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THE EUROPA MISSION: MULTIPLE EUROPA FLYBY TRAJECTORY DESIGN TRADES AND CHALLENGES

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With potential sources of water, energy and other chemicals essential for life, Europa is a top candidate for finding current life in our Solar System outside of Earth. This paper describes the current trajectory design concept for a multiple Europa flyby mission and discusses several trajectory design challenges. The candidate reference trajectory utilizes multiple Europa flybys while around Jupiter to enable near global coverage of Europa while balancing science requirements, radiation dose, propellant usage, and flight time. Trajectory design trades and robustness are also discussed.

INTRODUCTION

Europa is one of the four large satellites of Jupiter discovered by Galileo Galilei in 1610.[1] It is considered one of the most intriguing objects in the Solar System in part due to the possibility that it may have substantial amounts of liquid water, possibly as a global-scale ocean residing beneath a surface layer of ice.[2] Observations of Europa made by the Voyager 1 and 2 Spacecraft in 1979, and by the Galileo Orbiter from the late 1990s to the early 2000s returned evidence that not only strengthened the global-scale ocean hypothesis but, in addition, suggested that water within Europa may have other ingredients essential for life, such as energy from tidal heating and radiation and essential chemical compounds.

From our experience of life on Earth—where everywhere we find water, we find life—it is reasonable to focus the search for life in our Solar System on the search for water. If Europa indeed contains a global ocean, its volume is expected to be between two and three times the volume of all water of Earth's oceans.[3] Europa, then, has been an important science target for many mission concepts[4,5,6] in the recent decades; these include orbiters, flyby spacecraft, and landers.[7]

This paper describes a candidate reference trajectory concept for a mission to Europa capable of finding conclusive evidence of a liquid ocean, investigating the habitability of Europa, and identifying landing sites for potential future landed missions. This mission concept, referred to as the *Europa Mission*, is currently being developed jointly by the Jet Propulsion Laboratory (JPL), California Institute of Technology and by the Applied Physics Laboratory (APL), Johns Hopkins University. It is based on a single spacecraft with a comprehensive set of instruments that performs multiple close flybys of Europa to investigate its habitability and collect global information on ice shell thickness, composition, and surface geomorphology.

The ensuing results and analyses were developed assuming a notional Science Payload consisting of a shortwave infrared spectrometer (SWIRS), an ice penetrating radar (IPR), a stereo topographical imager (TI), a neutral mass spectrometer (NMS), Langmuir probes (LP), magnetometers (MAG), a radio science instrument, a high resolution reconnaissance camera (RC), and a thermal imager (ThI). The actual Science Payload recently selected (on May 26, 2015) by NASA for the Europa Mission[8] is very similar to our assumed notional payload and is discussed in § *Future Work*.

In the following sections we will describe some of the design trades and challenges associated with designing a candidate reference trajectory that orbits Jupiter and performs multiple close flybys of Europa to

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provide global coverage for the science investigations while balancing these science requirements with navigation complexity, radiation exposure, $\Delta\mathbf{V}$, flight time, and overall mission robustness.

MISSION DESIGN APPROACH

The design objective is to obtain a global-regional coverage of Europa using low altitude flybys, while balancing flight time, propellantexpenditure, and navigational complexity (e.g., time between flybys and time between maneuvers). However, trajectory design in the Jovian System exhibits unique challenges such as the radiation environment, the gravitational disturbance exerted by the Galilean moons, and the relatively long duration of solar conjunctions.

The radiation environment—due to Jupiter possessing the strongest magnetosphere of any planet in the Solar System—can render spacecraft electronic useless in a relatively short time if left unprotected. High radiation exposure results in increased shielding mass, which reduces the available payload mass. As illustrated in Figure 1, Europa's orbit is contained within a region of high radiation at $9.4R_J$*. For this reason, the spacecraft will experience high radiation exposure when it flies close to Europa. On the other hand, a trajectory capable of providing global mapping of Europa must rely on multiple close flybys at varying latitudes and longitudes. Furthermore, the trajectory should minimize *empty orbits*—those when the spacecraft enters a high radiation region but does not fly by Europa, which may occur during orbit phasing or during solar conjunction. The issue of avoiding flybys during solar conjunction will be discussed in a later section.

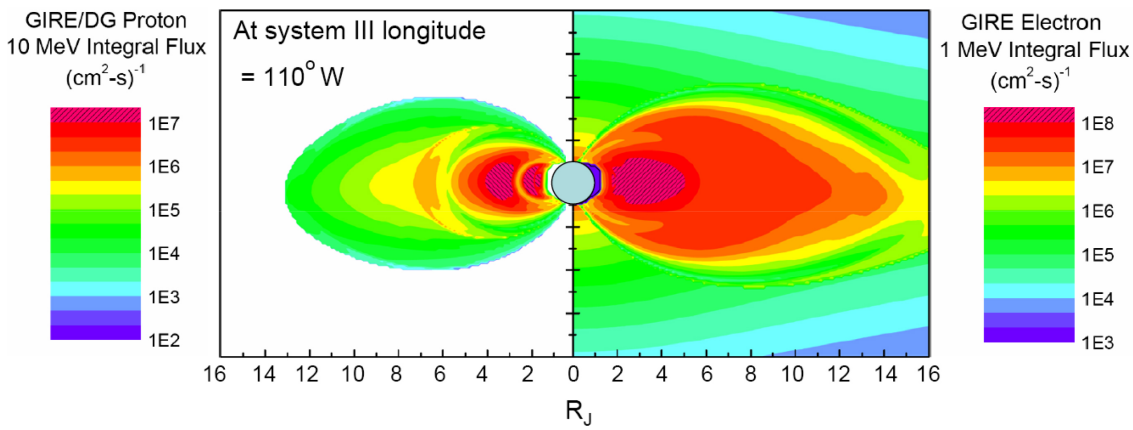


Figure 1. Contour plots of the GIRE/DG83 model E > 10 MeV integral proton (left) and E > 1 MeV electron (right) fluxes for the Jovian magnetosphere radiation region. The radiation environment at Jupiter is the strongest of any planet in the Solar System, and Europa's orbit is contained within a region of high radiation ($9.6R_J$). GIRE = Galileo Interim Radiation Electron model;[9] DG83 = Divine and Garrett 1983 model.[10] Figure courtesy of H. Garrett.

Flybys of the Galilean moons are used to control the transfers around Jupiter. When the trajectory is near planar non-targeted flybys of the other Galilean moons may occur. This can present a trajectory design challenge when moving from a lower fidelity two-body conic model to a higher fidelity model.

The candidate reference trajectory begins at Earth and reaches Jupiter either via a direct or multiple gravity assist interplanetary trajectory, (cf. § *Interplanetary Trajectory*). Upon arrival, on the incoming trajectory to the Jupiter's system prior to the Jupiter closest approach, the spacecraft implements a Ganymede gravity assist to reduce the $\Delta\mathbf{V}$ needed to capture into Jupiter's orbit, and subsequently performs multiple gravity assists of Ganymede and/or Callisto to reduce or *pump-down* the orbital energy. From that point on, the spacecraft performs a series of resonant and non-resonant flybys of Europa at different orbital locations to

*$R_J = 71,492$ km

obtain scientific measurements from regions delineated by the Science Definition Team (SDT). The Europa's SDT stressed the need for obtaining simultaneous complementary data sets at Europa and the need to obtain global-regional coverage with sufficent coverage and resolution in at least 11 of the 14 roughly equal-area "panels" distributed across Europas surface in Figure 2.

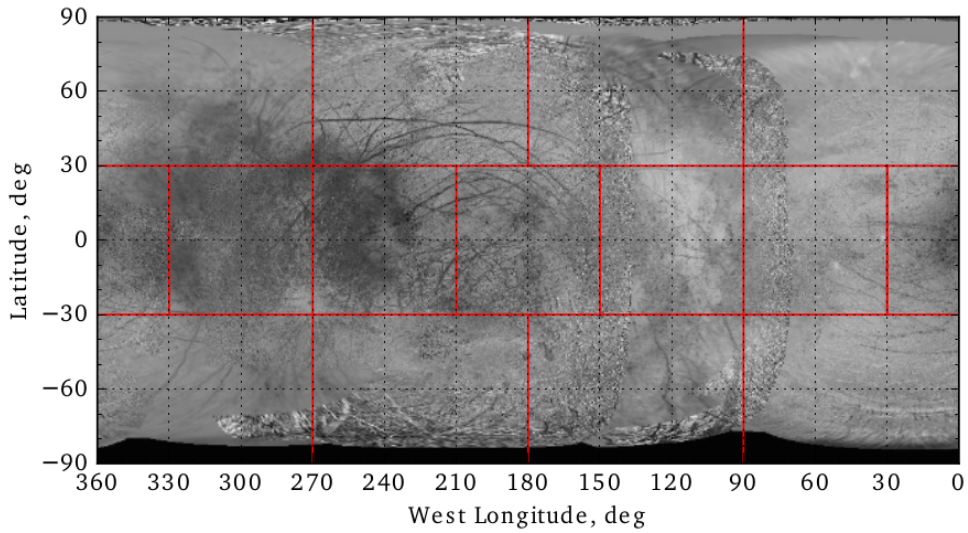


Figure 2. The fourteen roughly equal-area regions delineated by the Science Definition Team (SDT).

Mapping Europa with near global coverage with multiple flybys can be done with series of crank-over-the-top (COT) sequences.[11] COTs can be applied to systematically cover one hemisphere of Europa at a time. Starting from an equatorial orbit around Jupiter, COTs are a series of Europa flybys that increase the spacecraft inclination (cranking) up to the maximum inclination. If one continues to crank in the same direction, the inclination will then start to decrease, until the spacecraft's orbit plane has returned to an equatorial orbit. If the crank direction is reversed, the COT sequence will produce groundtracks that cross near closest approach. The process of using two COT sequences to produce overlapping ground tracks can be executed on either the anti-Jupiter or sub-Jupiter hemisphere of Europa. COT sequences that start with outbound flybys cover the anti-Jupiter hemisphere of Europa with close approaches occurring near the $180°$ meridian, and inbound flybys cover the sub-Jupiter hemisphere of Europa with close approaches near the prime meridian. This systematic method of Europa flybys will provide global coverage of Europa. The key benefit of a multiple flyby mission is that the spacecraft only dips into the harsh radiation environment to collect Europa science data and spends the remainder of the time outside the intense radiation and downlinking the data.

Accordingly, the candidate trajectory can be divided into eight stages:

Pump-Down Relies on resonant or non-resonant transfers of Ganymede and/or Callisto to reduce orbital inclination and orbital period, and align the line of nodes for near ideal Europa flyby geometry (lighting and relative velocity). At the end of this stage the spacecraft will have a near-equatorial orbit with an orbital period of about 14 days, with periapsis close to the COT-1 region.

