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Review

Science Overview of the Europa Clipper Mission

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ABSTRACT

The goal of NASA's Europa Clipper mission is to assess the habitability of Jupiter's moon Europa. After entering Jupiter orbit in 2030, the flight system will collect science data while flying past Europa 49 times at typical closest approach distances of 25–100 km. The mission's objectives are to investigate Europa's interior (ice shell and ocean), composition, and geology; the mission will also search for and characterize any current activity including possible plumes. The science objectives will be accomplished with a payload consisting of remote sensing and in-situ instruments. Remote sensing investigations cover the ultraviolet, visible, near infrared, and thermal infrared wavelength ranges of the electromagnetic spectrum, as well as an ice-penetrating radar. In-situ investigations measure the magnetic field, dust grains, neutral gas, and plasma surrounding Europa. Gravity science will be achieved using the telecommunication system, and a radiation monitoring engineering subsystem will provide complementary science data. The flight system is designed to enable all science instruments to operate and gather data simultaneously. Mission planning and operations are guided by scientific requirements and observation strategies, while appropriate updates to the plan will be made tactically as the instruments and Europa are characterized and discoveries emerge. Following collection and validation, all science data will be archived in NASA's Planetary Data System. Communication, data sharing, and publication policies promote visibility, collaboration, and mutual interdependence across the full Europa Clipper science team, to best achieve the interdisciplinary science necessary to understand Europa.

Keywords
Europa; Europa clipper; Ocean; Habitability; Icy moon; Jupiter.

INTRODUCTION

The Scientific Imperative for Europa Exploration

Jupiter's moon Europa may have conditions suitable for life as we know it. Evidence from magnetic induction and geology points to the existence of a global subsurface ocean today (McKinnon et al. 2009), and it is plausible that Europa's ocean could contain the appropriate chemical building blocks and have chemical sources of energy to support life (Vance et al. 2023, this collection). Europa is an ice-enshrouded world with interrelated geophysical processes spanning its deep interior, ocean and ice shell, surface, tenuous atmosphere, and surrounding space environment. For these reasons, the first two planetary science decadal surveys (National Research Council 2003, 2011) ranked Europa exploration as a top scientific priority. Ultimately, in 2015, NASA formally initiated the Europa Clipper project.

This paper provides a summary of the Europa Clipper mission and serves as an introduction to, and synopsis of, the more detailed information found in the accompanying papers of this topical collection. Section 1 summarizes the historical and modern perspectives of Europa science and habitability as the basis for its exploration by Europa Clipper. Section 2 describes the history of major Europa mission concepts, culminating with initiation of the Europa Clipper mission. Section 3 reveals the mission's science goal, objectives, cross-cutting science topics, and high-level requirements. Section 4 summarizes the science instruments and their capabilities and describes science investigations that use engineering subsystems. Section 5 provides an overview of the Europa Clipper flight system (spacecraft plus instrument payload), and Sect. 6 addresses the mission design and operations, including the science planning process, as well as science data products and archiving. Section 7 describes the science team structure and philosophy, including efforts toward equity, diversity, inclusivity, and accessibility. Section 8 notes coordination with ground- and space-based telescopes and other spacecraft missions. Section 9 concludes with an outlook for the mis- sion.

H1.1 Historical Perspective

1.1.1 Telescopic Era

The discovery of the four main moons of Jupiter by Galileo Galilei in 1610, and possibly independently by Simon Marius (Pasachoff and Leich 2015), provided the most convincing evidence for heliocentrism up to that time. Before the era of space-based exploration of the solar system, ground-based telescopic observations of Europa yielded basic information about its orbit, size, density, surface composition, and global albedo pattern (Alexander et al. 2009). About 15% smaller in radius than Earth's Moon, Europa was unique among the Galilean satellites with its highly reflective, relatively featureless surface, in contrast to the reddish color of Io and the lower albedo, relatively splotchy appearances of Ganymede and Callisto (e.g., Morrison and Cruikshank 1974). Water ice was identified on Europa's surface from spectral observations, and its slightly red color was attributed to polysulfide compounds or ice radiation damage (Johnson and McCord 1971).

1.1.2 First Visits: Pioneer and Voyager

The Pioneer 10 spacecraft made the first space-based flyby of Europa in December 1973 at a distance of 324,000 km (Fimmel et al. 1977; Alexander et al. 2009). The low-resolution image obtained showed low-albedo regions emplaced on a higher-albedo background surface.

The two Voyager spacecraft were the first missions to present Europa as a geologic world (Smith et al. 1979a, 1979b; Lucchitta and Soderblom 1982). Voyager 1's closest approach in March 1979 was a distant 734,000 km, but a series of thin, low albedo lines giving the moon the appearance of a cracked egg maintained an aura of suspense for the 206,000 km encounter by Voyager 2 in July 1979. In addition to the two main terrain types—bright, icy plains and lower albedo mottled terrain—Europa was wrapped in a tangle of lineaments. Some were linear, and others were curved, suggesting that they were in some way related to tidal deformation stresses. The moon contained apparently randomly placed pits and dark spots, most less than 10 km across. The surface showed only five fresh, large (10–30 km) im- pact craters (Lucchitta and Soderblom 1982), suggesting a geologically active moon, though it was noted that the smaller pits could be modified impact craters (Malin and Pieri 1986). There was no spectrometer on the Voyager spacecraft suitable for compositional identifi- cations and mapping, but the broadband filters on the cameras defined the color as slightly reddish, possibly due to sulfur-contamination from Io. Voyager's finding of active volcan- ism on Io was famously predicted just days prior as due to tidal heating (Peale et al. 1979), and this piqued interest in whether Europa might be analogously tidally heated, potentially containing a global liquid water ocean today or in the past (Cassen et al. 1982).

1.1.3 The Galileo Mission

While the Voyager data began to define Europa as a geologic world, the Galileo spacecraft hinted at Europa as a potentially habitable world. Galileo entered Jupiter orbit in December 1995 and ended its mission by impacting Jupiter in September 2003, typically making a flyby of one of the Galilean satellites with each orbit. Perhaps its greatest discovery was the near-certain existence of a subsurface ocean below an ice shell today (Pappalardo et al. 1999; McKinnon et al. 2009). Magnetometer measurements implied an induced magnetic moment of 120 nT around the moon, indicative of an electrically conducting layer that is most likely salty, liquid water (Kivelson et al. 2000). The interpretation of data from the Near Infrared Mapping Spectrometer (NIMS) suggested surface compounds related to freezing of liquid water leading to formation of hydrated salts (McCord et al. 1998; Carlson et al. 2009). Galileo gravity data and an inferred moment of inertia suggested an outer H2O-layer (ocean plus ice shell) thickness of 105–160 km (Schubert et al. 2009).

