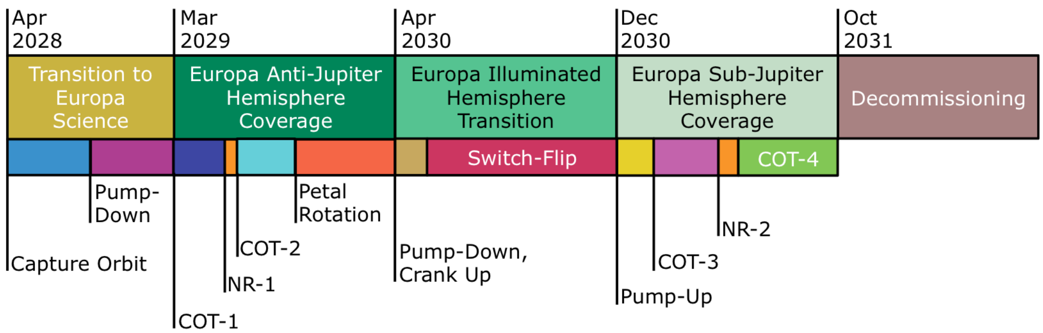

Figure 6. 13F7-A21 Tour Timeline. Five distinct mission phases with associated trajectory sub-phases.

A. Jupiter Approach and Transition to Europa Science

Approximately 14 hours prior to the Jupiter Orbit Insertion (JOI) maneuver, a 500 km Ganymede flyby would be utilized to reduce the magnitude of the maneuver. JOI would occur at periapsis at a range of 11.1 R_J (i.e., in the less intense outer regions of the radiation belts). Gravity losses would be negligible due to the small angle subtended by the burn arc. The spacecraft would then perform a periapsis raise maneuver (PRM) near apoapsis of a 202-day period capture orbit to counter solar gravity perturbations (which depress periapsis due to the orbit's orientation relative to the Sun) and target an outbound Ganymede flyby. Four Ganymede and two Callisto flybys would then be used to reduce spacecraft energy relative to Jupiter and orientate the spacecraft's orbit such that the relative velocities and lighting conditions at Europa would be acceptable for the model payload instruments (pump down sub-phase in Fig. 6).

Europa, the smallest of the Jupiter's four Galilean moons, has an orbit period of 3.55 days and is in a Laplace resonance with Io and Ganymede[§]. Like the majority of moons in our solar system, Europa is tidally locked. This synchronous rotation results in Europa always having nearly the same orientation relative to Jupiter, and hence, illuminated terrain is a function of where in Europa is in its orbit (Fig. 7). For flybys with spacecraft relative velocities commensurate with the model payload velocity requirements near Europa (Table 1), closest approach tends to be very near Europa's prime and 180° meridians. As a result, to obtain Sunlit observations at and around closest approach, Europa needs to be located near noon or midnight Jupiter local solar time (LST) in its orbit during flybys.

B. Europa Science Campaign 1: Anti-Jupiter Hemisphere Coverage

The first part of the Europa science tour would focus on Europa's anti-Jupiter hemisphere. Given the interplanetary trajectory arrival conditions at Jupiter, Europa's anti-Jupiter hemisphere is the most efficient (in time, TID, and ΔV) to reach with the lighting conditions required by the majority of the model payload instruments. Furthermore, for instruments operating in the spectrum near Jupiter's radio emission frequencies (i.e., IPR), measurements performed on Europa's anti-Jupiter hemisphere yield a much higher SNR by leveraging protection from Europa. This tour phase would consist of 24 Europa flybys with a duration of 13.3 months.

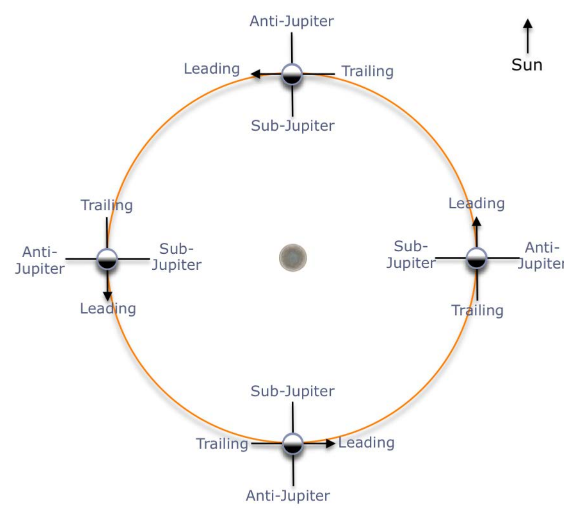

Figure 7. Europa's Orbit Characteristics. View from Jupiter's north pole, Sun-fixed towards top of page. Since Europa is tidally locked, the illuminated terrain is a function of where Europa is in its orbit.

