Europa Clipper Mission Analysis: Design of the 21F31 Reference Trajectory

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***Abstract* —Europa has been a prime target for space exploration ever since 1997, when the Galileo spacecraft magnetic measurements of Europa suggested the moon might hide a vast, salty ocean beneath its icy surface. To investigate its habitability, NASA developed Europa Clipper, which will be launched in October 2024 on a Falcon Heavy rocket from Cape Canaveral. After a 5.5-year interplanetary journey that includes one Mars gravity assist and one Earth gravity assist, Europa Clipper will reach Jupiter in April 2030 and insert into a 200-day orbit in the Jovian system. Subsequently, a complex gravity assist trajectory (tour) will commence. This paper will present the reference tour, 21F31, which is comprised of 53 flybys of Europa, 9 flybys of Callisto, 7 flybys of Ganymede and culminates with Ganymede impact to meet planetary protection requirements. The principles, design process, and evolution of tour designs—which leverage on more than two decades of research in astrodynamics and multiple interactions with planetary scientists and engineers—as well as the science objectives and mission constraints that drive the design of the tour will be covered in this paper. This paper is part of a series of papers describing the mission design and navigation analysis of Europa Clipper, which have been presented at different international conferences.**

I. INTRODUCTION

Europa is one of the most scientifically interesting targets of the solar system, as it may possess what are thought to be the three necessary ingredients for life: an extensive ocean of liquid water, an energy source, and a suite of biogenic elements. To explore the habitability of Europa, NASA will launch Europa Clipper mission in October 2024. Europa resides deep inside the gravity well of Jupiter, in a region of the magnetosphere with many trapped ionized particles, that when accelerated to near relativistic speeds, result in a radiation environment detrimental to unprotected spacecraft electronics. Europa Clipper will utilize a high number of Europa flybys, connected by resonant and non-resonant transfers to build up a global understanding of Europa. Science data is collected during high-radiation Europa flybys, and returned to Earth during the rest of the highly elliptical Jovian orbits, where the spacecraft is exposed to a much lower radiation dose.

Europa Clipper will reach the Jupiter system utilizing a Mars-Earth Gravity Assist (MEGA) interplanetary trajectory [1], with the opening day of the launch period on October 10, 2024. At Jupiter, Europa Clipper will execute a multi-moon tour, designed to meet the ∼300 requirements levied on the mission design. The tour is nearly ballistic, using on average just a few meters per second of deterministic maneuvers between flybys. All Level 1 requirements/objectives will be met over the nominal prime mission, which consists of 49 Europa flybys with closest-approaches at varying altitudes, longitudes and latitudes on both the sub-Jovian and anti-Jovian hemispheres.

This paper presents the tour design process, and the 21F31 tour that was selected as mission baseline. The tour is the product of many years of research in astrodynamics and seven design cycles that involved the Mission Design Team (mission analysis, navigation, and mission planning) and the Project Science Group (PSG).

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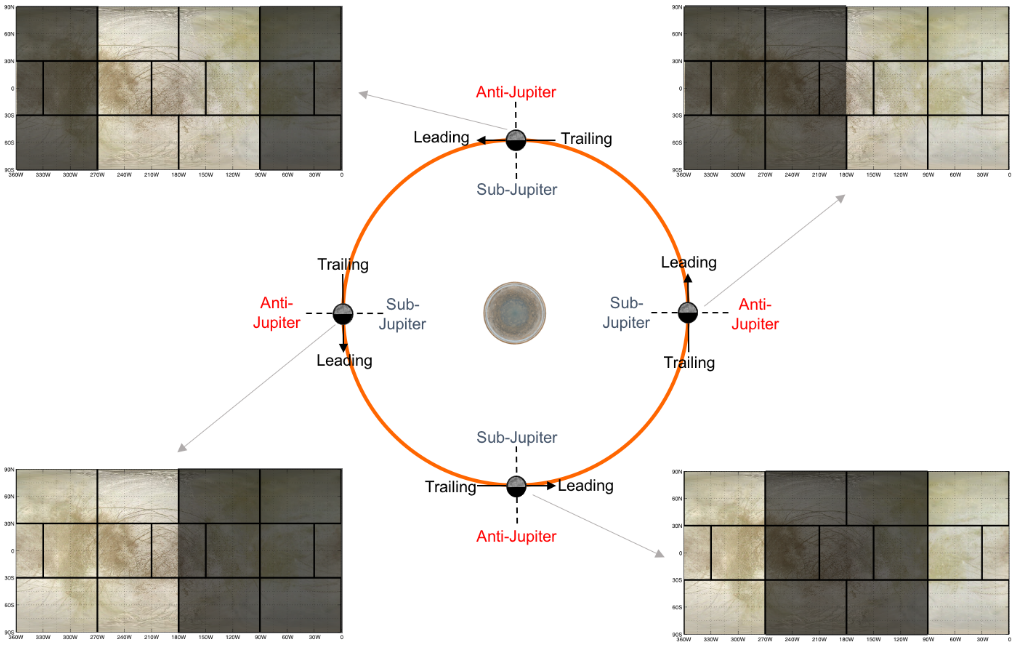


Fig. 1: Since Europa is tidally locked, Europa's terrain maintains the same orientation relative to Jupiter. Different part of Europa are illuminated depending on the position on the orbit. The 14 panels are defined by the PSG to assess "global-regional" coverage.

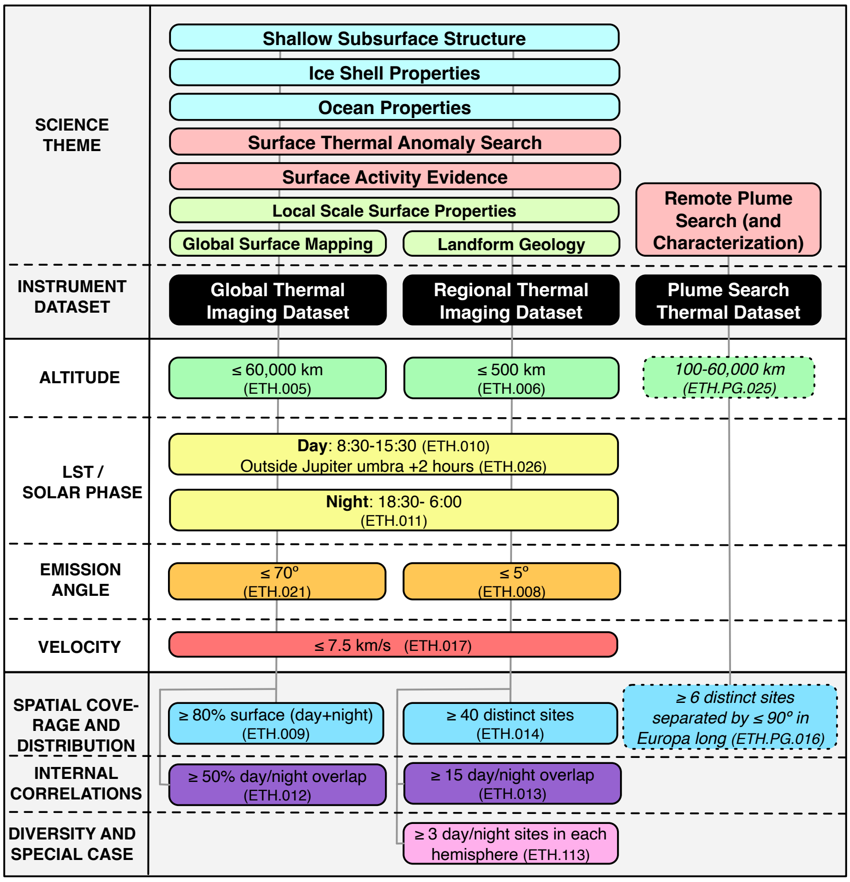
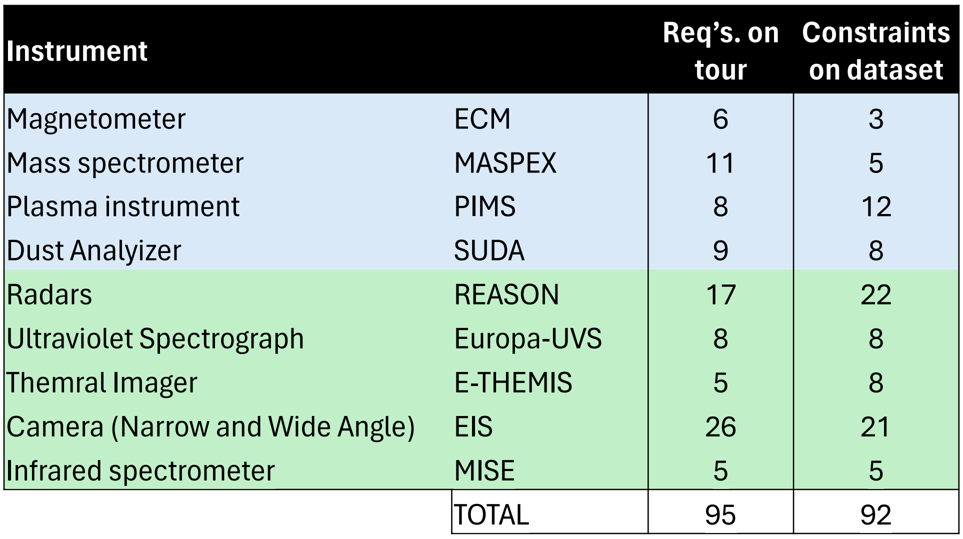


Fig. 2: Schematic of science requirements and planning guidelines levied on Mission Design by the thermal imager E-THEMIS.



Instrument		Req's. on tour	Constraints on dataset
Magnetometer	ECM	6	3
Mass spectrometer	MASPEX	11	5
Plasma instrument	PIMS	8	12
Dust Analyzer	SUDA	9	8
Radars	REASON	17	22
Ultraviolet Spectrograph	Europa-UVS	8	8
Themral Imager	E-THEMIS	5	8
Camera (Narrow and Wide Angle)	EIS	26	21
Infrared spectrometer	MISE	5	5
	TOTAL	95	92

Fig. 3: Science requirements levied on Mission Design by the different instruments.

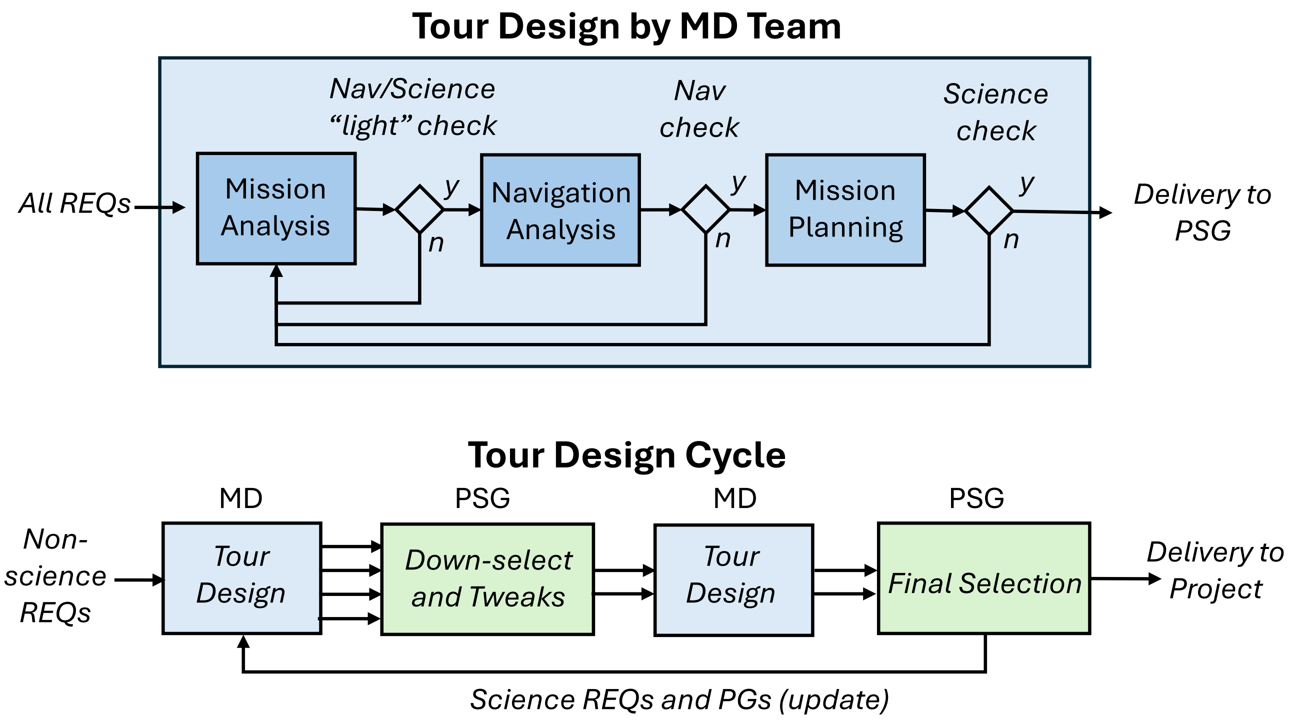


Fig. 4: Tour Design Process

II. EUROPA CLIPPER MISSION DESIGN

A. *The Jovian System*

The Galilean moons are the four largest moons of Jupiter. Discovered by the Italian astronomer Galileo Galilei in 1610, these moons are named Io, Europa, Ganymede, and Callisto. They are among the most fascinating objects in our celestial neighborhood and have captivated astronomers and space enthusiasts for centuries.