Our current understanding of the geologic evolution of Europa comes primarily from data returned by the Galileo spacecraft (Greeley et al. 1998, 2000; Bierhaus et al. 2009; Collins and Nimmo 2009; Doggett et al. 2009; Kattenhorn and Hurford 2009; Moore et al. 2009; Prockter and Patterson 2009; Daubar et al. 2024, this collection). Among the key findings are the identification of two distinct types of plains on the moon, one bluer in near-infrared reflectance; a complex and extensive system of lineae and bands that is likely in part shaped by diurnal tides; the presence of domes, pits, and low-albedo spots (imaged at lesser fidelity by Voyager 2), which collectively became known as lenticulae; rafting of large ice blocks in regions of chaos terrain; and surface materials with embayment relationships suggestive of emplacement as a liquid or slurry. Europa's geologic features show crosscutting relation- ships that suggest temporal evolution in its style of activity, with the brightest bands being among the most recent features. Dark dilational bands and elusive "subsumption" zones (Kattenhorn and Prockter 2014) demark areas of regional surface extension and compres- sion, respectively. Galileo data confirm that there are a small number of large (20 km) impact craters, suggesting an average surface age of 60 Myr, with a factor of three un- certainty (Zahnle et al. 2003). The exact processes and mechanism of resurfacing, and the relationship to liquid water, are ripe for further study.

1.2 Current Perspective

In the nearly twenty-five years since the Galileo mission returned its first data from Europa, our understanding of Europa, and the hypotheses as to how it operates, have matured to a level that warrants a return to Europa for in-depth scientific investigation.

The dearth of large impact craters as described above and the ubiquitous fresh-appearing surface lineaments both suggest a geologically young surface. The general stratigraphy sug- gests a history of early ridged plains formation, subsequently disrupted by the emplacement of bands, followed by episodes of significant and widespread crustal disruption forming chaos terrain (Doggett et al. 2009; Leonard et al. 2024; Daubar et al. 2024, this collection); this sequence suggests thickening of the ice shell with time (Pappalardo et al. 1999). Europa's induced magnetic field implies an extant briny ocean (Kivelson et al. 2000) beneath an ice shell ten to tens of kilometers thick (Howell 2021). Ice shell thickness and potential transport mechanisms have key implications for the exchange of material between Europa's surface and the ocean (Vance et al. 2023, this collection). The thickness and rheology of the ice shell are key controls on the presence and vigor of convection (Barr and Showman 2009) and are related to the distribution, mechanisms, and intensity of tidally dissipated heat (Moore and Hussmann 2009; Sotin et al. 2009). The presence and sustainability of a subsurface water ocean is linked to tidal flexing and internal heating in the ice shell and/or the silicate mantle below (Roberts et al. 2023, this collection). Tidal heating can potentially support volcanic activity on Europa's seafloor (Beˇhounková et al. 2021), which—by analogy to terrestrial sea-floor volcanism—could be a source of chemical reductants for metabolism (Vance et al. 2023, this collection). Europa is a cornerstone in the burgeoning field of icy world oceanography (e.g., Vance and Goodman 2009; Soderlund 2019), an example of the breadth and relevance of Europa and its subsurface ocean to comparative planetological studies.

Galileo infrared data revealed the presence of salts, particularly in chaos terrains where it is distinguished by a reddish color, suggesting active exchange processes operating in recent geologic time between the surface and the interior (Carlson et al. 2009; Becker et al. 2024, this collection). More recent studies are homing in on likely salt candidates, suggesting a key role for sodium chloride and correlation of NaCl with chaos terrains (Hand and Carlson 2015; Trumbo et al. 2019, 2022; Journaux et al. 2023). Recent James Webb Space Telescope (JWST) observations indicate carbon dioxide deposits spatially correlated with the chaos terrains, suggesting an endogenous source of carbon (Trumbo and Brown 2023; Villanueva et al. 2023).

Tantalizing evidence for active plumes on Europa comes from Earth-based telescopic data (Roth et al. 2014; Sparks et al. 2016), and from re-analysis of archived data from the Galileo magnetometer and plasma-wave instruments (Jia et al. 2018). This suggests the pos- sibility of transport of material from Europa's interior to the surface, atmosphere, and space environment, where it could potentially be detected remotely or sampled in situ by a space- craft. To date, JWST observations have not spotted active plumes (Villanueva et al. 2023), but the search will continue. If such Europa plumes are confirmed to exist and to be sourced from the interior, plausibly as sporadically active today, the ability to directly sample plume materials would provide an unmatched opportunity to better understand the interior compo- sition and habitability of Europa (Becker et al. 2024, this collection; Daubar et al. 2024, this collection).

Jupiter's powerful magnetic field, Io's continuous volcanic activity and corresponding torus of charged particles, and the icy Galilean satellites are a coupled system. Assessment of Europa's space environment is key to assessing the interaction between Jupiter's magnetic field and Europa, and measurements of Europa's tenuous and dynamic atmosphere are key to deciphering these interactions. The intense radiation environment modifies Europa's surface composition, and produces oxidants such as O_2 and H_2O_2. The transport of material from Io and interplanetary space, and their impact and implantation on Europa, indicates a need to disentangle compositional signatures that are endogenic from those that are exogenic.

From its interior to beyond its atmosphere, Europa is tantalizing: its vast subsurface ocean, enigmatic ice shell, intricate and bizarre surface features, intriguing surface com- position, dynamic atmosphere, and complex interactions with the space environment make it a high priority for exploration. Atop all of this, the probable presence of the three so-called "ingredients" or conditions necessary for life—water, bioessential elements, and energy— beg for scrutiny of Europa's astrobiological potential.

1.3 Habitability

The potential for finding life on Europa has given new momentum in recent decades to the exploration of ocean worlds in the outer solar system. The first strong indications of a subsur- face ocean at Europa (Kivelson et al. 2000) inspired research into how extraterrestrial oceans might support life even in the absence of direct energetic input from the Sun. Just a cou- ple decades earlier, oceanographers discovered vibrant ecosystems at Earth's deep sea hy- drothermal vents, supported entirely by highly reducing effluents created by the water–rock interactions (Baross and Hoffman 1985; Kelley et al. 2001), and multiple low-temperature metabolic reactions and organisms that do not require light (e.g., methanogens, sulfate re- ductants) have been known long before those discoveries. These revelations converged with direct evidence for plume activity at Saturn's small icy moon Enceladus (Dougherty et al. 2006; Porco et al. 2006; Spencer et al. 2006) and tantalizing evidence for analogous activity at Europa (Roth et al. 2014; Sparks et al. 2016, 2017; Jia et al. 2018), giving rise to a field of study focused on ocean worlds in the solar system and beyond (e.g., McCollom 1999; Zolotov and Shock 2004; Hendrix et al. 2019).

Europa is now suspected to have a global ocean directly in contact with its rocky seafloor, but this alone does not make it habitable. Life as we know it requires a suite of chemical elements and compounds, and the right physical conditions to take hold in an environment, survive, and reproduce. The ingredients for life are commonly defined as liquid water acting as a solvent, bioessential elements (C, H, N, O, P, and S) from which organic molecules can be built, and available sources of energy to support metabolic reactions (Hand et al. 2009). Physical and chemical conditions including a hospitable temperature, acidity, and salinity are also required. The amounts, types, and diversity of life in each setting will be determined by these conditions in terms of rate-limiting materials and supported metabolic processes (e.g., Shock and Holland 2007). At Europa, impacts, pervasive fractures, local disruption of the ice, and potential seafloor water–rock interaction may allow mixing of reductants and oxidants in the ocean over extended periods of time (e.g., Schmidt 2020). Sufficient re- ductants (organic matter, methane, HS^-, H_2) may exist together with oxidants (SO_4^{-2}, CO_2, HCO_3^-) in Europa's ocean to support microbial life as a consequence of water–rock reactions (Zolotov and Shock 2004). Some research suggests that strong oxidants produced through radiolytic processing at the surface may be a limiting factor to support life (e.g., Vance et al. 2016; Russell et al. 2017). Other work notes that reductants may be limited by a lack of fresh rock surfaces, given that faulting may be limited by overburden stress at Europa's seafloor depth (Byrne et al. 2024). The interrelationships of Europa's processes are explored in detail for constraining Europa's habitability by Vance et al. (2023, this collection).

