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Europa Clipper: First Year of Space Flight Operations

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Europa Clipper launched at 16:06 UTC on 14 October 2024, on a fully expendable SpaceX Falcon Heavy launch vehicle. It utilizes planetary gravity assists from Mars and Earth via a Mars-Earth Gravity Assist trajectory in two solar orbits over 5.25 years to reach the Jupiter system and explore the ocean world Europa. The launch phase was a critical event focused on putting the Flight System onto its interplanetary trajectory and completing critical deployment of the solar array. Following completion of the autonomous activities, the ground successfully established two-way communication to determine Flight System health and orbit. Europa Clipper's mission plan for interplanetary cruise leading up to the Mars flyby on 1 March 2025 was for the majority (but not all) of the first-time activities to take place during two characterization periods, known as Flight System Characterization Parts 1 and 2 (FSC1 and FSC2, respectively). All checkouts and deployments that enable the first trajectory correction maneuver (TCM-1) were defined as FSC1, while almost all the remaining checkout activities were defined as FSC2. FSC2 concluded roughly three months after launch, prior to entering a low data rate period. The Mars flyby afforded the opportunity to perform a key calibration for the Europa Thermal Emission Imaging System (E-THEMIS) and a flyby functional test for the Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON) instruments. By early May, Europa Clipper had a heliocentric distance over 2 AU, by which the Flight System could point the High Gain Antenna at Earth for an unlimited duration; periodic and episodic maintenance, calibration, and navigation activities continued during this period. This paper presents the overall strategy, plan, process, and early flight results and performance for Europa Clipper's first year of flight operations, including in-flight navigation and Flight System characterization. It also describes interesting and unique operations challenges encountered and overcome in flying Europa Clipper.

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Nomenclature

ΔDOR	=	Delta-Differential One-Way Ranging
3J	=	3-axis inertial reference
AL	=	Activity Lead
APL	=	Applied Physics Laboratory
ART	=	Anomaly Response Team
ATLO	=	Assembly, Test, and Launch Operations
AU	=	Astronomical Unit
BDS	=	Bulk Data Storage
C/A	=	Closest Approach
CAP	=	Cruise Activity Planning
CFDP	=	CCSDS File Delivery Protocol
CPU	=	Central Processing Unit
COLA	=	Collision on Launch Assessment
DSN	=	Deep Space Network
DDM	=	Downlink and Data Management
ECC	=	(DSN) Emergency Control Center
ECM	=	Europa Clipper Magnetometer
ECE	=	Europa Compute Element
EGA	=	Earth Gravity Assist
EIS	=	Europa Imaging System
EMEM	=	Europa Memory
EMI/EMC	=	Electromagnetic Interference/Compatibility
EPIC	=	Earth Point Inner Cruise
E-THEMIS	=	Europa Thermal Emission Imaging System
Europa-UVS	=	Europa Ultraviolet Spectrograph
FAD	=	FSC Activity Development
FR	=	Flight Rule
FS	=	Flight System
FSC1, FSC2	=	Flight System Characterization 1, 2
GDS	=	Ground Data System
GNC	=	Guidance, Navigation, and Control
G/RS	=	Gravity and Radio Science
HF	=	high frequency
HGA	=	High Gain Antenna
HRS	=	heat redistribution system
IMU	=	Inertial Measurement Unit
IC	=	Interplanetary Cruise
IOT	=	Instrument Operations Team
ISA	=	Incident, Surprise, Anomaly (Report)
iSOC	=	instrument operations location
JOI	=	Jupiter Orbit Insertion
JPL	=	Jet Propulsion Laboratory
KSC	=	Kennedy Space Center
LDR	=	Low Data Rate
LGA	=	Low Gain Antenna
LSP	=	Launch Services Program
MASPEX	=	MAss Spectrometer for Planetary Exploration / Europa
MEGA	=	Mars-Earth Gravity Assist
MGA	=	Mars Gravity Assist
MGA	=	Medium Gain Antenna
MISE	=	Mapping Imaging Spectrometer for Europa
MOS	=	Mission Operations System
MRO	=	Mars Reconnaissance Orbiter
MSA	=	Mission Support Area

NAC	=	Narrow Angle Camera
OD	=	Orbit Determination
OLR	=	Open Loop Receiver
ORT	=	Operations Readiness Test
OVRO	=	Owens Valley Radio Observatory
PIMS	=	Plasma Instrument for Magnetic Sounding
PXA	=	Post-Execution Activity Assessment
RadMon	=	Radiation Monitor
RCS	=	Reaction Control System
REASON	=	Radar for Europa Assessment and Sounding: Ocean to Near-Surface
REU	=	Remote Engineering Unit
RF	=	Radio Frequency
RWA	=	Reaction Wheel Assembly
SEFI	=	Single-Event Functional Interrupt
SEP	=	Sun-Earth-Probe (Angle)
SHARAD	=	Shallow Radar
SOC	=	(battery) state of charge
SPC1	=	Sun-Point Cruise 1
SPOC	=	Science Planning Operations Coordination
SRU	=	Stellar Reference Unit
SSC	=	Swedish Space Corporation
SUDA	=	SUrface Dust Analyzer
TCM	=	Trajectory Correction Maneuver
TRG	=	targeting maneuver
UTC	=	Coordinated Universal Time
VHF	=	very high frequency
WAC	=	Wide Angle Camera

I. Introduction

Is Europa habitable? NASA's Europa Clipper mission will explore Europa and assess its habitability utilizing a set of five remote-sensing instruments that cover the electromagnetic spectrum from thermal infrared to ultraviolet wavelengths, four in situ fields and particles instruments, a dual-frequency radar, and a gravity and radio science investigation. To evaluate the presence and characteristics of the ingredients for life, Europa Clipper focuses on the following objectives related to the interior (ocean and ice shell), composition, and geology of Europa:

- *Interior* (ocean and ice shell): Characterize the ice shell and any subsurface water, including their heterogeneity, the properties of the ocean, and the nature of the surface–ice–ocean exchange.
- *Composition*: Understand the habitability of Europa's ocean through composition and chemistry.
- *Geology*: Understand the formation of surface features, including sites of recent or current activity; identify and characterize high-science-interest localities.

Beyond these science objectives, Europa Clipper's habitability goal calls for consideration of cross-cutting science topics as well, such as current and recent activity, radiation environment, geodesy, and site reconnaissance for a potential future lander.[1]

The Europa Clipper mission architecture comprises:

- Launching on a Mars-Earth Gravity Assist (MEGA) trajectory in October 2024 using a commercial SpaceX Falcon Heavy vehicle (fully expendable configuration) and arriving at Jupiter in April 2030. The MEGA trajectory has a 5.25-year interplanetary cruise, including a perihelion as low as 0.82 AU and Mars and Earth gravity assists.[2]
- The mission concept is predicated on obtaining global-regional coverage of Europa (i.e., regional-scale data sets, distributed globally across Europa) via a complex network of flybys spanning approximately 4.3 years while the Flight System (FS; spacecraft and instrument payload) remains in a highly elliptical orbit around Jupiter. This approach enables the FS to quickly dip into the harsh radiation environment in which Europa resides to collect a large volume of Europa science data and, just as quickly, escape that environment such that the majority of the transfer time to the next Europa flyby would be available to downlink data, execute Orbital Trim Maneuvers, recharge the batteries, and perform any other spacecraft housekeeping activities largely free of radiation dose accumulation.[3]

- The spacecraft component of the FS is designed to permit all science instruments to operate and gather science data simultaneously.[4] Driving design considerations for the FS included high ionizing radiation, high electron flux, extreme temperature variations, electromagnetic cleanliness, and contamination control.

During the first year of flight, Europa Clipper successfully completed the critical launch activity. It is now in the second of three Inner Cruise subphases.

- Launch critical activities included launch, detumble, initial acquisition, solar array deployment, establishing power-positive attitude, and establishing telemetry and radiometric links.
- Sun-Point Cruise 1 (SPC1) began the day after launch. It is the first subphase of Interplanetary Cruise (IC) during which the FS High Gain Antenna (HGA) needed to stay pointed within 5° of the Sun. Communication was mostly performed using fan-beam antennas. SPC1 comprised FS characterization, periodic and episodic maintenance, calibrations, navigation activities, and the Mars Gravity Assist (MGA) on 1 March 2025.
- Earth Point Inner Cruise (EPIC) began when the FS crossed 2 AU outbound for the first time on 5 May 2025 and will continue through early April 2026 when the FS crosses 2 AU inbound. During EPIC, the FS can point the HGA at Earth for an unlimited duration. EPIC comprises primarily periodic and episodic maintenance, calibrations, and navigation activities.

Sections II–IV give an overview of the Europa Clipper mission, launch, and other first-year cruise operations activities, respectively. Sections V and VI describe spacecraft and subsystem performance and science instrument checkouts at a high level. Section VII describes the evolving Europa Clipper operations activity approach. Section VIII describes some surprising challenges that the project and mission operations team have overcome to date. Section IX concludes with a recap of key accomplishments and outlook for future mission phases.

II. First-Year Mission Overview

Mission phases help define the conceptual framework for a mission; they provide a common language for engineers and scientists when discussing specific mission periods. Each phase has a different focus, and it is convenient to define activity constraints on a phase-by-phase basis. The Europa Clipper operational timeline is divided into five phases: Launch, IC, Arrival, Tour, and Disposal, all of which are described in detail in Refs. 2 and 3.

The focus of IC is twofold: navigation of the FS to Jupiter via gravity assists from Mars and Earth, and characterization, maintenance, and calibration of the spacecraft and payload. In the event of the need for resource prioritization among conflicting activities, the priorities, from highest to lowest, have been and continue to be:

1) FS housekeeping
2) Trajectory maintenance
3) Deployment activities
4) FS characterization (investigations if needed)
5) Routine calibration activities

A. First-Year Mission Objectives

During the first year, most of the first-time activities took place during two FS characterization periods, known as Flight System Characterization Parts 1 and 2 (FSC1 and FSC2, respectively). FSC1 and FSC2 were not formal mission phases but rather groupings of activities for convenience of planning. All checkouts, deployments, and characterizations that enabled the first trajectory correction maneuver (TCM-1) were defined as FSC1, while many of the remaining checkout activities were defined as FSC2. The last FSC2 activity took place roughly four months after launch, although the only criterion for exiting FSC2 was completion of the activities constituting it.

Following FSC1 and FSC2, the primary objective of the MGA was to provide Europa Clipper with said gravity assist to enable the FS to reach the required Earth Gravity Assist (EGA) in December 2026. Mars closest approach (C/A) occurred at an altitude of 884 km on 1 March 2025 at 22:56:54 UTC. Although MGA was primarily focused on achieving a navigation objective, it afforded opportunities to conduct a point-source calibration for E-THEMIS and an instrument functional checkout for Radar for Europa Assessment and Sounding: Ocean to Near-Surface (REASON). MGA was also the first in-flight eclipse for Europa Clipper.

EPIC activities to date include additional calibration campaigns, checkouts, and health checks. Select activities include a REASON calibration opportunity with the Owens Valley Radio Observatory (OVRO), an FS update, the start of a series of FS self-compatibility tests, and the first maneuver targeting the December 2026 EGA.

B. Flight System Configuration and Key Subsystems

The Europa Clipper FS comprises the spacecraft and the payload required to carry out the science investigations. Figure 1 depicts the FS components and dimensions in its launch and cruise configurations. Figure 2 describes the telecom antenna layouts, characteristics, and activities for planned usage.

The 10 investigation/instruments are as follows: Europa Ultraviolet Spectrograph (Europa-UVS), an imaging ultraviolet spectrograph; Europa Imaging System (EIS), comprising a Wide-Angle Camera (WAC) and Narrow-Angle Camera (NAC); Mapping Imaging Spectrometer for Europa (MISE), a shortwave infrared spectrometer; Europa Thermal Emission Imaging System (E-THEMIS), a thermal imager; REASON, a high-frequency (HF) and very high-frequency (VHF) ice-penetrating radar; MAss Spectrometer for Planetary Exploration / Europa (MASPEX), a multibounce time-of-flight mass spectrometer; Surface Dust Analyzer (SUDA), a dual polarity, time-of-flight mass spectrometer; Europa Clipper Magnetometer (ECM), a set of fluxgate magnetometers mounted on a boom; Plasma Instrument for Magnetic Sounding (PIMS), a Faraday-cup based plasma instrument; and Gravity and Radio Science (G/RS), achieved through use of the FS telecom subsystem. More details about the Europa Clipper spacecraft and instrument suite are available in Refs. 1 and 4 as well as in the respective investigation papers.[5]

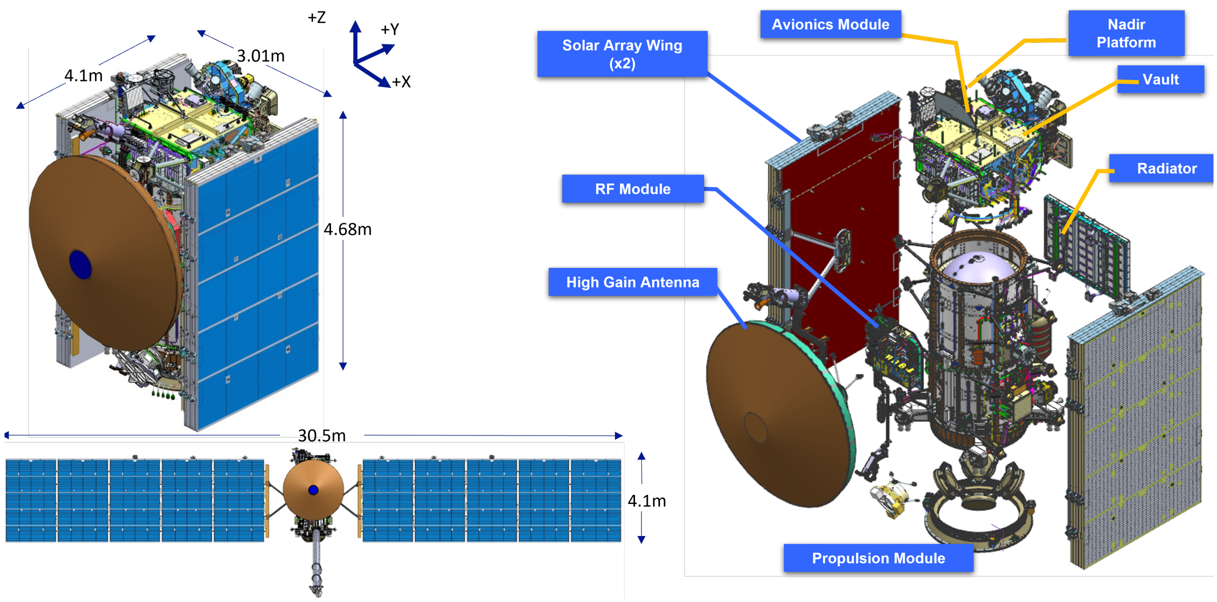


Figure 1. Europa Clipper FS configuration depictions—launch (upper left), cruise (lower left), and partial separation view (right).