Io, Europa, and Ganymede orbits are in a Laplace resonance. In particular, their orbital periods are in a 1:2:4 resonance: Ganymede's period is twice that of Europa, and Europa's period is twice that of Io. The small eccentricity of their orbits causes tidal heating, which keeps the water in liquid state under the surfaces of Europa, Ganymede and Callisto. The same process is responsible for the volcanic activity at Io; its ejecta are ionised and accelerated by the powerful magnetic filed of Jupiter, creating a belt of high-energy radiation particles that can damage a spacecraft electronics and make the exploration of Europa very challenging.

Like most the moons in the solar system, Europa is tidally locked. Europa's rotation period matches its orbital period, so that the moon always faces the same hemisphere to Jupiter (the sub-Jovian hemisphere). As Europa moves on its roughly 3.5 day orbit, and keeps its prime meridian towards Jupiter, it exposes different part of its surface to the Sun. The anti-Jovian hemisphere is illuminated when the Sun-Jupiter-Europa angle (SJE), is near 0°; while the sub-Jovian hemisphere is illuminated when SJE is about 180°. Figure 1 shows a Jupiter-centered plot of Europa's orbit, viewed from Jupiter's north pole in the rotating frame with the y-axis pointing to the Sun (top of the page), z-axis normal to Europa's orbital plane, and x-axis completing the right-handed rule. Also shown are maps of Europa with the fourteen roughly equal-area regions [2] and the surface illumination around Jupiter.

B. *Science Requirements*

On May 26, 2015, NASA officially selected 10 scientific instruments from 6 different U.S. research facilities and universities for the Europa Clipper payload. Over the subsequent years, a rich set of science measurement requirements have been developed to meet the Level 1 (L1) science requirements. A large sub-set of these requirements have been levied on Mission Design (trajectory design, navigation, and mission planning). Of the over 180 science requirements levied on Mission Design, about half are requirements that the data sets need to meet, and the other half are constraints on observations to be counted towards these data sets (such as illumination conditions or spatial resolution). As an example, the thermal imager E-THEMIS collects day and night images of large parts of Europa surface; one requirement specifies that at least 50% of the areas observed in the day are also observed in the night:

ETH.012 Global Day/Night Coverage *For the global thermal imaging dataset, at least* 50% *of the area covered on the dayside shall be covered by data acquired on the nightside.*

Additional requirements then define constraints the observations need to meet, for them to be included in the thermal imaging dataset. A graphical representations on the requirements levied by E-THEMIS is shown in Fig. 2 (see [3] for a complete description of science requirements on the Europa Clipper trajectory design). The number of science requirements per instrument is shown in Fig. 3.

On top of the science requirements, more than 100 Planning Guideline are defined by the PSG, to guide the Mission Design Team to deliver trajectories with the highest scientific return.

C. *Non-Science Requirements*

A multitude of non-science requirements are also levied on mission design, stemming from project policies, planetary protection, and the evolved capability and characteristics of the Flight System and Mission Operations System. The most driving requirements on the trajectory specify the maximum allocated mission ΔV, the time-of-flight for the tour, the accumulated total ionizing dose (TID)[1], as well operation constraints on the timing of the maneuvers and of the flybys. A subset of these requirements, and their compliance by 21F31_V6, is shown in the next section. More requirements levied on the navigation are specified in other papers[4–6]. Probability of impact requirements are described in detail in Campagnola at al.[7].

D. *Tour Design Cycle*

Given the full set of requirements and planning guidelines, the Mission Design Team computes candidate tours for consideration by the PSG. Figure 4 on the top shows the details of this mission design task. The tour designers compute preliminary tours in high fidelity model (Mission Analysis block) and then run a preliminary check of the requirements - for example, a simplified probability of impact analysis is performed assuming perfect knowledge, and a default scheduling is used to check a subset of science requirements. When non-compliances are found, the tour designers can try to mitigate them with trajectory changes, before passing the tours to the navigators.

Then a full navigation analysis (Navigation Analysis block) computes the spacecraft dispersion, the predicted and reconstructed knowledge, the probability of impact, and the compliance to the navigation requirements. If needed, the trajectories are passed back to the tour designers for adjustments.

Finally, the tours are passed to the mission planners, who use activity-scheduling rules and the APGenX software (Activity Plan Generator[8, 9]), to produce a timeline of activities that represents the project's best understanding of the planned operations profile. The mission planners then use VERITaS (Verification of Europa Requirements Integrating Tour and Science[3, 10]) to simulate the instrument observations, using the timeline of activities from APGenX, and to assess compliance to the science requirements and planning guidelines. VERITaS reports are analyzed by the tour designers, who have the opportunity to implement changes to the trajectories, before they are passed to the PSG. Fig. 5 and Fig. 6 show an example of VERITaS product for tour 21F31_V6, for the E-THEMIS requirement ETH.012 on the day/night coverage. The first figure shows the simulated coverage, and the second shows that the requirement is met with E28.

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[1] Total ionizing dose Si behind a 100mil Al, spherical shell (GRID3 radiation model)

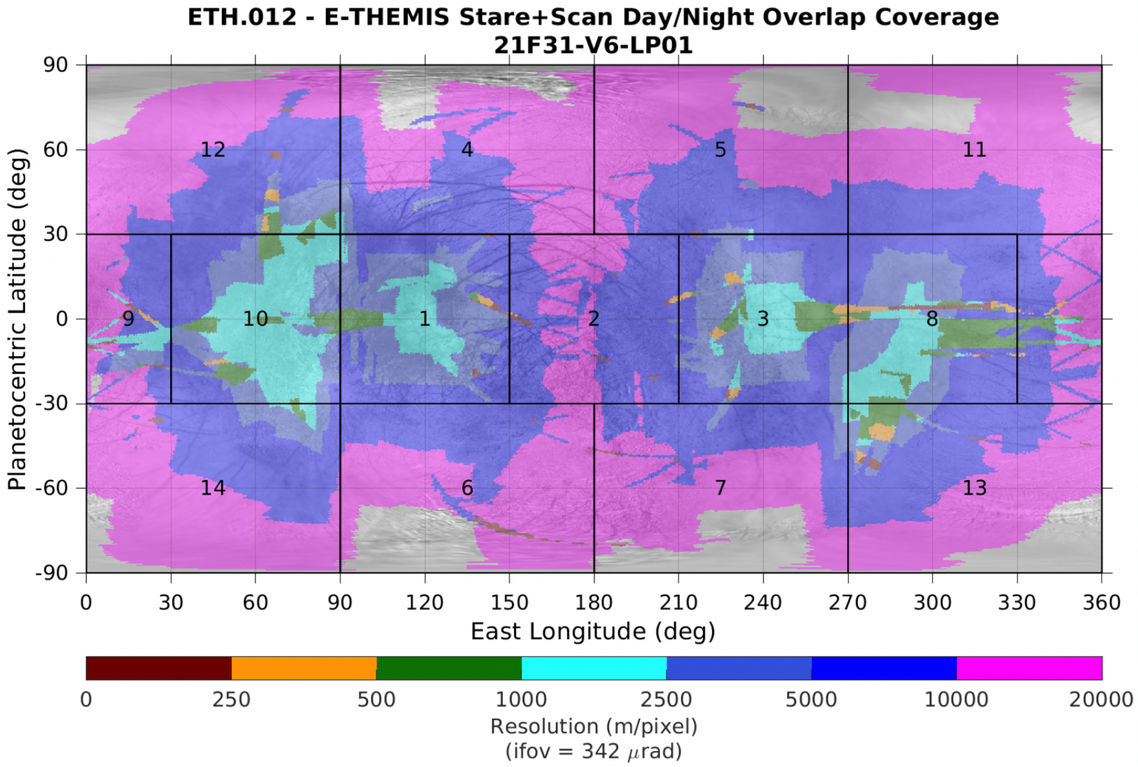

Fig. 5: Day/Night coverage by the thermal imager E-THEMIS for 21F31_V6, as simulated by VERITaS

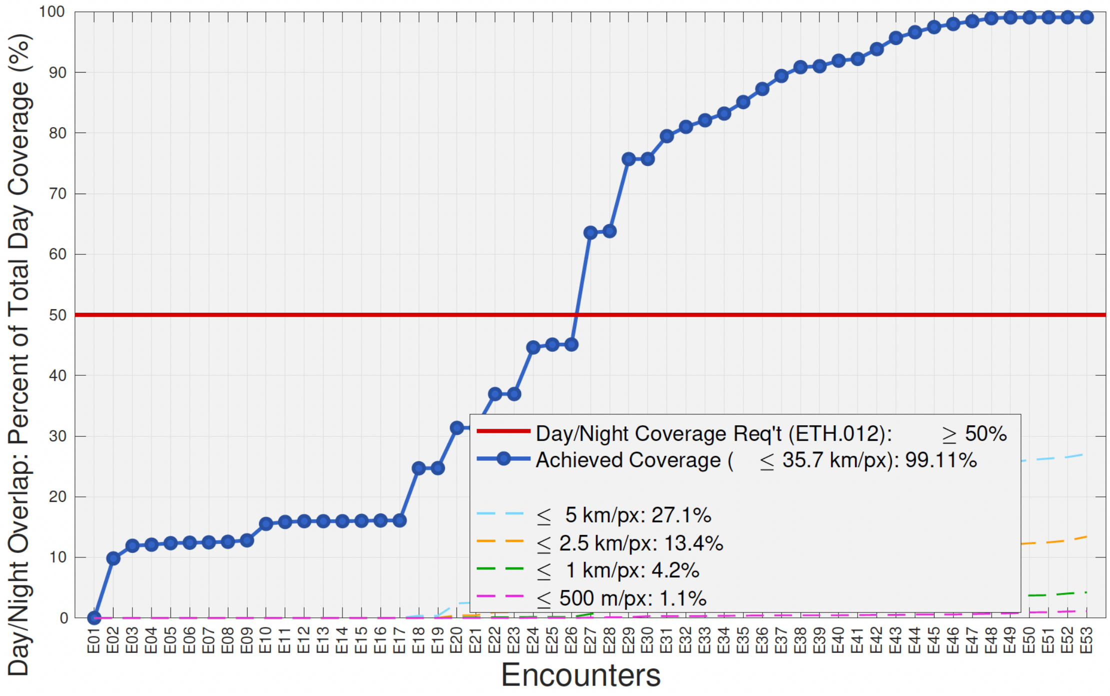

Fig. 6: Compliance to the Day/Night coverage requirement for 21F31_V6, as simulated by VERITaS

Tour Name	**13F7**	**15F10**	**17F12 V2**	**19F22/ F23**	**21F31 V4**	**21F31 V6**
Gate Review	**MCR**	**SRR/MDR**	**PDR**	**CDR**	**SIR**	**FRR**
Design Cycle					**6**	**7**
Launch Date	2021	2022	6/4/22	11/7/23	10/10/24	**10/10/24**
Arrival Date			12/23/24	9/29/29	4/10/30	**4/10/30**
Interplanetary Trajectory	VEEGA	Direct	Direct	VEEGA	MEGA	**MEGA**
Tour Duration (years)	3.5	3.4	3.7	3.84	4.27	**4.27**
EC1 Europa Resonance	4:1	4:1	4:1	4:1	6:1	**6:1**
Number of Flybys						
Europa	45	42	46	51	53	**53**
Ganymede	5	4	4	6	7	**7**
Callisto	9	8	9	7	9	**9**
No. of Night Side Europa Flybys			9	11	11	**11**
No. of Jupiter Orbits	76	79	70	77	79	**79**
Time between Flybys (days)						
Maximum	50	50		71.6	64.4	**64.4**
Minimum	5.5	8.3	5.4	5.7	9.4	**9.4**
Minimum (Europa-to-Europa)			10.1	10.6	13.8	**13.8**
Deterministic ΔV, post-PRM (m/s)	164	118	182	199	225.2	**214.8**
Maximum Inclination (deg.)	20.1	21.2	18.9	21	7.5	**7.7**
No. of Jupiter Eclipses	33	48	47	49	57	**57**
Maximum Eclipse Duration (hours)	4.5	8.8	9.15	9.22	7.8	**7.8**
Total Ionizing Dose (Mrad)[3]	2.82	2.99	2.5	2.88	2.97	**2.97**

Fig. 7: Europa Clipper history of baseline tours

The described mission design process takes about 3 to 5 months, and is challenging and time consuming for many reasons.

1. The tour design is complicated by the large amount of distant untargeted flybys, which require the design and optimization of the trajectory in high-fidelity model.
2. The science requirements are not formulated in a way that they can be directly translated into path or boundary constraints for a trajectory optimization program. This is because most requirements can only be evaluated after integrating the observations over the entire tour, for a chosen attitude and activity plan, conforming to mission system and flight system constraints. Instead, tour designers have to come up with tailored astrodynamics techniques or solutions to meet sets of requirements.
3. All tours must meet driving navigation requirements, like probability of impact or the predicted and reconstructed knowledge, which can be assessed only with a full navigation analysis, and cannot be included directly as constraints in the trajectory optimization[2].
4. Some measure of the scientific return of the tour can only be determined after the scheduler has optimized hundreds of thousand of activities (a process that can take days) and VERITaS has produced a vast report, with infographics and tables to help the mission designer find the best way to mitigate any non-compliances.