Because an ocean world's habitability is governed by interrelated properties and pro- cesses, characterizing the potential for subsurface life requires carefully orchestrated mea- surements by highly capable instruments and integrated data analyses across disciplines (Vance et al. 2023, this collection). The many studies that culminated in the design and implementation of the Europa Clipper mission (Sect. 2) took place as part of the evolving understanding of ocean world habitability and life, with many mission study participants (including authors of this paper) contributing to the current discourse in the field of astrobi- ology. The mission has a strategized flight system design and concept of operations to ensure all investigations can obtain data near-simultaneously in location and time (Sects. 4.1

and 5).

The goal, objectives, and architecture of the Europa Clipper mission can serve as guide- lines for future exploration of other icy ocean worlds. For example, environments within Europa's ice shell (in addition to its ocean) may be habitable. Are there perched briny chambers in the ice shell that could host life and would those be expected to also form on other icy ocean worlds? Could there be water-filled cracks and pores within the ice shell that rep- resent habitable regions? There could be more habitable niches in our solar system than currently imagined, and Europa Clipper's characterizations of Europa will help constrain how widespread they could be.

2 History of Major Europa Mission Concepts

The initiation of a Europa flagship mission, which ultimately became the Europa Clipper, has a storied past. Neufeld (2021) details this history from a space policy perspective, argu- ing that its initiation was complicated by the new competition-based model of missions of the early 21st century, coincident with initiation of planetary decadal surveys. Brown (2021) tells of the mission's initiation as a popular narrative, from the perspectives of some of the key people involved in the mission's backstory. These are both excellent in-depth summaries and complementary perspectives in understanding the motivations and situations that shaped policy decisions over the 20 years from the first Europa Orbiter studies to NASA's Phase A initiation of the "Europa Multiple Flyby Mission," which subsequently assumed the name Europa Clipper. Figure 1 illustrates the major Europa mission concepts described next.

2.1 Europa Orbiter

Coincident with the first images of Europa from the Galileo mission in mid-1996, NASA's administrator Dan Goldin asked JPL whether a small, dedicated mission could follow up on Galileo's findings at Europa (Neufeld 2021). A small Europa orbiter concept was first considered as a Discovery-class mission (Edwards et al. 1997). In the era of Goldin's "better, cheaper, faster" mantra, this concept evolved into the Europa Orbiter, which aimed to carry just 27 kg of instrument payload to Europa orbit. As technical studies demonstrated the realities of propulsion and radiation shielding requirements for such a mission, the resource needs grew. Following a 1999 community proposal call for instruments (NASA 1999) and subsequent review process, the mission was shelved by NASA in 2002. Most relevant to Europa mission concept evolution, it is noteworthy that the science objectives developed (NASA 1999) by the Europa Orbiter Science Definition Team (SDT) can be directly traced to those of Europa Clipper.

2.2 Jupiter Icy Moons Orbiter (JIMO)

The first planetary science decadal survey (National Research NRC 2003) endorsed Eu- ropa for the highest priority (non-Mars) flagship mission. New NASA Administrator Sean O'Keefe used this as a hook for his interest in the use of nuclear-electric propulsion in deep space. The Jupiter Icy Moons Orbiter (JIMO) mission was envisioned to orbit each of the three icy Galilean satellites in turn, carrying high-powered instruments that would perform a comprehensive study of the icy Galilean satellites and the Jovian system. The science goals and objectives for the mission were formulated by a Science Definition Team (SDT) in 2003 (Greeley and Johnson 2004). The overarching statement for the mission was: Explore the icy moons of Jupiter and determine their habitability in the context of the Jupiter system. The SDT established four goals spanning surface geology and geochemistry, interior, astrobiol- ogy, and Jupiter system. Given the key importance of Europa to understanding the potential habitability of icy worlds, the SDT recommended the inclusion of a Europa surface science package to perform in-situ investigations. With the departure of Sean O'Keefe from NASA, JIMO was "indefinitely deferred" from further implementation in 2005 by Administrator Michael Griffin. The JIMO mission concept collapsed under its own weight, with an esti- mated cost of >$27 B (NASA 2005). Nonetheless, the comprehensive SDT report laid a firm foundation for future Galilean satellite mission studies.

2.3 Europa Jupiter System Mission (EJSM)

In 2007, NASA embarked on establishing a set of four outer planet flagship mission studies that would compete to define the next flagship mission to the outer solar system. The targets for these were Europa, Ganymede and the Jupiter System, Titan, and Enceladus. Following completion of these studies, in 2008 NASA downselected to two concepts and joined ef- forts with the European Space Agency (ESA), with additional involvement from the Japan Aerospace Exploration Agency, to structure joint SDTs that would further develop the Eu- ropa Jupiter System Mission (EJSM) concept and the Titan Saturn System Mission concept. In February 2009, the EJSM concept (Greeley et al. 2010) was selected for continued de- velopment. EJSM envisioned a Jupiter Europa Orbiter (JEO) flown by NASA and a Jupiter Ganymede Orbiter (formerly Laplace) flown by ESA; each would investigate the Jupiter system, taking advantage of synergies and complementarities between the two missions, and each would enter orbit about its namesake satellite. The goal of JEO was to explore Europa to investigate its habitability, and its objectives were categorized as related to Europa's ocean, ice shell, composition, geology, and local environment. However, as NASA under Admin- istrator Charles Bolden was cutting back the planetary science budget (Neufeld 2021), the second planetary science decadal survey recommended that JEO's scope be reduced to make it less expensive (National Research Council 2011). The ESA component moved ahead sep- arately to become the JUpiter ICy moons Explorer (JUICE) mission (Grasset et al. 2013), and NASA's Europa mission concepts returned to the study phase.

2.4 Three Europa Mission Studies

In 2011, an SDT was established that specifically included members who were critical of the JEO concept. This group began with a clean sheet of paper, to consider options for a lower-cost Europa-focused mission. Following the path advised by a Goddard-based decadal survey white paper (Smith 2009), the group considered options of a small and focused Eu- ropa orbiter mission that emphasized geophysics and of a Jupiter-orbiting, multiple-flyby mission that emphasized remote sensing. A third option of a lander was considered as well (Pappalardo et al. 2013). Concepts were to focus on Europa, without the broader Jupiter system science that was a hallmark of JEO and EJSM, and it was accepted that not all the JEO science objectives would be achieved.