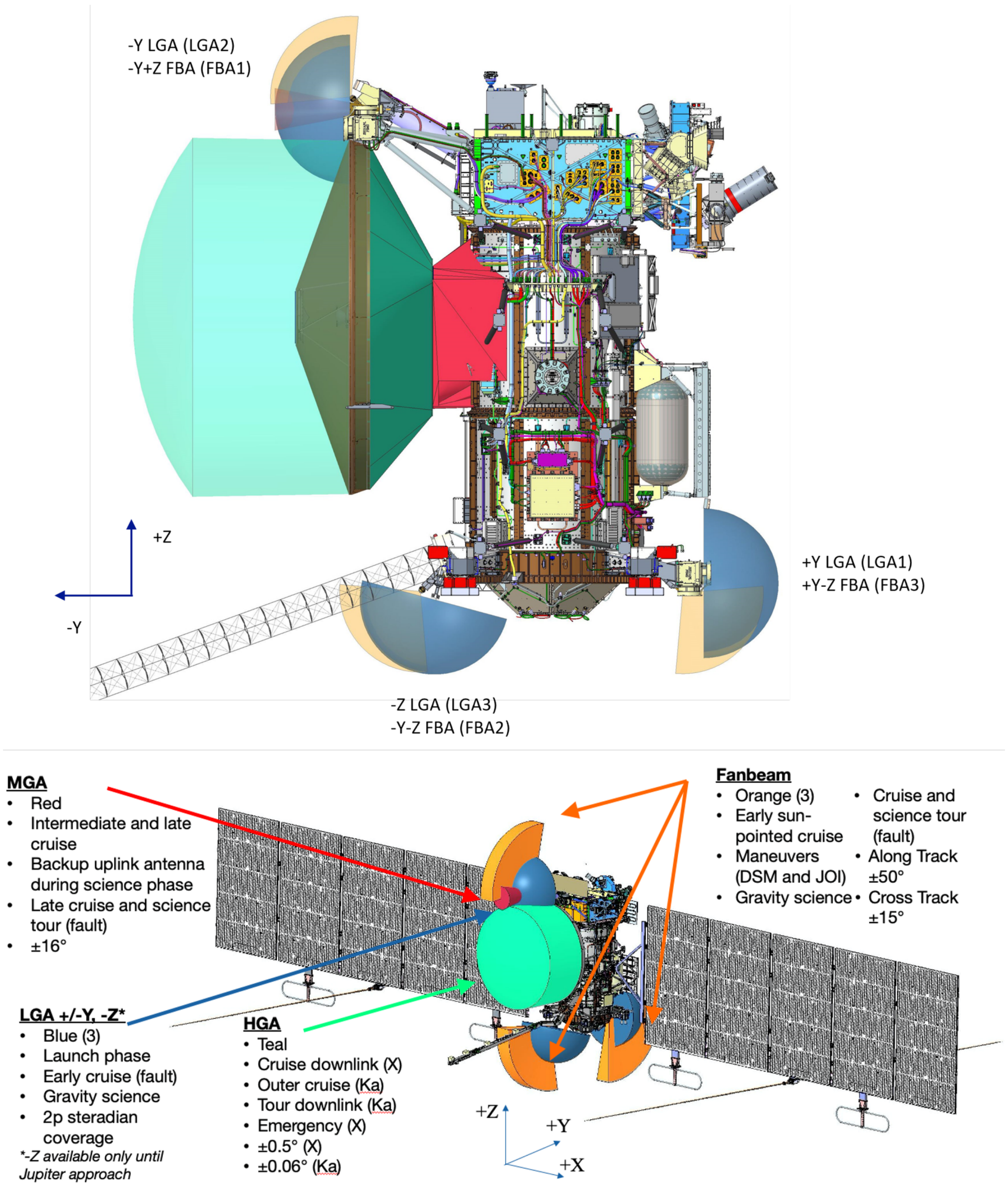


Figure 2. Europa Clipper FS telecom antenna depictions.

C. Launch and Interplanetary Trajectory

Figure 3 illustrates the MEGA interplanetary trajectory corresponding to the 14 October 2024 launch (the fifth day of the 21-day launch period). The trajectory was optimized to minimize post-launch ΔV under the constraints that both the EGA and MGA altitudes be greater than or equal to 300 km and 450 km, respectively, and that the Jupiter Orbit Insertion (JOI) maneuver be less than or equal to 950 m/s. To satisfy planetary protection requirements, a fixed aimpoint biasing strategy was used for all dates of the launch period. This strategy represented a trade-off optimizing applicability to all dates, probability of impact, and incurred cost in ΔV.

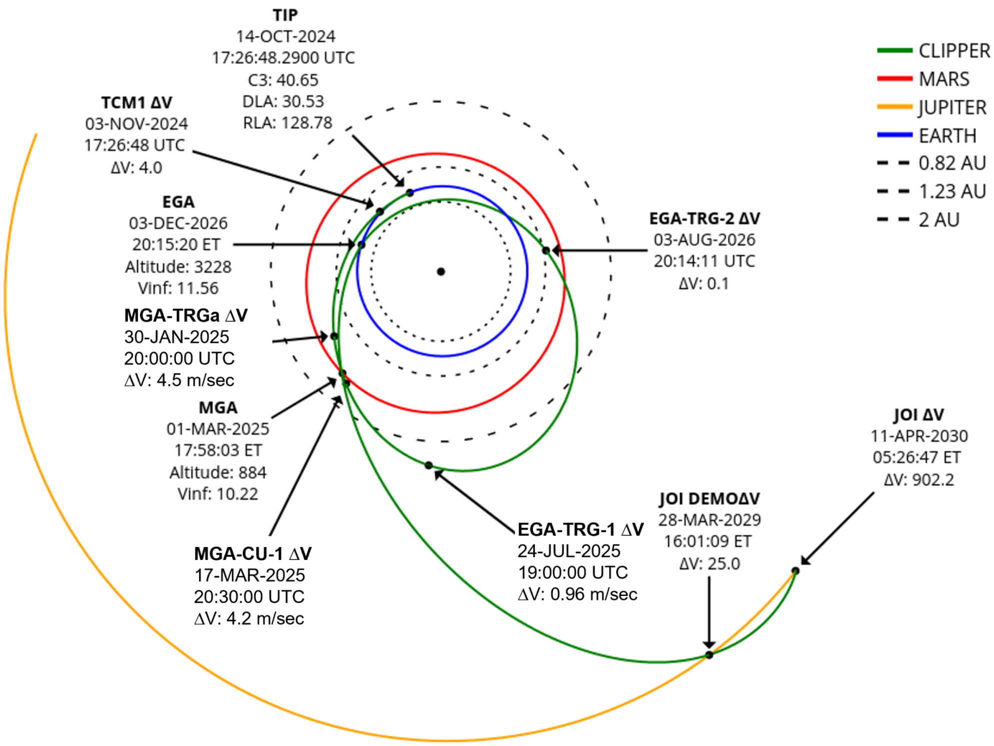


Figure 3. Europa Clipper interplanetary MEGA trajectory (update to corresponding figure in Ref. 3).

D. Ground Segment

Primary mission operations tasks are jointly carried out between the Jet Propulsion Laboratory (JPL) and the Johns Hopkins University Applied Physics Laboratory (APL). The mission operations system is distributed across both JPL and APL as well as distributed instrument operations locations (iSOCs). The Mission Operations System (MOS) interfaces with the Deep Space Network (DSN) and other necessary networks to command the FS and to receive telemetry and navigation data. The MOS architecture is illustrated in Fig. 4.

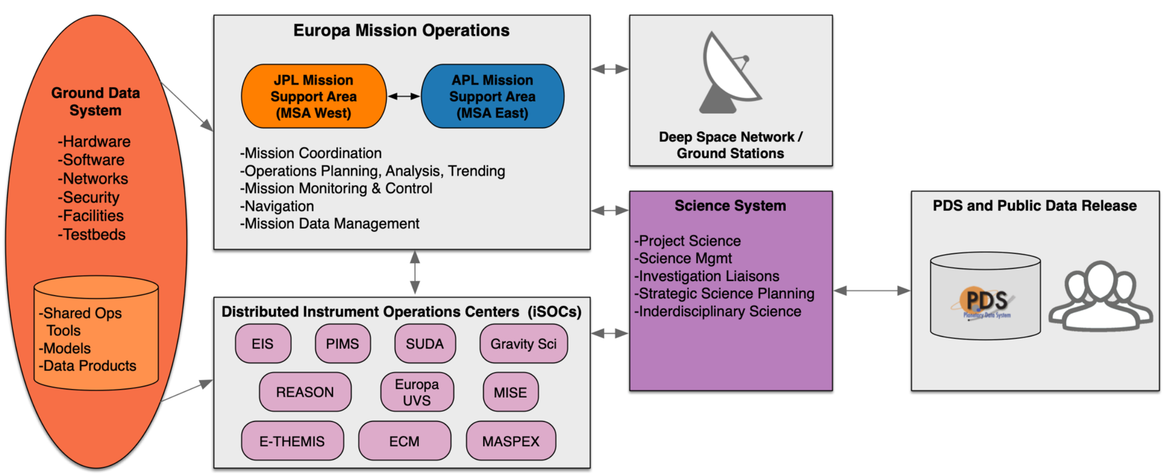


Figure 4. Europa Clipper's MOS distributed architecture.

JPL has the primary interface to the DSN for standard tracking, telemetry data, and command operations. In the future, APL will have an independent connection to support command/telemetry interfaces with the DSN for contingency cases if JPL is unavailable. The Ground Data System (GDS) is designed to support operations at all distributed locations as shown. Access to shared operations tools, shared models of instrument and spacecraft behavior, uplink and downlink data products, and real-time telemetry for the health and status of the spacecraft and instruments will be provided at APL, JPL, and the iSOCs based on the functionality required.

The Europa Clipper MOS relies on successful coordination and collaboration by geographically dispersed institutions. A map of each involved institution and its relevant facilities is shown in Fig. 5. Figure 6 depicts the operations organization for Europa Clipper in the first year of operations. Each operations team is responsible for a set of primary mission operations functions. Systems Engineering and operations system development and planning will continue into operations as well.[2]

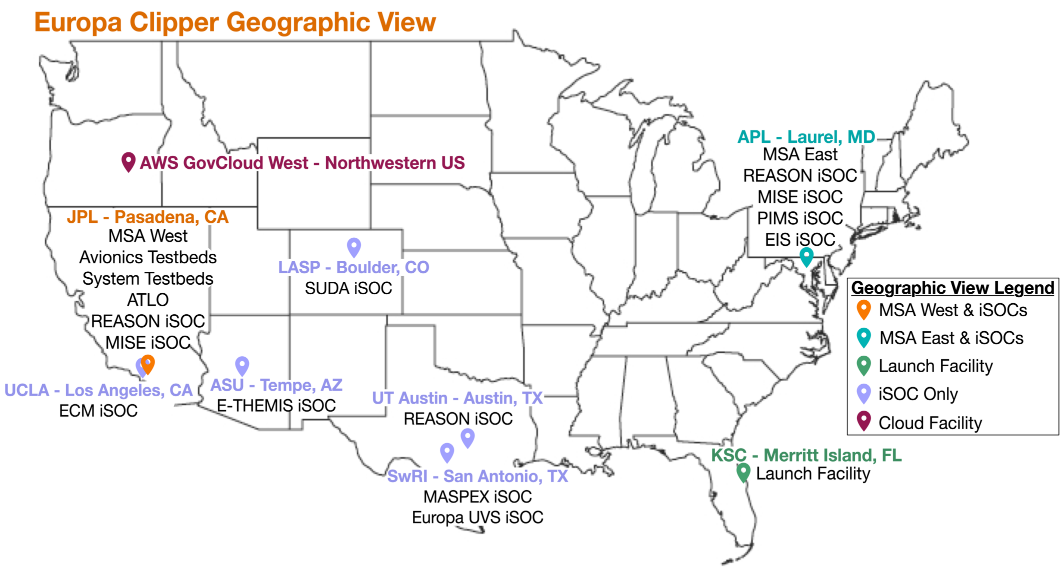


Figure 5. Geographic view of Europa Clipper operations locations.