At the end of this process, the candidate trajectories are passed to the PSG for evaluations, as show in Figure 4 on the bottom. The PSG down-selects candidate tours and recommends for some trajectory tweaks to further improve science, sometime beyond what was captured by the requirements and planning guidelines. Then the mission design is repeated and the tweaked trajectories are passed back to the PSG, which selects the baseline tour for the project for the upcoming gate review. This tour design cycle lasts about a year and has been repeated seven times in the last decade. Every iteration is used to consolidate requirements, add new, or declass others to planning guidelines. At the same time, tour designers use the feedback from PSG to improve astrodynamic techniques.

In 2021, at the end of the sixth cycle, the project decided to adopt the 21F31 trajectory as baseline (in particular, 21F31_V4). The seventh and final cycle was carried to further tweak the tour, producing 21F31_V6, which is presented in this paper. Figure 7 shows a history of past selected tours, with their main characteristics.

III. OVERVIEW OF TOUR DESIGN TECHNIQUES

The exploration of planetary systems relies on complex trajectories, designed with astrodynamics techniques that exploit the short time scales (days to weeks) of the underlying dynamical system. This section provides a brief overview of the main techniques used for Europa Clipper (the interested reader can find more information in the cited literature).

Tour design techniques are typically developed in simplified models, like the patched conics model (where the trajectory is split in conic sections, patched by instantaneous ΔV's, to simulate each moon flyby), or the three-body problem. The techniques help mission designers quickly identify promising strategies to meet specific science requirements. However, the spacecraft trajectories must ultimately be designed and optimized in higher fidelity models, which at minimum include the gravity field of the Sun, Jupiter (including J2), and the Galilean moons as point masses. This is particularly important for Europa Clipper, whose orbit regularly intersects the orbits of Europa, Ganymede, and Callisto. While a complete Europa Clipper tour in a patched-conics model can be designed in just a few days (even less, using global optimization tools), the same trajectory cannot be re-converged in high fidelity model unless a large amount of ΔV is used to correct for distant, untargeted flybys. For these reasons, Jovian tours are designed in small batches of 2-6 flybys (using the principles summarized in this section), which are then optimized in high fidelity model, before another batch of flybys is added.

A. *Resonant and non-resonant transfer*

This section uses a simplified patched conics model, where Jupiter is the main body, and spacecraft flybys occur at one moon only. The spacecraft trajectory is then composed by multiple elliptical transfer, which start and end with a moon flyby. When the orbital period of the spacecraft is commensurable to the orbital period of the moon, the spacecraft transfer is called resonant and is defined by the resonant ratio $n:m$. In this case, the spacecraft transfer starts and ends with two flybys at the same point of the moon's orbit, separated in time by m spacecraft revolutions and n moon revolutions.

If the orbital plane of the spacecraft is the same as that of the moon, the spacecraft could also re-encounter the moon at the other intersection between their orbits - in this case, the spacecraft transfer is called non-resonant, since the period is not anymore commensurable with the period of the moon. A non-resonant transfer is typically labeled as $m:n^{-}$ or $m:n^{+}$, where the $^{-}$ denotes and outbound-to-inbound transfer and a $^{+}$ denotes and inbound-to-outbound transfer. Other than the special case of a pi-transfer [3], the flybys of a non-resonant transfer do not occur on a line with the central body and, therefore, constrain the orbit plane of the non-resonant transfer to be the same as the moon[12].

B. *Pump and Crank Angles*

Right before a flyby, the spacecraft orbit is defined by the approach velocity relative to the moon, or V_∞ vector, which is represented in spherical coordinates by its magnitude, and by two angles: the pump and crank angles[13]. The pump angle determines the period of the spacecraft orbit, while the crank angle is mainly determining its inclination. After a flyby, the outgoing V_∞ vector is rotated from the incoming V_∞ vector by the bending angle of the flyby (in the flyby orbital plane around the moon), and will correspond to a change in the outgoing pump, crank or both angles .

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[2] Recent works by the team have tried to address this issue by optimizing trajectories with chance constraints [11]

[3] A pi-transfer is special case of a non-res where the time-of-flight is an integer multiple of the gravity assist body period plus 1/2. Pi-transfers are inclined over the orbit of the gravity assist body.

C. *Pump-downs, Petal rotations, COTs*

In a pump-only flyby, the incoming and outgoing crank angles are the same, and the bending angle from the flyby is utilized to change only the pump angle, and hence, only the spacecraft orbital period. In a crank-only flyby, the incoming and outgoing pump angles are the same, corresponding to some resonant transfer, and the bending angle from the flyby is utilized to change only the crank angle, and thus only the spacecraft orbital inclination.

A pumpdown sequence is sequence of resonant transfers connected by pump-only flybys. At each flyby, the pump angle increases and the period of the orbit decreases. Pumpdown sequences are typically used at the beginning of a moon tour to reduce the period of the capture orbit (i.e., the first orbit of the spacecraft in the Jovian system), which is usually very large to limit the magnitude of the orbit insertion maneuver. [4]

Petal rotations are sequences non-resonant orbits of alternating periods - longer and shorter - connected by pump-only flybys, which result in a rotation of the line of apsides. Petal rotations are used to change the orientation of the spacecraft orbit and also the location of the flyby on the moon's orbit.

A Crank-Over-the-Top is a sequence of resonant orbits connected by crank-only flybys. The crank angle is changed from its initial value (0° or 180°) to it complementary, so a COT sequence always starts and ends with a central body planar orbit. The groundtracks of the flybys of a COT are spread over one side of the moon, providing near global coverage over a hemisphere[5], and for this reason, COTs are also called pseudo-orbiters [14] and are used to map a moon without having to orbit it. The V_∞ and period determine the number of flybys needed for a COT and therefore the groundtracks spread[15].

The crank direction (positive or negative) of the COT sequence will dictate the direction the groundtracks build up over a given hemisphere. For a COT sequence starting with an inbound flyby, 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. 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. In contrast, for a COT sequence starting with an outbound flyby, the sign of the crank direction has the inverse effect. A negative crank direction places the gravity assist at the ascending node and yields south to north coverage, while a positive crank direction places it at the descending node and yields north to south coverage. For further details, see [16].

A few more techniques are used for the design of the Europa Clipper tours but are not summarized here. These includes the Tisserand Graph, COTs parametric analysis, techniques for leading-edge explorations, strategy for low-eclipse COTs, averaging techniques for fast TID computation, robust trajectory design and optimization [16–25].

IV. EUROPA CLIPPER BASELINE TOUR 21F31_V6

The Europa Clipper baseline tour 21F31_V6 is a high-fidelity, numerically integrated end-to-end trajectory that obtains global-regional coverage of Europa via a complex network of multiple flybys over the course of 4.3 years. There are 53 Europa flybys, 49 of which are within the Prime Mission and used to satisfy measurement requirements. In addition, 7 Ganymede and 9 Callisto flybys are used to manipulate the trajectory relative to Europa during the Prime Mission. The tour will reach a maximum Jupiter-centered inclination of 7.7° and has a total ionizing dose (TID[6]) of 2.97 Mrad up to the last Europa flyby. The entire tour can be broken into four distinct mission phases, with a number of the mission phases further broken down into trajectory sub-phases. Each mission phase and trajectory sub-phase of 21F31_V6 will be detailed in subsequent sections. Table 1 details the 21F31_V6 target flybys and Figure 10 illustrates the TID build-up over the course of 21F31_V6. An overview of the complete Jupiter tour trajectory is shown in Fig. 8.

A. *Transition to Europa Campaign 1*

Beginning with Ganymede-1 (G01), five Ganymede flybys and two Europa flybys are used to reduce the spacecraft energy relative to Jupiter and orientate the spacecraft's orbit to reach the correct Europa flyby conditions to begin Europa science acquisition. This sequence of Ganymede and Europa flybys (G01-G03,E01-E02,G04-G05) is referred to as the pumpdown sequence.

The first two Europa flybys will acquire Europa science, calibrate the instruments, and provide the operations team months to respond to any findings prior to the beginning of Europa Campaign 1 at E03. E01 is a 631 km altitude, night-side flyby with closest approach over the sub-Jovian hemisphere. E02 is a 278 km altitude flyby over the sunlit anti-Jovian hemisphere. For all instruments but PIMS, GS, and ECM, observations are taken only above 2000 km in the inbound leg, and starting 1.5 h past closest approach.

The pumpdown sequence has been intentionally under-utilized from a gravity assist ΔV / energy perspective, such that in the event of a JOI under-burn (or overburn) of up to 20 m/s and a burn outage of up to 2 hours, the mission can still reach the same Europa flyby E01 across all scenarios, and hence, the early Europa flybys and the entire Europa science tour can be executed without redesign [24].

Table 2 shows the ΔV from G00 to E04 for the pumpdown envelope, which encompasses the nominal JOI, together the with the 20 m/s underburn and overburn, and the 2h delay, as required by RQ105.442 and RQ111.943 (see Table 4). The most expensive case is the overburn case, which costs 45 m/s more than the nominal, and is used to bound the JOI contingency ΔV in the ΔV budget. Alternate pumpdowns reconnect to the Europa science tour at E04, rather than E01, and save up to 25 m/s in ΔV.

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[4] Parker Solar Probe has used a Venus pumpdown sequence to reduce the perihelion and get the spacecraft closer to the Sun

[5] The sub-Jovian hemisphere is covered if the COT starts with a crank angle of 0°; the anti-Jovian is covered if the COT starts with a crank angle 180°

[6] Total ionizing dose Si behind a100-mil Al, spherical shell.

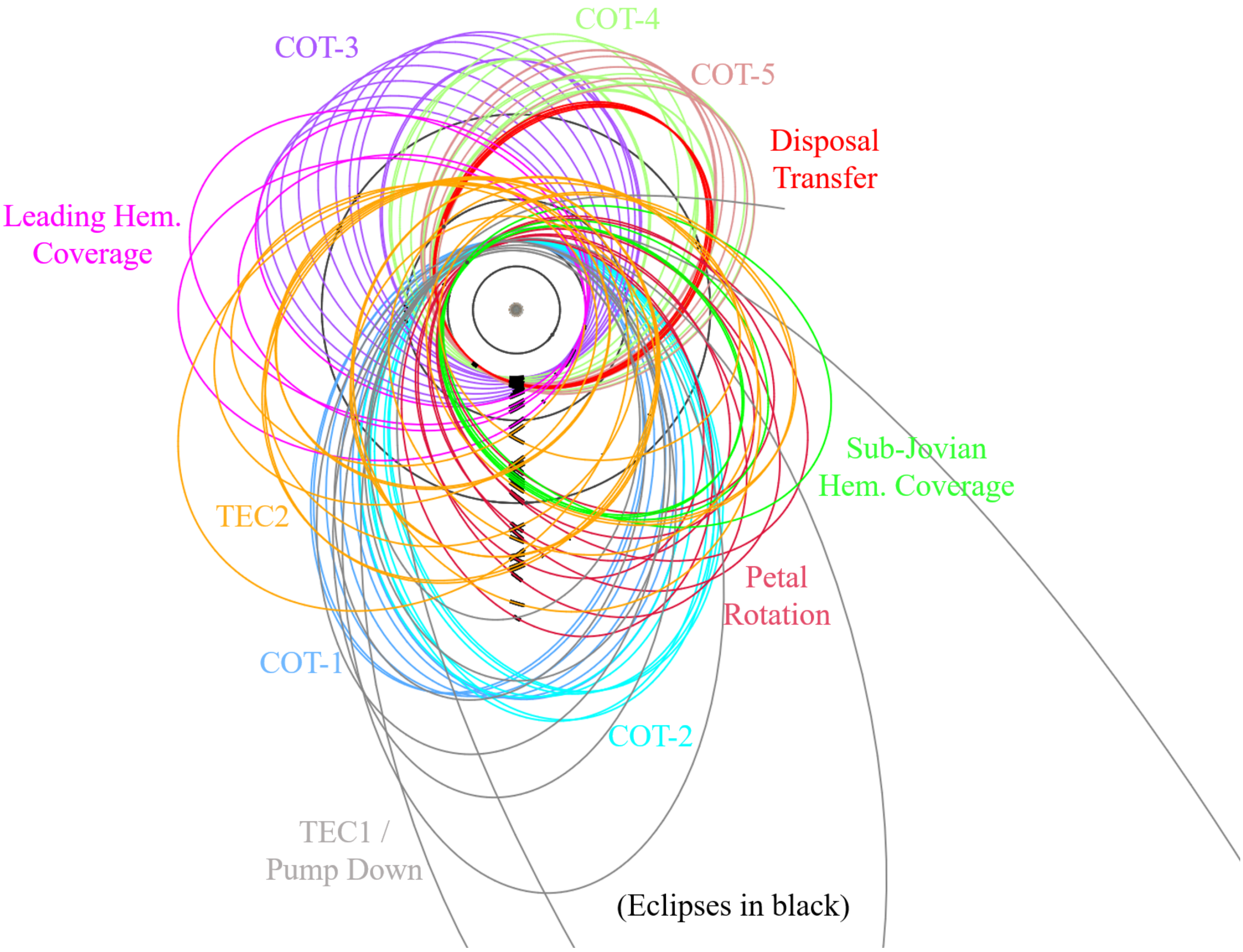


Fig. 8: 21F31_V6 Jupiter Tour overview.