B.1. Crank-over-the-top Sequence (COT)

The mission design technique used to systematically cover a specific hemisphere of Europa to attain global regional coverage is referred to as a crank-over-the-top (COT) sequence. A COT sequence begins with an equatorial orbit, and uses a number of resonant

[§] Ganymede, Europa and Io are in a 1:2:4 orbital resonance

Europa-to-Europa transfers[**] to increase the spacecraft's Jupiter relative inclination (referred to as cranking) up to the maximum inclination[††] (i_{max}). Continuing to crank in the same direction would then decrease the spacecraft's inclination, eventually returning to an equatorial orbit (denoting the end of the COT sequence). The spacecraft's V-infinity (V_∞) vector with respect to the gravity assist body would be rotated around 180º during this sequence of flybys, which results in a set of Europa flyby ground tracks with strong regional coverage.

When starting from an inbound flyby, the COT sequence changes the flybys to outbound, and vice versa, when starting with outbound flybys the COT sequence ends with inbound flybys. The transition occurs when the flight-path-angle is 0º, commensurate with when the sequence reaches i_{max}. COT sequences beginning with inbound flybys would render coverage of the sub-Jupiter hemisphere of Europa; COT sequences beginning with outbound flybys would cover the anti-Jupiter hemisphere of Europa. The number of flybys—and 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 orbit 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.

If the same period resonant transfers are used throughout a COT sequence (i.e., the ΔV imparted by the gravity assist is used only to change the spacecraft's inclination and not orbit period), all closest approaches will lie very near the prime or 180º meridians (i.e., longitudinally 90º away from gravity assist body's velocity vector). If different period resonant transfers are used during a COT sequence (i.e., the gravity assist is used to change the spacecraft's inclination *and* orbit period), the closest approach can be moved away from the prime or 180º meridians (see Section IV.D).

Lastly, the crank direction (positive or negative) of the COT sequence will dictate the direction the groundtracks build up over a given hemisphere. Cranking in the negative direction will place the gravity assist at the descending node of the spacecraft central body orbit, and the groundtracks will build up coverage from north to south. Similarly, cranking in the positive direction will place the gravity assist at the ascending node of the spacecraft central body orbit, and the groundtracks for the COT sequence will build up coverage from south to north. See references 22 and 23 for much more detail on COT sequences.

B.2. COT-1 and COT-2

The mission design for any Europa mission is a delicate balance of instrument coverage (both instrument-specific and the cumulative suite) and time spent near Europa. In the case of the Europa Clipper mission concept, this time near Europa equates to the total number of Europa flybys (or more specifically, the total number of spacecraft periapsis passages near Europa's orbital radius). While scientists would clearly prefer additional flybys (absent other constraints), they would come at the cost of additional passages through the harsh radiation environment near Europa. These passages increase the mission TID, which beyond a certain point, significantly drive up spacecraft complexity, costs, and mission risk. Too few flybys and the scientific objectives would not be met—a clear mission failure.

With an understanding of the density of groundtracks per COT sequence and how many flybys are required to fulfill the model payload instrument-specific coverage (Table 1) via parametric studies, the combination of spacecraft orbit resonance and V_∞ must be chosen. Table 4 summarizes a number of different single spacecraft rev (to minimize TID) combinations of resonance and V_∞ ranges that render six to seven flybys per COT sequence (assuming 100 km flybys), have a relative velocity that does not exceed 6 km/s (IPR and SWIRS upper bound), and have a groundtrack over Thera or Thrace Macula (while not a formal requirement, Thera and Thrace are the two locations the scientific community would choose to place a lander today given the

Table 4. Orbit Resonance and V_∞ range. Combinations resulting in six to seven flybys per COT sequence, and which place one groundtrack over Thera or Thrace.

Resonance	Period (days)	V_∞ Range (km/s)
3:1	10.65	3.55-3.69
4:1	14.2	3.92-4.02
5:1	17.75	4.17-4.25
6:1	21.3	4.35-4.43
7:1	24.85	4.5-4.56

[**] A resonant transfer is typically labeled as *m:n*, where m is the number of gravity-assist body revs and n is the number of spacecraft revs.

[††] 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.

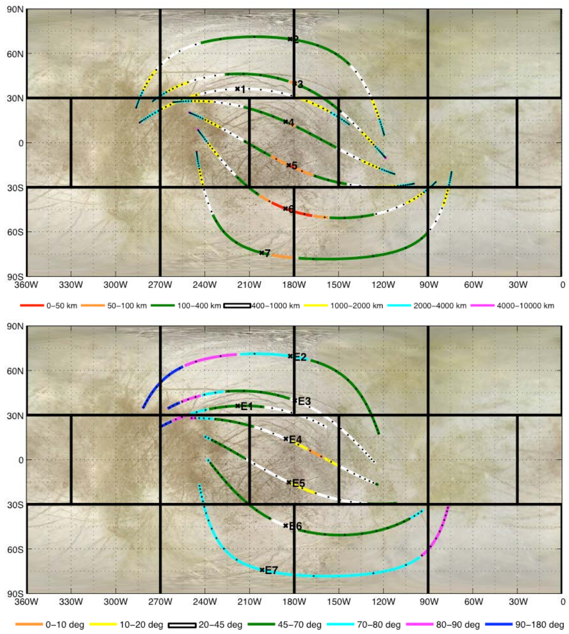

Figure 8. COT-1 Groundtracks. Color contoured by altitude (top) and solar phase (bottom). One-minute time ticks with closest approach marked with an "x" and numbered in accordance with Table 3.