The orbiter and multiple-flyby options were based on the premise that science investi- gations best achieved from an orbital mission would be assigned to that concept, and those best suited to a multiple flyby mission be assigned to that concept. For the initial mission concepts, a small orbiter would host a magnetometer, Langmuir probe, laser altimeter, and mapping camera, and it would perform gravity science. The multiple flyby mission would host an ice-penetrating radar, topographical imager, infrared spectrometer, and ion and neu- tral mass spectrometer. The small lander would host a mass spectrometer, Raman spectrom- eter, seismometer, magnetometer, imaging system, and microscopic imager, and the carrier element would include a reconnaissance camera; however, the lander concept was found to be too expensive. Based on the study report's findings (Europa Study Team 2012), and feedback at community town halls, the multiple flyby concept was judged as enabling the greater science return per dollar, compared to the small orbiter concept.

2.5 Birth of Europa Clipper

At NASA's request, a 2012 summer study was undertaken to understand the potential for augmenting the Europa multiple-flyby concept with geophysical capabilities that could im- prove ocean science (notably, magnetometry and gravity); for the small orbiter to augment ice shell, composition, and/or geology science objectives; and for each to include reconnais- sance capability to feed-forward to a potential future lander (Europa Enhancement Science Definition Team 2012). Informally, the SDT began referring to the multiple-flyby mission as Europa Clipper.

The Europa Clipper concept was grounded in the approach exploited by Cassini in in- vestigation of Saturn's large moon Titan: many flybys over time could build up coverage that is analogous to that from an orbital mission (Hansen et al. 2009). In the case of Europa, this approach has the advantage over an orbiter of permitting data acquisition in the intense radiation environment at Europa without subjecting the spacecraft to unacceptable levels of damage, and downlinking those data when in the relatively low radiation farther from Jupiter (Buffington 2014), as had been established by the Galileo mission (Johnson et al. 1992). The Europa Clipper concept explicitly did not include Jupiter system science but was overall quite responsive to most of the JEO science endorsed by the 2011 planetary science decadal survey (National Research Council 2011), thus meeting the survey's challenge for a slimmer and more affordable mission.

Beginning in Fiscal Year 2013, the United States Congress began augmenting NASA's Europa budget relative to the agency's budget requests, as spearheaded by Representative John Culberson of Texas (Neufeld 2021), who is an enthusiastic supporter of Europa ex- ploration (Brown 2021). In 2013, NASA issued a call for Instrument Concepts for Europa Exploration (ICEE 2013), aimed to mature instruments that could potentially fly on a small orbiter or multiple-flyby mission. In 2014, NASA issued an Announcement of Opportunity for instruments that might fly aboard a Europa orbiting or multiple-flyby mission (NASA 2014), ostensibly for a two-step down-selection process. With Bolden's backing, instrument selections for a Europa multiple-flyby mission were announced at a NASA press briefing held on May 26, 2015 (e.g., Showstack 2015), and the Europa Multiple Flyby Mission for- mally entered Phase A on June 17, 2015. The name Europa Clipper was adopted by NASA as the project passed into Phase B on February 15, 2017, just after Robert Lightfoot became NASA's Administrator.

3 Science Goal and Objectives for Europa Clipper

3.1 Science Goal

The search for life beyond Earth is of high scientific priority, and Europa is recognized by all three planetary science decadal surveys as one of the best sites in our solar system to search for extant life (NRC 2003, 2011; NASEM 2022). Europa Clipper is a mission to evaluate Europa's habitability, which can be assessed by focusing on the ingredients necessary for life (Sect. 1.3). The Europa Clipper mission seeks to address the NASA Planetary Science Division's strategic science goal "of ascertaining the content, origin, and evolution of the solar system and the potential for life elsewhere by investigating the capacity of Europa and its deep ocean to harbor life in the past, present, or future" (NASA 2022).

The primary goal of the Europa Clipper mission is stated as: Explore Europa to investi- gate its habitability. Overall, the mission's science plan is hypothesis-driven (encompassed within the phrase "investigate its habitability") while acknowledging the great potential in serendipitous discovery ("explore Europa"). It is important to note that Europa Clipper is not designed to be a life search mission, but it can lay the foundation for future missions such as a Europa lander (Hand et al. 2022) that might be able to directly search for and characterize potential biosignatures. The science team's Habitability Advisory Board (HAB) serves to assess and advise on how the mission's three objectives will be leveraged together toward achieving the mission's overall habitability goal.

3.2 Science Objectives

To evaluate the presence and characteristics of the ingredients for life, Europa Clipper fo- cuses on objectives related to the interior (ocean and ice shell), composition, and geology of Europa. Specifically, the Europa Clipper science objectives are (NASA 2022):

Interior (ocean and ice shell): Characterize the ice shell and any subsurface water, includ- ing their heterogeneity, ocean properties, and the nature of the surface–ice–ocean ex- change.

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.

In the next sections (3.2.1–3.2.3), we elaborate on the three mission objectives, summa- rized as interior, composition, and geology, and how they each map to 15 science "themes" of the mission. Then in Sect. 3.3, we discuss the several cross-cutting science topics, notably the search for and characterization of current or recent activity. The science objectives then flow to the formal Level 1 science objectives for the mission, discussed in Sect. 3.4.

3.2.1 Interior (Ocean and Ice Shell)

The interior-focused objective of the mission is: Characterize the ice shell and any subsur- face water, including their heterogeneity, ocean properties, and the nature of the surface– ice–ocean exchange. Here, "any" subsurface water is not meant to be interpreted as "all" subsurface water, but as to whether any detectable subsurface liquid water exists at Eu- ropa today, within the ice shell and/or as an ocean. Characterizing ocean properties includes further confirmation of the existence of an ocean, and its globally averaged properties of thickness, salinity, and composition—all of which are relevant to habitability. The exchange of materials among the surface, ice shell, and ocean is relevant to Europa's habitability, given that delivery of oxidants from its surface to the ocean would promote redox disequilibria in the ocean (Roberts et al. 2023, this collection; Vance et al. 2023, this collection), and oceanic material exposure to the surface is key in understanding the ocean's compo- sition (Becker et al. 2024, this collection) and for future exploration of the moon (Phillips et al. submitted). The Europa Clipper mission approaches this interior science objective by addressing five science themes:

Deep Subsurface Exchange: Deep vertical distribution of subsurface water, ice shell structure, and surface–ice–ocean exchange processes.

Shallow Subsurface Structure: Shallow vertical distribution of subsurface water, ice shell structure, and surface–ice exchange processes.

Ice Shell Properties: Thickness and thermophysical properties of the ice shell. Ocean Properties: Existence, thickness, salinity, and composition of the ocean.

Surface Thermal Anomaly Search: Thermal signatures of current or recent geological ac- tivity. (Theme shared with geology objective.)

Europa's interior will be explored with four principal approaches, meant to target dif- ferent aspects of the internal structure and properties: electromagnetic induction, subsurface sounding, tidal deformation, and thermal imaging. Magnetometry and plasma measurements can be used to derive coupled solutions for the thickness and conductivity of the ocean and the thickness of the ice shell. Subsurface sounding via radar can be used to constrain the thickness of the ice shell and map the vertical subsurface structure. Gravity and shape mea- surements can yield information on the tidal deformation of the ice shell, thereby allowing recovery of the combined strength and thickness of the ice shell. Thermal imaging can con- strain thermophysical properties of surface materials and reveal thermal anomalies caused by processes in the interior. These synergistic investigations will resolve existing ambigui- ties and degeneracies, providing information crucial for assessment of the habitability of this ocean world. The science team's Interior Working Group is tasked with building a frame- work for interpretation of measurements elucidating Europa's interior (Roberts et al. 2023, this collection).