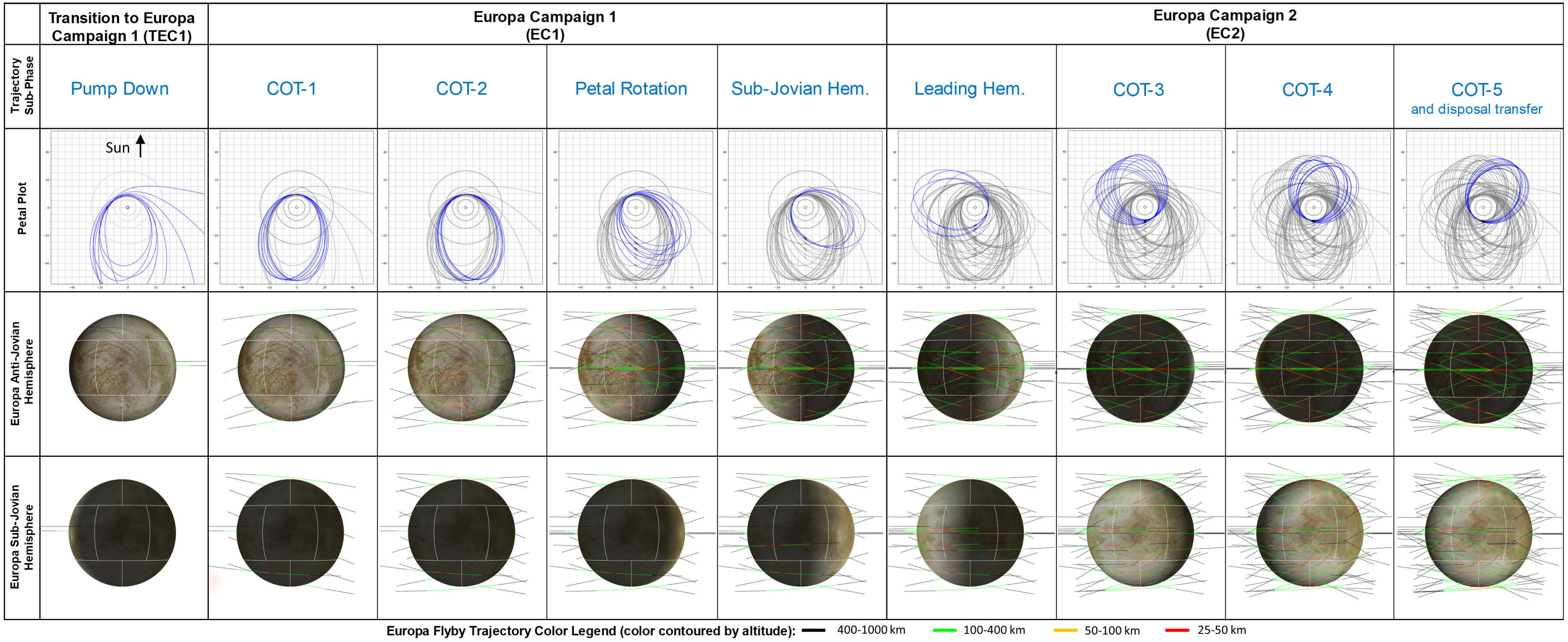


Fig. 9: Europa global-regional coverage build-up for the 21F31_V6 trajectory. Europa-centered trajectories are color contoured by altitude (see legend).

Table 1: 21F31_V6 Targeted Flybys. Closest approach and post-flyby Jupiter-centered orbital parameters.