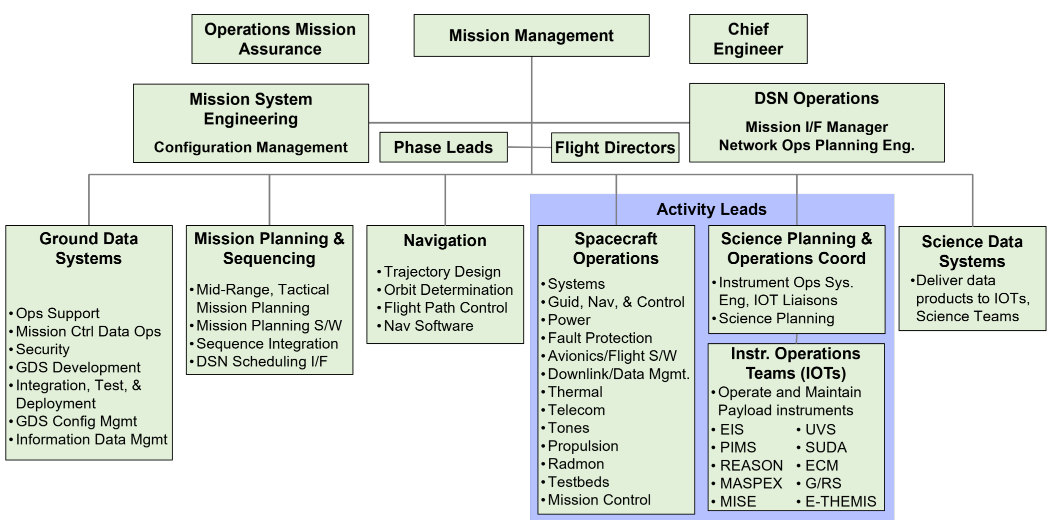


Figure 6. Europa Clipper early operations organization.

III. Launch and Early Operations Phase

Launch was the first of the two Europa Clipper critical events (the second will be JOI in 2030). Launch was a phase in and of itself; critical activities included launch, detumble, initial acquisition, solar array deployment, establishment of power-positive attitude, and reestablishing telemetry.

A. Launch Timeline

Europa Clipper launched on Monday, 14 October 2024 at 16:06:00 UTC. Figure 7 depicts the key operations events of the day-long Launch Phase/Activity. The day ended with the FS injected onto its interplanetary trajectory, commandable and power-positive, with the solar array deployed, HGA pointed at the Sun on Reaction Control System (RCS) attitude control, and temperatures stable and/or trending as expected—all confirmed through launch telemetry and radiometric data.

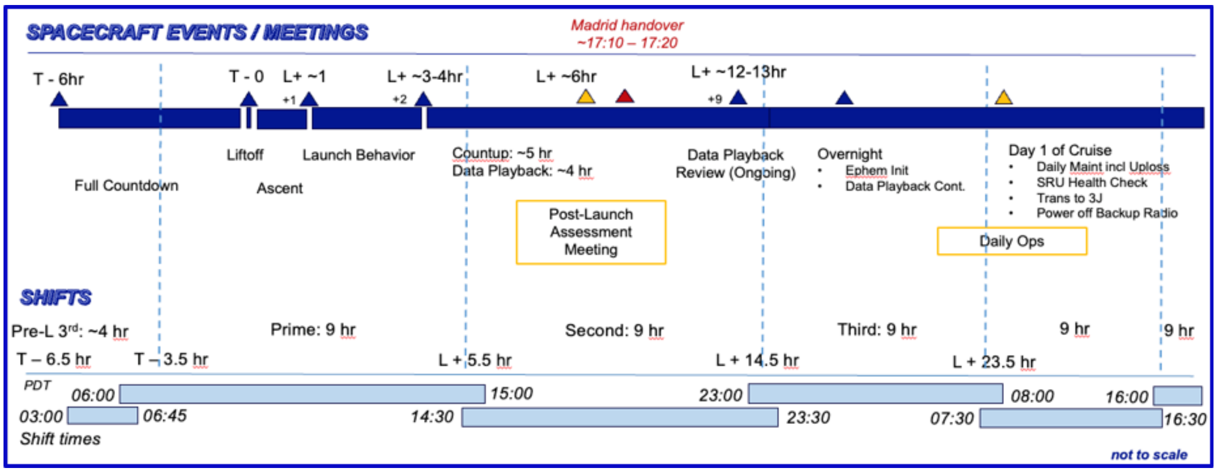


Figure 7. Europa Clipper timeline (launch through cruise start at Launch+1 day first shift). All times Pacific Daylight Time (UTC−07:00).

B. Launch Phase Performance

Activities up through countdown went smoothly; no noteworthy issues leading into countdown or during countdown contributed to any timeline margin erosion. There was a Collision on Launch Assessment (COLA) plan to be able to respond to a collision avoidance report delivered up to a couple of hours prior to launch with a sufficiently large probability of collision. In that scenario, there was a provision to elect to change the liftoff time up to 15 seconds earlier than nominal launch, at one second intervals. As it turned out, no COLA adjustment was required.

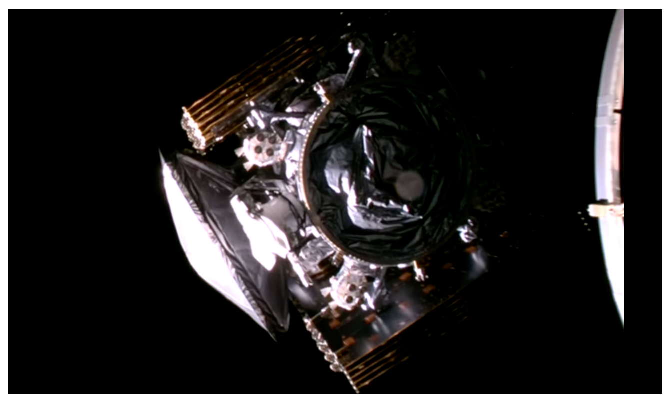


Figure 8. Europa Clipper separation from launch vehicle (image credit: NASA TV/SpaceX).

Using radiometric data provided by the DSN, Navigation delivered an orbit determination (OD) solution on launch day for ground station pointing updates. Navigation's delivery on the next day included data from all three DSN complexes. This solution had a Mahalanobis distance (distance from a probability distribution of representative injection cases) of 1.304, corresponding to a launch and injection within 1.5-sigma of the intended targets. In addition to the DSN support, antennas of the Swedish Space Corporation (SSC) South Point complex in Hawaii provided a second complex of (telemetry-only) coverage for initial acquisition.

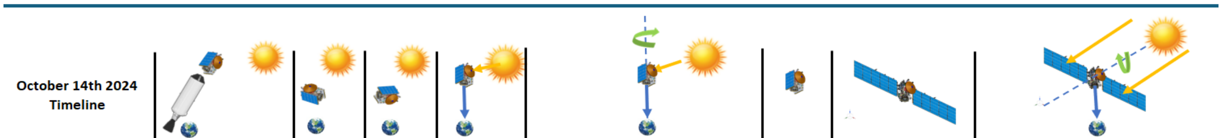
This phase concluded with a successful separation (Fig. 8), followed by successful initial acquisition and start of the autonomous Launch Behavior.

C. Autonomous Launch Behavior

The autonomous launch behavior duration spanned a little over 140 minutes. Figure 9 depicts the timing of the discrete behavior steps; the realized timing was consistent with predictions. The behavior successfully completed all required actions and left the FS in the intended final state. Highlights included the following:

- Clean initial acquisition occurred less than five minutes post-separation, as soon as the FS began transmitting (consistent with plans).

- Launch-specific Guidance, Navigation, and Control (GNC) capability worked well.
  - Good separation attitude and rates supported rapid Sun acquisition and start of thermal roll within five minutes of separation.
  - The RCS, corresponding controllers, and fault protection thresholds used for launch worked as planned.
- Solar array deployment was successful.
  - Array wing deployment duration was consistent with predictions.
  - Telemetry (voltage, current, and timing) was consistent with design and ground testing.
- Final planned FS configuration was achieved (+Z-pointed Low Gain Antenna 3 [LGA3] and Sun-pointed -Y-axis rotation [Fig. 2]) within a one-hour period.



Events	Sep	Mode Config	V&P	Detumble	Sun Search and point LGA	Thermal Roll	HDRM Release Sequence (8 of 9)	Re-assert thermal roll	Final HDRM Firing	Solar Array Deployment	Solar Array Settling	Rate Match	-Y on Sun & Roll about Y	End
UTC Time (hh:mm:ss)	-	17:08:35	17:08:59	17:12:06	17:12:08	17:13:04	18:13:18	18:47:18	18:47:41	18:53:56	19:03:56	19:04:26	19:04:47	19:29:19

Figure 9. Europa Clipper launch autonomous behavior timeline.

D. Launch Data Playback

Launch day data playback was successful; all data products downlinked according to schedule. With the above FS configuration, the telecom link was in a 30-minute in/out cycle; familiarity with this periodic commandability and downlink was planned for and practiced in Operations Readiness Tests (ORTs). Data volume to downlink at the end of the launch behavior was slightly over 10 megabytes, within the expected range. This information was captured in data products that were downlinked by the end of the second shift on launch day (after eight Y-axis rotations).

E. Anomalies or Surprises During the Launch and Early Operations Phase

Plans to launch Europa Clipper on 10 October (the opening of the MEGA launch period) were delayed due to impacts of Hurricane Milton. Figure 10 shows the forecast path of Milton as known three days prior. Ultimately, the path was very close to that shown here. NASA had a well-defined hurricane response plan: Project and launch personnel stayed off-site while a ride-out team was deployed at Kennedy Space Center (KSC) to keep essential infrastructure running. After the storm passed, the team performed initial damage assessments and handed off to other teams for further assessments and recovery efforts. Once KSC was deemed safe for access, the project and launch teams returned to work, ultimately setting 14 October as the new launch date. A similar launch slip scenario had been practiced by the operations teams in an ORT, which helped make the reset to the new date go smoothly.

Thanks go to all emergency responders who supported the response to the storm, both at KSC and across the communities impacted by Milton.

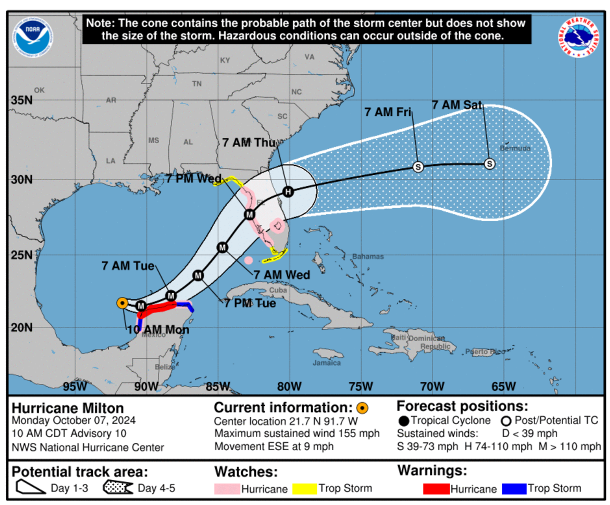


Figure 10. Hurricane Milton ground track (credit: National Weather Service—National Hurricane Center).

F. Lessons Learned from Launch Readiness and Execution

This section will not do justice to all the work leading up to Europa Clipper's successful launch. Nevertheless, it is worth highlighting that (a) the fidelity and coordination of the data simulated for the ORTs and (b) the thoroughness of the ORT scenarios (especially anomalous ones) played a large role in preparing the multicenter team for what was ultimately a successful launch.

IV. First-Year Cruise Trajectory and Operations

Continuing from launch, the first year of Europa Clipper operations takes us through the SPC1 subphase, comprising two FS characterization activity phases and the first Low Data Rate (LDR) activity phase. The remainder of the first year, ending roughly just after solar conjunction, comprises the first half of the EPIC subphase. Figure 11 describes the maneuver and MGA epochs, background sequence timing, evolving geometric properties of the interplanetary trajectory, and telecom and pointing approaches.