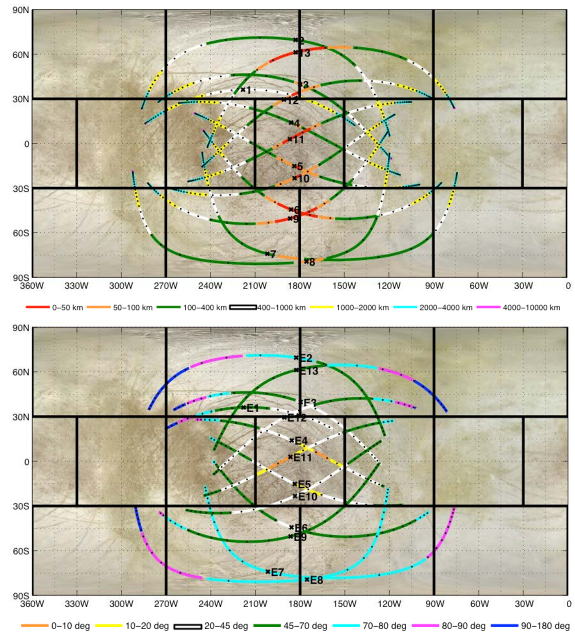

Figure 9. COT-1 and COT-2 Groundtracks. Color contoured by altitude (top) and solar phase (bottom). One-minute time ticks with closest approach marked with an "x" and numbered in accordance with Table 3.

current knowledge of Europa). Based solely on minimizing the total mission duration (and potentially operations costs), one would choose the 3:1 (or an even lower) resonance. However, operations costs are a function of not only the mission duration but also the frequency of events. Considering Cassini's operational limit of numerous back-to-back transfers was 1:1 resonance transfers with Titan (TOF=T_{sc}=15.9 days), and having to execute up to three maneuvers (two deterministic, one statistical) per Europa-to-Europa transfer similar to Cassini, the pre-Project put a lower bound on the mean TOF between a number of back-to-back Europa flybys to be 14 days. Lastly, as can be seen in Table 4, the lower the resonance, the slower the velocity; this coupled with the smaller eccentricities associated with decreasing the orbit period would increase the TID per orbit, and therefore, if chosen would increase the mission TID.

To meet science coverage requirements but also minimize the number of Europa flybys, the first COT sequence (COT-1) would begin with outbound Europa flybys (ending with inbound flybys) and would consist of six 4:1 resonant transfers with a V_∞ of approximately 4 km/s. A negative crank direction was chosen to place the Europa flybys at the descending node such that by the time the spacecraft would fly over Thera (on E6), navigation uncertainties would be reduced such that a minimum flyby altitude of 25 km could be executed to maximize the amount of reconnaissance data over this region (Fig. 8).

After COT-1, a nonresonant Europa transfer (E7 to E8) would then be implemented to return to an outbound Europa flyby (E8) such that the second COT sequence (COT-2) could again cover the anti-Jupiter hemisphere of Europa. This nonresonant transfer would also change the local solar time (LST) of the subsequent Europa flybys by approximately 0.75 hours counter clockwise.

COT-2 would again use 4:1 resonant transfers, but would crank in the positive direction and thereby place all flybys in the sequence at the ascending node. This would result in the COT-2 groundtracks intersecting the COT-1 sequence groundtracks (instead of running nearly parallel) per IPR requirements and completing the required coverage in five of the seven anti-Jupiter hemisphere panels. Similar to E6, the E9 groundtrack was intentionally placed over Thrace Macula (Fig. 9).

Finally, E14–E16 would be used to avoid solar conjunction (i.e., multi-rev transfers used to avoid any key spacecraft events when the Sun-Earth-Probe angle (SEP) is low, which corresponds to very noisy Doppler data and sparse communication with the spacecraft) and set up the last sub-phase in the Europa anti-Jupiter hemisphere coverage campaign, referred to as "petal rotation."

B.3. Petal Rotation

The petal rotation phase of the mission was designed principally for gravity science observations. Utilizing a series of nonresonant transfers, alternating between increasing and decreasing the period of the orbit, every other flyby from E17 through E24 would have near repeat equatorial groundtracks (Fig. 10). By pumping up with outbound flybys and pumping down with inbound flybys—corresponding to the line-of-apsides rotating counter-clockwise, the flyby closest approaches would be in view of Earth for more than the gravity science objective requirement of ±2 hours, and would occur at different Europa true anomalies (and hence sampling the gravitational potential near the same body fixed locations at different tidal phases). Lastly, by leveraging the V_∞ up slightly to values near 4.1 km/s, $4{:}1^-$ and $5{:}1^+$ non-resonant transfers can be utilized via low altitude Europa flybys to maximize gravity science measurement quality (see reference 28 for definition and naming convention of nonresonant transfers).