Jupiter Orbit Number	Encounter Tag	Time of C/A (TCA) (ET/TDB)	Hemisphere (Anti-Jovian or Sub-Jovian)	Altitude (km)	LST (hrs)	Latitude (Planetocentric) (deg)	E. Longitude (deg)	Solar Phase Angle (deg)	Panel of Europa	Ground Speed (km/s)	True Anomaly of Body (deg)	Jupiter LST of Body (hrs)	Jupiter Mag Sys III Latitude (deg)	Jupiter Mag Sys III Longitude (deg)	Inbound/ Outbound Flyby	Orbit Resonance (Body:S/C)	Encounter Duration (days)	Prev Apojove to C/A (days)	C/A to Next Apojove (days)	Jupiter Orbit Duration (days)	Apojove After C/A (RJ)	Jupiter Range at TCA (RJ)	Jupiter Range at Perijove (RJ)	S/C Orbit Inclination (deg)	Earth Range (au)	Sun Range (au)	SEP Angle (deg)
0	G00	10-Apr-2030 17:23:53.084	Anti-Jovian	202.8	15.5	-1.09	246.23	52.0	n/a	8.44	24.7	10.9	1.7	78.0	I	28.35:1.35	202.86	N/A	101.48	N/A	265.42	14.97	11.26	3.41	4.550	5.396	144.4
1	G01	30-Oct-2030 14:09:19.702	Sub-Jovian	250.0	1.1	28.04	278.69	150.6	n/a	8.01	167.2	18.4	-8.6	4.9	O	9.00:1.00	64.40	101.38	31.41	132.79	119.95	15.00	10.31	1.48	6.242	5.353	24.3
2	G02	02-Jan-2031 23:49:21.738	Sub-Jovian	883.2	0.4	14.73	272.49	167.0	n/a	6.55	176.5	18.1	5.1	99.8	O	5.00:1.00	35.77	33.00	17.02	50.02	78.73	15.01	9.52	0.71	6.194	5.333	26.7
3	G03	07-Feb-2031 18:17:27.696	Sub-Jovian	4037.9	24.0	7.08	269.06	175.8	n/a	3.40	186.9	17.9	-5.2	281.1	O	3.82:0.86	27.35	18.75	13.11	31.85	65.90	15.00	8.81	0.51	5.809	5.322	56.1
4	E01	07-Mar-2031 02:41:01.003	Sub-Jovian	629.0	22.5	4.88	302.57	157.1	8	4.68	24.2	14.3	8.5	180.7	O	5.76:0.76	20.47	14.24	10.24	24.49	53.21	9.29	8.41	0.44	5.397	5.310	79.7
5	E02	27-Mar-2031 14:04:12.612	Anti-Jovian	276.0	12.6	1.96	239.97	9.5	3	5.61	314.5	8.4	-3.9	270.8	I	4.72:1.41	16.76	10.23	8.06	18.29	42.01	9.34	8.06	0.49	5.069	5.304	98.2
6	G04	13-Apr-2031 08:16:11.145	Sub-Jovian	2603.4	12.0	0.06	85.08	2.9	n/a	3.99	195.1	18.1	3.2	229.4	O	2.50:0.50	17.85	8.70	8.92	17.62	50.12	15.00	8.06	0.46	4.809	5.302	114.3
7	G05	01-May-2031 04:43:04.184	Sub-Jovian	3015.6	23.8	2.96	86.07	177.5	n/a	3.69	19.4	5.9	-9.5	346.8	I	3.68:1.27	26.35	8.93	13.57	22.50	60.40	14.95	9.24	0.56	4.569	5.296	132.0
8	E03	27-May-2031 13:03:43.315	Sub-Jovian	49.8	22.5	-44.95	333.60	128.7	13	4.80	59.0	12.2	8.0	186.4	O	6.00:1.00	21.29	12.78	10.52	23.30	52.75	9.33	9.24	1.92	4.321	5.282	159.7
9	E04	17-Jun-2031 20:05:25.247	Anti-Jovian	50.0	12.1	-62.43	181.66	60.4	7	4.70	72.6	12.0	-8.9	9.0	O	6.00:1.00	21.30	10.77	10.56	21.33	52.63	9.37	9.24	4.17	4.260	5.275	177.3
10	E05	09-Jul-2031 03:15:10.934	Anti-Jovian	50.0	11.8	-31.36	179.15	29.5	6	4.65	87.0	11.8	7.9	186.9	O	6.00:1.00	21.31	10.74	10.61	21.35	52.58	9.40	9.34	5.32	4.332	5.268	154.5
11	E06	30-Jul-2031 10:43:49.397	Anti-Jovian	35.0	11.7	-5.74	179.11	6.0	2	4.70	102.3	11.7	-9.7	354.8	O	6.00:1.00	21.31	10.70	10.65	21.36	52.53	9.43	9.41	5.56	4.522	5.260	132.5
12	E07	20-Aug-2031 18:12:39.128	Anti-Jovian	85.0	11.6	21.13	178.38	23.9	2	4.55	117.9	11.6	9.2	162.4	I	6.00:1.00	21.31	10.66	10.70	21.35	52.54	9.45	9.43	4.62	4.795	5.253	111.6
13	E08	11-Sep-2031 01:40:59.579	Anti-Jovian	50.0	11.4	48.24	177.55	50.6	4	4.66	133.6	11.5	-9.8	330.1	I	6.00:1.00	21.31	10.61	10.73	21.34	52.58	9.47	9.41	2.64	5.113	5.246	92.0
14	E09	02-Oct-2031 09:11:00.446	Anti-Jovian	100.0	11.1	77.30	173.80	79.4	4	4.51	149.7	11.4	8.6	137.0	I	6.06:1.06	21.53	10.58	10.76	21.34	52.68	9.47	9.40	0.31	5.435	5.238	73.4
15	E10	23-Oct-2031 21:47:36.935	Anti-Jovian	25.0	12.9	74.02	181.30	76.2	5	4.71	189.1	12.7	8.8	139.8	O	6.00:1.00	21.31	10.76	10.59	21.35	52.55	9.48	9.42	2.43	5.731	5.230	55.4
16	E11	14-Nov-2031 05:19:15.639	Anti-Jovian	35.0	12.7	41.75	178.92	44.5	4	4.68	205.7	12.7	-8.4	305.7	O	6.00:1.00	21.32	10.73	10.62	21.35	52.52	9.48	9.44	4.21	5.965	5.223	38.1
17	E12	05-Dec-2031 12:59:00.922	Anti-Jovian	64.9	12.1	-5.83	170.63	4.7	2	4.59	222.9	12.6	5.7	107.5	O	13.00:2.00	46.16	10.70	11.56	22.25	55.94	9.48	9.46	3.91	6.122	5.215	21.1
19	E13	20-Jan-2032 16:47:48.272	Anti-Jovian	50.0	12.8	1.40	185.09	12.2	2	4.62	257.4	12.3	0.4	244.0	I	6.00:1.00	21.32	11.52	10.72	22.24	52.61	9.43	9.39	4.00	6.141	5.198	15.3
20	E14	11-Feb-2032 00:30:00.339	Anti-Jovian	35.0	12.2	-45.70	177.16	44.5	6	4.65	274.3	12.3	-4.3	45.1	I	6.00:1.00	21.31	10.60	10.74	21.35	52.67	9.40	9.32	2.07	5.999	5.190	32.2
21	E15	03-Mar-2032 07:57:28.107	Anti-Jovian	100.0	11.9	-79.03	174.06	77.7	6	4.45	290.4	12.2	5.0	213.7	I	6.01:1.01	21.34	10.57	10.74	21.31	52.70	9.36	9.28	0.76	5.773	5.183	49.4
22	E16	24-Mar-2032 16:00:49.880	Anti-Jovian	201.3	13.6	-14.14	197.31	26.6	2	4.05	309.0	12.3	-9.1	3.4	I	5.01:1.01	17.78	10.59	8.98	19.58	45.66	9.36	9.23	1.09	5.483	5.175	67.0
23	E17	11-Apr-2032 10:50:20.082	Anti-Jovian	24.7	14.0	16.51	202.60	34.6	2	4.44	324.6	12.4	-8.9	4.6	I	4.10:1.10	14.55	8.80	7.28	16.08	38.31	9.34	9.15	0.38	5.209	5.169	82.2
24	E18	26-Apr-2032 00:02:03.869	Anti-Jovian	74.6	13.1	-1.17	155.40	16.7	2	4.25	11.0	14.7	-9.6	333.7	O	4.95:0.95	17.57	7.27	8.78	16.05	45.52	9.32	9.17	0.44	4.977	5.164	95.1
25	E19	13-May-2032 13:43:25.761	Anti-Jovian	49.7	14.8	-0.57	201.38	42.4	2	4.31	5.5	13.3	8.9	139.1	I	4.10:1.10	14.54	8.79	7.26	16.05	38.30	9.32	9.18	0.46	4.704	5.157	111.3
26	E20	28-May-2032 02:42:10.812	Anti-Jovian	99.2	13.9	0.26	155.22	29.2	2	4.19	50.1	15.5	7.1	115.3	O	4.94:0.94	17.56	7.28	8.77	16.05	45.51	9.35	9.17	0.45	4.500	5.153	125.4
27	E21	14-Jun-2032 16:08:23.750	Anti-Jovian	34.7	15.7	0.25	202.37	54.9	2	4.38	44.4	14.1	-6.3	289.0	I	4.09:1.09	14.53	8.79	7.26	16.05	38.27	9.35	9.20	0.44	4.298	5.146	143.1
28	E22	29-Jun-2032 04:57:31.924	Anti-Jovian	74.6	14.8	-0.25	156.69	41.4	2	4.26	88.3	16.3	-3.4	270.3	O	4.95:0.95	17.57	7.27	8.78	16.05	45.45	9.41	9.23	0.45	4.184	5.143	158.4
29	E23	16-Jul-2032 18:42:00.188	Anti-Jovian	24.7	16.4	-1.64	201.92	66.5	2	4.41	81.9	14.9	1.0	74.4	I	4.10:1.10	14.57	8.80	7.26	16.06	38.23	9.40	9.27	0.53	4.120	5.135	177.2
30	E24	31-Jul-2032 08:16:10.859	Anti-Jovian	98.6	15.5	16.01	152.24	54.2	2	4.30	128.7	17.3	-5.5	31.4	O	5.00:1.00	17.77	7.30	8.78	16.08	45.60	9.46	9.23	0.50	4.138	5.132	166.9
31	E25	18-Aug-2032 02:45:39.764	Sub-Jovian	34.4	3.3	-12.82	329.69	129.0	8	4.67	144.8	17.3	-3.9	42.8	O	4.00:1.00	14.20	8.99	6.93	15.92	38.14	9.44	9.30	0.33	4.240	5.126	148.0
32	E26	01-Sep-2032 07:28:29.590	Sub-Jovian	2706.3	2.7	-5.23	323.10	138.7	8	1.66	154.7	17.1	-5.2	282.9	O	7.98:2.32	28.35	7.27	6.26	13.53	35.28	9.42	9.16	0.40	4.376	5.121	133.3
34	C01	29-Sep-2032 15:52:37.156	Sub-Jovian	1333.0	17.1	-8.73	68.32	77.2	n/a	3.34	297.6	0.6	7.6	198.2	O	1.73:1.46	28.81	9.17	5.42	14.59	40.18	26.22	NaN	0.60	4.765	5.125	105.5
36	G06	28-Oct-2032 11:13:26.386	Anti-Jovian	1653.9	17.0	-13.30	261.60	75.0	n/a	3.51	130.1	11.4	8.1	125.3	I	1.31:0.83	9.37	7.19	6.81	14.00	30.77	14.99	10.37	0.32	5.186	5.095	79.3
37	C02	06-Nov-2032 20:06:00.423	Anti-Jovian	203.2	2.8	1.17	113.78	137.3	n/a	3.97	41.3	7.4	8.0	189.4	I	1.00:1.00	16.68	2.55	11.36	13.92	37.48	26.21	NaN	0.27	5.326	5.095	71.3
38	C03	23-Nov-2032 12:28:04.238	Anti-Jovian	4641.3	1.8	0.49	99.71	152.9	n/a	1.33	41.6	7.2	-0.6	66.6	I	1.55:1.55	25.87	5.32	12.91	18.23	42.64	26.21	NaN	0.28	5.557	5.090	57.1
39	C04	19-Dec-2032 09:24:05.857	Anti-Jovian	603.8	1.4	0.04	257.10	159.4	n/a	3.37	239.9	20.2	-1.0	61.0	O	1.27:1.27	21.15	12.96	3.66	16.63	33.62	26.44	NaN	0.28	5.858	5.092	35.8
41	C05	09-Jan-2033 12:59:43.715	Anti-Jovian	1460.5	21.6	0.14	105.66	143.3	n/a	2.54	336.4	2.5	5.8	105.3	I	2.59:2.59	43.17	3.74	12.21	15.94	40.47	26.17	NaN	0.29	6.007	5.088	19.1
43	C06	21-Feb-2033 17:05:07.940	Anti-Jovian	10055.6	21.7	0.85	260.58	145.9	n/a	0.72	187.3	16.4	9.3	176.5	O	1.00:1.00	16.68	12.30	5.26	17.56	37.65	26.56	NaN	0.27	6.010	5.059	14.7
44	C07	10-Mar-2033 09:30:36.629	Anti-Jovian	3064.5	21.1	1.82	252.88	136.6	n/a	1.73	188.0	16.3	-2.6	51.8	O	1.49:1.81	24.79	11.43	3.55	14.98	33.48	26.55	NaN	0.17	5.913	5.054	27.6
46	G07	04-Apr-2033 04:26:39.641	Anti-Jovian	969.3	7.0	0.00	109.06	75.6	n/a	3.55	128.0	11.5	-8.7	2.9	O	3.50:1.18	25.06	7.68	10.95	18.63	52.13	15.01	12.29	0.14	5.677	5.045	46.8
47	C08	29-Apr-2033 05:59:00.665	Anti-Jovian	627.5	20.8	-2.48	257.22	131.9	n/a	4.42	182.6	15.7	6.4	208.5	O	1.00:1.00	16.68	14.12	5.72	19.84	42.08	26.53	NaN	0.35	5.346	5.037	66.9
48	C09	15-May-2033 22:24:18.553	Anti-Jovian	3678.5	20.2	-8.16	250.04	122.9	n/a	2.12	181.9	15.6	2.6	83.6	O	0.71:0.57	11.74	10.96	4.63	15.59	38.78	26.55	NaN	0.92	5.095	5.032	80.7
49	E27	27-May-2033 16:04:58.230	Sub-Jovian	89.0	19.0	-16.78	25.39	104.1	9	4.45	196.0	5.2	9.0	151.0	I	5.07:1.07	18.01	7.11	9.01	16.12	45.69	9.45	9.35	0.49	4.923	5.037	90.7
50	E28	14-Jun-2033 16:25:42.114	Sub-Jovian	34.4	16.9	1.97	329.14	72.9	8	4.64	235.4	6.8	-10.0	334.6	O	3.88:0.88	13.77	9.00	6.90	15.90	37.92	9.42	9.32	0.45	4.643	5.031	106.8
51	E29	28-Jun-2033 11:00:14.080	Sub-Jovian	55.6	17.8	-0.41	28.28	87.2	9	4.61	201.7	3.8	8.5	180.9	I	5.08:1.08	18.04	6.88	9.03	15.91	45.73	9.45	9.31	0.44	4.448	5.030	119.7
52	E30	16-Jul-2033 11:51:18.575	Sub-Jovian	24.4	15.6	4.73	328.78	54.5	8	4.68	245.5	5.6	-9.9	348.2	O	3.88:0.88	13.78	9.01	6.89	15.90	37.91	9.40	9.31	0.49	4.226	5.023	137.6
53	E31	30-Jul-2033 06:35:35.651	Sub-Jovian	125.0	15.2	75.91	6.87	80.1	12	4.34	212.9	2.6	8.1	189.1	I	4.00:1.00	14.21	6.89	7.26	14.15	38.09	9.45	9.23	3.08	4.105	5.023	151.9
54	E32	13-Aug-2033 11:36:13.133	Sub-Jovian	50.0	14.7	56.54	359.67	64.5	11	4.53	224.4	2.6	-1.7	59.9	I	4.00:1.00	14.21	6.95	7.23	14.17	38.01	9.44	9.30	5.46	4.027	5.019	167.1
55	E33	27-Aug-2033 16:32:04.857	Sub-Jovian	35.0	14.6	34.67	358.93	49.3	11	4.58	235.5	2.5	-7.0	292.9	I	4.00:1.00	14.20	6.98	7.18	14.16	37.95	9.42	9.37	7.08	4.007	5.016	177.0
56	E34	10-Sep-2033 21:27:06.814	Sub-Jovian	50.0	14.4	13.00	358.29	38.1	9	4.53	246.5	2.4	9.2	167.5	I	4.00:1.00	14.20	7.03	7.12	14.15	37.92	9.40	9.40	7.70	4.046	5.013	161.7
57	E35	25-Sep-2033 02:21:45.886	Sub-Jovian	25.0	14.3	-8.77	357.80	35.9	9	4.60	257.2	2.3	-4.7	42.1	O	4.00:1.00	14.20	7.08	7.06	14.15	37.94	9.39	9.39	7.27	4.143	5.009	146.4
58	E36	09-Oct-2033 07:15:58.763	Sub-Jovian	35.0	14.2	-30.40	357.23	44.2	13	4.57	267.7	2.2	-4.9	275.9	O	4.00:1.00	14.20	7.14	7.01	14.15	38.01	9.37	9.35	5.84	4.288	5.006	131.5
59	E37	23-Oct-2033 12:10:02.018	Sub-Jovian	50.0	14.1	-51.96	356.60	58.9	13	4.52	278.1	2.1	9.1	150.8	O	4.00:1.00	14.20	7.19	6.97	14.17	38.10	9.36	9.28	3.64	4.471	5.003	117.1
60	E38	06-Nov-2033 16:59:30.224	Sub-Jovian	35.0	13.7	-72.12	352.89	74.9	13	4.55	288.3	2.0	-6.7	28.5	O	3.99:0.99	14.15	7.23	6.95	14.18	38.09	9.36	9.20	1.04	4.679	5.000	103.2
61	E39	20-Nov-2033 20:39:55.440	Sub-Jovian	857.5	11.7	-21.26	328.66	22.9	8	2.81	293.4	1.6	-8.1	301.8	O	6.89:1.89	24.45	7.21	6.05	13.25	34.04	9.33	9.22	0.44	4.899	4.997	90.0
63	E40	15-Dec-2033 07:33:38.340	Sub-Jovian	25.0	11.4	-72.54	8.45	73.9	14	4.39	270.1	22.7	5.4	213.3	I	7.00:2.00	24.86	6.02	6.36	12.39	34.15	9.38	9.19	2.49	5.273	4.992	68.2
65	E41	09-Jan-2034 04:16:24.445	Sub-Jovian	49.8	11.8	-14.41	16.03	15.9	9	4.28	289.4	22.6	9.3	169.4	I	4.00:1.00	14.19	6.07	7.18	13.24	38.02	9.34	9.28	3.26	5.601	4.988	47.4
66	E42	23-Jan-2034 08:45:04.567	Sub-Jovian	100.0	10.5	-29.53	358.95	37.8	9	4.16	297.6	22.4	-1.9	57.7	I	4.00:1.00	14.20	7.01	7.14	14.15	37.99	9.33	9.31	4.69	5.749	4.985	35.9
67	E43	06-Feb-2034 13:26:49.353	Sub-Jovian	49.8	8.9	-36.93	337.86	57.4	13	4.30	306.7	22.2	-7.5	298.5	I	7.00:2.00	24.86	7.05	6.22	13.27	34.00	9.32	9.32	6.56	5.861	4.983	24.7
69	E44	03-Mar-2034 10:01:26.810	Sub-Jovian	35.0	10.1	15.96	358.30	31.4	9	4.36	323.4	22.1	-1.9	259.6	O	7.00:2.00	24.85	6.21	6.14	12.35	34.03	9.29	9.29	5.81	5.964	4.978	5.6
71	E45	28-Mar-2034 06:32:25.171	Sub-Jovian	24.9	12.3	63.07	33.67	61.7	12	4.36	341.2	21.9	4.3	223.0	O	4.00:1.00	14.20	6.28	7.02	13.30	38.07	9.29	9.25	3.09	5.940	4.975	13.3
72	E46	11-Apr-2034 11:13:35.807	Sub-Jovian	25.0	9.7	62.29	356.28	66.2	11	4.35	350.4	21.8	5.7	104.0	O	4.00:1.00	14.20	7.18	6.99	14.17	38.12	9.29	9.23	0.47	5.872	4.973	23.9
73	E47	25-Apr-2034 16:07:08.969	Anti-Jovian	50.0	23.4	86.81	203.67	91.6	5	4.26	0.4	21.7	-9.5	339.5	O	4.00:1.00	14.19	7.21	6.99	14.20	38.08	9.30	9.18	2.49	5.766	4.971	34.6
74	E48	09-May-2034 20:46:26.809	Anti-Jovian	35.0	21.6	52.12	179.69	118.6	4	4.26	9.2	21.6	4.3	222.6	O	4.00:1.00	14.20	7.20	7.03	14.23	38.03	9.31	9.22	4.88	5.626	4.969	45.4
75	E49	24-May-2034 01:40:00.259	Anti-Jovian	35.0	21.5	19.49	179.03	137.6	2	4.25	19.2	21.5	4.6	97.0	O	4.00:1.00	14.21	7.17	7.09	14.26	37.98	9.32	9.28	5.88	5.457	4.967	56.3
76	E50	07-Jun-2034 06:36:07.320	Anti-Jovian	50.0	21.4	-12.43	178.52	139.8	2	4.21	29.4	21.4	-9.6	331.0	I	4.00:1.00	14.21	7.11	7.15	14.26	37.98	9.33	9.31	5.25	5.264	4.966	67.5
77	E51	21-Jun-2034 11:32:53.744	Anti-Jovian	35.0	21.2	-45.16	177.58	123.5	6	4.26	39.5	21.4	6.5	204.9	I	4.00:1.00	14.21	7.06	7.19	14.25	38.03	9.33	9.27	3.13	5.055	4.964	79.1
78	E52	05-Jul-2034 16:30:06.621	Anti-Jovian	75.0	20.7	-79.44	170.09	98.6	6	4.15	49.7	21.3	1.3	77.5	I	4.07:1.07	14.46	7.02	7.22	14.24	38.18	9.33	9.25	0.31	4.838	4.963	91.1
79	E53	20-Jul-2034 03:32:05.874	Sub-Jovian	69.4	9.0	-8.12	330.19	46.2	9	4.23	85.2	22.9	6.8	115.7	O	12.68:3.67	12648.65	7.24	5.61	12.85	32.16	9.36	9.25	0.45	4.619	4.963	103.9
83	G08	03-Sep-2034 04:46:13.000	Anti-Jovian	0.0	13.3	-14.12	156.24	25.9																			