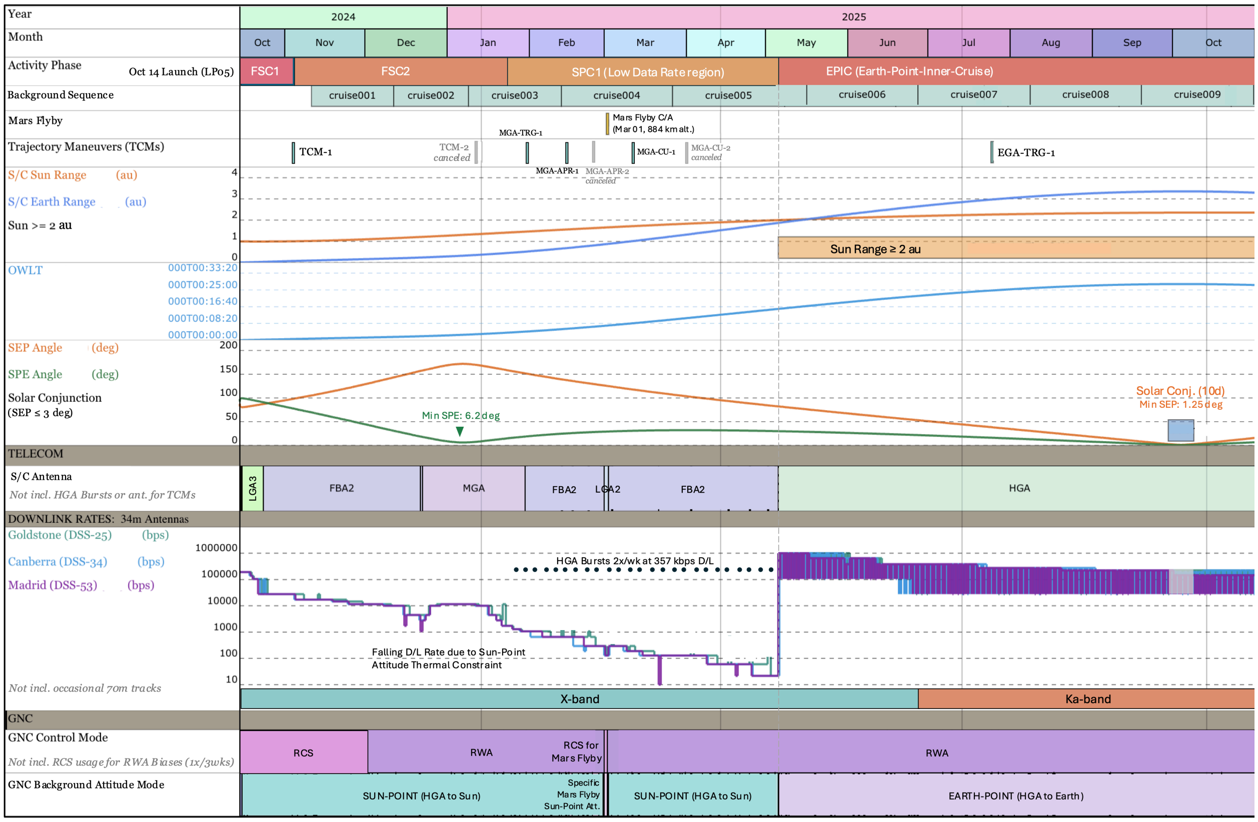


Figure 11. Europa Clipper first-year activity geometry and high-level FS milestones/approaches.

A. Description of First-Year Trajectory Geometry, High-Level FS Milestones

The post-launch trajectory for the first year of cruise operations activities is demarcated by the first outbound crossing of the 2 AU Sun range. Prior to that passage, due to thermal considerations, the FS needed the HGA to be pointed within 5° of the Sun (GNC Attitude Mode "SUN" in Fig. 11). Telecom started with LGA usage but was mostly fan-beam-based, with brief HGA "bursts" (slews to Earth) that provided increased downlink capacity and more accurate ranging measurements. Activities prior to 2 AU passage included FS characterization, periodic and episodic maintenance, calibrations, and navigation activities plus the MGA (1 Mar 2025). After the 2 AU passage, the FS could point the HGA at Earth for unlimited duration (GNC Attitude Mode "EARTH" in Fig. 11). With this pointing ability, the Ka-band capability was commissioned and used regularly, resulting in yet more downlink performance. Activities after 2 AU include more periodic and episodic maintenance, calibrations, and navigation activities.

B. Flight System Characterization Part 1

FSC1 was the set of mandatory activities required to get to execution of the first Trajectory Correction Maneuver (TCM-1), plus other strongly desired activities (e.g., starting spacecraft maintenance, configuring for FSC2 and beyond). It spanned from Launch+1 day to Launch+19 days, ending with TCM-1 execution on Launch+20 days. Mandatory activities established the following:

- Command loading of ephemeris tables from FS file system into memory for GNC use (given nominal injection)
- 3-axis inertial reference (3J) pointing and safing response
- Initial power on and checkout of star tracker health and performance
- Solar array articulation health/phasing checkout
- Frequency identification (for post-launch configuration)
- Tank pressurization, active pressure control checkout
- Homing the MISE scan mirror (to prevent propellant contamination)

For efficiency, other important planned activities were safely included to establish the following capabilities:

- Post-launch telecom reconfiguration (power off the backup radio and transition prime radio to cruise mode)
- Nominal cruise thermal pump configuration
- Parameter update to enable 3J safing (rather than a “rotisserie roll”) in the event of a compute element swap
- Radiation monitor (RadMon) data collection
- SpaceWire instrument commanding (including first in-flight power on of the avionics high-rate controller)
- More efficient data product collection (enabling data product compression)
- Start of avionics checkout

Concurrent with this was the rollout of a set of GDS automation capabilities; TCM-1 design also kicked off roughly midway through this period. All planned activities were executed per the pre-launch schedule (more on the FSC development and execution process in Section VII).

C. Flight System Characterization Part 2

FSC2 was planned to cover the period between TCM-1 execution and LDR; it comprised the following:

- ECM deployment
- REASON HF and VHF dipole deployments—For the REASON VHF deployment, the receive-only data set was used to detect the change in the shorted/stowed condition and a comparison with the expected galactic noise post-deployment.
- EIS—NAC launch lock release.[††††]
- GNC—After the above deployments, the final frequency identification activities were completed. This was followed by the controller update, Reaction Wheel Assembly (RWA) control commissioning, and transition to RWA control. Other GNC-related FSC2 checkout activities spanned GNC sensor and articulation functionality (solar array drive range of motion, prime Inertial Measurement Unit [IMU], Stellar Reference Units [SRUs], and the prime Sun-facing Digital Sun Sensor heads).
- Avionics—Maintenance in FSC2 focused on register dumps, shared record dumps from both Remote Engineering Units (REUs), checksums and NAND power cycles for Single-Event Functional Interrupt (SEFI) mitigation, and confirmation of backup string health.
- Propulsion—The engine manifold was flushed by firing all 24 engines, 12 per fully redundant branch to prevent iron nitrate deposition. Data was passively collected during the engine firings to support RCS control prior to the transition to RWA control to update propellant utilization models.
- Telecom—Telecom configuration management was transitioned to background sequences (see Section VII.B). Flight Directors continued to direct data rate stepping beyond the modeled and sequenced prediction, based on real-time margin assessments.
- Thermal—Thermal operations in FSC2 focused on demonstrating monthly runs of all six pumps to maintain mechanism health of the thermal redundancy. Closed-loop heater control was monitored as the spacecraft Sun range increased, with few thermal zones requiring setpoint updates due to lower-than-expected temperature conditions. Data was passively collected to update models and predictions for future cruise.
- Power—Power was largely unconstrained during FSC2 due to the large margins in the Sun-pointed configuration for a solar array designed for low-irradiance-low-temperature operations. After successful

[††††] ECM, REASON, and EIS/NAC deployment verifications were performed using aggregated high-rate data captured by the IMU and tell-tale telemetry, where available. For some events, 2-way Doppler residuals corroborated that the events had occurred.

completion of the deployments, the team reduced the battery setpoint to ~60% to remain in family with lifetime predictions.
- Other checkouts, risk-reduction activities, calibrations, investigations, data configuration changes, data dumps, etc.

Altogether, 52 unique planned activities were developed and executed. An additional 24 unplanned command products were executed. Thirty-one of the planned products were built in-flight, and seven activities were deferred (more in Sections VII and VIII).

D. Navigation and Maneuver Execution

Europa Clipper OD is based on radiometric two-way and three-way Doppler data, two-way sequential ranging data, and Delta-Differential One-Way Ranging (ΔDOR) data. Doppler and ranging have been collected for X/X-band and X/Ka-band (up/down) combinations, and there have been X-band and Ka-band ΔDORs collected as well. All radiometric data quality to date has been nominal. For example, observed ranging offsets from transponder delays are meter-level; RMS scatter of HGA range residuals have been less than 0.5 m (both as expected).

In addition to the post-launch delivery assessment, OD solutions were provided for maneuver builds, background sequence development, and a science ephemeris update. Aside from changes to the timing of future thrusting activities, orbit solutions predicted better than 1-sigma.

While there will be many targeted flybys at Jupiter[‡‡‡‡], the first year of Europa Clipper operations had one such event—the targeting for the MGA (and the start of targeting for the EGA in 2026). From launch to MGA, the FS was under RCS control through mid-December, and then on RWA control for much of the duration thereafter. Given that, the navigation dynamic modeling focused on (a) monitoring RCS/maneuver performance from the FS and (b) trending solar radiation pressure and thermal reradiation behavior. All RCS and maneuver activities were consistent with GNC and Navigation expectations; during RWA control, the FS was so dynamically quiet one could see (and model) thermal reradiation effects due to solar array temperature differences on the order of ~1°C. OD solutions after the final pre-encounter maneuver showed a <3 km miss relative to target (well within 1-sigma); a subsequent predict update for a REASON activity at Mars 10 days out was accurate to ~0.1 km.

The standard polling for maneuver go/no-go decisions spans the following categories:
- Orbit Determination (Navigation)—Are OD solutions consistent and stable?
- Maneuver Design (Navigation)—Are OD errors small relative to the designed targeting correction? Are ΔV implementation errors small relative to the designed velocity change?
- FS Capability (Spacecraft)—Is the spacecraft healthy, including GNC/Propulsion/Fault Protection functionality, and performing in accordance with expectations to execute the maneuver on schedule?
- Maneuver Products (Sequencing)—Are maneuver products validated through appropriate methods (testbeds, inspection)?
- Human Factors (all teams)—Are teams on schedule to support the maneuver execution? Are teams in a position to identify and address mistakes/changes? Are team members alert and sufficiently rested?

In addition, for the MGA approach maneuvers, the following criterion was added: Is the ΔV cost of not performing the given maneuver low (with the threshold level determined a priori to be on the order of 10–30 m/s[§§§§])?

Table 1. Europa Clipper Launch to Mars maneuvers and execution performance.

Maneuver	Design/Executed ΔV Magnitude (m/s)	Maneuver Epoch (UTC)	Burn Duration (mm:ss.s)	# of engines used
TCM-1	4.646/4.606	03-NOV-2024 17:26:48	07:05.7	4
TCM-2	cancelled	--	--	--
MGA-TRGa	4.562/4.535	30-JAN-2025 20:00:00	07:19.8	4
MGA-APR-1	0.0503/0.0508	14-FEB-2025 20:00:00	00:6.6	2
MGA-APR-2	cancelled	--	--	--
MGA-CU-1	4.174/4.154	17-MAR-2025 20:30:00	06:57.9	4
MGA-CU-2	cancelled	--	--	--

(Engines are commanded in pairs, starting with two at burn start, adding two every 300 s of commanded burn time.)

‡‡‡‡ The navigation strategy designed to fly the Europa Clipper reference trajectory, including the results of OD covariance and flight-path-control analyses, is described in more detail in Ref. 6; Ref. 7 describes the interplanetary trajectory designed to meet NASA Planetary Protection requirements and reduce the probability of impact at Mars (and subsequent targeted encounters).

§§§§ This level was the amount of ΔV risk (in the form of downstream ΔV cleanup cost) that the project was willing to accept (with discussion) for MGA. This criterion level, and the criteria in general, will be reassessed for future targeted flyby maneuvers.

Table 1 summarizes planned and executed maneuvers, including the difference between the design and reconstructed ΔV magnitudes. The Gates maneuver execution error model predicted FS performance well; all executed maneuvers were within 1.5-sigma. The stability of the OD solutions allowed for early data cutoffs and navigation product delivery for the first Trajectory Correction Maneuver (TCM-1) and MGA targeting maneuver (MGA-TRGa). Furthermore, overall OD accuracy, combined with nominal maneuver execution performance, enabled cancellation of three of the seven planned maneuver opportunities through post-MGA clean-up. Given these decisions and FS performance to date, when compared to the Monte Carlo accumulated and per-maneuver ΔV_{99} statistics, Europa Clipper has realized a little over 10 m/s in savings.

E. LDR Period, Mars Gravity Assist and Flyby Activities

Figure 11 depicts the gradually decreasing overall data downlink capacity with increasing Earth-FS distance after FSC2 in the LDR subphase. To continue to enable a fuller visibility into the FS state at this point in the mission, as well as facilitate off-nominal and/or unplanned commanding and improve ranging data quality, the baseline plan was augmented to allow for two-hour sessions when the HGA was Earth-pointed (the "spikes" over 100 kbps in the figure). These were successfully executed roughly twice per week.