COT-1 Uses resonant transfers of Europa to cover the anti-Jovian hemisphere from north to south.

COT-2 Uses resonant transfers of Europa to cover the anti-Jovian hemisphere from south to north.

Petal Rotation A series of near-equatorial non-resonant Europa transfers, alternating between increasing and decreasing the period of the orbit, to *rotate* the location of closest approach counter-clockwise (as seen from Jupiter's pole) along Europa's orbit.[12]

Switch Flip Relies on resonant and π-transfers of Europa and Callisto to flip the location of closest approach to the opposite side of Europa's orbit.

COT-3 Uses resonant transfers of Europa to cover the sub-Jovian hemisphere from north to south.

COT-4 Uses resonant transfers of Europa to cover the sub-Jovian hemisphere from south to north.

Impact Finalizes the mission with a planned collision of the spacecraft with Ganymede or Callisto.

In the candidate reference trajectory flybys of Ganymede and Callisto are only used for gravity assist purposes.

All instruments desire global observations and measurements, with a majority of instruments preferring or requiring illuminated observations. Since Europa is tidally locked, the same terrain has the same orientation relative to Jupiter (cf. Figure 3). For this reason, illumination is a function of Europa's location in its orbit. Figure 4 shows the notional location of selected mission stages* in the orbit plot in the rotating coordinate frame. Note for orbit figures, it is advantageous to display the view from Jupiter's northern hemisphere centered at Jupiter in the rotating frame with the y-axis pointing to the Sun, z-axis normal to the Jupiter orbit plane, and x-axis completing the right rule. In such configuration, lighting condtions are clearly understood.

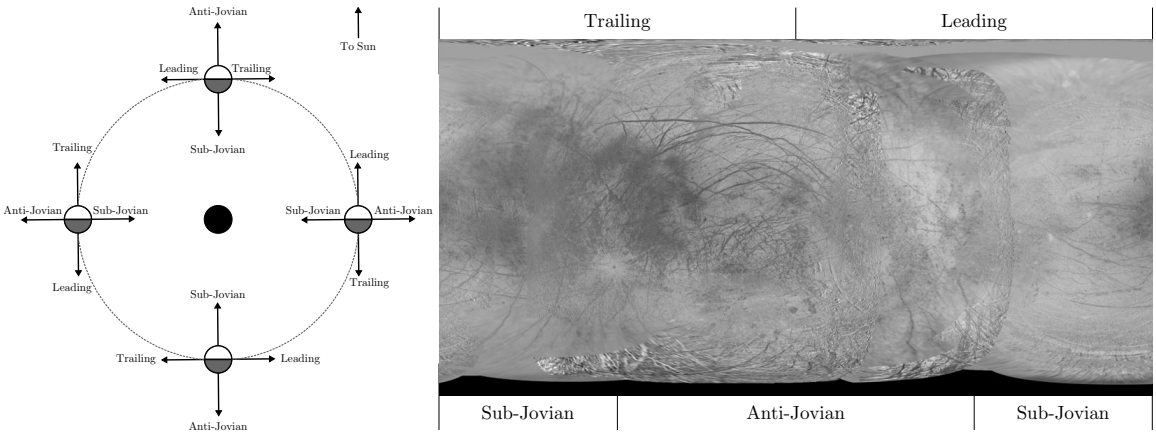


Figure 3. The majority of the instruments require or prefer illuminated observations. Given that Europa is tidally locked, the same Europa terrain always has the same orientation relative to Jupiter. (left) Jupiter centered plot viewed from the Jupiter's north pole in the rotating frame with the y-axis points to the Sun, z-axis normal to the Jupiter orbit plane, and x-axis completing the right rule.

Another important challenge in the trajectory design process is the concept of robustness. If a flyby is missed and its groundtrack is needed to fulfill a particular science objective, then the design of the trajectory must be robust enough to repeat that groundtrack at a later time, or still meet the overall science objective if that flyby was missed. This will be discussed in more detail in a subsequent section.

INTERPLANETARY TRAJECTORY

For all developed candidate reference trajectories, the spacecraft would launch from Kennedy Space Center in Florida, on a NASA-selected launch vehicle. For concept design, 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 are investigated. In this paper, we will discuss both options, but will focus on the SLS as the baseline. For the required delivery masses to Jupiter, the EELV would require either a Venus-Earth-Earth gravity assist (VEEGA) trajectory or a Earth-Venus-Earth-Earth gravity assist (EVEEGA) trajectory, whereas the SLS launch vehicle can go direct (Earth to Jupiter).

*The *Pump-Down*, *Switch Flip*, and *Impact* stages are not shown in this diagram.

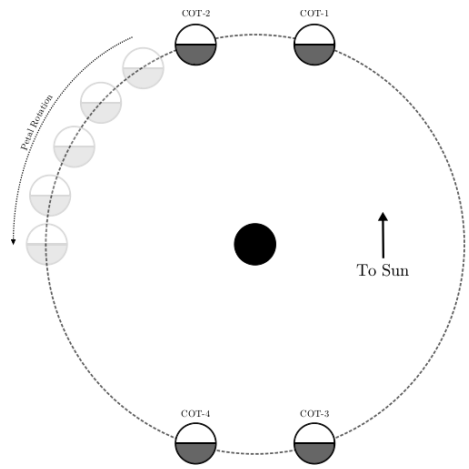


Figure 4. Jupiter centered plot viewed from the Jupiter's northern hemisphere in the rotating frame with the y-axis points to the Sun, z-axis normal to the Jupiter orbit plane, and x-axis completing the right rule. The spacecraft performs a series of resonant and non-resonant transfers to encounter Europa at different locations along its orbit.

For the direct launch option, the middle of the launch period is June 14, 2022 (Figure 5(a)) with a maximum C_3 during the launch period of approximately $82\ km^2/s^2$. The Jupiter arrival date is fixed to two dates throughout the launch period, a December 24, 2024 arrival for the first six days of the launch period and March 5, 2025 for the remaining launch dates. The two arrival dates were utilized to decrease the C_3 variation across a 21-day launch period to increase delivery mass to the Jupiter system, and thus, increase system dry mass margin. The flight time for the direct launch ranges from 2.55 to 2.71 years. For the EVEEGA interplanetary transfer, the launch period opens May 25, 2022 and closes June 14, 2022 (Figure 5(b)) followed by an Earth flyby on May 24, 2023, a Venus flyby on November 23, 2023, a Earth flyby on October 21, 2024, another Earth flyby occuring on October 22, 2026, and lastly arriving at Jupiter on January 15, 2030, with a total flight time of 7.64 years.

For the direct launch option, the satellite tour designs for the two arrival dates are similar with identical flyby sequences and geometry from the second Europa flyby (E2) onward. This constraint simplifies the tour design in the Jupiter system by having only a single tour design for the entire launch period, and helps to maintain a dry mass margin greater than 35%, which is required by the Europa Project prior to SRR (System Requirements Review).

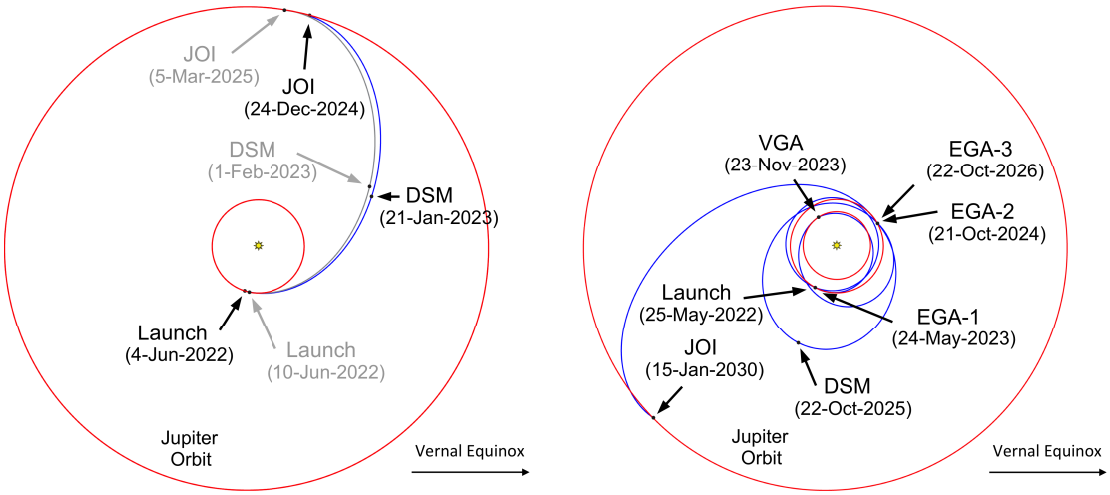
A summary of the launch options are listed in Table 1*.

SATELLITE TOUR

The baseline Jupiter tour discussed in this paper is a fully integrated trajectory with flight-level fidelity, and one of many tours developed for this study. The Jovian portion of the baseline trajectory, 14F8-S22, begins after JOI and consists of 45 Europa, 5 Ganymede, and 7 Callisto flybys over the course of 3.68 years (Figure 6). The tour reaches a maximum Jovicentric inclination of 21.2 deg, has a deterministic $\Delta\mathbf{V}$ of 174 m/s (post perijove raise manuever (PRM)), and has a total ionizing dose (TID) of 3.14 Mrad.

As mentioned in the above section, the tour consists of a pump down sequence using 5 Ganymede flybys used to reduce energy relative to Jupiter and sets 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

*Naming convention for the candidate reference missions is YYTN-VL, where YY = calendar year the mission was designed, T = type of mission (F = multiple flyby), N = sequential number of tour developed, V = launch vehicle assumed (A = Atlas V 551; S = SLS; D = Delta IV Heavy), L = launch year. For example, 14F8-S22, was a flyby mission launching on an SLS in 2022, designed in 2014, and is the eighth reference mission designed.



(a) 2022 Earth-Jupiter Direct Interplanetary Trajectory. 21-day launch period opens June 4, 2022 and closes June 24, 2022 with an arrival date of December 24, 2024 (first six days of the launch period) or March 5, 2025 (remainder of the launch period).

(b) 2022 EVEEGA Interplanetary Trajectory. 21-day launch period opens May 25, 2022 and closes June 14, 2022 with an arrival date of January 15, 2030.

Figure 5. 2022 Interplanetary Trajectory Options

Table 1. Summary of Interplanetary Trajectory Options

Case	13F7-A21	14F8-S22	15F9-A22
Launch Vehicle	EELV	SLS	EELV
Launch Year	2021	2022	2022
Launch Period	Nov. 15 - Dec. 5	Jun. 4 - 24	May 25 - Jun. 14
Trajectory Type	VEEGA	Direct	EVEEGA
Flight Time to Jupiter	$6.4\ y$	$2.7\ y$	$7.6\ y$
Total ΔV[*]	$1,218\ m/s$	$1,181\ m/s$	$1,092\ m/s$

[*]Deterministic value for the interplanetary and tour $\Delta\mathbf{V}$.