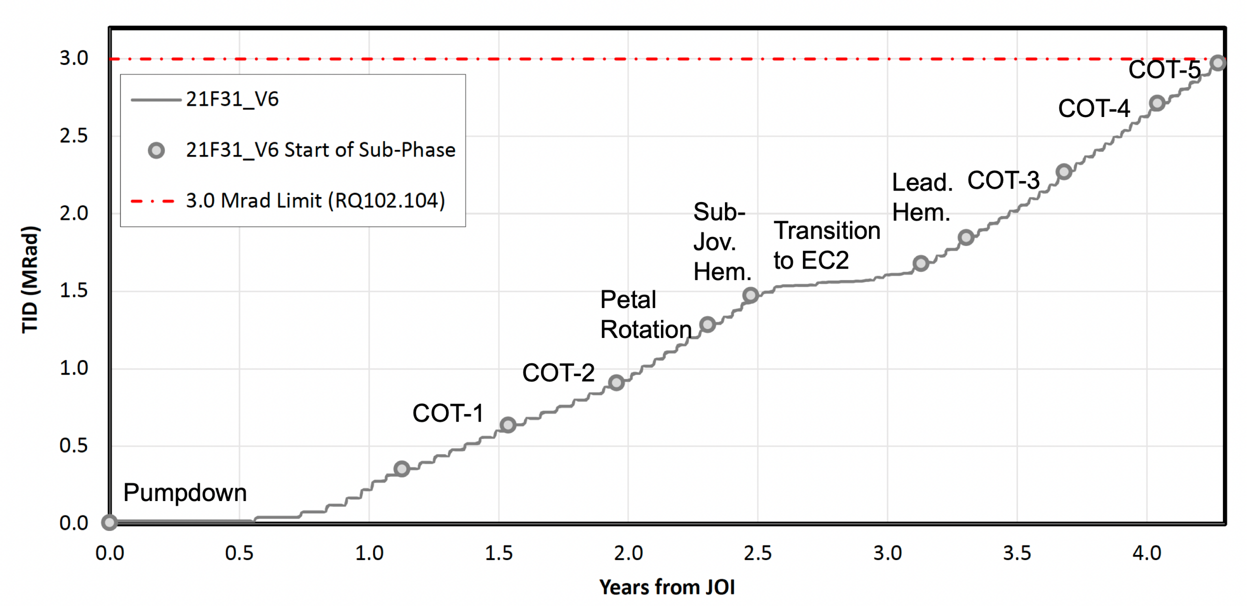


Fig. 10: 21F31_V6 TID profile (Si behind a 100-mil Al spherical shell, GRID3 radiation model). Markers indicate the beginning of each trajectory sub-phase.

Table 2: Envelope of pumpdowns. Alternate pumpdowns converge to 21F31_V6 at E04, all other pumpdowns converge to 21F31_V6 at E01

Case	ΔV **to E04, m/s**	$\Delta(\Delta V)$**, m/s**
Nominal	964	0
Delay	984	20
Delay, alt.	*976*	*12*
Underburn	969	5
Overburn	1009	45
Underburn + Delay	1000	36
Underburn + Delay, alt.	*975*	*11*
Overburn + Delay	992	28

B. *Europa Campaign 1: Anti-Jovian Hemisphere Coverage*

Trajectory design for any Europa mission is a delicate balance of instrument coverage and time spent near Europa. In the case of the Europa Clipper mission, the time near Europa equates to Europa flybys. While scientists would clearly prefer a very high number of flybys (absent other constraints), these flybys come at the cost of additional traversals through the harsh radiation environment near Europa. Each periapsis passage incrementally increases the mission TID, and beyond a certain point, significantly drives up the flight system mass and complexity, mission costs, and mission risk. On the other hand, if there are too few flybys, the scientific objectives will not be met nominally or will be brittle to any science acquisition outages.

The first part of the 21F31_V6 Europa science tour will focus primarily on Europa's anti-Jovian hemisphere. Given the interplanetary trajectory arrival conditions at Jupiter, Europa's anti-Jovian hemisphere is the most efficient (in time, TID, and ΔV) to reach with the lighting conditions required by the majority of the instrument payload. Furthermore, the REASON instrument, which operates in a portion of the electromagnetic spectrum near Jupiter's radio emission frequency, prefers coverage of Europa's anti-Jovian hemisphere first since measurements performed over this hemisphere yield a much higher SNR due to Europa shielding the flight system from the 9 MHz emissions from Jupiter. The 21F31_V6 Europa Campaign 1 consists of 24 Europa flybys over the course of 15 months.

COT-1 and COT-2 The first COT sequence (COT-1) begins with outbound Europa flybys, and consists of seven 6:1 resonant transfers with a V_∞ of approximately 4.4 km/s.

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 were 1:1 resonance transfers with Titan (TOF=T_{sc}=15.9 days), and having to execute up to three maneuvers (two that can be deterministic, one that is only statistical) per Europa-to-Europa transfer similar to Cassini, the Project put a lower bound on the mean TOF between a number of back-to-back Europa flybys to be 14 days. While 4:1 resonant transfers would also meet the 14-day minimum transfer between Europa flybys, and reduce the total TOF, the project chose to utilize 6:1 resonant transfers for COT-1 and COT-2 to relax the operation schedule at the beginning of the mission.

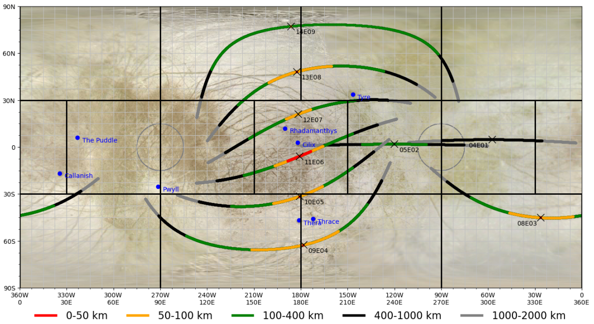
COT-1 traverses Europa's anti-Jovian hemisphere from south to north (negative crank direction), as shown in Fig. 11(a-c). The direction of the crank is chosen to minimize the amount and duration of Jupiter eclipses[16]. The last flyby of COT-1 is a 6:1$^+$ non-resonant Europa transfer (E9 to E10) and is implemented to return to an outbound Europa flyby (E10) such that the second COT sequence (COT-2) can be initiated to again cover the anti-Jovian hemisphere of Europa.

COT-2 again utilizes 6:1 resonant transfers, but cranks in the positive direction to traverse the anti-Jovian hemisphere from north to south (Fig. 11(d-f)). The result of reversing the crank direction of COT-2 with respect to COT-1 is the cumulative set of groundtracks have a high number of intersections (instead of running nearly parallel) which is needed by the REASON instrument for a number of their datasets. The E14 flyby of COT-2 has its groundtrack over Thera. At the end of COT-2, two Europa flybys (E16 and E17) are used to reduce the period from a 6:1 resonant transfer to 5:1, and then to a 4:1$^+$ non-resonant transfer to begin the next trajectory sub-phase of Europa Campaign 1.

Petal Rotation and night-side, sub-Jovian Hemisphere Coverage A series of six non-resonant transfers are utilized to obtain substantial equatorial coverage of panels 1, 2, and 3 (Fig. 13(a-c)). By repeatedly alternating between increasing and decreasing the orbit period (referred to as pumping up and pumping down the orbit energy), and furthermore, by using outbound flybys to pump up and inbound flybys to pump down, three sets of two groundtracks each can be obtained over the equatorial region of Europa's anti-Jovian hemisphere. Note the V_∞ needed to be decreased slightly with propulsive maneuvers (i..e, V_∞ leveraging) to a value near 4.0 km/s in order to enable the ability to alternate between 4:1$^-$ and 5:1$^+$ non-resonant transfers, both of which are fully reduced (i.e., not multi-rev transfers that have empty orbits that increase TID without attaining additional Europa data) to minimize TID build up during this portion of 21F31_V6.

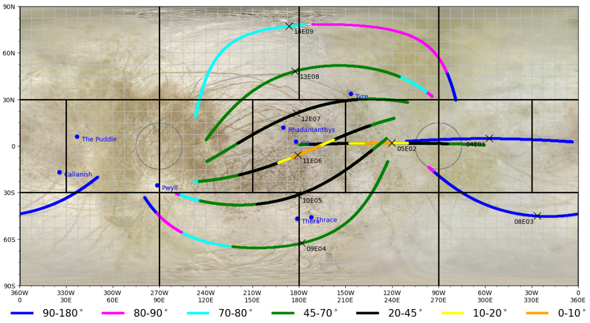
These flybys are very useful for gravity measurements since the flyby closest approaches are in view of Earth and will occur at different Europa true anomalies, and hence, sample the gravitational potential near the same body fixed locations at different tidal phases. An additional benefit of utilizing non-resonance transfers in this manner is the line-of-apsides rotates counter-clockwise (hence the name, "petal rotation"), which acts to move the Europa flybys counter-clockwise, eventually rendering Europa's trailing hemisphere illuminated at the time of the flybys – a feature highly sought after by a number of instruments.

Following the six non-resonant transfers of the petal rotation, 5:1 and 4:1 resonant transfers are implemented so that the flyby connecting them (E25) is an outbound, pump-down flyby. As a result, E25 has a closest approach over the night-side, sub-Jovian hemisphere (Fig. 13(d-f)), at about 3 AM local solar time, which is needed by both E-THEMIS high-resolution dual (sun-lit and unlit) coverage (RQ110.669/ETH.113) and PIMS plasma local time coverage (RQ106.136/PIM.011).



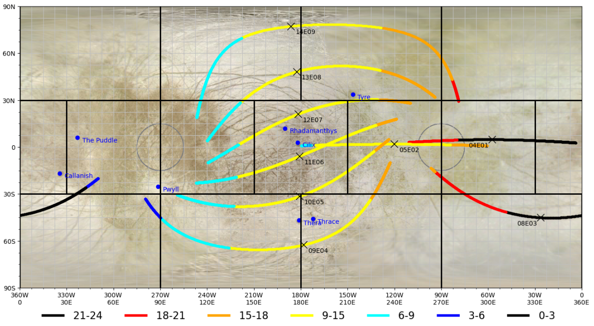
(a) COT-1: Altitude

(b) COT-2: Altitude



(c) COT-1: Solar Phase

(d) COT-2: Solar Phase



(e) COT-1: LST

(f) COT-2: LST

Fig. 11: COT-1 and COT-2 groundtrack plots. COT-1 plots also include the early Europa flybys E01 and E02 from the pump down. Color contoured with closest approach marked with an “x” and numbered in accordance with Table 1.

C. *Transition to Europa Campaign 2*

Before sunlit observations over Europa's sub-Jovian hemisphere can be collected to complete the global-regional coverage of Europa, the Europa flyby location must be moved to near the Jupiter-anti-Sun line (i.e., the opposite side of Jupiter as the Europa Campaign 1), while making sure to avoid flybys in Jupiter's shadow. This can be accomplished in a number of ways, including: petal rotation using Europa flybys (i.e., continuing the previous trajectory sub-phase), Ganymede flybys, or Callisto flybys; different types of cyclers; a Europa π-transfer; or a "switch-flip." A switch-flip consists of three non-resonant transfers (typically π-transfers) between two bodies that significantly change the LST of the departure body flyby location. For 21F31_V6, a petal rotation with Callisto flybys is utilized for it typically requires less ΔV and TID, at the expense of more Jupiter eclipses and sometimes an increased TOF[16].

The last flyby of Europa Campaign 1 (E26) reduces the spacecraft period and targets a Callisto flyby (C01) with a V_∞ of 4.8 km/s. The Callisto flyby increases the periapsis of the orbit around Jupiter so that the spacecraft is exposed to lower TID rates. A Ganymede flyby (G06) is then utilized to leverage the V_∞ at Callisto down to 3.6 km/s. A lower V_∞ at Callisto is preferred, so that the spacecraft orbits of the petal rotations have higher periapsis, and fewer petals are needed to rotate the line of apsis, yielding to further savings in TID and TOF. Starting from C03, the sequence of non-resonant transfers 2:2$^-$, 1:1$^+$, 3:3$^-$ rotates the line of apsis. The 3:3$^-$ is a 43 days transfer during which a solar occultation occurs. Another Ganymede flyby (G07) is then used to leverage up the V_∞ at Callisto to 5.1 km/s, and the final Callisto flybys set up the C09 to E27 non-resonant transfer, which effectively places the subsequent Europa flybys so that the leading hemisphere is illuminated. In total, the transition phase includes 9 Callisto flybys and 2 Ganymede flybys, using 10 m/s in 8 months.

D. *Europa Campaign 2: sub-Jovian Hemisphere Coverage*

Much like Europa Campaign 1, Europa Campaign 2 is accomplished utilizing a number of COT sequences. Europa Campaign 2 starts with a sequence of flybys to cover the leading hemisphere, followed by two sun-lit sub-Jovian COTs, and a final night-side, anti-Jovian COT.

The Leading Hemisphere coverage is achieved with two pairs of Europa petals composed of 5:1$^+$ and 4:1$^-$ non-resonant transfers. Of the four flybys connecting them, two (E28 and E30) are low-altitude, outbound, pump-down flybys with closest approaches at about 330° east longitude, where the spacecraft will be under 1200 km while within 15° of the leading point (0° latitude and 270° longitude) and has LST between 9:00-15:00 for MISE regional scale measurement (MIS.PG.019) (Fig. 14(a-c)).