The major activity during the LDR period was the MGA and associated flyby activities. The primary objective of the MGA was to provide Europa Clipper with the necessary inertial ΔV addition (on the order of 1800 m/s) to reach the planned EGA in December 2026. It was also the first eclipse event for Europa Clipper (a 51-minute event shortly after Mars C/A). In addition, the Mars encounter afforded opportunities to conduct the following investigation instrument calibration and checkout activities:

- E-THEMIS point source calibration
- REASON Mars flyby instrument functional checkout

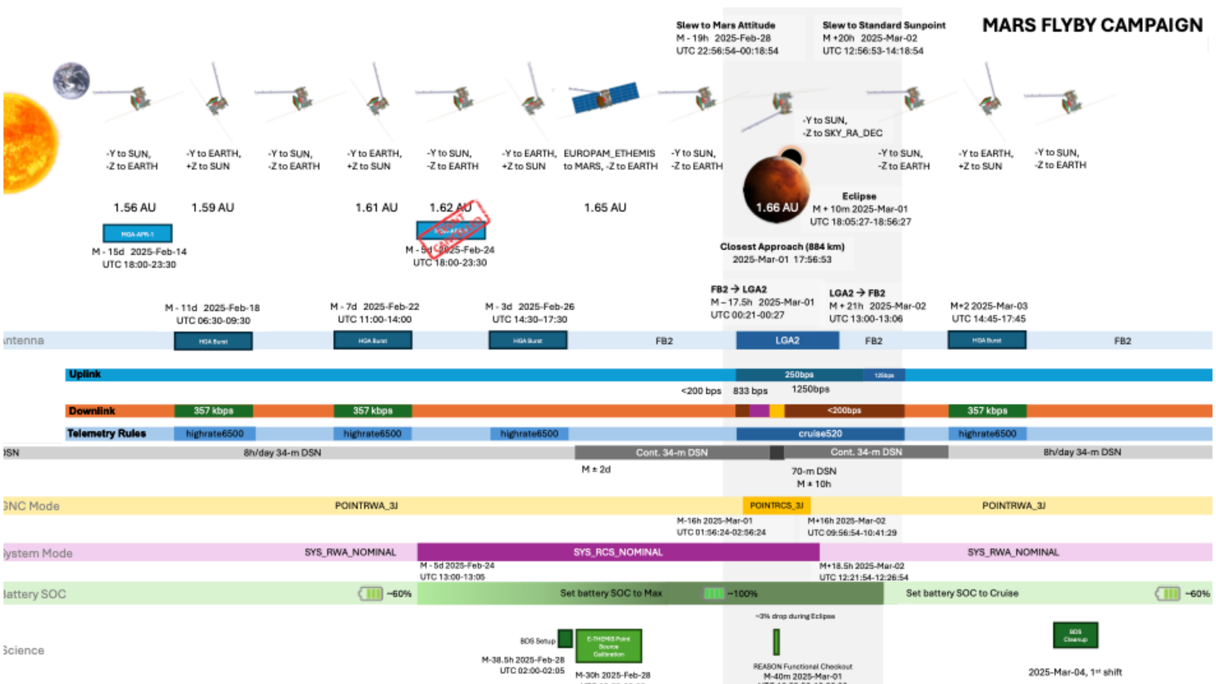


Figure 12. Europa Clipper Mars flyby activities.

Figure 12 depicts the Mars flyby activity timeline. These activities were coordinated with those of the following Mars-orbiting assets:

- Mars Reconnaissance Orbiter's (MRO's) Shallow Radar (SHARAD) observed the same region as REASON about 20 minutes later.
- THEMIS on Mars Odyssey obtained data of the same area that E-THEMIS covered at a similar time.

The instrument data was all downlinked after the transition to EPIC in May. Figure 13 depicts highlights of recent press releases announcing these activities.[*****][†††††]

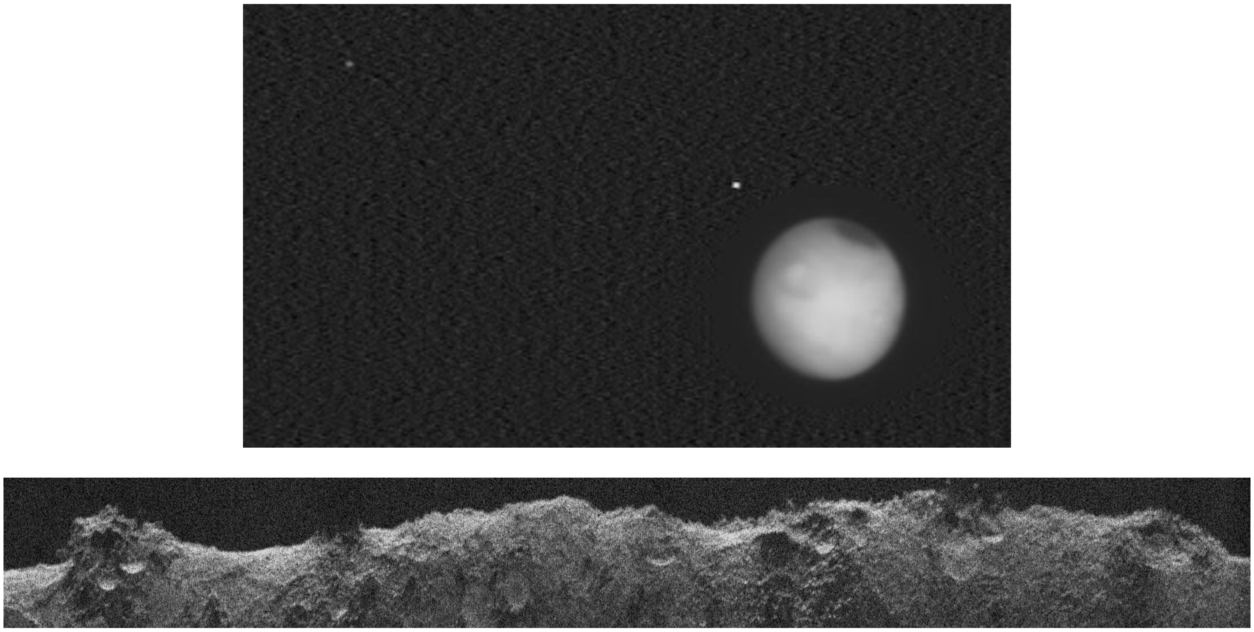


Figure 13. Mars flyby activity reporting. Top: E-THEMIS Infrared composite image of Mars, including Phobos and Deimos. Bottom: REASON radargram of 900 km groundtrack near Mars equator.

F. Earth-Point Inner-Cruise

EPIC phase planning (revising the baseline Mission Plan) benefitted from the shared experience of working through FSC1, FSC2, LDR, and the Mars flyby. From this, there were (a) revised estimates of durations and data downlink for baseline activities, (b) identified needs for new activities, (c) calibrations of team throughput rate for parallel activity preparation and execution, and (d) gradual addition of matured activities to the background sequence. Higher visibility FS activities in EPIC to date have included:

- First EGA targeting maneuver (EGA-TRG-1).
- Updating onboard Flight Software to Release 10.5.—This update addressed findings from pre-launch testing and post-launch experience in Avionics, Fault Protection, GNC, and Thermal subsystems, as well as some cross-cutting items and the new “Canary Box” subsystem.
- First round of in-flight “self-compat” tests—These focused on Electromagnetic Interference/Compatibility (EMI/EMC).
- Initial checkout of the “Canary Box”—The Canary Box (an assembly comprising several MOSFET devices, mounted to Europa Clipper’s vault) serves as a potential investigation, trending, and alert system for MOSFET health. This information could be used during tour to inform the state of equivalent MOSFET applications within the FS and decide whether operational changes are needed to mitigate MOSFET risks.
- First conjunction period—Conjunction period (Sun-Earth-Probe [SEP] Angle <3°) spanned 28 September to 8 October with minimum SEP (1.25°) on 3 October. Class 2 CCSDS File Delivery Protocol (CFDP) Downlink (data product playback via Ka-band) continued through most of conjunction. As expected,[8] (a) CFDP acknowledgements from ground were inhibited until after conjunction, and (b) the number of open transactions grew until after conjunction. Telecom/CFDP worked well; nonetheless, some interesting findings about CFDP performance required some cleanup.
- Additional instrument and FS subsystem maintenance, checkouts, test activities, and calibrations.

[*****] https://www.jpl.nasa.gov/images/pia26567-europa-clipper-captures-mars-phobos-and-deimos/

[†††††] https://www.jpl.nasa.gov/images/pia26568-europa-clipper-team-produces-radargram-from-mars-flyby-data/

V. Spacecraft and Subsystem Activities and Performance

Through the activity phases to date, the spacecraft health and status have been and continue to be nominal. The Spacecraft team has been operating the FS and monitoring performance with established procedures and policies. The highest-value steps in establishing understanding of performance include (a) the activity development process (see Section VII), (b) on-console operations, and (c) post-activity telemetry review.

A. Spacecraft Team Adjustments and Review Activities

The Spacecraft team was deeply staffed with engineers involved in the design, implementation, and pre-launch testing. After the successful launch and early operations, much of the first year has been focused on documenting, training, and role consolidation as the team safely transitions to a smaller size appropriate for quieter cruise operations. Subsystems have updated procedures based on in-flight experiences. Subsystem-level training has also been progressing as spacecraft activity development has decreased. Operations chair duties are and continue to be consolidated across the roles of Flight Director, Systems Lead, Downlink and Data Management (DDM), and Mission Control or "ACE" chair roles.

Trending reviews have been held across all subsystem areas, starting at a bi-weekly cadence, and are now at a quarterly pace. Subject matter experts serve as reviewers, and notable findings are addressed and tracked. In addition, there have been activity-focused reviews (Post-Execution Activity Assessments, or PXAs), which have provided opportunities for more detailed data review and have been a springboard for lessons learned to be rolled into future activity instances. Also, consumables tracking processes are in effect (e.g., reaction wheel revolutions, valve cycles, solar array articulations); all consumables to date are within expected ranges.

B. Subsystem Health and Status Summaries

1. Avionics/Flight Software

Regularly scheduled activities (NAND power cycles, monthly maintenance, backup Europa Compute Element [ECE] syncs, file system checksums) all completed nominally. Key metrics (e.g., time synchronization/drift, Central Processing Unit [CPU] utilization, interface health, memory errors, hardware voltages, temperatures, Bulk Data Storage (BDS) performance, REU performance) are nominal, with minor errors safely dispositioned and changes correlated to other spacecraft activities. Pre-launch Flight Software release R10.4.3 was successfully updated to R10.5.

2. Guidance, Navigation, and Control

Seventeen of 19 planned activities through Mars flyby were completed nominally; two were deferred due to scheduling and staffing circumstances (see Section VIII). Maintenance activities continue nominally. Most nominal GNC functionality has been exercised (15 of 18 nominal operating modes at time of Mars flyby). Consumable consumption rate is nominal; the prime mission is expected to conclude with margin. Many routine maintenance actions and functions have been exercised (e.g., maneuvers [Table 1], hardware calibrations, RWA unbalanced biases, parameter updates, solar array articulation, vector loads, and data product collection); and other functionality demonstrated after 2 AU crossing (e.g., solar array Sun tracking, RWA swap, RWA balanced biases). Overall, GNC hardware and software are performing nominally.

3. Telecom

Post-launch radio frequency (RF) checkout and telecom reconfig completed nominally; Ka-band "toe-dip" and checkout completed after passing 2 AU in EPIC phase. Various telecom configurations were used to enable real-time communications for activities with attitude changes (e.g., early TCMs, various GNC calibrations, Mars flyby, HGA bursts). Downlink is performing ~3 dB better than pre-launch predictions. Hardware thermal and power properties are within expectations; there are no significant issues with any antenna/rate combination. Provided 10 bps downlink after FS reset per plan for the R10.5 Flight Software update. Ka-band (downlink) rate-stepping has been demonstrated, and this will be included as part of the background sequence process.

4. Downlink and Data Management[‡‡‡‡‡]

The DDM team adroitly made post-launch adjustments. They updated CFDP timer values to support lower data rates in late-FSC2 and LDR, and again to support HGA bursts. They updated the data product configuration table to flag data for auto-compression, which facilitated FSC instrument checkout activities as well as activities during the LDR duration. All telemetry selection rule files[§§§§§] were also updated to respond to team needs.[******] Through the

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[‡‡‡‡‡] Europa Clipper was the first JPL mission to use Class 2 CFDP protocol for uplink and downlink. APL prior experience facilitated adoption of this capability.

[§§§§§] Sets of on-board logic-based rules that determine the type of channelized telemetry to be downlinked and its priority.

[******] Including the additions of the mirthfully named "franken6500" (for HGA bursts and other high downlink rate periods) and "zippy_clippy" (developed for the R10.5 Flight Software update).

Mars flyby, over 6 GB of data products (comprising over 5,500 files) were produced and downlinked, including 0.68 GB of filtered instrument data through the BDS; on-board auto-compression of data products reduced downlink volume by 1.3 GB; ~10 GB of instrument data were recorded to the BDS and held for filtering and downlink after passing 2 AU; and uplink CFDP class 2 has had over 1,200 transactions with none failed.

5. Fault Protection

There was a light set of adjustments to fault protection. Parameters were updated per plan after the launch behavior and frequency identification, after a change in uploss timer strategy, and to improve SRU performance (Section V.D). Around 90% of the monitors have been active in flight; those that have not are mostly associated with configurations not yet exercised and/or hardware not yet powered on. At the time of the writing of this manuscript, there have been no system responses and only a small set of local responses. All error counts have been trended and safely dispositioned. Uploss timer settings have been safely managed in response to changing conditions and activities (this will be touched upon in Section VIII).

6. Power

Battery setpoint management was key to first-year activities. Time spent at 100% battery state-of-charge (SOC) is treated as a consumable. Per the plan, SOC was brought down after launch to a cruise setting of 60%. It was subsequently brought back to 100% temporarily for the Mars flyby (and subsequent eclipse) and as well for the R10.5 Flight Software update. Performance to date for 100% SOC is to plan with healthy margin.

Average load power is within model predictions, while some post-launch changes are being assessed. Power converter efficiency is as expected (averaging 89%), as are solar array power margin, bus voltage telemetry, bus balance trending, and battery temperature trending.

7. Propulsion

Nominal execution of characterization activities (tank pressurization, iron nitrate flush, frequency identifications), maneuvers (Table 1), and background activities (RCS deadband control, RWA momentum dumps). Both engine sets reported nominal performance; maneuver engine performance demonstrated nominal durations and small errors. active pressure control performance (response rates, cutoff thresholds) is nominal. There are no concerns with consumables tracking (valve cycles, throughput, propellant consumption). Overall, all hardware has been exercised and is performing nominally.