This mission phase would also get a number of illuminated IPR groundtracks in panels 1 and 3, thereby completing coverage in all seven anti-Jupiter Europa panels, and would benefit SWIRS and topographic imaging coverage as the trailing hemisphere becomes more illuminated.

C. Europa Illuminated Hemisphere Transition

Before data could be collected on Europa's sub-Jupiter hemisphere to complete the global-regional coverage of Europa, the observational lighting conditions need to be changed such that Europa's sub-Jupiter hemisphere would be Sunlit (i.e., place the Europa flybys near 0/24 LST, but without occurring in Jupiter's shadow). This can be accomplished by petal rotation via Europa (continuing the flyby sequence in the previous sub-section), Ganymede, or Callisto, cyclers[29], a Europa pi-transfer, or a "switch-flip." A switch-flip is defined as three non-resonant transfers (typically pi-transfers) between two bodies that significantly change the LST of the departure body flyby location. In this case of 13F7-A21, a Europa-Callisto switch-flip was utilized.[22]

E25–E27 would be used to decrease the spacecraft orbit period and increase its inclination to set up the Europa-Callisto pi-transfer (E28-C3). Once at Callisto, two Callisto flybys (C3 and C4) would then be used to increase orbit period and inclination necessary to reach an 8.8-day Callisto pi-transfer (C5-C6). C6–C8 would then reduce period and inclination to set up the C9-E29 non-resonant transfer placing all subsequent Europa flybys close to the Sun-Jupiter line on the far side of Jupiter that would render the sub-Jupiter hemisphere of Europa Sunlit. Finally, E29 and E30 would be used to pump up the orbit (using multi-rev transfers to avoid key events taking place during solar conjunction) to set up COT-3. This phase would use seven Callisto and five Europa flybys (Fig. 11) and take 5.6 months.

D. Europa Science Campaign 2: Sub-Jupiter Hemisphere Coverage

Much like the anti-Jupiter hemisphere phase, the sub-Jupiter hemisphere tour phase would be accomplished with two COT sequences. The first, COT-3, would begin with inbound flybys located at the descending node, and utilize five 4:1 resonant transfers (E31–E35) to attain large latitudinal coverage from north to south (Fig. 12). A nonresonant Europa transfer (E36 to E37) would then be implemented to return to an inbound Europa flyby (E37).

The second, COT-4, would utilize an alternating combination of 4:1 and 7:2 resonant transfers. While this strategy would result in a longer *TOF* and a higher TID (7:2 resonance has two periapsis passages between Europa flybys), the closest approaches would be pulled away from the 180° meridian far enough to place a large portion of the groundtrack in the equatorial leading and trailing panels (panels 10 and 12) of the anti-Jupiter hemisphere (Fig. 13). Lastly, by placing the flybys at the ascending node the IPR groundtracks crossings requirement would be accomplished.

E. Spacecraft Decommissioning

Planetary protection may require that before control of the spacecraft is lost, actions would be taken to minimize the probability of biological contamination of Europa resulting from spacecraft impact. A number of spacecraft disposal options exist to preclude Europa impact including Jovian body impactors (Jupiter, Io, Ganymede or Callisto), long-term stable Jupiter system orbits, and Jupiter system escape. The current pre-Project baseline plan calls for decommissioning the spacecraft via impact with Ganymede.

E. ΔV Budget

As previously mentioned, the spacecraft propellant tanks would be loaded up to the launch vehicle capability and the flight system would be designed to launch on any given day in the launch period without reconfiguration or modification. The propellant tanks would be sized from the maximum expected value (MEV) of the total ΔV required to confidently execute the 13F7-A21 trajectory. Table 5 summarizes both the current best estimate (CBE) and MEV for the total ΔV needed to execute the 13F7-A21 trajectory. The two totals are composed of computed values from covariance analyses, monte carlo simulations, and estimated values.[30-32]

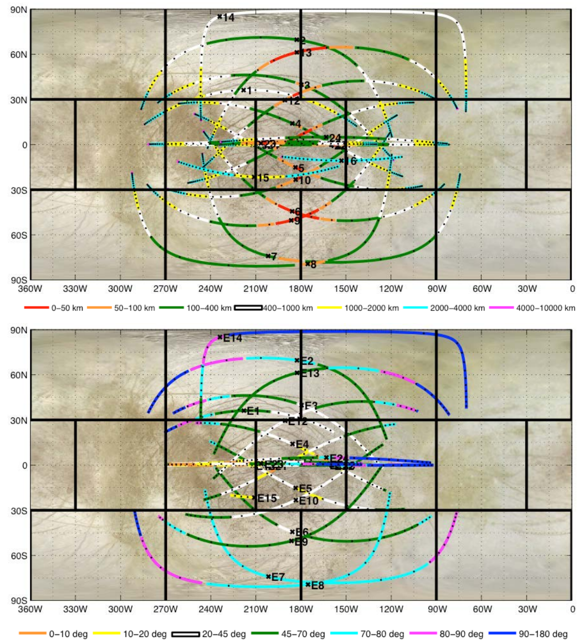

Figure 10. COT-1–Petal Rotation Groundtracks. Color contoured by altitude (top) and solar phase (bottom). One-minute time ticks with closest approach marked with an "x" and numbered in accordance with Table 3.