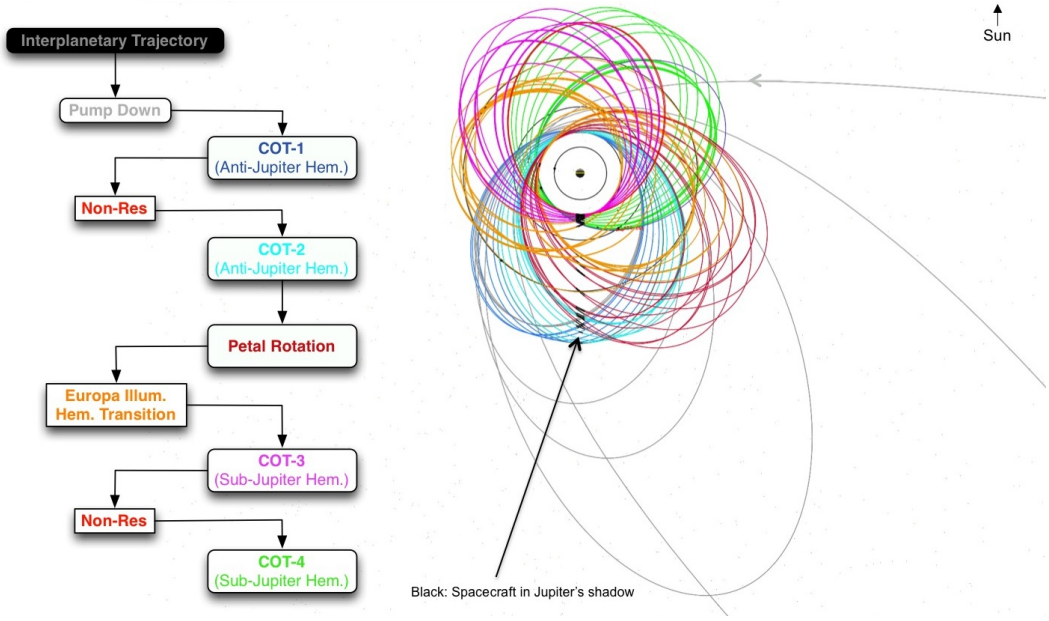


Figure 6. 14F8-S22 trajectory viewed from Jupiter's northern hemisphere, centered at Jupiter in the rotating frame with the y-axis points to the Sun, z-axis normal to the Jupiter orbit plane, and x-axis completing the right rule. Gray: pump-down; blue: COT-1; cyan: COT-2; maroon: petal rotation; orange: 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.

would be well illuminated. This is followed by COT-1, COT-2 and the petal rotation, where the latter is designed principally for gravity science observations, but is also very useful for IPR and trailing hemisphere coverage for SWIRS. It uses a series of non-resonant transfers, alternating between increasing and decreasing the orbit periods ($4:1^+$ and $5:1^-$ in our case) which rotates the line-of-apsides counter-clockwise and produces alternating repeated equatorial groundtracks. The next phase is the Europa illuminated hemisphere transition phase which rotates the orbit such that the illumination is now in the sub-Jupiter hemisphere of Europa instead of the anti-Jupiter hemisphere. This phase requires the spacecraft orbit period to decrease and the inclination to increase to setup the correct geometry for Europa-to-Callisto π-transfer. This phase also includes a Callisto π-transfer, and a Callisto-to-Europa π-transfer. This places the next set of Europa flybys approximately 180 deg from the location of the Europa flybys in COT-2. This is followed by COT-3 and COT-4 which again steps through the groundtrack coverage but over the now sun-lit sub-Jupiter hemisphere of Europa.

Details of the 14F8-S22 tour are listed in Table 2. Details for 13F7-A21 can be found in Reference 6. Details for 15F9-A22 and 15F10-S22 can be found in the Appendix. The tables include detailed information on the flybys for the entire tour. Figure 7 shows all the flyby groundtracks color contoured by altitude for 14F8-S22 at the end of COT-4. Closest approaches are marked with an "x" and numbered according to flybys from Table 2. The build up of the groundtracks are in Figure 8-13, with both the altitude contours and the local time contours.

Figure 14 shows the cumulative potential opportunities coverage for the Short Wave Infrared Spectrometer (SWIRS) and the Topographical imager opportunity for 14F8-S22.

The mission operations will be nearly identical for all Europa flybys. Maneuver locations are also the same per orbit with determinisitic manuevers located 3 days post flyby for clean up, a targeting maneuver near apoapsis, and a statistical maneuver located 3 days prior to the next flyby. In Figure 15, a representative

Table 2. Detailed 14F8-S22 tour summary.

Phase	Flyby	In /Out	Date (ET)	Alt (km)	B-plane (deg)	$\mathbf{V}_\infty$ (km/s)	Incl. (deg)	SEP (deg)	m	n	Next enc. (days)	Lat (deg)	W. Lon (deg)
Pumpdown	0G0	I	04-Mar-2025 22:50	500	0	8.06	3.6	88	28.3	1	202.3	–	–
	1G1	O	23-Sep-2025 05:35	150	-172	6.41	3.5	69	7	1	50.1	–	–
	2G2	O	12-Nov-2025 07:49	100	-136	6.46	0.3	115	4	1	28.6	–	–
	3G3	O	10-Dec-2025 22:23	3541	-177	6.42	0.1	145	3	1	21.5	–	–
	4G4	O	01-Jan-2026 09:36	100	-173	6.46	0.5	170	10.9	2.9	38.8	–	–
COT-1	7E1	O	09-Feb-2026 04:48	6573	-9	4.16	0.6	146	4	1	14.1	–	–
	8E2	O	23-Feb-2026 08:12	100	-75	3.94	3.0	131	4	1	14.2	72.6	181.6
	9E3	O	09-Mar-2026 13:08	100	-48	3.95	4.9	116	4	1	14.2	43.4	179.2
	10E4	O	23-Mar-2026 18:03	50	-19	3.95	5.7	102	4	1	14.2	14.1	178.3
	11E5	I	06-Apr-2026 22:59	50	15	3.94	4.8	89	4	1	14.2	-16.0	177.4
	12E6	I	21-Apr-2026 03:51	25	47	3.94	2.7	77	4	1	14.2	-45.7	176.8
	13E7	I	05-May-2026 08:45	25	79	3.93	0.3	65	4.1	1	14.5	-77.3	170.9
COT-2	14E8	O	19-May-2026 20:46	100	81	3.96	2.9	53	4	1	14.2	-79.0	187.5
	15E9	O	03-Jun-2026 01:42	25	54	3.97	5.1	42	4	1	14.2	-49.9	180.2
	16E10	O	17-Jun-2026 06:35	50	26	3.97	6.2	31	4	1	14.2	-21.1	179.2
	17E11	I	01-Jul-2026 11:29	25	-5	3.97	5.8	21	4	1	14.2	7.0	178.9
	18E12	I	15-Jul-2026 16:13	100	-17	3.99	5.0	10	11	3	39.1	18.1	189.3
	21E13	I	23-Aug-2026 17:43	100	-86	4.00	2.3	19	4	1	14.2	73.8	127.3
	22E14	I	06-Sep-2026 22:16	25	-54	4.04	0.6	29	7.1	2	25.3	54.0	204.5
Petal Rotation	24E15	O	02-Oct-2026 05:11	50	3	4.08	0.5	49	8.9	2	31.7	-3.4	148.6
	26E16	I	02-Nov-2026 21:09	2615	0	4.13	0.5	76	4.1	1	14.6	-0.2	208.5
	27E17	O	17-Nov-2026 10:39	30	0	4.08	0.5	89	4.9	1	17.6	-0.1	155.2
	28E18	I	05-Dec-2026 00:07	25	0	4.08	0.5	106	4.1	1	14.6	0.3	201.7
	29E19	O	19-Dec-2026 13:22	100	0	4.09	0.5	121	4.9	1	17.6	-0.1	153.9
	30E20	I	06-Jan-2027 02:41	25	-1	4.07	0.5	139	4.1	1	14.5	1.1	201.4
	31E21	O	20-Jan-2027 15:47	50	10	4.05	0.1	156	5	1	17.7	-9.5	154.9
	32E22	I	07-Feb-2027 07:25	50	38	3.92	1.8	176	0.1	0.1	1.0	-37.0	189.3
	32G (NT)	O	08-Feb-2027 07:56	31470	-119	6.67	1.8	177	4.3	1.9	30.9	–	–
	34E23	I	11-Mar-2027 05:12	50	-50	4.02	0.4	148	4.1	1	14.5	50.4	196.2
Crank Up, Switch Flip, Pump Up	35E24	O	25-Mar-2027 17:21	25	-80	3.92	3.4	133	4	1	14.2	77.8	186.4
	36E25	O	08-Apr-2027 22:01	50	-87	3.90	6.2	118	7	2	24.8	70.0	238.2
	38E26	O	03-May-2027 18:20	1106	-134	3.91	7.5	94	3	1	10.6	37.8	311.8
	39E27	O	14-May-2027 09:43	3129	-141	3.89	8.2	85	1.5	2.6	25.3	–	–
	42C1	I	08-Jun-2027 16:14	250	86	2.92	18.2	64	2	3	33.3	–	–
	45C2	I	12-Jul-2027 00:31	100	113	2.92	20.0	38	1	1	16.6	–	–
	46C3	I	28-Jul-2027 16:06	1712	62	2.93	21.2	25	0.5	0.5	8.3	–	–
	46C4	O	05-Aug-2027 22:38	951	51	2.96	20.8	19	3	4	50	–	–
	50C5	O	24-Sep-2027 23:21	250	58	2.96	14.8	19	2	3	33.3	–	–
	53C6	O	28-Oct-2027 07:27	108	73	2.98	3.2	45	2	3	33.4	–	–
	56C7	O	30-Nov-2027 16:17	2842	178	2.93	3.1	74	7.1	2.6	25.1	–	–
	59E28	I	25-Dec-2027 19:28	60	-110	3.76	0.3	97	3.1	1	11.1	70.0	52.3
	60E29	O	05-Jan-2028 20:57	458	178	3.72	0.4	108	4.8	1.9	17.2	-2.6	319.4
COT-3	62E30	I	23-Jan-2028 01:02	100	-146	3.81	1.3	125	3	1	10.6	33.3	37.4
	63E31	I	02-Feb-2028 16:37	25	-151	3.80	2.7	137	7	2	24.9	27.8	22.6
	65E32	I	27-Feb-2028 13:15	50	-179	3.78	2.6	164	4	1	14.2	-0.9	14.9
	66E33	I	12-Mar-2028 17:19	25	-107	3.83	5.4	178	7	2	24.9	62.7	324.2
	68E34	I	06-Apr-2028 14:09	25	146	3.83	3.7	152	4	1	14.2	-33.0	17.3
	69E35	O	20-Apr-2028 18:47	50	-153	3.82	4.8	137	7	2	24.9	23.1	340.6
	71E36	O	15-May-2028 15:36	25	132	3.86	2.6	112	7	2	24.9	-46.0	357.2
	73E37	O	09-Jun-2028 12:01	25	108	3.87	0.5	89	6.9	2	24.5	-70.9	351.0
COT-4	75E38	I	03-Jul-2028 23:59	404	151	3.88	1.5	69	4	1	14.2	-28.8	23.4
	76E39	I	18-Jul-2028 04:12	25	116	3.96	4.0	57	4	1	14.2	-61.4	1.4
	77E40	I	01-Aug-2028 09:10	100	145	3.95	5.5	46	4	1	14.2	-30.8	359.8
	78E41	O	15-Aug-2028 14:10	100	179	3.95	5.4	35	4	1	14.2	1.4	359.4
	79E42	O	29-Aug-2028 18:55	25	-150	3.96	4.0	24	4	1	14.2	29.8	358.4
	80E43	O	12-Sep-2028 23:17	100	164	3.92	4.7	13	10	3	35.5	-13.0	333.6
	83E44	O	18-Oct-2028 12:03	100	-112	4.02	2.1	14	10	3	35.5	64.7	355.0
EOM	86E45	O	23-Nov-2028 00:15	700	-67	4.06	0.2	42	1.9	1.1	13.8	67.1	135.5
	88G5	O	06-Dec-2028 20:22	100	-78	6.46	5.1	54	N/A	N/A	N/A	N/A	N/A