Following the last 4:1$^-$ transfer, COT-3 begins with inbound flybys, located at the descending node, and utilize eight 4:1 resonant transfers (E31 to E38) to attain large latitudinal coverage from north to south (Fig. 14(d-f)). A 7:2$^-$ non-resonant Europa transfer (E39 to E40) is implemented to return to an inbound Europa flyby (E40) and to change the location of the subsequent set of inbound flybys by a sufficient amount in the clock-wise direction so the flybys do not occur in Jupiter eclipse. Next, COT-4 utilizes seven 4:1 Europa resonant transfers (E40 to E46) with latitudinal coverage from south to north (Fig. 15(a-c)). A 7:2 resonant flyby was required between E44 and E45 to avoid a flyby during solar conjunction.

The last COT sequence, COT-5, uses six 4:1 resonant transfers (E47 to E52) to provide night-side coverage of the anti-Jovian hemisphere (Fig. 15(d-f)), which allow dual (sun-lit and unlit) coverage of the same terrain for E-THEMIS. A final Europa flyby (E53) is used to setup the decommissioning of the spacecraft.

E. *Spacecraft Decommissioning*

Planetary protection requirements dictate that before control of the spacecraft is lost, actions must be taken to negate the probability of biological contamination of Europa that could result from flight system impact. The 21F31_V6 trajectory implements flight system decommissioning via impact with Ganymede on September 3, 2034, 45 days after the last Europa flyby (E53). The impact occurs at 14.1° S. latitude and 156.2° E. longitude, at 13:20 LST, visible from the Earth (Fig. 12). Previous targeted flybys of Ganymede are also shown, with the traces color coded by altitude.

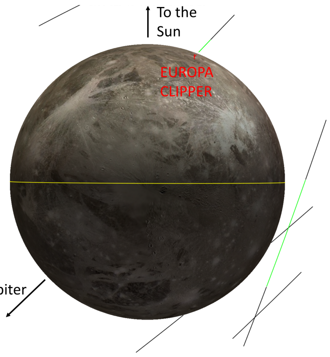
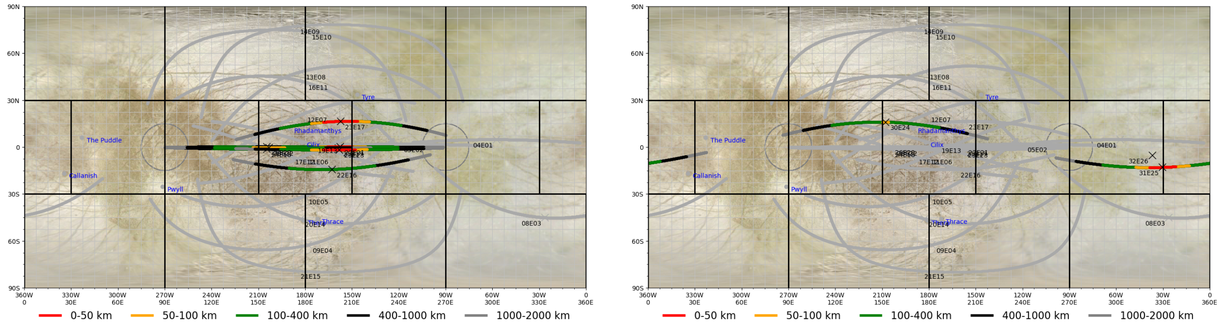
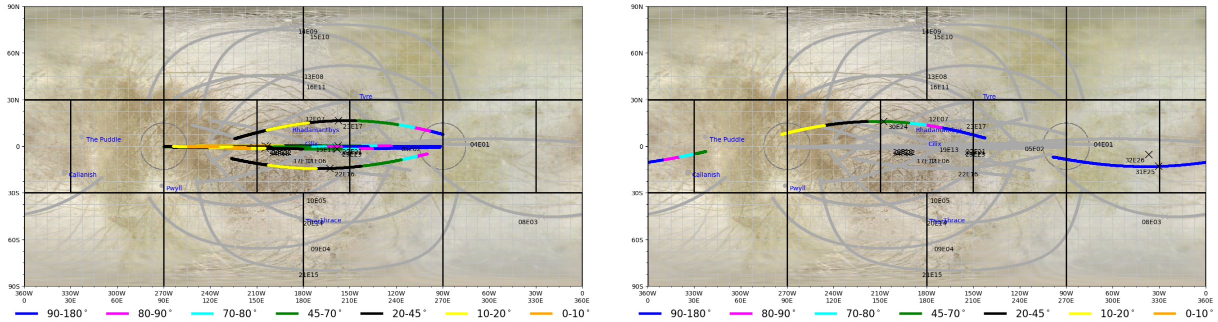


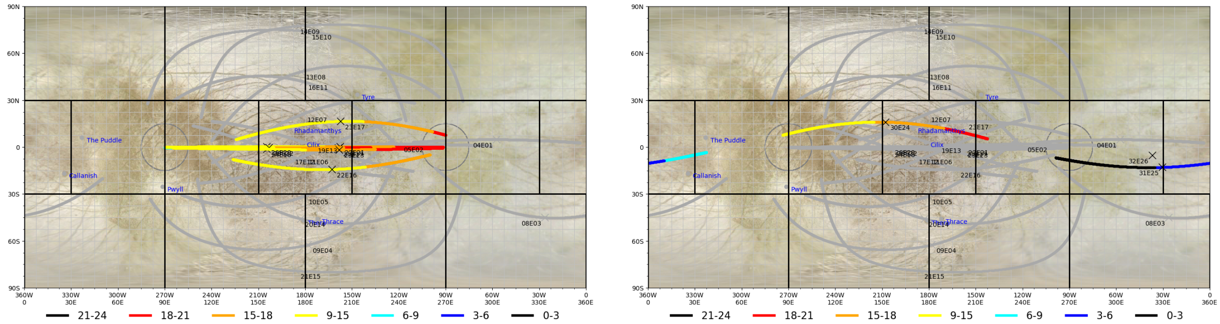
Fig. 12: Spacecraft disposal with Ganymede impact, view from above south pole.



(a) Petal Rotation: Altitude *(b)* Night-side sub-Jovian Hemisphere: Altitude

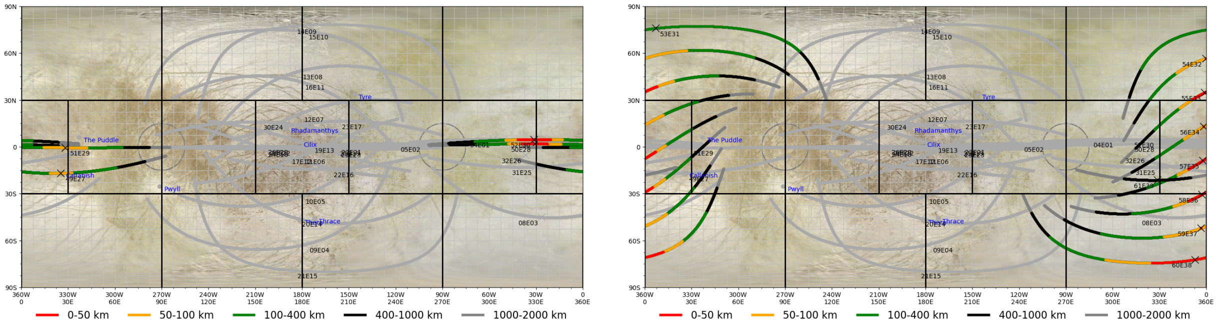


(c) Petal Rotation: Solar Phase *(d)* Night-side sub-Jovian Hemisphere: Solar Phase

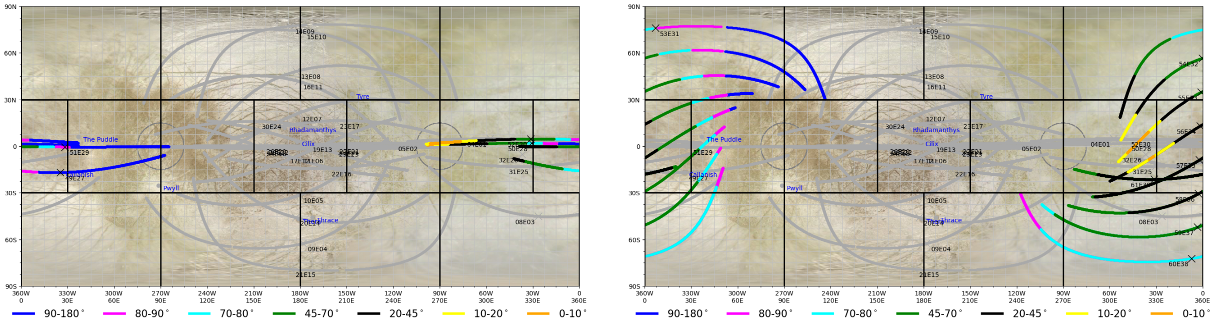


(e) Petal Rotation: LST *(f)* Night-side sub-Jovian Hemisphere: LST

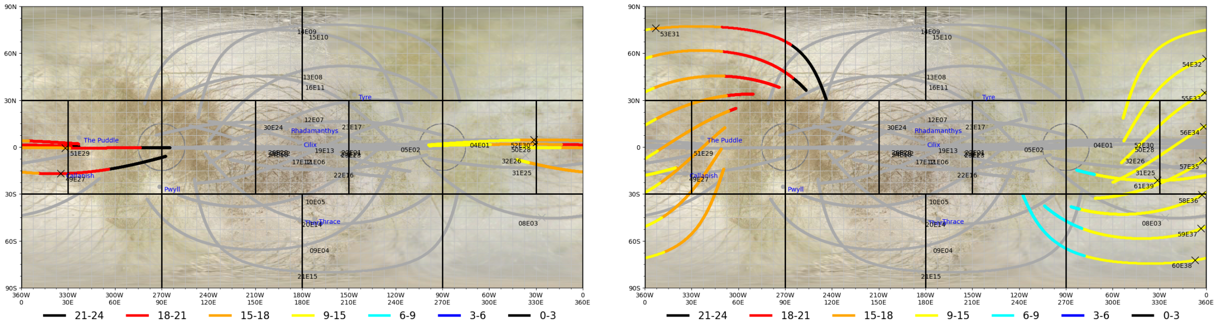
Fig. 13: Petal Rotation and night-side sub-Jovian Hemisphere Groundtrack Plots. Color contoured with closest approach marked with an "x" and numbered in accordance with Table 1.



(a) Leading Hemisphere: Altitude *(b)* COT-3: Altitude

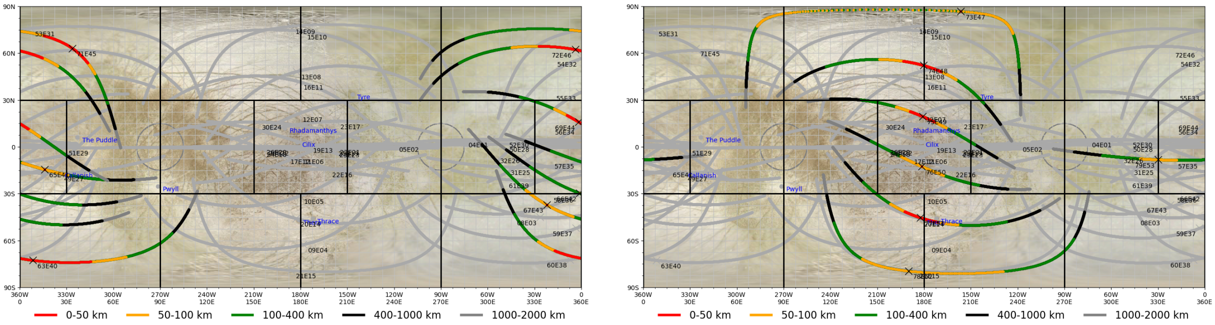


(c) Leading Hemisphere: Solar Phase *(d)* COT-3: Solar Phase

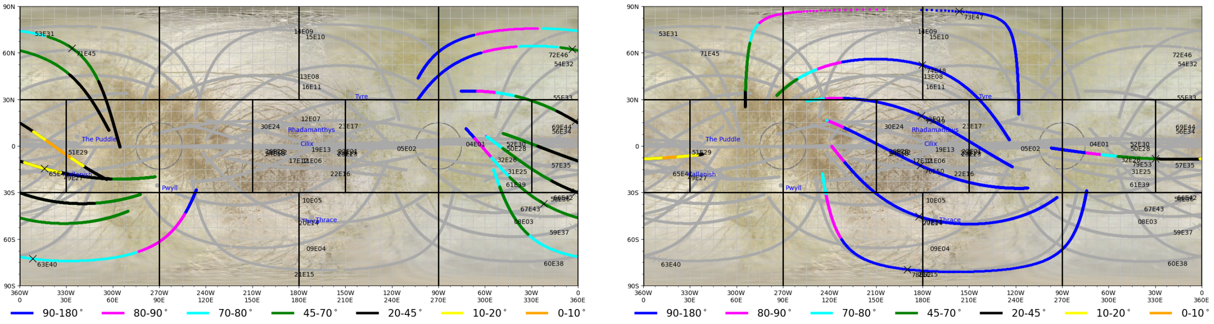


(e) Leading Hemisphere: LST *(f)* COT-3: LST

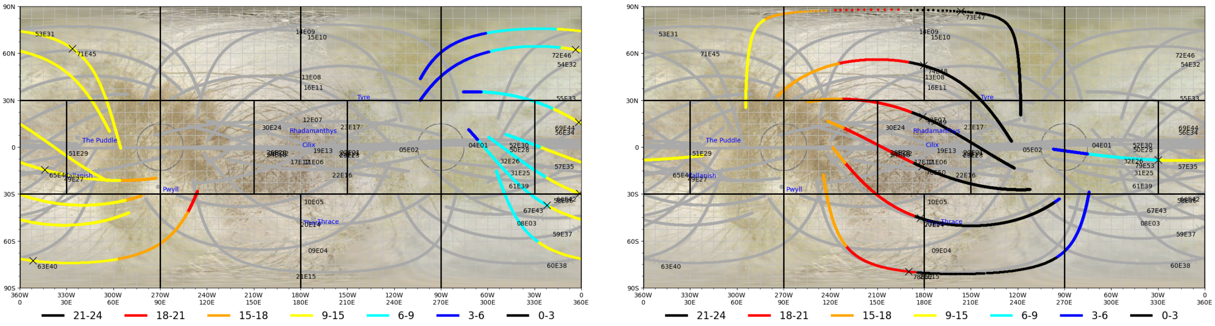
Fig. 14: Leading Hemisphere and COT-3 Groundtrack Plots. Color contoured with closest approach marked with an “x” and numbered in accordance with Table 1.