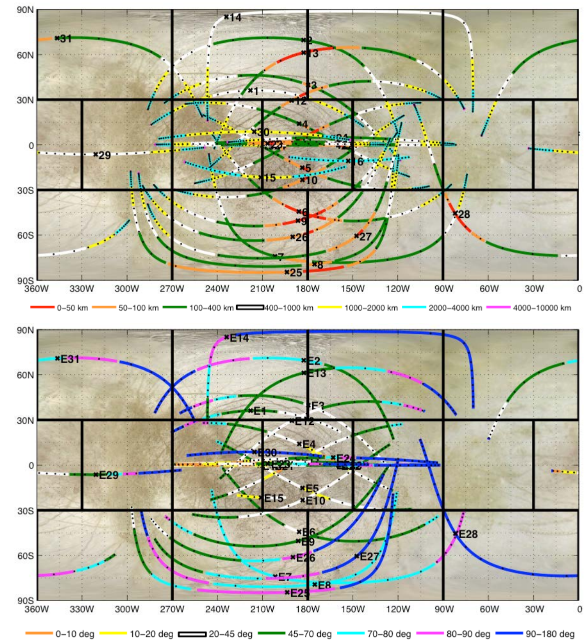

Figure 11. COT-1–Switch-flip Groundtracks. Color contoured by altitude (top) and solar phase (bottom). One-minute time ticks with closest approach marked with an "x" and numbered in accordance with Table 3.

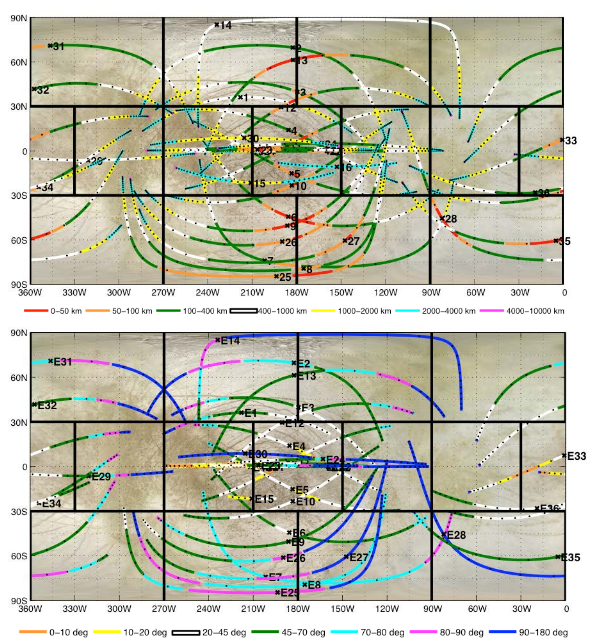

Figure 12. COT-1–COT-3 Groundtracks. Color contoured by altitude (top) and solar phase (bottom). One-minute time ticks with closest approach marked with an "x" and numbered in accordance with Table 3.

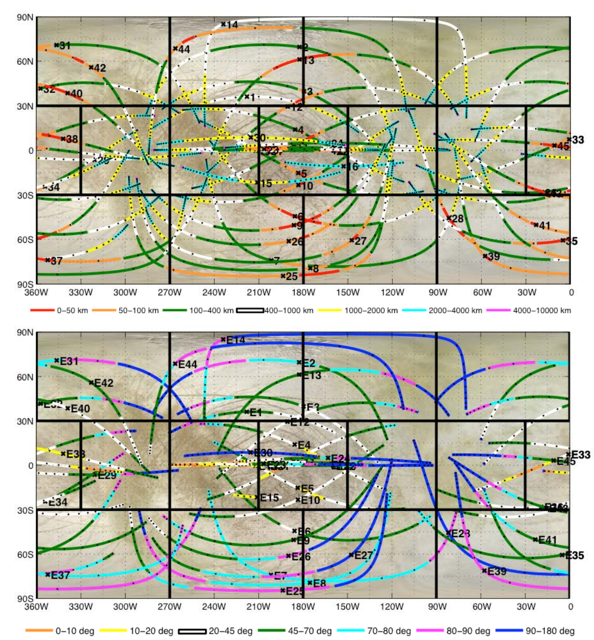

Figure 13. COT-1–COT-4 Groundtracks. Color contoured by altitude (top) and solar phase (bottom). One-minute time ticks with closest approach marked with an "x" and numbered in accordance with Table 3.