Solar conjunction between E12/E13, C4/C5, and E43/E44. B-plane = B-plane angle relative to the satellite's mean equator of epoch; V_∞ = Hyperbolic excess velocity; In/Out = inbound (I) or outbound (O) flyby; Incl. = spacecraft central body mean equator inclination with respect to Jupiter; m = integer number of gravity assist body orbits; n = integer number of spacecraft orbits; NT = Non-targeted flybys. flyby naming convection is of the form MBN, where M = number of orbits around Jupiter, B = flyby body, and N = sequential number of flyby body B.

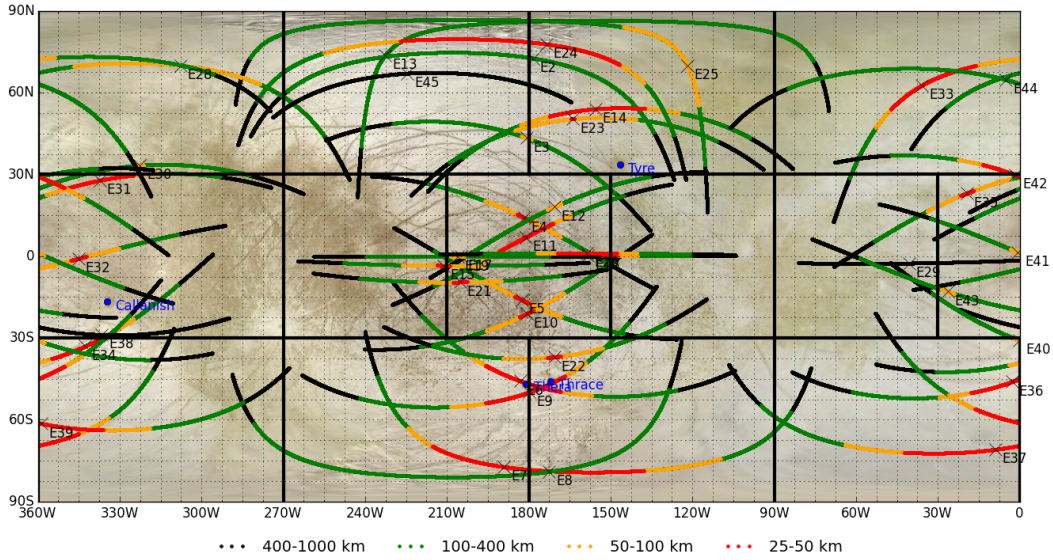
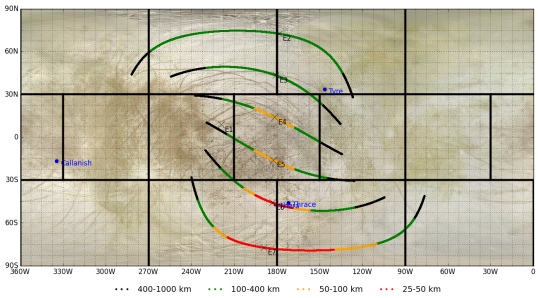
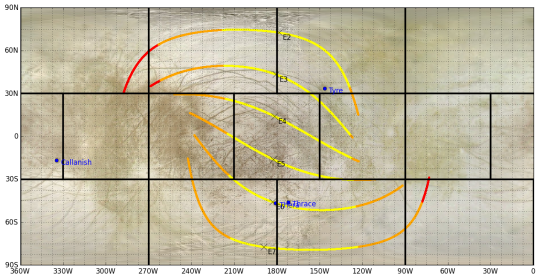


Figure 7. 14F8-S22 groundtrack plot at Europa. Color contoured by altitude. Closest approach marked with an "x" and numbered according to Table 2.



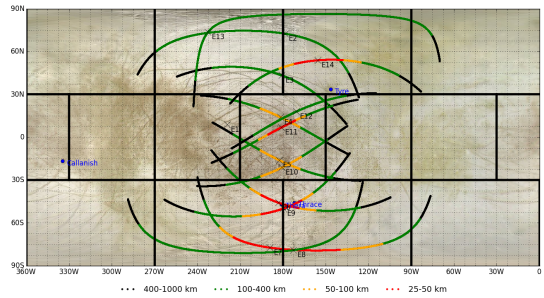
(a) altitude contour



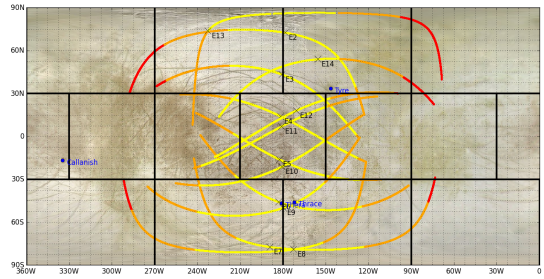
(b) local time contour

yellow: 09-15, orange: 06-09 & 15-18, red: 03-06 & 18-21, black: 21-03.

Figure 8. COT-1 Groundtracks



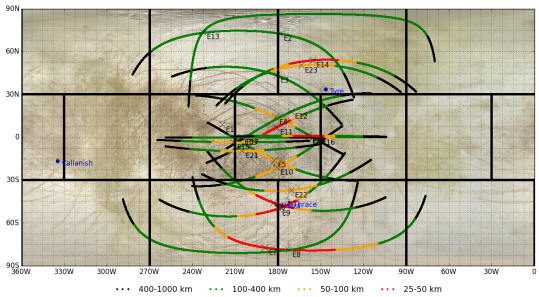
(a) altitude contour



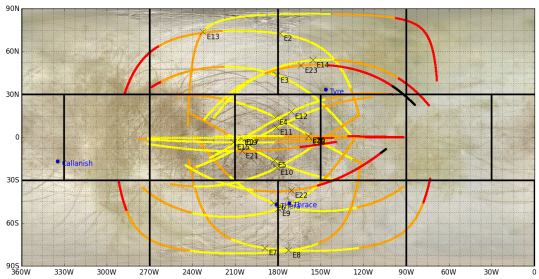
(b) local time contour

yellow: 09-15, orange: 06-09 & 15-18, red: 03-06 & 18-21, black: 21-03.

Figure 9. COT-2 Groundtracks



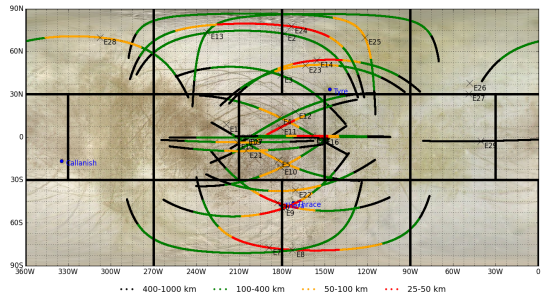
(a) altitude contour



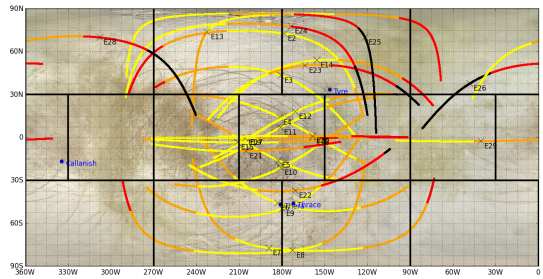
(b) local time contour

yellow: 09-15, orange: 06-09 & 15-18, red: 03-06 & 18-21, black: 21-03.

Figure 10. Petal Rotational Groundtracks



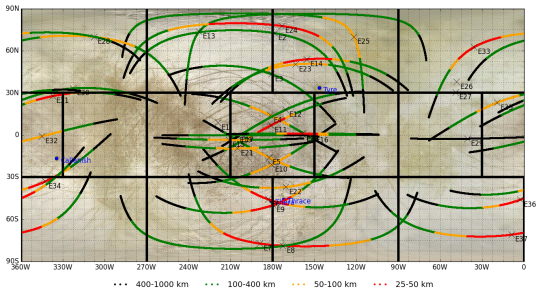
(a) altitude contour



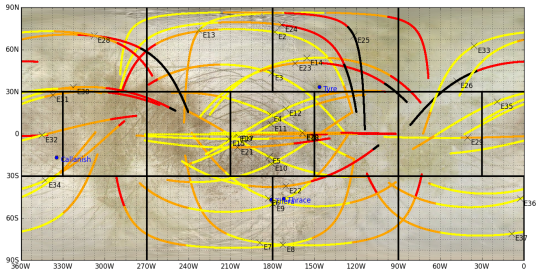
(b) local time contour

yellow: 09-15, orange: 06-09 & 15-18, red: 03-06 & 18-21, black: 21-03.