8. Thermal

Post-launch activities (pump transitions, heat redistribution system [HRS] maintenance) completed nominally. HRS trending shows a steady pump current draw, with pressures and temperatures well within nominal ranges. Spacecraft temperature trending has shown continued (but slowing) decreases with increasing Sun range this year. Overall, in-flight performance is nominal and within accepted model analysis uncertainties; ongoing model updates are in progress to further improve correlation of key components and incorporate post-flight changes.

9. Radiation Monitor

RadMon was turned on at Launch+4 days as part of FSC1 activities. Its checkout was delayed (Section VIII) but was completed after the Mars flyby. RadMon has remained on since then and has operated nominally with no issues. No noticeable total ionizing dosage increase has been observed to date, nor have any transient charge rate monitoring events yet been detected.

C. Spacecraft Anomaly Responses

The Spacecraft team is continually assessing operations for mission risk as well as identifying, assessing, and resolving anomalies. Incident, Surprise, and Anomaly (ISA) reports are the primary means by which such events are communicated across the team and with Operations Mission Assurance, Mission Management, and other stakeholders. On some occasions, when a timelier triage is needed, an Anomaly Response Team (ART) is formed to further assess root causes and develop spacecraft, instrument, and mission recovery plans. ISAs and ARTs are also used to track work beyond spacecraft operations (see more in Sections VI and VII).

A small number of spacecraft-related ARTs were convened during this first year of operations; two warrant mention here.

1. IMU Fault Detection Anomaly

The launch version of the flight software was found to not properly handle an IMU error flag; “bad” IMU data could be treated as if it were “good,” potentially rendering some fault protection ineffective. The ART team in this case expanded their scope to (a) include potential related IMU and SRU issues and (b) respond to recommendations made by GNC and Flight Software technical advisory groups. There was a small (likelihood) risk while operating below 2 AU that if the IMU “lied” the FS would drift away from the planned pointing orientation, resulting in thermal excursions to the spacecraft or instrument hardware that would violate temperature limits.

This "IMU/SRU" ART, working with the GNC Technical Advisory Group, made recommendations for how to operate until the flight software could be updated. Recommendations included adjusting a Sun-loss timing parameter to make up for the potentially ineffective fault protection; sequencing behaviors to force a return to intended (background) attitudes after particular off-Sun activities; and swap SRU optical heads. Ultimately, this issue was corrected with the update to Flight Software release R10.5.

2. Higher than Expected Rate of Correctable Errors in EMEM NAND

The ECE Europa Memory (EMEM) and BDS NAND were experiencing correctible errors that were higher than expected by pre-launch analysis but in family with what was observed during thermal/vacuum testing. The system can correct for much higher rates than have been observed to date in flight. Per the "NAND" ART, there was no immediate concern to FS operations, and the vehicle is expected to be safe for the remainder of the mission. In-flight activities are planned to gather more diagnostics to further assess root-cause possibilities and allow for continual monitoring of the NAND throughout the duration of the mission. Additional ground testing is being done to help assess the likelihood of the correctable errors getting worse over time in the space environment and attempt to narrow down the root cause.

D. Spacecraft Lessons Learned

Based on early Europa Clipper spacecraft and subsystem experiences, lessons learned that should be applied to future operations and future missions include:

- *Multi-center (APL/JPL) partnership*—Sharing multi-center state-of-the-practice experiences has been mutually beneficial. On-console activities are led and conducted from operations centers at both institutions. The team has demonstrated strong and positive collaboration throughout all activities and investigations (more in Section VIII).
- *Tactical telecom approach*—Maintaining a tactical ability to increase data rates as understanding of the telecom performance evolved was key for the prompt return of risk-reduction characterization data prior to entering LDR. Similarly, the evolving telecom performance allowed for the rapid execution of activities beyond planned data rate levels.
- *CFDP*—Use of Class 2 (fully acknowledged uplink and downlink) CFDP has autonomously handled many of what would have been manual retransmissions of data, saving countless hours of manual definition, preparation, and execution of commands, through a changing range of uplink and downlink data rates.
- *Growing background sequence utilization*—With every planning cycle the background sequence now handles more routine activities (see Section VII.D). This also saves countless hours of on-console operations, allowing the spacecraft to execute activities autonomously and enabling the team to focus more on future activities.
- *Chair consolidation*—As the Spacecraft team staffing reduces to a smaller size for the remaining years of cruise operations, on-console chairs are cross-training and consolidating their roles (see Section V.A), ensuring suitably robust functional coverage.

VI. Science Instrument Commissioning

By the time of the Mars flyby, all instruments had been powered on in flight, and there had been successful deployments of REASON's HF and VHF antennas, ECM, EIS's NAC launch lock, and Europa-UVS's launch locks and detector door. There have also been successful checkouts of all instruments, and as stated in Section V, activity development, on-console operations, and post-activity trending and review (e.g., PXAs) have been helpful in accruing understanding of instrument performance.

A. Investigation/Instrument Health and Status Summaries

1. ECM

The following activities were all completed nominally: Pre-Deployment Aliveness Test, Boom Deployment, Post-Deployment Checkout and Interference Check, and Magnetic Background Calibration. Three items are of note:

- ECM was able to measure the total rotation of each of the three fluxgates and determine that the boom had completely deployed.[9] In addition, "boom shake" was observed when the boom reached full extension. The frequency of the boom shake at each of the fluxgates was consistent with the normal modes of the boom at each sensor location.
- ECM observed a noise increase shortly after spacecraft transition to RWA, ultimately determined to be a measurement of the space environment (and not related to the RWA or the FS).
- ECM thermal control has required adjustments to the control limits, and there is a small thermal risk should the FS reset while ECM is turned off. Therefore, ECM has been turned on for the time being.

2. EIS

Both the NAC and WAC have had nominal post-launch checkouts, with nominal thermal and power/voltage performance. The (body-fixed) WAC will have its cover deployment in spring 2027 after Europa Clipper passes through 2 AU for the last time, and the (gimbaled) NAC will have its cover deployment later in the year after passing through 3 AU.

3. E-THEMIS

E-THEMIS had a nominal post-launch checkout; the science review of instrument health and safety telemetry indicates the instrument is healthy. The major instrument event of this first year was the Mars flyby point-source calibration (Fig. 13).

4. Europa-UVS

In addition to the successful deployments, the low-voltage commissioning was completed nominally. The high-voltage commissioning was started in January, but completion was delayed due to the Eaton fire until May (see Section VIII). The completion of the commissioning was less convenient due to the longer round-trip light time; waiting until passing 2 AU (and having more continuous HGA Earth-pointing) ameliorated this somewhat.

5. G/RS

G/RS utilizes the telecom subsystem along with the DSN to collect radio Doppler measurements. G/RS measurements are nominal and within key performance requirements (e.g., 1-sigma accuracy of <0.1 mm/s at 60 sec count interval for SEP >30°). Using the DSN's Open Loop Receiver (OLR), the G/RS team provided engineering support to Telecom for initial acquisition at launch, early antenna changes, and the RF checkout and Mars flyby (the latter as an end-to-end Instrument Operations Team (IOT) exercise with no science being performed).

6. MASPEX

Limited low-voltage checkout was completed nominally. External heaters were successfully handed over to Operational Control Mode; the instrument warmed up to operational temperature range. Low-voltage power supplies were successfully enabled, and the High Conductance Valve and internal heaters were successfully operated. The first mechanical maintenance activity (operating the Cryocooler) was successfully performed. The MASPEX door opening is scheduled for 2027 (after passing through 2 AU for the last time).

7. MISE

The scan mirror homing (at Launch+16 days) and post-launch checkouts were completed nominally with some minor anomalies, which were quickly dispositioned (see Section VI.B for additional context). Thermal performance agrees with model predictions, as does power usage and (test pattern) data noise levels.

8. PIMS

Post-launch checkout completed nominally. At the time, PIMS observed a "feature" in their checkout data. The team requested to collect more data in late March, coordinating synergistic observations with Parker Solar Probe. Analysis is continuing, and ongoing operations are being coordinated with ECM.

9. REASON

In addition to the successful deployments and Mars flyby Engineering Functional Checkout Test, REASON conducted an OVRO Active VHF Antenna Characterization (results are pending). There are no commanding, power, or thermal issues or concerns. Transmitter power levels are within expected ranges, and receive-only data power levels are within 2–3 dB of numerical expectations.

10. SUDA

SUDA passed all checks. Thermally, the operational heater checkout was nominal, as was the subsequent handover from the spacecraft-controlled survival heaters to the SUDA-controlled operational heaters. Power draw is as expected, as is the high-voltage checkout. The SUDA door deployment is also scheduled for 2027.

B. Instrument Anomaly Responses

A small number of instrument-related ARTs were convened during this first year of operations; two warrant mention here:

1. MISE Scan Platform Anomaly

Sporadic mechanical stalls of MISE's scan mirror were expected prior to launch. In response, an effective autonomous scanner recovery macro was implemented. However, during post-launch checkout, it was found that the recovery macro did not clear a stall event. The root cause was tracked down to an idiosyncrasy and bug in the MISE flight software; corrections are underway.

2. ECM Fluxgate Thermal Behavior Anomaly

A parameter update activity for the fluxgate sensor heater setpoints resulted in an unintended rapid rise in temperature. It was also found that fluxgate temperatures were found to be colder than those expected by the pre-launch thermal model. Furthermore, one of the fluxgates showed a temperature oscillation. The ART convened for these issues and provided recommendations for how to more closely manage ECM thermal control as a function of heliocentric distance, FS activity, battery SOC, and FS attitude. ECM heater setpoints and deadbands were revised, which resolved the issues.

C. Instrument Lessons Learned

At this point, the project is still moving into phases with increased focus on instrument activities (remaining deployments, calibrations, etc.). Early in operations, it was safe and efficient to have the investigation IOT members support initial activities in the Mission Support area. As the project now performs instrument activities on a more routine basis, the ongoing Science/Instrument Operations Working Group series has helped foster cross-pollination across the IOTs and with the Science Planning Operations Coordination (SPOC) team.

Also in the first year, in addition to ongoing instrument activities, a Thread Test was carried out for a representative tour scenario to bring to light driving needs for the IOTs; this was well-received across the IOTs, SPOC, and Mission System Engineering. This work culminated in a face-to-face meeting across the IOTs at the Project Science Group meeting, which further fostered strong cross-pollination across the teams.

VII. Mission Activity Development Approach

This section describes the evolution of the "what" of Mission Plan activities into the "how" of validated commands and sequences, starting prior to launch and continuing into the first year of operations.[††††††]

A. Original and Revised Approach for Uplink Planning

High-fidelity mission-level simulations early in the Europa Clipper project life cycle informed key spacecraft trades, helped assess impacts to operability, and quantified how well the scientific objectives of the mission could be achieved.[11] From this came a vision for a simulation framework capable of supporting a mission into operations.[12] The approach was seen as addressing challenges facing legacy uplink planning approaches (Fig. 14).[‡‡‡‡‡‡] The intent was to implement and validate enough of this framework prior to launch to be used in cruise operations on a smaller scale; ensuing development during cruise would be needed to complete the system to be used for tour operations.

The GDS design to implement this framework (integrating planning, sequencing, and spacecraft and instrument activity operations) was referred to as Aerie/Merlin. Due to challenges in completing its validation prior to launch, Aerie/Merlin scope prior to launch was narrowed to background sequence support; heritage/legacy tools and processes were adopted for launch and early operations.

With that decision, starting prior to launch and continuing through FSC1, FSC2, and the Mars flyby, the flight product development process had an activity-by-activity emphasis. This was referred to as the FSC Activity Development (FAD) approach and was supplemented with a nascent background sequence. After the Mars flyby, with proportionally fewer "first-time" activities, the project started to migrate to a paradigm in which all activities are either part of or integrated with the background sequence; this is referred to as the Cruise Activity Planning (CAP) process.

[††††††] Ref. 10 elaborates on early cruise operations planning and implementation.