V. Comparison with 11F5-A21

The 11F5-A21 trajectory was the developed in response to NASA's Planetary Science Division (PSD) request to conduct a study to examine a set of reduced-scope options (with respect to the Jupiter Europa Orbiter mission (JEO)) for exploring Europa that met the NASA cost target of $2.25B ($FY15, excluding cost of 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 report[16], and a Jupiter orbiter with a large number of Europa flybys. NASA PSD later (November 2011) directed a lander mission concept also be investigated. These requests from PSD stemmed from serious concerns over mission cost based on NASA's independent cost estimate and the 2011 NRC Planetary Decadal Survey recommendation 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." [25]

The 11F5-A21 trajectory not only demonstrated the feasibility of a multiple Europa flyby mission, but also revealed the many advantages such a mission architecture could possess over a Europa orbiter or lander.[22] During the development of 11F5-A21, the model payload only consisted of four instruments, and did not include a gravity science investigation. Specifically, the original model payload included: Ice-Penetrating Radar (IPR), Shortwave Infrared Spectrometer (SWIRS), Topographical Imager (TI), and an Ion Neutral Mass Spectrometer (INMS). As can be seen in Table 6, 13F7-A21 is longer in duration for a number of reasons. First, a slightly longer pump down sequence was implemented utilizing two Callisto flybys in unison with four Ganymede flybys (as opposed to just Ganymede flybys in 11F5-A21) to improve lighting conditions during COT-1 and COT-2. Second, due to the increased size of the model payload, and hence a larger number of investigation objectives, a higher number of Europa flybys were needed. The density of groundtracks per COT sequence was increased and the petal rotation phase was added. Third, in order to not significantly increase the TID of 13F7-A21 above the 11F5-A21 TID, a Europa-Callisto switch-flip was used instead of a Europa-Ganymede switch flip. While the latter is more time efficient, it comes at the cost of a higher TID (Fig. 14). Lastly, unlike 11F5-A21, solar conjunction was accounted for in 13F7-A21.

Table 5. 13F7-A21 ΔV Summary.

Maneuver Activity	CBE ΔV (m/s)	MEV ΔV (m/s)
Earth Bias Removal	75	75
Interplanetary Statistical (ΔV99)	55	60
Deep Space Maneuver(s) (DSMs)	93	100
Jupiter Orbit Insertion (JOI)	839	839
JOI Clean-up Maneuver (ΔV99)	17	17
Periapsis Raise Maneuver (PRM)	122	122
Tour Deterministic	164	164
Tour Statistical (ΔV99)	223	223
Biased/split JOI	4	4
Spacecraft disposal	5	5
TOTALS	1597	1609

Legend	
Estimated ΔV	
Statistical ΔV	Deterministic ΔV

Table 6. 13F7-A21 and 11F5-A21 comparison.

Key Parameters	11F5-A21	13F7-A21
Launch Date	Nov. 2021	Nov. 2021
Interplanetary Trajectory	VEEGA	VEEGA
Total Tour Duration	2.4 years	3.5 years
Time to 1st Europa	10.9 months	11.9 months
Number of Flybys:		
Europa	34	45
Ganymede	9	5
Callisto	0	9
Time between Flybys:		
Maximum*	28.7 days	50.0 days
Minimum	3.5 days	5.5 days
Mean	15.5 days	18.3 days
Switch-flip	Europa-Ganymede	Europa-Callisto
Deterministic ΔV post-PRM	157 m/s	164 m/s
Maximum Inclination	15°	20.1°
Maximum Eclipse Duration	6.8 hours	4.5 hours
Total Ionized Dose (TID)	2.86 Mrad	2.83 Mrad