3.2.2 Composition

The composition-focused objective of the mission is: Understand the habitability of Eu- ropa's ocean through composition and chemistry. Composition encompasses characterizing materials in the ocean, ice shell, surface, atmosphere, and local space environment, while chemistry implies identifying the properties and interactions of these constituents. The Eu- ropa Clipper mission approaches this composition-science objective by addressing six sci- ence themes:

Global Compositional Surface Mapping: Global surface composition and chemistry, in- cluding distribution and large-scale variability of materials.

Landform Composition: Surface constituents, focusing on non-water-ice and any carbon- containing compounds, on a regional and landform scale.

Atmospheric Composition: Composition and sources of non-ice volatiles, particulates, and plasma in the atmosphere, ionosphere, and possible plumes, within Europa's Hill sphere (<8.5 Europa radii, RE).

Space Environment Composition: Composition and sources of non-ice volatiles, particu- lates, and plasma in the space environment, outside of Europa's Hill sphere (>8.5 RE). Remote Plume Search and Characterization: Remote detection and characterization of active plumes. (Theme shared with geology objective).

In Situ Plume Search and Characterization: In-situ detection and characterization of re- cent or active plumes.

Much of our understanding of the composition and chemistry of Europa's ocean will be learned indirectly, through studies of the surface, atmosphere, and local space environment, which can be directly interrogated through remote sensing and in-situ techniques. In turn, composition and chemistry are critical parameters in understanding the potential habitability of Europa's ocean (Becker et al. 2024, this collection). The science team's Composition Working Group is tasked with ensuring that the Europa Clipper mission meets its objective to understand Europa's ocean through composition and chemistry via a high-level, cross- instrument and cross-discipline, composition-driven approach.

3.2.3 Geology

The geology-focused objective of the mission is: Understand the formation of surface fea- tures, including sites of recent or current activity; identify and characterize high science interest localities. The geology objective encompasses the formation, evolution, and expression of geomorphic structures on the surface. Local sites of high science interest might include areas of current or recent activity, such as plume sources or geological features that show evidence of change or correlation to thermal anomalies. The Europa Clipper mission approaches the geology science objective by addressing six science themes:

Global Surface Mapping: Global distribution and relationships of geologic landforms. Landform Geology: Morphology, topography, geology-composition correlations, and di- versity of landforms.

Local-Scale Surface Properties: Local-scale morphological, thermophysical, and me- chanical surface properties.

Remote Plume Search and Characterization: Remote detection and characterization of active plumes. (Theme shared with composition objective.)

Surface Thermal Anomaly Search: Thermal signatures of current or recent geological ac- tivity. (Theme shared with interior objective.)

Surface Activity Evidence: Surface properties and/or changes indicative of current or re- cent activity.

Europa's ice-based geology provides an unparalleled opportunity to investigate the dy- namics of the ice shell, surface–ice–ocean exchange processes, and global-scale tectonic and tidal forces. Geological investigations include using remote sensing techniques to search for and characterize current or recent activity in the form of active plumes, and evidence for surface changes or extremely fresh surface exposures. Integration of multiple datasets from all of Europa Clipper's instruments will be key to significantly advancing our understand- ing of Europa's geology. In turn, understanding geologic features, their formation, and any recent activity are key inputs for constraining Europa's habitability. Europa Clipper's Ge- ology Working Group is coordinating investigations that will accomplish Europa's geology objective. Outstanding issues and open questions about Europa's geology and details of how Europa Clipper will address them are discussed in Daubar et al. (2024, this collection).

3.3 Crosscutting Science Topics

Beyond the focus of Europa Clipper's three science objectives, the Europa Clipper's habit- ability goal calls for consideration of cross-cutting science topics as well. Four such topics stand out: current and recent activity, radiation environment, geodesy, and reconnaissance for a potential future lander. During development, the Europa Clipper team has had a "focus group" in each of these areas, to ensure that these topics are addressed holistically. Each of these topics is briefly discussed next, in turn.

3.3.1 Current and Recent Activity

Europa Clipper will investigate the possibility of current or recent activity: evidence for and subsequent characterization of current or recent activity can be made through the detailed in- vestigations within any of the three primary Europa Clipper science objectives. The moon's geologically young surface (Zahnle et al. 2003; Bierhaus et al. 2009) suggests that geologic processes have acted in the recent past to erase older terrains, and these processes may con- tinue to the present day so could be observable by Europa Clipper. These processes could include cryovolcanism, tectonism, impact cratering, sublimation, and generation of plumes; see Daubar et al. (2024, this collection) for description of the specific proposed formation mechanisms for stratigraphically recent landforms such as chaos terrain and some younger ridges and bands. Active processes could indicate the presence of a subsurface ocean and whether it currently affects the surface, elucidate subsurface structure and dynamics, and constrain relative ages of surface features. A key example of potential current activity is plumes that have been tentatively detected through Hubble Space Telescope observations (Roth et al. 2014; Sparks et al. 2016, 2017) and through reanalysis of Galileo field and par- ticle data (Jia et al. 2018). Europa Clipper will continue the search for and characterize any plumes or plume deposits (Becker et al. 2024, this collection; Daubar et al. 2024, this col- lection). Other examples of current indications of activity could include thermal anomalies that might accompany ongoing geologic activity, direct observations of physical or composi- tional surface changes, and recently emplaced surface materials. Details on these indicators of current and recent activity, the search strategy, and how the integrated instrument suite on Europa Clipper will investigate them are provided in Daubar et al. (2024, this collection) and Becker et al. (2024, this collection).

3.3.2 Radiation Environment

Europa resides at the edge of Jupiter's immense and intense radiation belts. A benefit of the Europa Clipper mission design is that the spacecraft spends relatively little time in this dangerous environment; instead, it flies by Europa to collect vital data before spending the rest of each Jupiter orbit in the relatively benign middle magnetosphere. Europa itself is per- manently bathed by energetic particles that speed past the moon on Jupiter's magnetic field lines. Europa's tenuous exosphere provides some protection but many of these particles im- pact the surface and are associated with darkened features on Europa (Paranicas et al. 2001). Europa Clipper measurements of Europa's plasma and radiation environment will provide vital data to characterize the impact of these precipitating particles and context for other Eu- ropa data. Specifics on how Europa Clipper interrogates the local radiation environment are provided by Meitzler et al. (2023, this collection), and instrument-specific descriptions are provided by Westlake et al. (2023, this collection) and Kivelson et al. (2023, this collection).

3.3.3 Geodesy

The study of Europa's geodesy connects many investigations pursued by Europa Clipper. A common geodetic framework is needed for the co-registration of datasets and for over- all consistency between science, engineering, and operations; this is also important to any potential future landed mission. That framework is defined by the rotation state and shape of Europa. The Europa Clipper project has adopted the official International Astronomical Union reference frame (Archinal et al. 2018). Unknowns include the potential existence of librations at different periods. Other key geodetic parameters that will be better constrained from the Europa Clipper observations include Europa's obliquity and pole position and the ephemeris of Europa and the other icy Galilean satellites. Europa's reference frame will be firmed up after the arrival of Europa Clipper, starting with refining the position of the prime meridian, and the reference frame will be improved throughout the mission based on increasing spatial and temporal coverage. Geodetic observations of Europa further include the gravity field and the tidal Love number k2 through gravity science (Mazarico et al. 2023, this collection), as well as another tidal Love number h2 through a combination of altimetric and imaging observations (Blankenship et al. 2024, this collection; Turtle et al. 2024, this collection). The tidal Love numbers determine the response of Europa to tidal forcing by Jupiter and depend on the moon's internal properties, in particular the presence and depth of an ocean. These properties bring complementary information to other investigations aimed at constraining Europa's interior (Roberts et al. 2023, this collection).