[‡‡‡‡‡‡] Challenges: Initial strategic plans are only implicitly related to final command products, serial planning leads to significant iteration and rework due to dependencies between separately planned activities, and lack of software support for resolution of activity contention and negotiation increases workforce and time required for planning.[13]

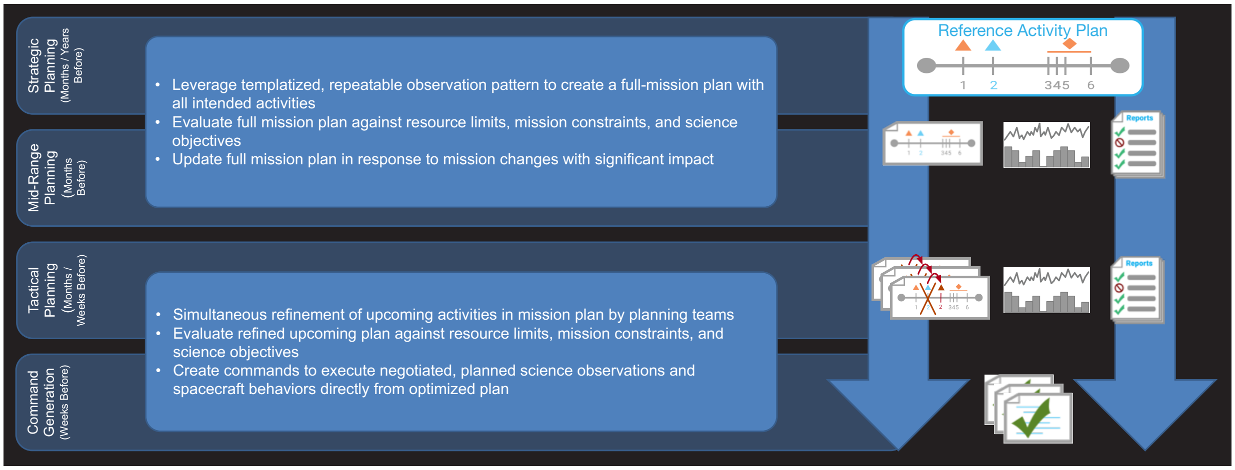

Figure 14. Original Europa Clipper approach for uplink planning.[13]

B. FSC Activity Development Process

Figure 15 depicts the FAD process; all early complex activities and select contingency activities were produced with this workflow. All FSC1 products (through TCM-1 at Launch+20 days) were verified and approved in this manner prior to launch. Furthermore, all critical-path products required for the transition to RWA control (Section IV.C) at Launch+47 days were approved prior to launch as well. FSC product development began in the summer of 2024, with a pause in October (from Launch−10 days through Launch+8 days), thus ensuring the team was ready with key early activity uplink products and able to support said activity execution without the distraction of upcoming product generation.[§§§§§§]

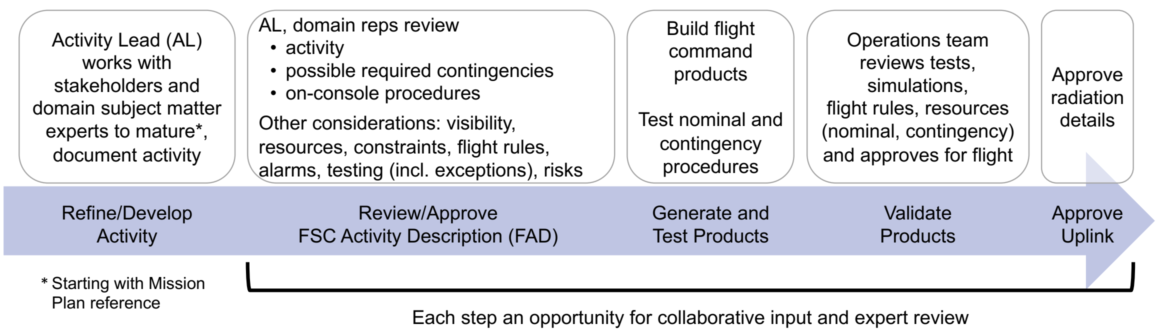

Figure 15. FAD maturation process.

Subphase leads were used for FSC1 and FSC2[*******] to carry out the refinement and implementation of the plans. These leads were responsible for the overall integrity of the phase and individual activities executed therein. Examples of items that were managed included spacecraft configuration changes over time, activity initial and final condition requirements, spacecraft resources, and periodic maintenance schedules. The subphase lead role was key to maintaining awareness of unavoidable state dependencies among activities.

Not quite concurrent with the FAD process, starting about one month after launch, the first background sequence was built, tested, uplinked, and executed. Initially covering the most labor-saving functions (e.g., telecom configuration changes), each successive background sequence has taken on more repetitive functions. Background sequence development uses an approach with up to three passes of increasing maturity/review.

C. General Activity Development Process

In contrast to the more complex/first-time activities, there were activities of a "general" nature that were typically scoped to a single domain or did not appear in the Mission Plan (i.e., had minimal resource impacts). These were

[§§§§§§] FSC processes were very documentation-focused by design, with the intent of establishing a pool of reference material that integrated FS behaviors, command practices, telemetry, and idiosyncrasies.
[*******] Phase leads were used to similar effect for the launch, LDR, and EPIC phases. MGA/MFB also had a subphase lead.

referred to as General Activity Developments (GADs). GADs tended to be reactive to ongoing mission event needs. Examples include:

- Diagnostic commands (e.g., create new downlink data products)
- Onboard parameter or file updates
- Updates to previously approved products (e.g., individual commands that were part of an FSC activity)
- Building blocks that can be used by the background sequence (e.g., maintenance activities)
- Contingency actions (e.g., swap devices)

Given the simpler nature of GAD activities, the GAD process is a streamlined version of the FAD process, intended to simplify product build/test/review while still managing risk (e.g., having all stakeholders review and approve products prior to uplink).

D. Cruise Activity Planning Process

The operations teams accrued shared experiences with the FAD and GAD processes through successful activity execution and review. After the Mars flyby, the teams were ready to shift philosophically from "background + one-at-a-time activity development" to a unified "CAP period" concept. The "quanta" of work products would shift from individual activities to an ensemble of activities spanning a duration (six weeks at present). Everything would be integrated with the background sequence into a unified cruise activity plan (some exceptions would remain); given that, the three-pass approach is still used. Table 2 describes the timing for a given cruise cycle. The subphase lead role and responsibilities transferred over to Cruise Directors for each cycle.

Table 2. CAP milestones.

Milestone	Time Prior to Execution Start	Objective
CAP Kickoff	13 weeks	Approve activity list and resource allocation, process choices
Integration Gate Review	6 weeks	Confirm "Implementation-Review-level" maturity before proceeding with "first pass" of sequence build phase Activities not reaching required maturity removed from plan
Integrated Product Validation Review	3 weeks (Health and Safety follow-up if needed 1 week out)	Approve completion of integration plan, validated by team Authorize proceeding to Command Approval

The team created two measures by which one can see the transition to the more efficient CAP process. Figure 16 depicts the change in the proportion of on-console commanded activities to those running from the background sequence. Figure 17 shows the corresponding reduction of the number of on-console shifts.

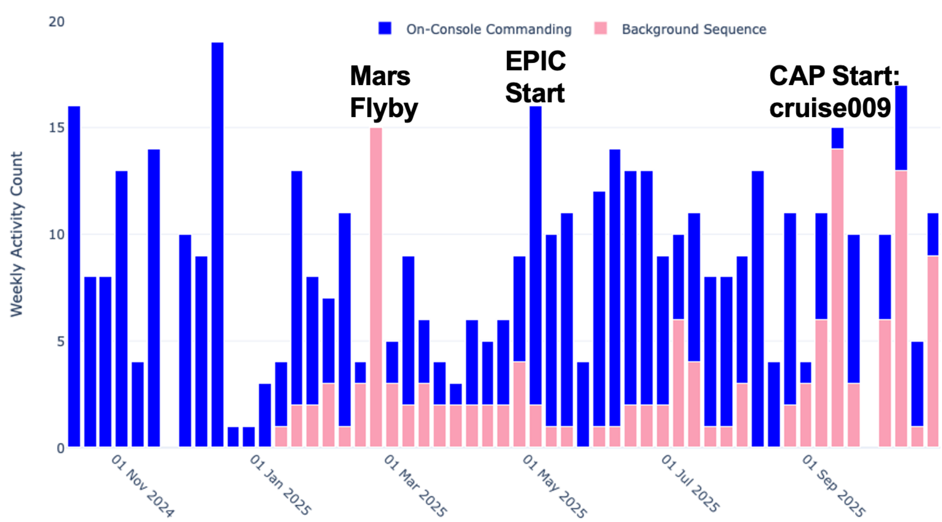

Figure 16. On-console vs. background sequence activities (basic system maintenance activities not included).

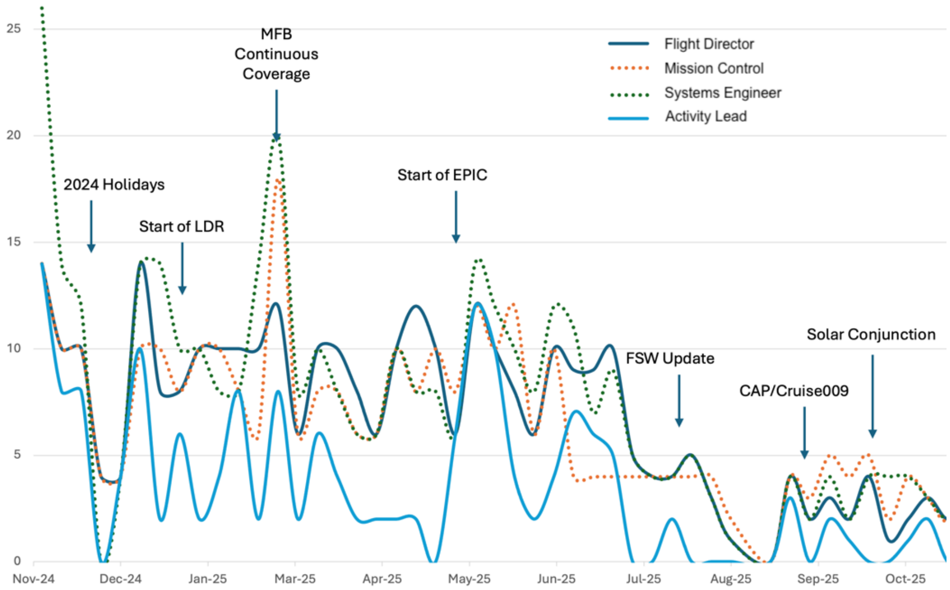

Figure 17. On-console shifts per week for primary roles.

E. Flight Rules

Flight Rules (FRs) are an essential component of activity and uplink product development, validation, and risk management. Prior to launch, FRs and associated constraints learned through testing were incorporated into mission operations controlling documentation. FR work was triaged and prioritized to focus on launch and early interplanetary cruise. Activity compliance with FRs was performed through manual inspection or more automatically with software tools (depending on the nature of the FR).[†††††††] Stepping back after the MGA, it was becoming evident that communication across Flight Operations to add or update FRs, as well as readiness of the corresponding FR enforcement tools and procedures, could be streamlined. In response, the project transitioned FR documentation, definition, implementation, and verification and validation tracking to JIRA, a commercial agile project management tool, as its issue tracking features align well with FR management use cases. Table 3 describes the FR categories and current totals.

Table 3. FRs, guidelines, and idiosyncrasies.

Criticality	Description	Number
A (FR/Constraint)	Risk of significant impact to the FS or the mission. Violations may result in damage to the hardware, loss of Level 1 Science objectives, and/or risk of spacecraft safing.	252
B (FR/Constraint)	Risk to mission return. Loss or delay of data but still meeting overall objectives. Includes risk of instrument safing, if there is no subsequent risk of hardware damage or spacecraft safing.	170
C (Guideline)	Represents “best practices” for operations. Documents best practice and/or previously tested methodology. Impact of violation does not risk the hardware, mission, or significant amount of data.	237
I (Idiosyncrasy)	Documents behavior of the system that might not be intuitive but is expected for various reasons.	303

F. Lessons Learned

Lessons learned from early operations activity development tended to fall into three categories: processes, communication, and resources.

[†††††††] It was originally envisioned that Aerie/Merlin would have been used to perform a large fraction of the checks; given the reduced scope, more heritage/legacy tools (e.g., SEQGEN) were further adapted for FR checks.

1. Processes

Having the FAD strategic planning and development process for important/first-time activities provided three benefits. First, by limiting the amount of tactical and point-wise builds for baseline activities, the operations teams could use tactical processes as intended for surprises, misses, and anomaly resolutions (e.g., demonstrated near-term needs). Second, having tested activity products "on the shelf" pre-launch helped the team build confidence in achieving the execution schedule. Third, the team was able to keep descope and anomaly response plans "close to their heart" throughout the FAD process; even when more plausible anomaly drivers diminish in likelihood, anomalies outside of the technical planning scope can still occur (see Section VIII).

Another process lesson learned came in the transition from FAD-focused to CAP-focused operations. The team was able to simplify and streamline activity development processes as first-time capabilities continued to be realized and execution risk decreased. As part of this evolution, the team would evaluate whether the documentation of the first/early instances sufficiently addressed the knowledge retention needs of the mission (see Section IX) and identified key areas where this approach will need to continue.

2. Communications

While the various forms of communication have not been mentioned (texts, emails, workflow collaboration tools, etc.), one that stood out was having a (first daily, now weekly) Flight Timeline meeting. In addition to communicating status and short-term paths forward, it was an effective venue to quickly triage and disposition any surprises and/or anomalies in the context of the near-term planned execution schedule.

3. Resources

Having the extended team in place in preparation for the activities from launch through TCM-1 was beneficial for final activity preparation and potential anomaly investigation/resolutions. And as with other missions, having continuous DSN coverage enabled flexibility in shift timing to accommodate real-time visibility needs as well as staffing flexibility.

Finally, having a strong pool of Activity Leads (ALs) has been instrumental in the success of the operations phases to date. ALs refine activity scope, develop the products and procedures, test the products, and manage their respective activities to execution (on-console if necessary) in-flight. Many ALs accrued experience in testbed sessions during Assembly, Test, and Launch Operations (ATLO); this experience was key in achieving the ambitious objectives of the early mission phases and subphases, which also reduced risks to ensuing cruise operations.

VIII. Anomalies, Challenges, and Responses

A. Incident, Surprise, and Anomaly Reports

Some of the more formidable spacecraft and instrument challenges (i.e., requiring the convening of an ART) have been described in sections V.C and VI.B; they are part of a larger set of anomalies that the project has detected and addressed to date. Figure 18 describes the logged ISA reports, broken out by type and status. A large fraction of the anomalies has been found to be related to minor problems (e.g., newly characterized idiosyncrasies in the FS and ground software); these have been resolved with simple configuration changes, procedure updates, and/or updates to FRs. There were, however, a small set of anomalies (including issues detected pre-launch) that required a Flight Software update as part of the resolution process; the majority of these were closed with the update to Release 10.5.