* Excluding the 200 and 50 day orbits post JOI and G1

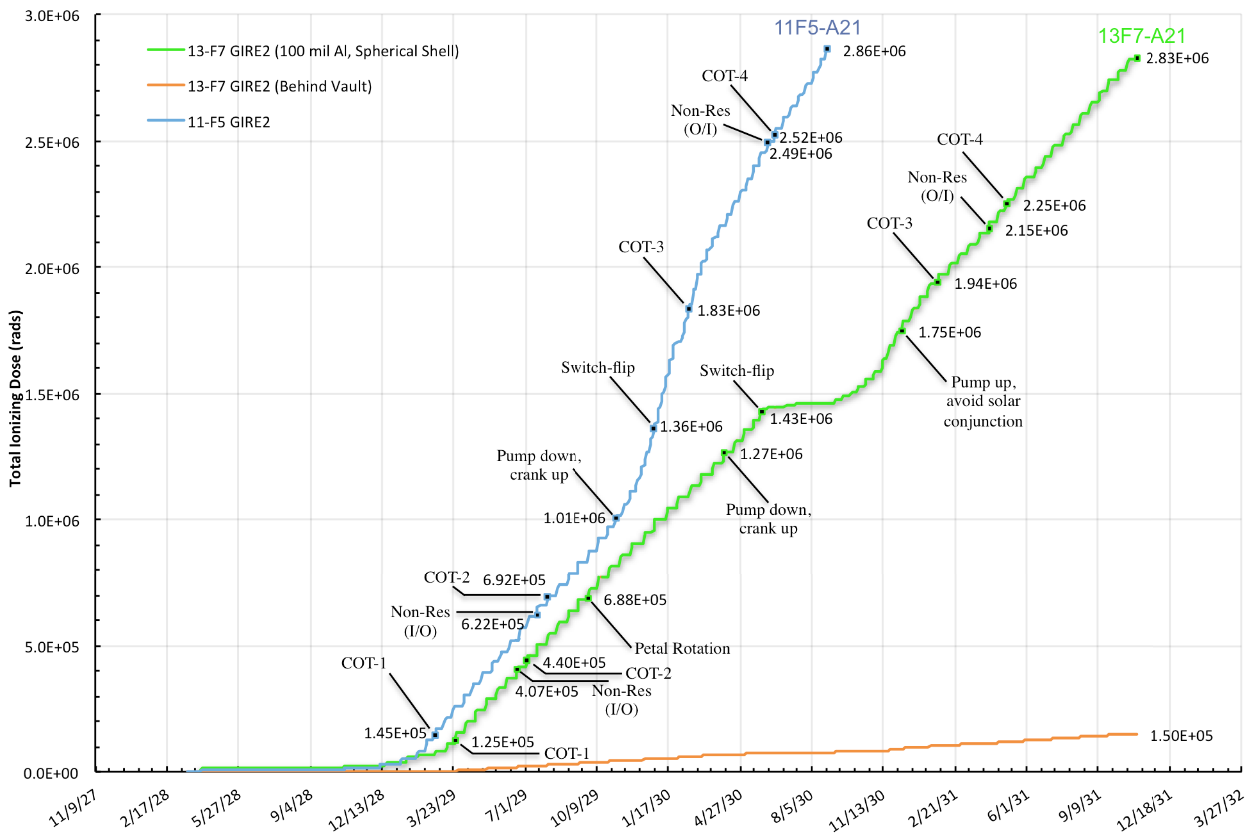

Figure 14. TID Build Up. Total ionizing dose as a function of time. 11F5-A21 (blue) and 13F7-A21 (green) behind a 100 mils thick spherical shell of aluminum. 13F7-A21 TID inside vault (orange).

VI. Pre-Project Updates

Two major updates have occurred since the inception of 13F7-A21: 1) the baseline launch date has moved to 2022 due to overall schedule alignment, and 2) NASA's SLS is now the baseline launch vehicle. Since the Clipper spacecraft design will maintain compatibility with the SLS and EELV's, the latter has very little impact on mission design. Furthermore, The Europa Clipper Mission Design Team is already designing a Jupiter tour (with the same characteristics as 13F7-A21) using the arrival conditions of the 2022 Earth-Jupiter direct interplanetary trajectory (Fig. 4). Similarly, the former necessitates the design of a new Jupiter tour connected to 13F7-A21 backup interplanetary trajectory, an Earth-Venus-Earth-Earth gravity assist trajectory (EVEEGA) launching in May 2022 (Fig. 15). An EVEEGA is necessary since there is not a high performance 2022 VEEGA trajectory available. The EVEEGA trajectory is the 2023 VEEGA trajectory with an Earth-Earth transfer appended to it, so while the EVEEGA would have a longer 7.58 years in *TOF*, only a single tour needs to be developed for the prime and backup EELV interplanetary trajectories.

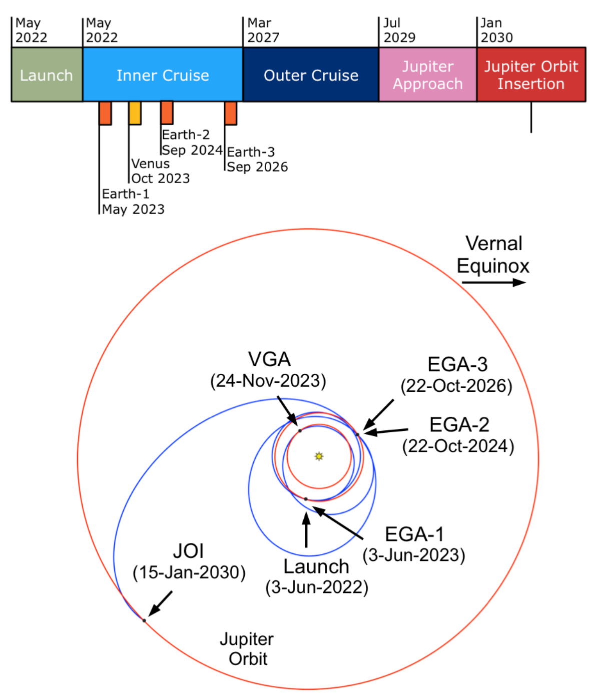

Figure 15. 2022 EVEEGA Interplanetary Trajectory. Timeline with 21-day launch period opening in May 2022 and interplanetary trajectory with optimal Jun. 3, 2022 launch date.

VII. Conclusion

The Europa Clipper mission would be a major step forward in understanding the habitability of Europa, the habitability across our own Solar System, and ultimately, beyond. The major enabling component of the Europa Clipper mission concept is the trajectory design, which would weave a complex network of flybys that with a spacecraft armed with a highly tuned arsenal of instruments, could achieve global regional coverage to meet a myriad of scientific objectives, and do so with greater scientific quality and quantity, as well as lower risk and cost than a Europa orbiter mission. Furthermore, a multiple flyby architecture allows for much more flexibility in terms of reacting to anomalies and discoveries.