3.3.4 Reconnaissance for a Potential Future Lander

Potential follow-up missions to Europa have been studied by NASA, notably the Europa Lander mission concept (Hand et al. 2022). A lander or similar in-situ surface and/or sub- surface mission is a logical future step in the exploration of this ocean world (Phillips et al. 2020) and would provide ground-truth and detailed measurements to address key questions, including, but not limited to, astrobiology investigations (Hendrix et al. 2019). Collection of reconnaissance data is not a requirement for Europa Clipper; however, whatever the next Europa mission looks like, it is almost certain that it will rely on the data collected by Eu- ropa Clipper. Therefore, the collection of reconnaissance data by Europa Clipper will be critical for identification of potential landing sites that satisfy criteria for both science value and engineering safety, for a future landed mission. The high-resolution, multi-investigation datasets that permit reconnaissance are obtained only near the closest approach (100 km altitude) of each close flyby. Thus, one of the close approach locations of the Europa Clipper tour (and/or a location viewed during a potential extended mission) has a high likelihood of being the landing site for a future landed Europa mission. The definition of close approach locations that fulfill landing site reconnaissance needs is outlined in Daubar et al. (2024, this collection) and Phillips et al. (submitted), which provide detailed information on the reconnaissance strategy for a future landed mission.

3.4 Science Requirements

3.4.1 Program-Level Requirements

The formal high-level (Level 1) science requirements and mission success criteria of the Europa Clipper mission are documented in NASA's Europa Clipper Program Level Re- quirements Agreement (NASA 2022). The three Europa Clipper science objectives (interior, composition, and geology), plus the cross-cutting science topic on current and recent activity (see Sect. 3.3.1), comprise the four science categories of Europa Clipper's Level 1 science requirements. In turn, these four Level-1 science categories map to nine Baseline Science Requirements and eight Threshold Science Requirements, along with four Mission Success Criteria. These program-level requirements are summarized and mapped in Table 1. The science themes that follow from the three science objectives (summarized for each sci- ence objective in Sect. 3.2) map to the Europa Clipper project's internal "Guiding Level 2" science requirements, which are instrument specific and summarized in Table 2.

3.4.2 Science Traceability and Alignment Framework

The science of Europa and the Europa Clipper mission is inherently cross-disciplinary, with program- and project-level science areas that must be addressed through a combination of investigations to achieve full success. To assess the various contributions and their sensitiv- ity, two related tools were developed by the Europa Clipper systems engineering team in conjunction with Project Science leadership: the Project-domain Science Traceability and Alignment Framework (P-STAF) and the Measurement-domain Science Traceability and Alignment Framework (M-STAF) (Susca et al. 2017; Jones-Wilson et al. 2018).

The P-STAF links the Europa Clipper science investigations to the Level-1 requirements, designating investigation contributions as Primary, Independent, Supportive, or Enhancing. Using a set of hierarchical relations, the P-STAF permits quantitative assessment of science impacts for various systems trade studies. The M-STAF is a means to express science mea- surement requirements in a machine-readable language, which feeds into the quantitative evaluation made through the P-STAF.

These tools, when incorporated into the analysis of potential Jovian tours (Sect. 6.1.2), provide a means to determine when and the degree to which the science requirements are met, along with a measure of science margin. This information can, in turn, help to guide science-based assessments during mission development. The P-STAF is necessarily some- what subjective, and its interpretation must be guided by the Project Scientist. With these caveats fully in mind, these tools have proved extremely valuable in enabling rapid science assessments in trade studies and other decision-making processes during mission development.

4 Payload Overview

4.1 Synergistic and Comprehensive Payload for Exploring Europa

As a flagship-class NASA mission, Europa Clipper possesses a comprehensive payload of scientific instruments that will be used to study Europa and its space environment, and to assess Europa's habitability (Fig. 2). Nine instruments were chosen by NASA1 through com- munity competition (Sect. 2.5), broadly divided into descriptive categories of remote sensing and in-situ measurements. Morover, spacecraft engineering subsystems provide science data in two additional areas. The principal (Level 2) science requirements addressed by each of the NASA-selected science investigations are summarized in Table 2.

The remote sensing instruments cover a wide swath of the electromagnetic spectrum with only minor gaps: coverage from 0.055–0.206 μm for the Europa Ultraviolet Spectro- graph (Europa-UVS), from 0.350–1.05 μm for the Europa Imaging System (EIS) Narrow Angle Camera (NAC) and Wide Angle Camera (WAC), from 0.8–5.0 μm for the Mapping Imaging Spectrometer for Europa (MISE), and from 7.0–70 μm for the Europa Thermal Imaging System (E-THEMIS). Sub-meter resolution will be obtained by EIS NAC on the closest flybys (25–100 km altitude), with best pixel scales from 100 km altitude for EIS WAC (22 m), Europa-UVS (209 m), MISE (25 m), and E-THEMIS (12 m). These opti- cal remote-sensing instruments will together perform imaging, compositional mapping, and searches for color, albedo, or textural differences characteristic of plume deposits. EIS will obtain data on the albedo, color, and surface landforms. Europa-UVS and EIS will search

1The originally selected magnetometer was the Interior Characterization of Europa using Magnetometry (ICEMAG), which would have included two fluxgate and two scalar/vector helium magnetometers; this in- vestigation was terminated by NASA in March 2019, and replaced with the Europa Clipper Magnetometer (ECM) as a project-provided magnetometer instrument.for and characterize any active plumes, and Europa-UVS will characterize Europa's tenuous atmosphere. E-THEMIS will map daytime and nighttime temperatures to characterize the regolith, erosional processes, and the thermal state of the ice shell and surface. The Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON) is an ice-penetrating radar instrument that has both high frequency (HF) and very high frequency (VHF) antennas operating at 9 and 60 MHz frequency (33.3 and 5 m wavelength), respectively. REASON will be used to map the distribution of surface and subsurface materials, including possible brines and salts, search for the ice–ocean interfaces, characterize the moon's regolith, and gather data to understand exchange processes in Europa's subsurface; it will also provide topographic profiles through altimetry.

The in-situ experiments will offer a similarly comprehensive view of the magnetic field and particle environment encompassing Europa. The Mass Spectrometer for Planetary EX- ploration – Europa (MASPEX) and the Surface Dust Analyzer (SUDA) will identify the major atmospheric components, including volatiles, and characterize their connection to ge- ologic features, possible plumes, and the subsurface ocean. The Plasma Instrument for Mag- netic Sounding (PIMS) will characterize Europa's ionosphere and the Jovian magnetosphere and their influence on observed magnetic fields. The Europa Clipper Magnetometer (ECM) will characterize Europa's induced magnetic field to constrain the ocean and ice shell thicknesses and ocean conductivity. Finally, the Gravity and Radio Science (G/RS) experiment will characterize Europa's time-varying gravitational tides (k2) to confirm the existence of Europa's subsurface ocean.