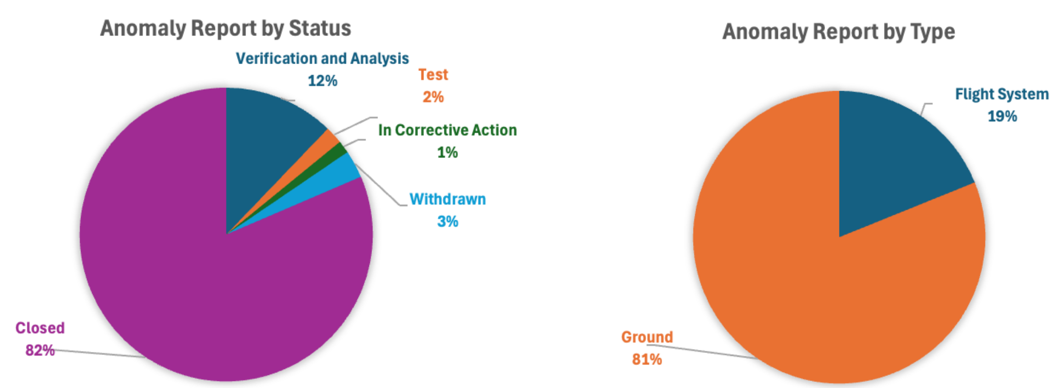

Figure 18. Europa Clipper first-year inflight anomaly statistics.

B. JPL High Winds and Eaton Fire Incident

The most significant challenge to Europa Clipper operations to date has been the Eaton fire, caused by high winds in early January. The fire began on the evening of Tuesday, 7 January 2025, in Eaton Canyon in the San Gabriel Mountains, northeast of JPL. A powerful Santa Ana wind event drove the fire into foothill communities, particularly Altadena, where many JPL employees reside.

This was the first full week of the calendar year. MSA-East at APL had been closed Monday and Tuesday due to a powerful blizzard (unofficially named Winter Storm Blair). Members of the Europa-UVS IOT were at MSA-West that week conducting their instrument High Voltage checkout. The ensuing timeline follows (all times Pacific Standard Time [UTC-8:00]):[‡‡‡‡‡‡‡]

- *Tuesday, 7 January (early morning)*—Due to high winds, JPL employees were encouraged to work from home Tuesday and Wednesday. MSA operations were underway; most team members were given the opportunity to leave as appropriate.
    - Per practice at this point, Europa Clipper was operating with a Command Uploss Timer of five days, expiring early Sunday, 12 January (08:24 am).
- *Tuesday (late afternoon)*—FS operations for the day concluded nominally. Mission Management, with project concurrence, decided to have a midday start on Wednesday (by which time the winds would have abated) with minimal on-Lab staff in MSA-West. Remaining team members returned home.
- *Tuesday (early evening)*—The Eaton fire event began in the Altadena/Pasadena area.
    - By late evening, JPL directed mandatory telework for Wednesday, save for designated personnel. Europa Clipper halted spacecraft operations, abandoning the delayed start proposed earlier that day.
    - Throughout the night and into the morning, the high winds and fire impacted neighborhoods near JPL as well as JPL itself. Hundreds of project team members, including JPL colleagues and retirees, were evacuated overnight, many of whom lost their residences or sustained significant damage (Figure 19).[14]
- *Wednesday, 8 January (shortly after 6:00 am)*—For safety, JPL management decided to completely evacuate the Laboratory within the hour. Europa Clipper operations issued shutdown commands to project venues, including MSA-West. The MSA-West building was shut down as well as most of JPL's Space Flight Operations Facility.
    - JPL leadership emphasized prioritizing safety of all employees and their families.
    - Email and Microsoft Teams services remained stable except for email list groups, which were out of order until Friday that week.[§§§§§§§]
- *Wednesday (~8:30 am)*—DSN started activating their Emergency Control Center (ECC) at the Goldstone complex in response to the fire. ECC team personnel as needed/available drove to the Goldstone complex; the ECC was fully activated by later that afternoon.
    - Staff at MSA-East returned on-site after Winter Storm Blair.
    - MGA-TRG originally scheduled for 11 January was cancelled.
    - Europa-UVS IOT members were released and soon after safely returned to their home areas.[********]
- *Wednesday (early evening)*—Communicating with the operations leads, the team triaged near-term priorities (i.e., take care of yourselves and only after that do what is necessary to recover in time to execute the maneuvers needed to perform the MGA and ensure FS health and safety). FS safing, while undesirable and a first for the mission at this point, was a "next-level" priority.
- *Thursday, 9 January (morning)*—Given that the start of the LDR activity phase was only 16 days away, operations priorities continued to be elaborated upon as follows:
    - Activities that <u>must</u> be done to ensure FS health in LDR
    - Activities that would incur substantial cost/schedule risk (or known impact) if not performed at this time
    - Activities that incur moderate risk if not performed
- *Thursday (late afternoon)*—Project provides a plan restoring the Europa Clipper Operations venue, including storage, server, and service dependencies; a restoration timeline (using minimal on-Lab support); and uploss timer radiation options.

[‡‡‡‡‡‡‡] DSN portions of the timeline provided by Jim Buckley, DSN Manager, in a JPL "Mission Chronicles" briefing.
[§§§§§§§] This caused delays to email announcements to larger team/project distributions, which was mitigated by explicitly addressing all team members in emails in the interim.
[********] The High Voltage checkout was completed in May; the longer round-trip light time resulted in a longer execution period.

- *Friday, 10 January (2:00 pm)*—DSN essential functions were conducted from the ECC from the time it was fully activated until Friday at 2:00 pm, when DSN Operations were relocated back to JPL. DSN Operations personnel were relocated to the Peraton Operations Center in Monrovia, CA, at that time.
  - APL team members working from MSA-East reset the Command Loss Timer for 14 days.[††††††††]
  - The team established a first cut of the high-priority activities for execution prior to LDR.
- *Tuesday, 14 January (afternoon)*—Remaining Europa Clipper venues brought back online. Project revises the epoch for the MGA targeting maneuver to 30 January (with a new "MGA-TRGa" label for all products).
- *Wednesday, 15 January (2:00 pm)*—DSN operations personnel were relocated to JPL Spaceflight Operations Facility in a return to nominal operations.
- *Thursday, 16 January*—Access to JPL continues to remain restricted to personnel performing critical tasks that cannot be done remotely.
- *Tuesday, 21 January*—JPL open to any personnel who needed to be on site, though telework was strongly encouraged.
- *Tuesday, 28 January*—JPL fully reopened, holds Community Gathering to honor JPL's dedicated community efforts to support the Lab and one another in response to the fires.
- Family home recovery and rebuilding efforts continue through the present.

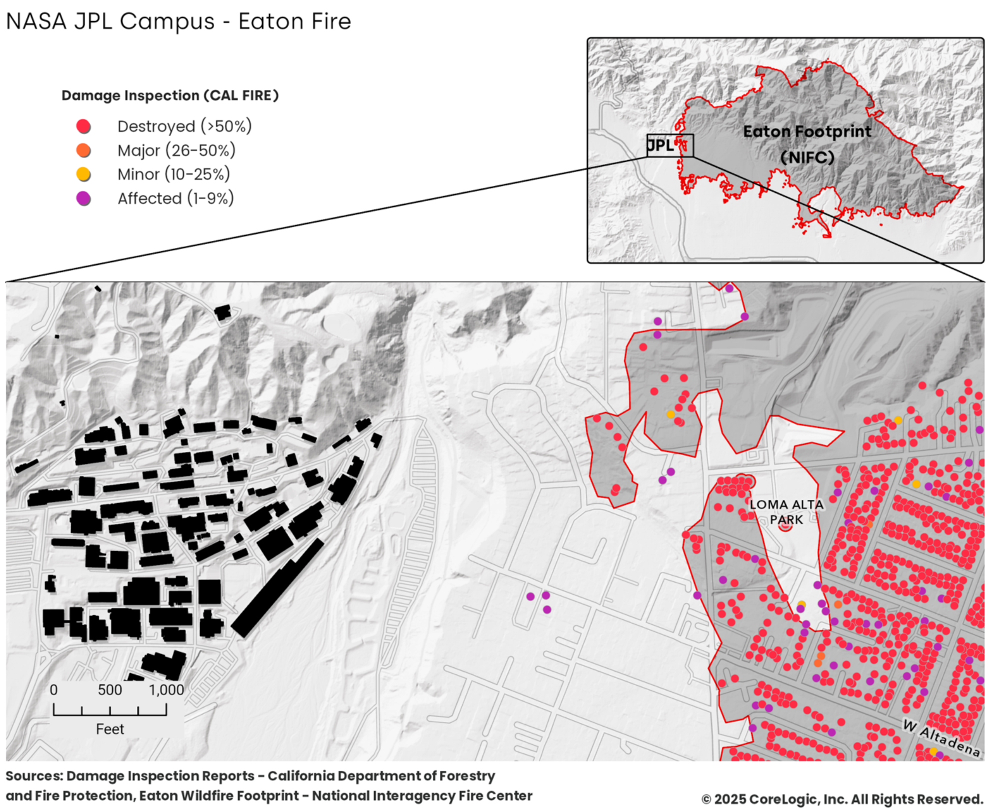

Figure 19. Eaton Fire Structure Status, Proximity to JPL.

C. Incidents Lessons Learned

1. ART Interaction with Flight Operations

As can be seen in Fig. 18, most of the incidents have been successfully addressed and closed. The model of using the ART (staffed with people not immediately on-console) facilitates in-depth analyses and determinations of root cause and mitigation steps, leading to timely closures of key ISAs. In other cases, once the root cause is better understood, the ART turned over ownership of the issue resolution steps to the Flight Operations team. This promoted strong "ownership of the problem" behaviors for the team members (e.g., better knowledge transfer to other and future team members).

[††††††††] In parallel there was a safe mode recovery team starting to assemble the safing recovery strategy that ultimately was not needed.

2. *Continuous Prioritization*

Team leads are encouraged to report status and prioritize concerns in the following manner: (0) Personnel Health and Safety, (1) Flying System Health and Safety, (2) Terrestrial System Stability (and efficiency improvements), (3) Flying System Nominal Operations, (4) Strategic Operations, and (5) Resource Management. This ordering proved effective in tactically dealing with the facility and team impacts during the fires.

3. *Prior Planning (MSA-East–MSA-West Operations)*

The Europa Clipper GDS design, supported by tabletop exercises between APL and JPL engineers prior to launch, supported the scenario of having MSA-West in an off-nominal status for multiple days. The planned response was for MSA-East personnel to physically access MSA-East to perform Health and Safety functions with support from MSA-West personnel as possible; this went to plan. More scenarios will need to be exercised before reaching Jupiter.

4. *Uploss Timer Management*

The project had been using shorter uploss timer durations, driven by the desire to not lose much time and go right to safing should an FS problem occur. The possibility of ground system problems resulting in loss of contact (and thus driving longer uploss timer durations) was examined prior to launch (see above) but could have been given more weight when the threat of winds was first announced in early January 2025.

IX. Major Takeaways and Path Forward

One year after launch, the Europa Clipper FS is healthy, stable, and performing in a predictable manner. All instruments have been turned on and have completed basic functional checks. Some have been checked out in more detail (ECM, PIMS, E-THEMIS, REASON, and Europa-UVS), yet others have completed intermediate checks (MASPEX, EIS/NAC and WAC, MISE, and SUDA). The spacecraft and instrument operations teams continue to mature and evolve cruise processes for developing commanding sequences; this will evolve over cruise into the tools and processes that will be used in the Jupiter tour. Several trajectory correction and targeting maneuvers have been executed with excellent performance by flight and ground. A handful of technical issues have been identified and addressed. Amid this, the Flight Operations team size has settled at cruise staffing levels while supporting a variety of ongoing spacecraft and instrument activities; training strategies and documentation are used to ensure appropriate knowledge retention during this long-duration mission.

The project has transitioned from the early phases/subphases (e.g., FSC, MGA) to EPIC. With the accrual of shared experience, the Flight Operations teams are taking repeated activities, such as subsystem and instrument periodic maintenance, and including them in background sequences in each cruise cycle, with more activities added as new activities are completed. Several instrument activities have been implemented through the CAP process with regular interactions between Instrument Operations Teams at their home institutions and the SPOC team. The team has completed their installation of a major Flight Software update (R10.5) that had been in work since before launch.

Looking ahead, the Flight Operations team will continue to implement new spacecraft and instrument activities, with the number of activities picking up significantly in Outer Cruise; the project is looking forward to the opening of covers and completion of instrument characterizations for EIS/NAC and WAC, SUDA, MASPEX, and MISE. The team will continue to refine tools and processes to facilitate day-to-day operations. Steps are being taken to develop the capabilities needed for the science tour (IOT needs are being identified and candidate capabilities are being assessed). This work will progress throughout cruise with a plan to be complete by JOI. For the near future, two activities stand out:

- *Interstellar Object 3I/ATLAS*—The project plans to perform an instrument calibration with this object as a target in early November.
- *EGA*—The project is soliciting possible observations, calibrations, and engineering activities that could provide the most benefit during this flyby opportunity in December 2026.

The above has been successfully carried out under unprecedented challenges. In honor of those affected and everyone who has contributed to mission success, the project uplinked the following message:

> One year ago today, we watched our spacecraft leave Earth and begin its journey.
> Since then, it has performed deployments, maneuvers, observations, and more.
> It has shown us robustness and reliability that we will need for years to come.
> And that success is not just a measure of the quality of a spacecraft design...
> ...but of the dedicated team that has taken us this far.
> Thank you to everyone who has worked so hard to keep us sailing!
> May the rest of the journey to Europa be as smooth as our first year!

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