(a) COT-4: Altitude *(b)* COT-5: Altitude



(c) COT-4: Solar Phase *(d)* COT-5: Solar Phase



(e) COT-4: LST *(f)* COT-5: LST

Fig. 15: COT-4 and COT-5 Groundtrack Plots. COT-5 plots also include the last Europa flyby (E53) from the disposal transfer subphase. Color contoured with closest approach marked with an "x" and numbered in accordance with Table 1.

F. ΔV *Budget*

The flight system's minimum ΔV capability (1593 m/s) is the case where the dry spacecraft mass is at its allocation of 3241 kg and the propellant tanks are filled to their 2750 kg capacity, which when combined with 10 kg of pressurant, corresponds to the maximum wet mass of 6001 kg . As can be seen in Table 3, the baseline mission MEV ΔV is 1507 m/s.

The encumbered margin of 50 m/s is intended to provide the ability to make other trajectory adjustments to achieve, for example, repeating a Crank-over-the-Top (COT) trajectory sequence or perhaps recovering from a single, anomalous flyby. The baseline trajectory has an unencumbered MEV ΔV of 86 m/s.

In Table 3, the Planetary Flyby Biasing for MEGA 2024 is included in the interplanetary deterministic and statistical ΔV budget. Additionally, the JOI Gravity Losses are included in the interplanetary phase, since JOI is modeled as a finite burn.

Table 3: ΔV Budget.

	2024 MEGA	
	CBE ΔV (m/s)	MEV ΔV (m/s)
I.P. Det. ΔV + JOI Demo + JOI + PRM	1007	1007
Interplanetary Statistical (ΔV99)	25	25
Planetary Flyby Biasing	-	-
JOI Gravity Losses	-	-
JOI Statistical Component (ΔV99)	4	4
Contigency ΔV: Underburn/Overburn/Delayed JOI	0	45
JOI Clean-up Maneuver (ΔV99)	27	27
Contigency ΔV: launch on LP 22-23, COLA L-15s	0	3
Tour Deterministic	218	223
Tour Statistical (ΔV99)	51	53
Contigency ΔV: Post-Approach Maneuver Safing(s)	0	70
Encumbered Margin (Post-Launch Traj. Changes)	50	50
Sub-totals	**1382**	**1507**
ΔV Requirement (Interplanetary Traj. Specific)	1593	1593
ΔV Margin	211	86

G. *Requirements Validation*

Table 4 summarizes the requirements (with required value(s)) on the trajectory analysis that do not include the science measurement requirements, as well as an assessment of 21F31_V6 against these requirements. Requirements on the navigation are discussed in another table. Most of the requirements are levied on Mission Design, but a couple are levied on Flight System Engineering, Project System Engineering, or Mission Operation Systems. Table 4 is color coded as such: green - compliant, and red - non-compliant. The following non-compliance is found in Table 4:

RQ102.140: Max eclipse duration after TEC2

The required value is 3.25 hrs, to protect battery Depth of Discharge (DoD) in EC2 for worst case scenario of a long eclipse just prior to, or subsequent, a high latitude Europa flyby, where all instruments would be operating but the solar arrays would not be illuminated. 21F31_V6 has eclipses of 3.8, 3.7 and 3.3 hrs. The eclipses are 24 to 16 hrs prior to the flyby closest approaches and the flybys are all low latitude, so the arrays are well lit for power generation, hence, DoD not significant. A waiver for this requirement was approved by the project.

With respect to the science measurement requirements, 21F31_V6 meet all the requirements and the majority of the planning guidelines. Figure 16 shows in particular when the requirements are met. The figure only shows requirements on the data sets - the others are implicitly met by selecting the observations with the correct geometry. For 23 requirements, compliance is met by the entire tour and not at a specific encounter.

V. CONCLUSIONS

This paper presents the baseline tour 21F31_V6 for the Europa Clipper, NASA's next flagship mission that will be launched in October 2024 to study the habitability of the Jovian moon Europa. 21F31_V6 is the first selected Europa Clipper tour to meet all the science requirements levied on mission design, as well as the majority of the planning guidelines and non-science requirements. Since the project has no plan for further develop tours, 21F31_V6 is the trajectory that Europa Clipper will fly, unless contingencies occur. This tour is the product of more than a decade of tour developments, which produced many dozens of candidate tours, including 31 Europa Clipper officially-released tours, documented in several publications.

The paper also describes the tour design process, with seven design cycles over the span of a decade, in which candidate tours were designed by the Mission Design Team, and evaluated by the Project Science Group. In each cycle, the Mission Design Team computed candidate tours and assessed their compliance to the requirements. The tour design is complicated by the multibody dynamics governing the spacecraft motion in the Jovian system, and by the fact that the science and navigation requirements cannot be directly transcribed into constraints on the trajectory. Navigation requirements such as those on the probability of impacts, and on the spacecraft predicted and reconstructed knowledge, are assessed with a full navigation analysis. Compliance to the science requirements and planning guidelines is checked by simulating the instrument observations in a process that includes the modeling of the flight system, the definition of the mission plan, and the optimization of the planned activities.

VI. ACKNOWLEDGEMENT

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 2024 California Institute of Technology. Government sponsorship acknowledged.

Table 4: Set of requirements on the trajectory design excluding the science measurement requirements.

	Requirement Subject	Required/Constrained Value	21F31_V6 Value	Allocated	AFID	ID
Entire Mission	Prime Launch Opportunity	Baseline Launch Vehicle Launch Year: 2024	Launch Period: Oct 10-30, 2024	MD	RQ102.107	320223
	Back Up Launch Opportunity	Within 14 months of the prime opportunity	2025 EMEGA	MD	RQ104.453	320465
	Launch Vehicle	Falcon Heavy	✓	MD	RQ102.142	320250
	Mission duration	Maximum Mission Duration < 11.3 years	9.9 years	PSE	RQ102.119	320233
	Trajectory duration	Maximum Trajectory Duration < 11.3 years	9.9 years	MD	RQ102.123	320235
	Mission ΔV	≤ 1593 m/s	CBE ΔV: 1382 m/s, MEV: 1507 m/s	MD, FSE	RQ112.144	1005866
	Communication During Key Events - Mission Activities	SEP angle >3°, Earth in view	Min SEP at flyby: 5.58° (E44), Min SEP at mnvr: 3.36° (E44-CU)	FSE, MOS	RQ102.129	320241
	Maximum Aphelion	5.6 AU	Max: 5.5 AU on ~05-OCT-2029 ET (during initial capture orbit)	MD	RQ102.125	320237
Launch and Interplanetary	Launch Period Duration	≥21 days	21 days (10/10-10/30, 2024)	MD	RQ107.245	336496
	Launch Window Duration	15s for COLA	✓	MD	RQ105.437	320671
	TCM-1 Timing for ΔV Computation	ΔV necessary for TCM-1 at L + 30 days	Launch + 30 days	MD	RQ103.374	320346
	Probability of Mars impact by Flight System	≤1x10^-2 (for 50 years post-launch)	Max value 0.25x10^-4	MD	RQ104.629	336358
	Probability of Mars impact by Launch Vehicle	≤1x10^-4 (for 50 years post-launch)	Max value 0.92x10^-4	PSE	RQ104.630	339731
	Minimum Earth Flyby Altitude	300 km	Min Alt in launch period: 3138 km	MD	RQ100.966	320162
	Minimum Mars Flyby Altitude	450 km	471.2 km	MD	RQ112.146	1005868
	MicroMeteroids/Orbital Debris (MMOD) Impact Risk	≤ 0.01 probability when within 40,000 km of Earth (objects ≥10 cm in diameter)	Max value 1.8x10^-6	MD	RQ104.478	320469
	Minimum Perihelion	0.65 AU	0.82 AU	MD	RQ102.131	320243
Jupiter Orbit Capture and Pump-down	JOI_Assisting Jupiter Moon Flybys	≤ 2 prior to JOI	1 prior (Ganymede)	MD	RQ103.342	320320
	Solar Eclipses During JOI-Related Jupiter Moon Flybys	Not permitted prior to JOI completion	None	MD	RQ103.339	320317
	Maximum JOI ΔV	≤950 m/s	919.5 m/s (ΔV99 for LP23)	MD, FSE	RQ111.941	902327
	Jupiter Capture Orbit Period	≤260 days	202.1 days (nominal)	MD	RQ103.381	320350
	JOI Sun-Earth-Probe (SEP) Angle	>3° for [-15 days, +12 days] centered at JOI	Min: 12.8° at JOI-15d	MD	RQ105.435	320669
	Pump Down Resilience to JOI Variations	Europa-1 (E1) maintained for JOI +/-20 m/s	✓	MD	RQ105.442	320676
Tour	Minimum Jupiter Distance	8 RJ (no Io gravity assist)	Min: 8.1 RJ (E02-G04)	MD	RQ102.097	320215
	Maximum TID	3.0 Mrad(Si) behind spherical shell of 100 mils Al	2.89 Mrad	MD	RQ102.104	320221
	Jupiter Tour Duration	≤4.3 years	4.20 years	MD	RQ.112.147	1005869
	Probability of Jovian Moon Impact Post Targeting Maneuver	≤1x10^-3	Max value is 0.325x10^-3 at E45-TRG	MD	RQ102.118	320232
	Probability of Europa Impact Due to Unplanned Delta-V After an Approach Maneuver	≤1x10^-4	POI given safing 4% at E49, with 30° attitude constraint	MD	RQ109.488	694669
	Probability of Impact per Transfer	≤1x10^-3	Max Value is 8.8x10^-4 at PRM-CU-1	PSE	RQ109.562	693482
	Maximum Eclipse Duration	9.2 hrs. (prior to EC2)	Max: 7.8 hrs (C03-C04)	MD	RQ102.106	320222
		3.25 hrs. (After TEC2)	3.9 hrs, 3.7 hrs, 3.3 hrs	MD	RQ102.140	320249
Disposal	Disposal Impact Target	Ganymede or Callisto	Impacts Ganymede	MD	RQ102.130	320242
	Flight System Disposal Duration	≥30 days (with SEP>3°) and ≤90 days, after the last Europa flyby	45 days	MD	RQ102.089	320210

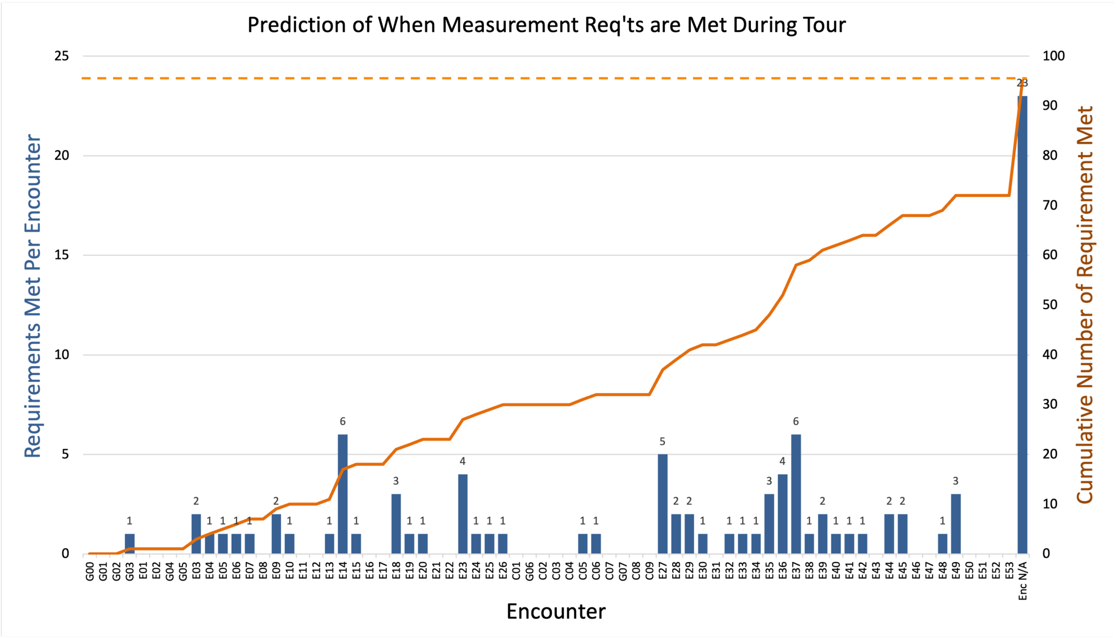


Fig. 16: Histogram of when each unique science requirement is met in the tour and the accumulation of the total number of requirements met over all encounters.

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