Figure 11. Switch-Flip Groundtracks



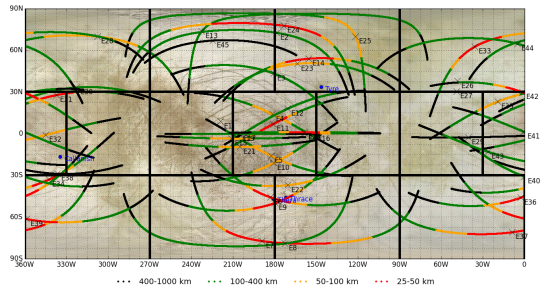
(a) altitude contour



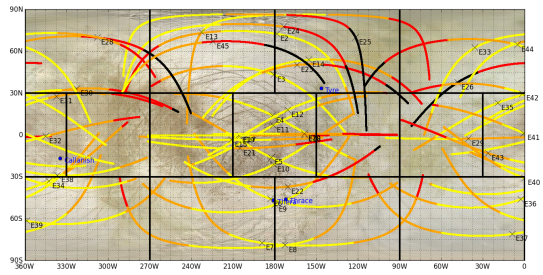
(b) local time contour

yellow: 09-15, orange: 06-09 & 15-18, red: 03-06 & 18-21, black: 21-03.

Figure 12. COT-3 Groundtracks



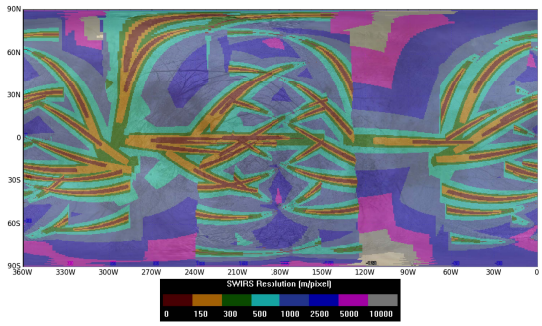
(a) altitude contour



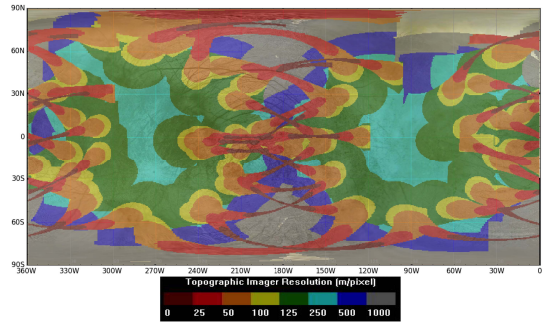
(b) local time contour

yellow: 09-15, orange: 06-09 & 15-18, red: 03-06 & 18-21, black: 21-03.

Figure 13. COT-4 Groundtracks



(a) SWIRS observation opportunities



(b) Topographical Low-Res imaging opportunities

Figure 14. Resolution coverage for 14F8-S22

Europa flyby with a close approach of 25 km and $V_{c/a} = 4.5\ km/s^*$ is shown with notional location of the start and end time of payload observations. Magnetometers and the Langmuir probes are assumed to have observation opportunities throughout the orbit.

For 14F8-S22, solar conjunctions (minimum Sun-Earth-Probe (SEP) angle) are encountered during COT-2, during the illuminated hemisphere transition phase (more specifically, during the switch-flip), and toward the end of COT-4. Around solar conjunction, sufficient time for orbit determination and maneuvers is required. While approaching conjunction, no maneuvers are placed below SEP = 5 deg. Outbound from conjunction, the earliest maneuver is approximately 2 days after SEP = 10 deg, or approximately at SEP = 12 deg. Due to these guidlines multi-rev transfers are required and, thus, *empty orbits* exist. Figure 16 shows a notional timeline for the three conjunction events in 14F8-S22 with the flyby and maneuver locations around conjunction. Also included in the figure are the location of the inbound SEP = 5 deg and outbound SEP = 10 deg and SEP = 12 deg events. Note, manuevers obey the above guidelines, but at a cost of extra TID due to the empty orbits. For example, conjunction occured after E12 during COT-2. If conjunction didn't occur the COT sequence would continue with the 4:1 resonance to the next Europa encounter 14.2 days later, but because of conjunction an 11:3 resonance was selected, which added two empty orbits with no Europa flybys and extended the next encounter to 39.1 days.

COMPARISONS TO OTHER TOURS

While this paper was heavily focused on the 14F8-S22 trajectory, other tours exist[5,6] and are mentioned in this paper. In this section, the other tour options are discussed and are summarized in Table 3. More specifically, we will discuss the tour progress from 2013 to current: 13F7-A21, 14F8-S22, 15F9-A22, and 15F10-S22. These tours have been very similar in mission phases, with the key difference being the interplanetary trajectory, and thus, the start dates of the tour (except for 15F10-S22, which is a variation of 14F8-S22). Both 13F7-A21 and 15F9-A22 assume an Atlas V 551 (or equivalent EELV) launch. 13F7-A21 uses a VEEGA trajectory launching in 2021 with a flight time of 6.4 years and an arrival date in April 2028. 15F9-A22 uses a EVEEGA trajectory launching in 2022 with a flight time of 7.6 years and an arrival in January 2030. 14F8-S22 and 15F10-S22 assume a SLS direct launch in 2022 to Jupiter, with a flight time of about 2.7 years and an arrival in early 2025.

These different arrival dates affect the eclipse duration because of Jupiter's declination, which has roughly a 12-year cycle, with a minimum declination around July 2026. When Jupiter is near zero declination eclipses will be more prominent. They will be longer during the anti-Jupiter hemisphere illumination campaigns when thte spacecraft is traveling slower near apoapsis (cf. Figure 6; COT-1, COT-2, and the beginning of the petal rotation). With the exception of 13F7-A21, the maximum eclipse durations is approximately 8.8 hours. 13F7-A21 has a significantly shorter maximum eclipse duration of 4.5 hours, and this is due to the fact that

*c/a = closest approach

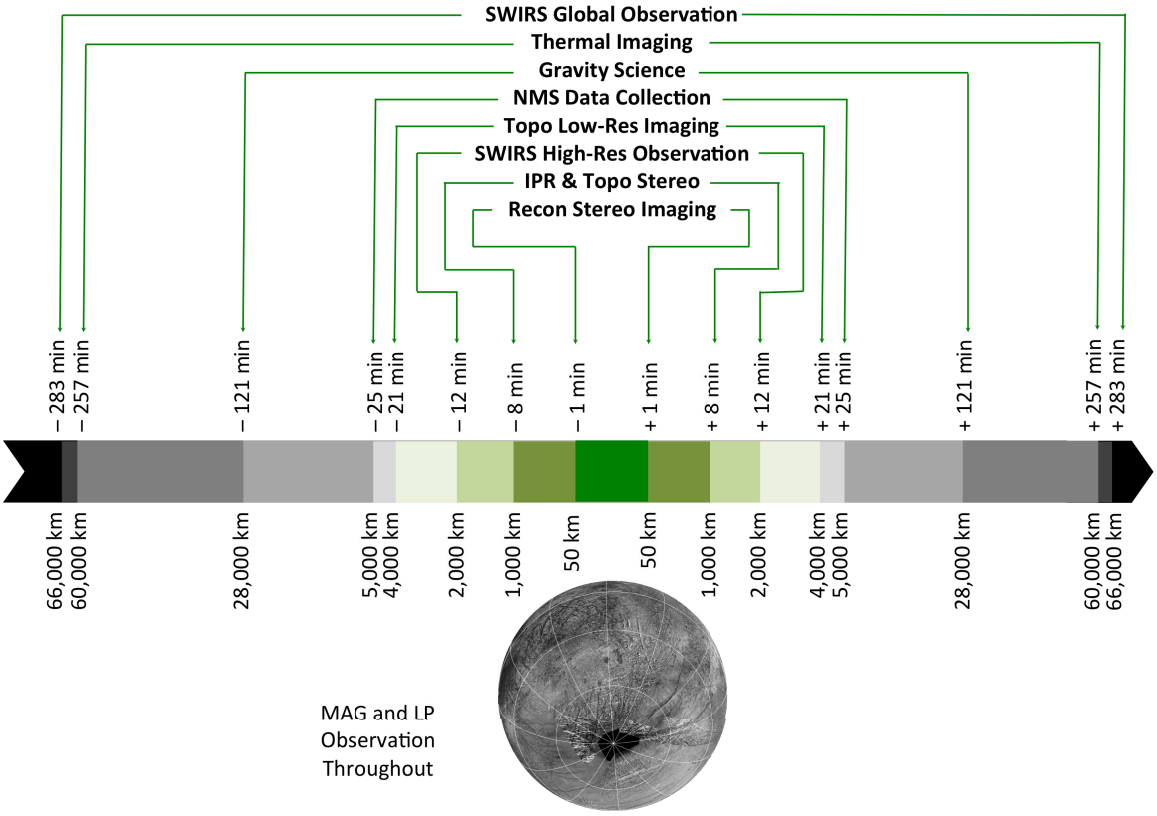


Figure 15. Representative Europa flyby diagram. Close approach at 25 km and $V_\infty = 4.5km/s$. SWIRS = shortwave infrared spectrometer, IPR = ice penetrating radar, Topo = topographical imager, NMS = neutral mass spectrometer, LP = Langmuir probes, MAG = magnetometers.

13F7-A21 executes COT-1 and COT-2 when the solar declination with respect to Jupiter is near a maximum, while the other tours are approaching near zero declinations. For example, for 14F8-S22 the first Europa encounter is February 2026, and Jupiter approaches minimum declination during COT-1 and COT-2.

MISSION ROBUSTNESS

Unexpected conditions may arise in any space mission; it is the goal of the Europa project to be tolerant to a finite set of such conditions. More specifically, the goals to be able to meet all baseline scientific investigations even if science data from one or more flybys are lost. A loss of data for a flyby can be a result of many reasons, such as radiation effects on the spacecraft resulting in safing of the spacecraft or individual instruments, human commanding error, or navigation error. All of the candidate reference trajectories described in this paper already have built in some robustness in the Jovian tour by exceeding the baseline science objectives for many instruments: Reconnaissance Imaging, Magnetometer, Gravity Science, IPR, and SWIRS (high-resolution). For example, the IPR coverage for 14F8-S22 has coverage of all 14 panels, but only requires 11 of 14 panels for the baseline investigation. However, some science objectives are very close to the baseline requirement, and a loss of a flyby could result in not meeting their science objective.