Europa Clipper was deliberately designed such that during a nominal Europa flyby all the instrumentation can gather data simultaneously. Figure 3 illustrates the field of view (FOV) of each of the optical remote sensing instruments, which are co-boresighted and nadir-pointed and mounted on the stable "nadir deck" (Fig. 2a; also see Sect. 5). The EIS NAC (2-axis gimbal) and MISE (1-axis scan mirror) instruments can view off-nadir dur- ing a flyby, pointing independently of the spacecraft. Europa-UVS and E-THEMIS, and color imaging by EIS NAC, rely on spacecraft scanning when viewing from afar to build a large-area image; all can operate in pushbroom mode through a flyby. The REASON VHF (4) and HF (2) antennas are all affixed to the solar arrays (Fig. 2), ensuring consistency in electromagnetic compatibility with respect to the arrays, and the antenna long-axes are parallel to the direction of travel and parallel to Europa's surface during a flyby. The in-situ instruments most sensitive to directionality, MASPEX and SUDA, are ram-pointed (i.e., in the direction of spacecraft motion). Generally agnostic to spacecraft orientation are ECM, which has three sensors affixed to an 8.5-m-long boom, and PIMS which has two separated sensors (PIMS Upper and PIMS Lower) each with two Faraday cups with broad fields of view. Gravity science can be performed with any of six spacecraft antennas (3 fixed fanbeam, 2 low-gain, and 1 medium-gain) that are appropriately directed toward Earth for tracking during a given flyby.

The ability to observe Europa with all instruments simultaneously is greatly beneficial for four key reasons. (1) The science of Europa, hence the science requirements of Europa Clipper, are cross-cutting and best addressed synergistically through observations that are overlapping in location and time. (2) Given the Jovian radiation environment near Jupiter, observing time is the mission's most significant limited resource, so simultaneous observing capability maximizes the science potential. (3) Repeating a basic template of observations for every instrument and every flyby reduces operational complexity. (4) A science team operates better together when there is little need for resource competition or significant negotiation (cf. Vertesi 2020a).

The following sections provide further detail for each of the nine Europa Clipper sci- ence instruments, plus gravity science and radiation science. Completed hardware for each science instrument is shown in Fig. 4.

4.2 Remote-Sensing Instruments

4.2.1 Europa Ultraviolet Spectrograph (Europa-UVS)

To study Europa at ultraviolet wavelengths, Europa Clipper will employ the Europa Ul- traviolet Spectrograph (Europa-UVS) instrument (Fig. 4a; Retherford et al. 2024, this col- lection). The sixth and most recent instrument in a line of ultraviolet spectrographs that extends back to Rosetta's Alice instrument, the design and fabrication of the Europa-UVS instrument leverages a significant degree of heritage from its predecessors: Rosetta-Alice, New Horizons' Pluto-Alice, the Lunar Reconnaissance Orbiter's Lyman Alpha Mapping Project, Juno-UVS, and Europa-UVS's sister instrument, JUICE-UVS, which is flying on ESA's JUICE mission. The Europa-UVS microchannel plate (MCP) uses a set of borosili- cate glass plates, which makes it less sensitive to gamma rays than typical MCPs. In addi- tion, the MCPs have an atomic layer coating of MgO to make the detector resistant to the gain degradation, which traditional MCPs are subject to. The MCP detector has a deadtime <1 µs and dark noise counts an order of magnitude lower than required (Davis et al. 2021). While operating in histogram mode, the detector can be configured to bin data in the spatial and spectral dimensions in a customized set of bin sizes to optimize data volume for a given observation.

The specific capabilities of the Europa-UVS instrument allow it to investigate Europa's atmosphere, search for and characterize any active plumes, explore the surface composition of Europa, and provide information about the interaction between Europa and the Jovian magnetosphere. Ultraviolet photons with wavelengths between 55 and 206 nm enter the in- strument through a slit that defines its field of view. Most observations with Europa-UVS, such as stellar occultations observations, airglow/aurora mapping, and Jupiter transit imag- ing, will employ the main entrance airglow port (AP) with a 7.3° 0.1° field of view (FOV). While observing through the AP, Europa-UVS has an angular resolution of 0.16° (2.8 mrad). The high-spatial-resolution port (HP) consists of an aperture door that stops down the AP and permits observations of bright objects at resolutions higher than that possible through the full AP. Use of the HP provides a finer angular resolution of 0.12° (2.0 mrad) at the expense of a decreased signal-to-noise ratio (SNR). A separate solar port (SP) has its aper- ture offset from the AP by 40° and can support observations of occultations of the Sun by Europa. A pick-off mirror directs light entering through the SP onto the instrument's main optical path. The bottommost portion of the Europa-UVS slit, with a 0.2° 0.2° FOV, is sized wider to accommodate the angular size of the Sun at Jupiter's orbital distance with margin. Europa-UVS can acquire data at a spectral resolution of 2 nm or better across most of its spectral range. This allows oxygen emission lines at 130.4 and 135.6 nm to be cleanly separated from the 133.5-nm solar carbon lines reflected by Europa's surface and permits mapping of Europa in emission lines tied to atomic species of specific interest.

During closest approach, the instrument will be configured to observe Europa's aurora, tenuous atmosphere, or surface, as optimized for the geometry of the encounter. Prior to and following the nadir-pointed phase, Europa-UVS will be used to scan the satellite, creating UV maps of auroral and atmospheric emissions and surface reflectance. Observations to be implemented farther from closest approach to Europa include Jupiter transit observations, during which Europa will be scanned with Europa-UVS as it transits the illuminated disk of Jupiter. These observations will allow the full disk of Europa to be imaged in the ultraviolet using reflected light from Jupiter as an illumination source, and they will provide a pow- erful means of probing Europa's tenuous atmosphere and of searching the limb for plume activity. Solar and stellar occultation observations by Europa provide a particularly sensitive means of measuring the composition and structure of Europa's atmosphere. Thousands of UV-bright stars have been identified as candidate occultation stars, and >100 occultation observations are planned. O2 absorption will be easily detectable, with constraints placed on H2, H2O, CO2, SO2, and CO abundances in Europa's atmosphere. Should the path of a stellar occultation traverse a Europa plume, Europa-UVS can provide unique and detailed information on the abundance of any other gas constituents present within the plume, in- cluding hydrocarbons such as C2H2.

4.2.2 Europa Imaging System (EIS)

The Europa Imaging System (EIS) (Turtle et al. 2024, this collection) has been designed to explore Europa through global high-resolution coverage, three-dimensional digital terrain models (DTMs), and meter-scale imaging. EIS consists of two visible imaging cameras, the Wide Angle Camera (WAC, Fig. 4b) and the Narrow Angle Camera (NAC, Fig. 4c). The WAC has a 48° 24° FOV and a 218- µrad instantaneous FOV (iFOV), achieving 11 m/pixel, 45-km wide cross-track imaging swaths from 50-km altitude. The NAC has a 2.35° 1.17° FOV and a 10- µrad iFOV, achieving 0.5 m/pixel, 2-km wide cross-track imag- ing swaths from 50-km altitude.