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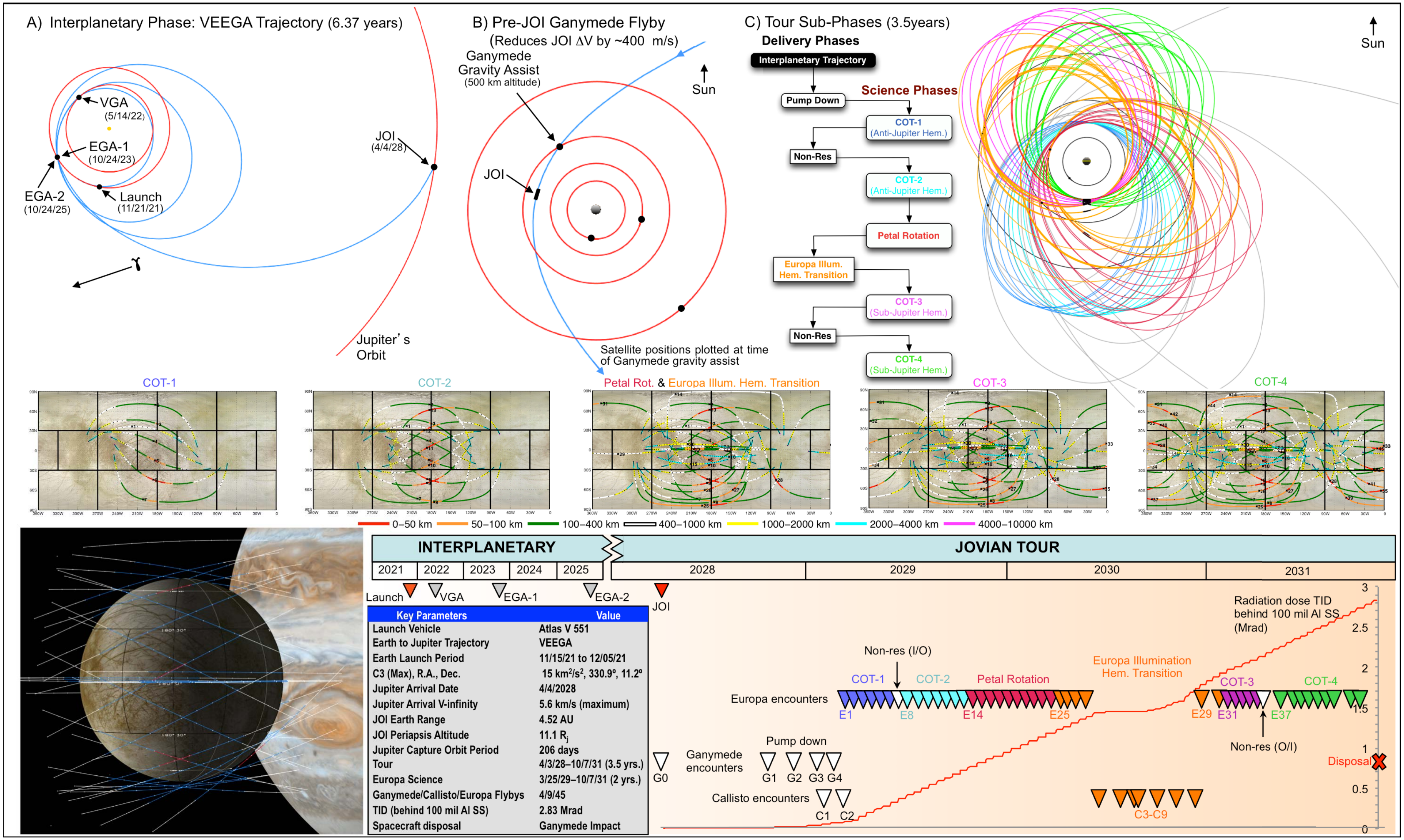

Key Parameters	Value
Launch Vehicle	Atlas V 551
Earth to Jupiter Trajectory	VEEGA
Earth Launch Period	11/15/21 to 12/05/21
C3 (Max), R.A., Dec.	15 km²/s², 330.9°, 11.2°
Jupiter Arrival Date	4/4/2028
Jupiter Arrival V-infinity	5.6 km/s (maximum)
JOI Earth Range	4.52 AU
JOI Periapsis Altitude	11.1 R_j
Jupiter Capture Orbit Period	206 days
Tour	4/3/28–10/7/31 (3.5 yrs.)
Europa Science	3/25/29–10/7/31 (2 yrs.)
Ganymede/Callisto/Europa Flybys	4/9/45
TID (behind 100 mil Al SS)	2.83 Mrad
Spacecraft disposal	Ganymede Impact

Figure A.1. Europa Multiple-Flyby Mission Design Concept. 13F7-A21 trajectory designed to explore Europa and investigate its habitability.