Furthermore, not all flybys are weighted equally and some flybys are much more critical to a specific science investigation than others. For example, during the petal rotation phase of the mission, alternating repeated equatorial flybys are used to bring down the uncertainity of the gravity Love number of Europa, which is linearly correlated to the thickness of the outermost ice shell.[13]

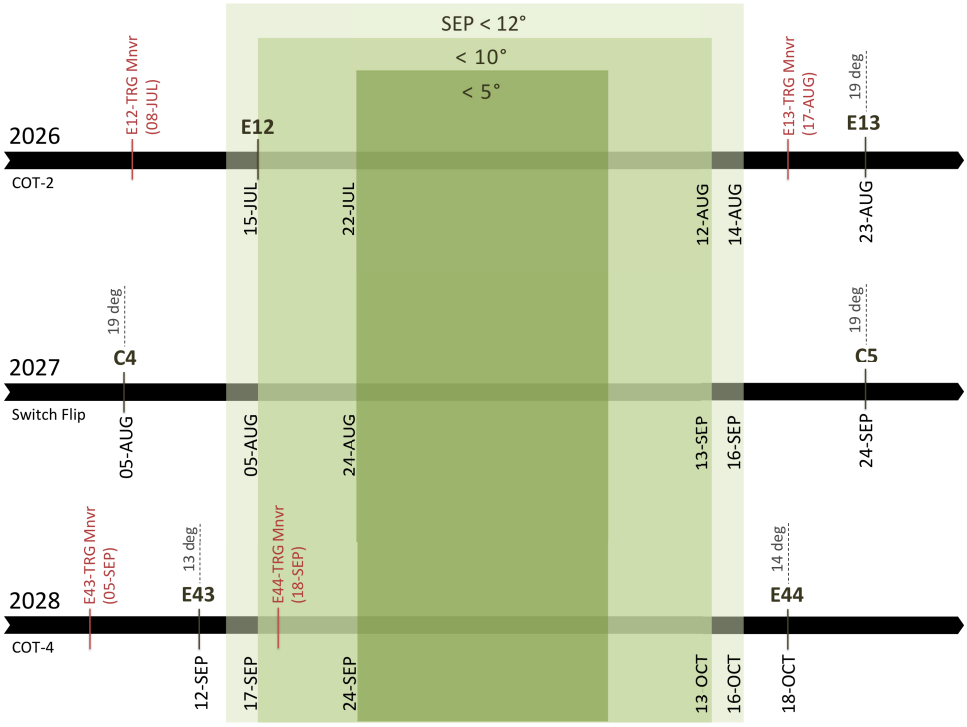


Figure 16. Timeline diagram of conjunction events for 14F8-S22. SEP = Sun-Earth-Probe (spacecraft) angle. TRG Mnvr = targeting maneuvers

Table 3. Comparisons with other Europa Tours

Tour	13F7-A21	14F8-S22	15F9-A22	15F10-S22
Launch Date	Nov. 2021	Jun. 2022	Jun. 2022	Jun. 2022
Flight Time to Jupiter	6.4 yrs	2.7 yrs	7.6 yrs	2.7 yrs
Tour Duration*	3.5 yrs	3.7 yrs	3.3 yrs	3.4 yrs
Number of Flybys				
Europa	45	45	40	42
Ganymede	5	5	5	4
Callisto	9	7	8	8
Time Between Flybys**				
Maximum	50.0 days	50.0 days	78.7 days	50 days
Minimum	5.5 days	8.3 days	8.3 days	8.3 days
Mean	18.3 days	20.1 days	20.0 days	20.0 days
Tour ΔV***	164 m/s	174 m/s	152 m/s	124.6 m/s
Total ΔV***	1,218 m/s	1,181 m/s	1,092 m/s	1,132 m/s
Maximum Inclination	20.1°	21.2°	19.8°	21.2°
Maximum Eclipse Duration	4.5 hrs	8.8 hrs	8.8 hrs	8.8 hrs
Total Ionized Dose (TID)+	2.82 Mrad	3.14 Mrad	2.74 Mrad	2.82 Mrad

* To the last Europa science flyby.

** Does not include the post-JOI orbit.

*** Deterministic value only

+Calculated using GIRE-2 model from G0 to last Europa flyby; Si behind 100 mil Al; spherical shell

From a mission design perspective, one can mitigate the potential impact of losing the science from a particular flyby by either adding flyby(s) or designing the mission with plenty of margins. For the latter case: redesign the tour such that all science objectives are met with plenty of margins, or increase the the mean flight time between flybys allowing for more time to address any issues, which mitigates risk propagating across numerous flybys. The cost ($\Delta\mathbf{V}$, time, and TID) of these changes is currently being investigated.

For the case of adding flybys to recover the science from a missed flyby, there are a number of options we can adopt. The simplest option is to do nothing during the prime tour and make up missed flybys in an extended mission. Another option is to add additional flybys *a priori*, which can be done by increasing the density of groundtracks in a particular sequence or by adding more flyby sequences (e.g., an additional COT sequence). This makes each individual flyby less important in the cumulative set at the expense of flight time and TID. Another option is to add decision branch points throughout the tour such that if the tour is proceeding as expected, the mission continues with the baseline, but if something unexpected arises or if something interesting was observed and needs to be revisited, then one switches to a contingency tour, built *a priori*. This option will require many variations to the baseline tour. An example is illustrated in Figure 17, where after COT-2, one evaluates the state of the mission. If all is nominal, then we proceed along the tour, i.e., continue along Tour-1. However, if a small anomaly occurred which can be fixed quickly (i.e., within a few days), then one will continue on an alternating tour, Tour 2 in our example. If a major anomaly occurred, and may take weeks to fix, we will want to go outside the radiation region while addressing the anomaly, and continue along a new tour, Tour 3. These branching tours must be designed *a priori*.

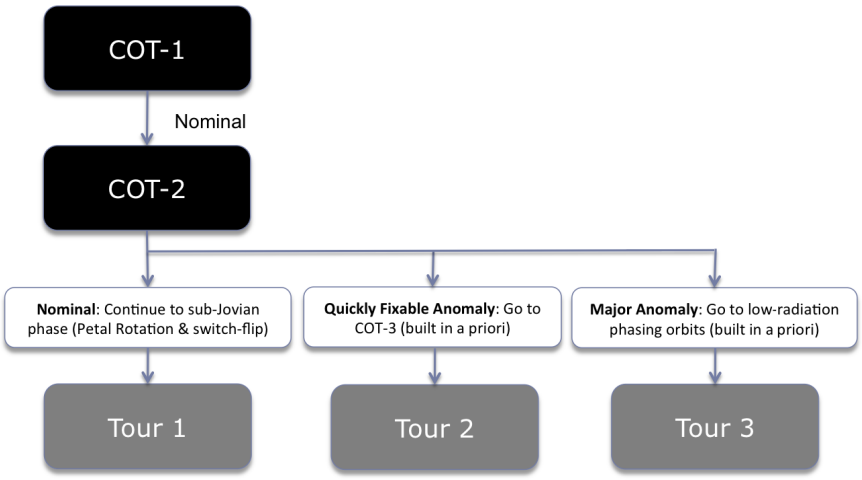


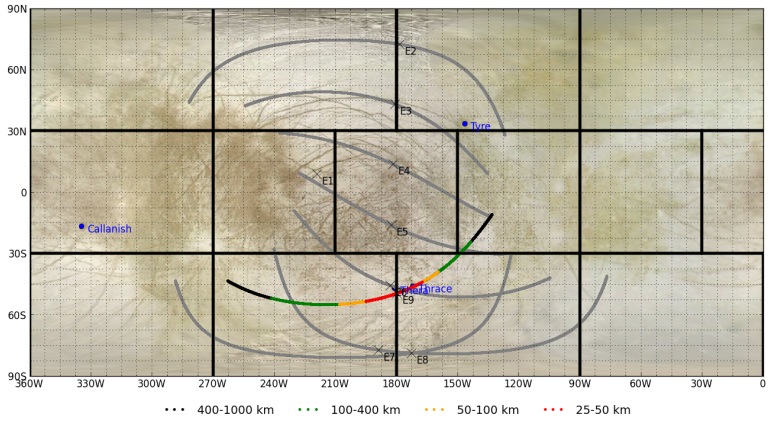
Figure 17. An example decision tree for selecting which tour to continue on depending if an anomaly occurs or not. These branching tours must be designed a priori.

Lastly, a "reverse-crank" strategy can be implemented, where for a particular flyby, one can reverse the crank angle direction of the next flyby, which 'reverses' the effect of the previous flyby. The following flyby will then repeat the initial flyby's groundtrack. Figure 18 shows an example of a "reverse-crank" strategy for E9 in COT-2. This process does not need to be designed in advance, but will require action no later than $\approx$7 days after the initial flyby in question, i.e., prior to the targeting maneuver of the next flyby. However, the tour downstream from the reverse-crank will need to be redesigned. If built in *a priori* to the COT sequences, one can move the reverse-crank almost anywhere in COT sequences with repeat resonances.

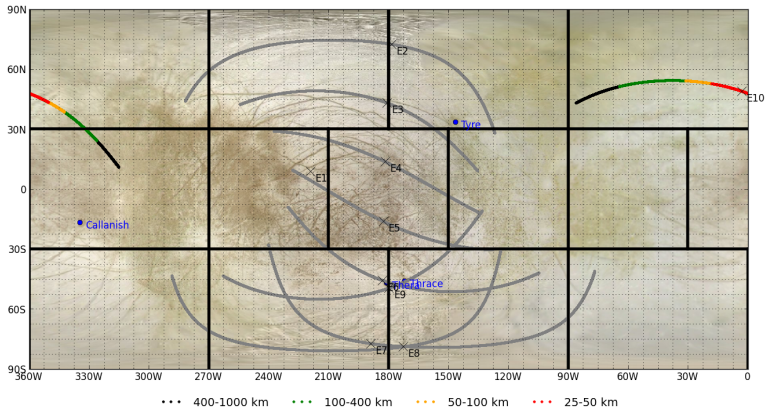
A summary of the options of adding flybys and their approximate $\Delta\mathbf{V}$ cost is listed in Table 4.

FUTURE WORK

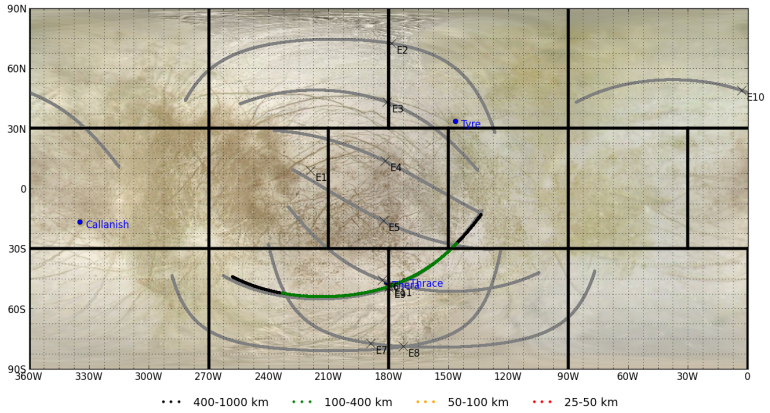
As previously mentioned, the science instruments for the Europa project have been announced by NASA. As details of the requirements from the instruments are released, the project will evaluate their effects on the mission and the current tours. The mission design team will work with the instruments' principal investigators



(a) E9



(b) E10 (reverse-crank)



(c) E11 (repeat E9 groundtrack)

Figure 18. Example of reverse-crank for the COT-2 Groundtracks

Table 4. Cost of adding flybys in the tour.

Option	Cost
Reverse-crank	$\Delta\mathbf{V} \approx 25$ to 30 m/s
Increase the density of groundtracks per COT sequence*	$\Delta\mathbf{V} \approx 5$ m/s per flyby
Add additional COT sequence	$\Delta\mathbf{V} \approx 5$ m/s per flyby in COT sequence
Add additional petal rotation transfers	$\Delta\mathbf{V} \approx 5$ m/s per flyby
Design decision point(s) in a priori	Varies depending on the chosen route

*For a given orbit period, the number of flybys increases/decreases as $\mathbf{V}_\infty$ increases/decreases, and for a given $\mathbf{V}_\infty$, the number of flybys increases/decreases as the spacecraft period decreases/increases.

to make any necessary updates. Although some adjustments to the tour are expected, we do not anticipate major re-designs due to the instrument selection.

CONCLUSION

The Europa Mission would be a major step forward in understanding the habitability and existence of life on Europa. The current set of candidate trajectories provides global regional coverage of Europa using multiple Europa flybys over the course of about 3.5 years. Although an orbiter mission had been investigated in the past and is often used to provide global coverage of a body, the current architecture meets the scientific goals with lower risk and cost. This multiple flyby architecture would operate in a less compressed timeline and allows for a much more agile and robust mission being able to react to unexpected anomalies or discoveries. With the current operations strategy, the spacecraft only dips down to the higher radiation evironment when collecting science data at Europa, then spends a majority of the time away from Europa and away from the harsher radiation environment while downlinking the data. This strategry allows for higher total data return than an orbiter, which would have a much shorter period to downlink. In addition, a flyby mission does not have to perform a Europa orbit insertion maneuver which can range between 450-600 m/s, allowing more mass allocation for science and shielding. Furthermore, the current flyby mission requires approximately one year from JOI to the first Europa flyby. An orbiter mission would require additional time to get to Europa ($\approx$2.5 years), and mission duration at Europa would only be a few months. Lastly, since the spacecraft is not in orbit around Europa, spacecraft disposal can be directed to other bodies, such as Callisto, or allow for extended science campaigns after the primary mission.

ACKNOWLEDGMENT

The authors would also like to thank Emily Manor-Chapman and Casey Heeg for the SWIRS and Topographic Imager resolution coverage analyses used in this paper, and Chen-Wan Yen and Ralph Roncoli for the interplanetary trajectory analyses. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Copyright 2014 California Institute of Technology. Government sponsorship acknowledged.

APPENDIX

Tour details for 15F9-A22 and 15F10-S22 can be found in Table A1 and Table A2, respectively.

REFERENCES

[1] G. Galilei, "Sidereus Nuncius," Report published by Thomas Baglioni in the Republic of Venice (now Italy), March 1610.

[2] *A Science Strategy for the Exploration of Europa*. National Academy Press, 1999.

[3] R. T. Papalardo, "Seeking Europa's Ocean," *Galileo's Medicean Moons: their impact on 400 years of discovery* (C. Barbieri, S. Chakrabarti, M. Coradini, and M. Lazzarin, eds.), No. 269 in Proceedings IAU Symposium, International Astronomical Union, 2010, pp. 101–114.

[4] J. R. Johannesen and L. D'Amario, "Europa Orbiter Mission Trajectory Design," *Advances in the Astronautical Sciences*, Vol. 103, No. 3, 1999, pp. 895–908.

[5] B. Buffington, S. Campagnola, and A. Petropoulos, "Europa Multiple-Flyby Trajectory Design," *AIAA/AAS Astrodynamics Specialist Conference, 13 - 16 August 2012, Minneapolis, Minnesota AIAA 2012-5069*, 2012.

[6] B. Buffington, "Trajectory Design for the Europa Clipper Mission Concept," *AIAA/AAS Astrodynamics Specialists Conference, Space 2014, August 2014, San Diego, CA*, 2014.

[7] K. Clark, "2007 Europa Explorer Mission Study: Final Report (Publicly released version)," *Clusters of Galaxies* (J. Kaastra, ed.), 2007. D-41283, November 01, 2007.

[8] F. Chou and L. Cantillo, "NASA's Europa Mission Begins with Selection of Science Instruments," National Aeronautics and Space Administration Press Release 15-104 (http://www.nasa.gov/press-release/nasa-s-europa-mission-begins-with-selection-of-science-instruments)., May 2015. [Online; accessed July 19, 2015].

[9] G. H. B., J. I., R. J. M., E. R. W., C. G. A., and M. R. W., "Galileo interim radiation model. Jet Propulsion Laboratory Report D-24811. Jet Propulsion Laboratory, Pasadena.," 2002.

[10] D. N. and G. H. B., "Charged particle distributions in Jupiters magnetosphere," *J. Geophys. Res.*, Vol. 88, 1983, pp. 6889–6903.

[11] B. Buffington, N. Strange, and S. Campagnola, "Global Moon Coverage Via Hyperbolic Flybys," 2012.

[12] R. Anderson, B. Buffington, and S. Campagnola, "Analysis of Petal Rotation Trajectory Characteristics," *AIAA/AAS Astrodynamics Specialist Conference, AIAA-2014-4350, San Diego, California, August 4-7, 2014*, 2014.

[13] X. Wu, Y. E. Bar-Sever, W. M. Folkner, J. G. Williams, and J. F. Zumberge, "Probing Europa's hidden ocean from tidal effects on orbital dynamics," *Geophysical Research Letters*, Vol. 28, No. 11, 2001, pp. 2245–2248, 10.1029/2000GL012814.

Table A1. Detailed 15F9-A22 tour summary.

Phase	Flyby	In /Out	Date (ET)	Alt (km)	B-plane (deg)	$\mathbf{V}_\infty$ (km/s)	Incl. (deg)	SEP (deg)	m	n	Next enc. (days)	Lat (deg)	W. Lon (deg)
Pumpdown	0G0	I	15-Jan-2030 00:40	300	5	7.97	5.1	62	28.3	1.3	202.2	–	–
	1G1	O	05-Aug-2030 06:01	649	176	6.27	5.1	95	8	1	57.3	–	–
	2G2	O	01-Oct-2030 12:03	150	118	6.35	1.2	47	11	2	78.7	–	–
	4G3	O	19-Dec-2030 04:48	494	172	6.33	0.5	15	3	1	21.5	–	–
	5G4	O	09-Jan-2031 15:51	838	171	6.32	0.1	32	2	1	14.3	–	–
	6G5	O	21-Jan-2031 22:58	5023	174	6.31	0.3	44	3	1.8	24.0	–	–
COT-1	8E1	O	16-Feb-2031 22:00	1564	-26	4.01	0.6	63	4	1	14.2	26.2	214.9
	9E2	O	03-Mar-2031 02:09	350	-75	3.91	3.2	76	4	1	14.2	73.4	178.4
	10E3	O	17-Mar-2031 07:04	100	-49	3.92	5.2	89	4	1	14.2	44.7	180.4
	11E4	O	31-Mar-2031 11:58	100	-20	3.92	5.9	102	4	1	14.2	15.2	180.1
	12E5	I	14-Apr-2031 16:53	50	14	3.92	5.2	116	4	1	14.2	-15.4	181.7
	13E6	I	28-Apr-2031 21:48	25	48	3.92	3.0	130	4	1	14.2	-46.2	182.5
	14E7	I	13-May-2031 02:44	98	79	3.92	0.6	144	4.1	1.1	14.5	-78.2	190.0
COT-2	15E8	O	27-May-2031 14:55	100	84	4.03	3.0	160	4	1	14.2	-81.2	165.0
	16E9	O	10-Jun-2031 19:15	50	51	3.94	5.2	175	4	1	14.2	-46.7	179.6
	17E10	O	25-Jun-2031 00:02	50	18	3.94	5.9	170	4	1	14.2	-13.9	180.6
	18E11	I	09-Jul-2031 05:00	25	-16	3.94	5.0	154	4	1	14.2	16.9	181.5
	19E12	I	23-Jul-2031 09:58	50	-48	3.94	2.8	140	4	1	14.2	47.1	182.3
	20E13	I	06-Aug-2031 14:55	25	-82	3.93	0.3	125	4.1	1.1	14.2	80.4	191.9
Petal Rotation	21E14	O	21-Aug-2031 03:12	25	5	4.09	0.4	111	4.9	0.9	17.6	-5.5	205.1
	22E15	I	07-Sep-2031 16:26	100	1	4.10	0.5	95	4.1	1.1	14.6	-1.1	156.9
	23E16	O	22-Sep-2031 05:50	100	0	4.11	0.5	82	4.9	0.9	17.6	0.2	206.2
	24E17	I	09-Oct-2031 18:55	100	0	4.10	0.5	67	4.1	1.1	14.6	-0.3	157.4
	25E18	O	24-Oct-2031 08:14	100	0	4.09	0.5	55	4.9	0.9	17.6	0.2	206.2
	26E19	I	10-Nov-2032 21:21	100	0	4.10	0.5	41	4.1	1.1	14.6	-0.4	157.6
	27E20	O	25-Nov-2032 10:37	100	0	4.06	0.5	29	4.9	0.9	17.6	0.1	206.0
	28E21	I	13-Dec-2032 00:12	100	2	4.04	0.6	15	4.1	1 .1	14.5	-2.1	160.2
Crank Up, Switch Flip, Pump Up	29E22	O	27-Dec-2032 12:23	499	-155	4.01	0.5	4	10	3	35.6	24.6	33.6
	32E23	O	01-Feb-2032 01:54	100	158	4.30	0.6	24	12	4.4	42.5	-22.0	49.4
	37C1	I	14-Mar-2032 13:52	300	-124	2.77	10.5	59	2	3	33.3	–	–
	40C2	I	16-Apr-2032 22:15	272	-149	2.78	12.4	87	1	1	16.6	–	–
	41C3	I	03-May-2032 13:44	50	-81	2.79	18.6	102	1	1	16.7	–	–
	42C4	I	20-May-2032 05:21	1826	-64	2.79	19.8	118	0.5	0.5	8.3	–	–
	42C5	O	28-May-2032 11:39	554	0	2.76	17.7	126	1	1	16.6	–	–
	43C6	O	14-Jun-2032 03:08	154	-148	2.75	15.0	143	2	3	33.3	–	–
	46C7	O	17-Jul-2032 11:37	1653	-111	2.75	8.1	178	1	1.5	15.2	–	–
	48E24	I	01-Aug-2032 17:02	2470	134	3.76	7.2	166	3	1	10.6	-37.4	313.7
	49E25	I	12-Aug-2032 08:09	100	88	3.78	4.4	154	7	2	24.8	-65.0	247.3
COT-3	51E26	I	06-Sep-2032 03:30	100	-168	3.96	4.7	128	4	1	14.2	9.2	342.7
	52E27	I	20-Sep-2032 07:47	50	-110	3.99	7.2	114	7	2	24.9	57.8	31.4
	54E28	I	15-Oct-2032 04:30	25	161	3.97	6.1	91	4	1	14.2	-19.8	344.4
	55E29	O	29-Oct-2032 08:55	50	-148	3.97	7.5	79	7	2	24.9	25.3	19.9
	57E30	O	23-Nov-2032 05:41	25	118	3.97	5.0	57	4	1	14.2	-52.9	335.0
	58E31	O	07-Dec-2032 10:05	50	172	3.94	4.6	46	7	2	24.9	-9.7	18.9
	60E32	O	01-Jan-2033 06:49	25	113	3.97	1.9	26	7	2	24.9	-65.0	4.8
	62E33	O	26-Jan-2033 03:40	1049	47	4.02	0.5	6	7.9	2	28.0	-47.4	217.7
COT-4	64E34	I	23-Feb-2033 04:50	50	104	4.03	2.4	16	4	1	14.2	-75.1	356.8
	65E35	I	09-Mar-2033 09:41	25	126	4.03	4.6	27	4	1	14.2	-49.4	0.3
	66E36	I	23-Mar-2033 14:32	50	151	4.03	5.8	38	4	1	14.2	-23.5	1.1
	67E37	O	06-Apr-2033 19:22	25	179	4.04	5.7	49	4	1	14.2	2.4	1.6
	68E38	O	21-Apr-2033 00:13	50	-152	4.05	4.3	60	4	1	14.2	28.2	2.3
	69E39	O	05-May-2033 05:04	25	-124	4.06	2.0	72	4	1	14.2	54.0	3.2
	70E40	O	19-May-2033 10:03	308	-91	4.10	0.7	84	7.6	1.6	26.9	85.4	309.7
EOM	72C8	I	15-Jun-2033 07:45	0	0	531	0.8	107	N/A	N/A	N/A	N/A	N/A

Solar conjunction between G2/G3, E21/E23, and E33/E34. B-plane = B-plane angle relative to the satellite's mean equator of epoch; $\mathbf{V}_\infty$ = Hyperbolic excess velocity; In/Out = inbound (I) or outbound (O) flyby; Incl. = spacecraft central body mean equator inclination with respect to Jupiter; m = integer number of gravity assist body orbits; n = integer number of spacecraft orbits; NT = Non-targeted flybys; flyby naming convection is of the form MBN, where M = number of orbits around Jupiter, B = flyby body, and N = sequential number of flyby body B.

Table A2. Detailed candidate version 15F10-S22 tour summary.

Phase	Flyby	In /Out	Date (ET)	Alt (km)	B-plane (deg)	$\mathbf{V}_\infty$ (km/s)	Incl. (deg)	SEP (deg)	m	n	Next enc. (days)	Lat (deg)	W. Lon (deg)
Pumpdown	0G0	I	04-Mar-2025 22:50	500	0	8.06	3.6	88	28.3	1	202.3	–	–
	1G1	O	23-Sep-2025 05:36	150	-172	6.41	3.5	69	7	1	50.1	–	–
	2G2	O	12-Nov-2025 07:51	100	-136	6.46	0.3	115	4	1	28.6	–	–
	3G3	O	10-Dec-2025 22:25	3540	-177	6.42	0.1	145	3	1	21.5	–	–
	4G4	O	01-Jan-2026 09:38	100	-173	6.46	0.5	170	10.9	2.9	38.8	–	–
COT-1	7E1	O	09-Feb-2026 04:48	6572	-9	4.16	0.6	146	4	1	14.1	–	–
	8E2	O	23-Feb-2026 08:13	100	-75	3.94	3.0	131	4	1	14.2	72.6	181.6
	9E3	O	09-Mar-2026 13:08	100	-48	3.95	4.9	116	4	1	14.2	43.4	179.2
	10E4	O	23-Mar-2026 18:04	50	-19	3.95	5.7	102	4	1	14.2	14.1	178.3
	11E5	I	06-Apr-2026 23:00	50	15	3.94	4.8	89	4	1	14.2	-16.0	177.4
	12E6	I	21-Apr-2026 03:52	25	47	3.94	2.7	77	4	1	14.2	-45.7	176.8
	13E7	I	05-May-2026 08:46	25	79	3.93	0.3	65	4.1	1	14.5	-77.3	170.9
COT-2	14E8	O	19-May-2026 20:46	100	81	3.96	2.9	53	4	1	14.2	-79.0	187.4
	15E9	O	03-Jun-2026 01:42	25	54	3.97	5.1	42	4	1	14.2	-49.8	180.2
	16E10	O	17-Jun-2026 06:36	50	26	3.97	6.2	31	4	1	14.2	-21.1	179.2
	17E11	I	01-Jul-2026 11:30	25	-5	3.97	5.8	21	4	1	14.2	7.1	178.9
	18E12	I	15-Jul-2026 16:14	100	-17	3.99	5.0	10	11	3	39.1	18.2	189.3
	21E13	I	23-Aug-2026 17:44	100	-86	4.00	2.3	19	4	1	14.2	73.8	127.3
	22E14	I	06-Sep-2026 22:17	25	-54	4.04	0.6	29	7.1	2	25.3	54.1	204.5
Petal Rotation	24E15	O	02-Oct-2026 05:12	50	3	4.08	0.5	49	8.9	2	31.7	-3.4	148.6
	26E16	I	02-Nov-2026 21:10	2608	0	4.13	0.5	76	4.1	1	14.6	-0.2	208.5
	27E17	O	17-Nov-2026 10:40	25	0	4.08	0.5	89	4.9	1	17.6	0.0	155.2
	28E18	I	05-Dec-2026 00:09	25	0	4.08	0.5	106	4.1	1	14.6	0.3	201.7
	29E19	O	19-Dec-2026 13:23	100	0	4.09	0.5	121	4.9	1	17.6	-0.1	153.9
	30E20	I	06-Jan-2027 02:42	25	-1	4.07	0.5	139	4.1	1	14.5	1.2	201.4
	31E21	O	20-Jan-2027 15:48	50	9	4.05	0.1	156	5	1	17.7	-9.2	154.9
	32E22	I	07-Feb-2027 07:29	50	36	3.92	1.7	176	0.1	0.1	1.0	-35.1	188.7
	32G (NT)	O	08-Feb-2027 07:59	31073	-123	6.66	1.7	177	4.2	1.9	15.0	–	–
	34E23	I	11-Mar-2027 05:17	100	-49	4.01	0.4	148	4.1	1	14.5	49.5	196.4
Crank Up, Switch Flip, Pump Up	35E24	O	25-Mar-2027 17:29	25	-80	3.93	3.4	133	4	1	14.2	78.2	186.7
	36E25	O	08-Apr-2027 22:08	50	-88	3.91	6.2	118	7	2	24.8	70.2	239.9
	38E26	O	03-May-2027 18:27	1140	-130	3.92	7.6	94	3	1	10.6	40.7	308.0
	39E27	O	14-May-2027 09:48	3215	-139	3.90	8.3	85	1.5	2.6	25.3	–	–
	42C1	I	08-Jun-2027 16:48	250	86	2.93	18.3	64	2	3	33.3	–	–
	45C2	I	12-Jul-2027 01:06	100	114	2.93	20.1	38	1	1	16.6	–	–
	46C3	I	28-Jul-2027 16:41	1633	62	2.93	21.2	25	0.5	0.5	8.3	–	–
	46C4	O	05-Aug-2027 23:12	911	50	2.97	20.8	19	3	4	50	–	–
	50C5	O	24-Sep-2027 23:56	552	60	2.97	15.6	19	2	3	33.3	–	–
	53C6	O	28-Oct-2027 08:03	100	70	2.98	4.2	45	2	3	33.4	–	–
	56C7	O	30-Nov-2027 16:56	2791	169	2.94	3.0	74	7.1	2.6	25.1	–	–
	59E28	I	25-Dec-2027 19:20	100	-111	3.82	0.3	97	3.1	1	11.1	68.9	52.0
	60E29	O	05-Jan-2028 21:21	488	177	3.78	0.4	108	4.8	1.9	17.2	-2.5	318.0
COT-3	62E30	I	23-Jan-2028 00:58	100	-145	3.86	1.3	125	3	1	10.6	34.3	38.5
	63E31	I	02-Feb-2028 16:32	100	-149	3.86	2.7	137	7	2	24.9	29.0	24.3
	65E32	I	27-Feb-2028 13:04	50	-168	3.85	3.2	164	4	1	14.2	9.5	15.6
	66E33	I	12-Mar-2028 17:38	25	-154	3.88	4.3	178	4	1	14.2	22.5	359.2
	67E34	O	26-Mar-2028 22:37	100	168	3.88	3.6	164	4	1	14.2	-13.4	358.5
	68E35	O	10-Apr-2028 03:35	50	131	3.89	1.5	148	4	1	14.2	-48.6	357.8
	69E36	O	24-Apr-2028 08:19	25	143	3.88	0.5	133	6.9	2	24.5	-37.8	336.6
COT-4	71E37	I	18-May-2028 12:14	100	143	3.87	0.5	109	4	1	14.2	-37.3	21.0
	72E38	I	02-Jun-2028 00:40	50	124	3.92	1.5	96	4	1	14.2	-53.3	0.0
	73E39	I	16-Jun-2028 05:30	25	155	3.93	4.0	84	4	1	14.2	-21.3	358.7
	74E40	O	30-Jun-2028 10:19	50	-171	3.94	5.5	72	4	1	14.2	10.8	358.3
	75E41	O	14-Jul-2028 15:09	100	-137	3.95	5.4	60	4	1	14.2	41.4	357.3
	76E42	O	28-Jul-2028 19:55	155	-103	3.96	0.2	49	2.4	2.8	40.9	75.6	0.9
EOM	79C8	I	07-Sep-2028 16:58	50	-112	6.46	5.2	17	N/A	N/A	N/A	N/A	N/A

Solar conjunction between E12/E13 and C4/C5. B-plane = B-plane angle relative to the satellite's mean equator of epoch; $\mathbf{V}_\infty$ = Hyperbolic excess velocity; In/Out = inbound (I) or outbound (O) flyby; Incl. = spacecraft central body mean equator inclination with respect to Jupiter; m = integer number of gravity assist body orbits; n = integer number of spacecraft orbits; NT = Non-targeted flybys. flyby naming convection is of the form MBN, where M = number of orbits around Jupiter, B = flyby body, and N = sequential number of flyby body B.