The NAC has a two-axis gimbal, which allows independent pointing and enables near- global coverage, adding capability and flexibility with minimal impact to spacecraft op- erations or other instruments. The cameras have identical rapid-readout, radiation-hard 4096 2048-pixel complementary metal oxide semiconductor detectors and can operate in both framing and pushbroom imaging modes. Six broadband filters enable color observa- tions when in pushbroom mode. Real-time processing during pushbroom imaging provides additional capabilities, including WAC 3-line stereo, digital time delay integration (TDI) to increase SNR, and readout strategies to measure and correct pointing jitter.

The NAC's high-resolution imaging will enable a detailed investigation of Europa's ge- ology; for example, stereo observations will be used to characterize geological structures and color observations will be used to search for evidence of recent activity. Global mapping at 100 m/pixel and regional stereo will be used to study global geologic relationships and provide context for observations by other instruments. High-phase-angle imaging will be used to search for faint plumes. Limb fits will constrain the ice shell thickness.

The WAC will perform pushbroom stereo imaging to generate stereo DTMs for three- dimensional geologic mapping. Pushbroom color imaging will be used to identify surface units and characterize recent activity. Ground track imaging swaths and stereo DTMs provide context and characterize cross-track clutter for radar sounding.

Together, the EIS WAC and NAC will image >90% of Europa's surface at 100-m pixel scale (while previously, only 14% of Europa has been imaged at 500 m/pixel). They will acquire data critical for integration with other science investigations, including cartographic and geologic mapping, regional and high-resolution digital topography, color and photometric data products, a database of plume-search observations, and a geodetic control network that can be tied to radar altimetry.

4.2.3 Mapping Imaging Spectrometer for Europa (MISE)

The Mapping Imaging Spectrometer for Europa (MISE) (Fig. 4d; Blaney et al. 2024, this collection) uses infrared reflectance spectroscopy to map the surface composition at the spatial scales relevant to geologic processes on Europa. Measurement of infrared spectral characteristics enable the identification and mapping of organics, salts, acid hydrates, water ice phases, altered silicates, radiolytic compounds, and warm thermal anomalies. MISE will map compositionally diagnostic properties at 14 sites with <50 m/pixel spatial, and with 10 km/pixel scale with images acquired at or below 40,000 km altitude. MISE will return infrared spectral information for each pixel in each acquired image (hence the full MISE image is referred to as a "cube").

High-resolution spectral information from local-to-global perspectives will be used to establish the composition of specific landforms. Surface and subsurface geologic processes, including recent or current activity, and surface–ocean exchange can be inferred using these measurements. Salt chemistry observable on Europa's surface likely reflects both ocean–ice chemical interactions, which provide the starting chemistry, and the geologic processes that may alter that chemistry as material makes its way to the surface, e.g., fractional crystalliza- tion of brines. Europa's surface is dominated by water, as ice or in hydrated materials. By determining ice crystallinity and radiolytic products in the ice, the thermal and radiolytic history of the surface can be inferred; for example, young surfaces will lack radiolytic im- plantation signatures. Thermal emissions from small, relatively high-temperature hot spots can also be mapped, permitting the identification of recent cryovolcanic events.

The distribution maps of astrobiologically relevant compounds (specifically, organics and salts) and their geologic context can contribute to assessment of whether Europa's ocean is capable of supporting life. The generally accepted ingredients for an environment capable of hosting life as we know it include liquid water, bioessential elements, and a source of free energy. MISE will pursue three lines of evidence to assess habitability: 1) the presence and distribution of organics including complex organics such as amino acids; 2) salt chemistry of the ocean; and 3) evidence of current and recent surface changes as a proxy for internal activity.

MISE is a pushbroom, Dyson imaging spectrometer, covering the spectral range 800–5000 nm with a spectral resolution of 10 nm. The optics employ a 30° along-track scan mirror to provide target motion compensation at low altitudes and increase coverage at high altitudes. The instrument has an iFOV of 250 µrad (full angle), corresponding to images with better than 10 km/pixel resolution at an altitude of 40,000 km. The FOV is 4.3° in the cross-track direction, and from 0.75° to 4° in the along-track direction. To achieve sufficient data quality, the detector and spectrometer must operate at cryogenic temperatures during data acquisitions. To achieve the required cryogenic temperatures, the instrument uses a hy- brid passive-active cryogenic thermal architecture, consisting of one pulse-tube cryocooler coupled to a radiator. Most of the acquired MISE data are buffered, processed, and com- pressed within the instrument prior to being sent to the spacecraft avionics for storage then downlink.

4.2.4 Europa Thermal Emission Imaging System (E-THEMIS)

The Europa Thermal Emission Imaging System (Fig. 4e, E-THEMIS) (Christensen et al. 2024, this collection) is a nadir-pointed three-band thermal infrared imager that will map temperatures and detect heat flow anomalies (“hot spots”), identify passive thermal sig- natures of geologically recent changes, and reveal the physical properties of surface ma- terials. Specifically, E-THEMIS observations will be used to derive thermal inertia, block abundance, regolith thickness, porosity, internal heterogeneities, and surface roughness. E- THEMIS may also detect plumes if they have an infrared thermal emission signature. As such, E-THEMIS will provide critical information to determine Europa’s nature and evo- lution, with an emphasis on recent and ongoing activity. Moreover, data generated by E- THEMIS will help identify scientifically interesting and safe landing sites for future mis- sions.

E-THEMIS will acquire observations during two distinct phases of each Europa en- counter. First, the entire disk will be imaged both day and night at moderate spatial resolution (10 km/pixel) in all three bands during global scans, to distinguish thermal inertia, albedo, and heat flow variations. Second, near closest approach, multi-kilometer wide swaths of the surface will be imaged at high spatial resolution (<100 m/pixel) to distinguish geologic landforms from their surroundings.

To achieve these aims, E-THEMIS is designed with broad spectral range over three bands (7–14 µm, 14–28 µm, and 28–50 µm) to measure surface temperature as cold as 90 K; high radiometric precision (<0.2 K at 90 K) and accuracy (<2 K at 90 K) to distinguish subtle lateral temperature variations; and a wide FOV (i.e., 5.7° cross-track by 4.3° along-track) resulting in moderate-to-high surface resolution depending on altitude. The instrument can operate in framing mode, where full frame images are collected and optionally co-added in time in each band, or in TDI mode, where consecutive rows are offset to remove the spacecraft motion and then summed to increase SNR. Images will be composed of up to 448 cross-track pixels with a 10.1-km wide image swath from 100 km.

4.2.5 Radar for Europa Assessment and Sounding: Ocean to Near-Surface (REASON)

Sounding with the Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON) (Figs. 4f and 4g; Blankenship et al. 2024, this collection) will address key ques- tions regarding Europa’s habitability—including the existence of any liquid water—using radar sounding, altimetry, ranging, reflectometry, and plasma analyses. These investigations require a dual-frequency radar instrument with simultaneous shallow and full-depth sound- ing that is designed for performance robustness in the challenging environment of Europa.

The scattering and dielectric properties of the upper brittle layer will reveal clues about Europa’s geology, while deeper attenuation and possible strong dielectric interfaces may provide a direct measure of the nature of subsurface liquids and other non-ice materials. The longer HF wavelength band of the dual-frequency system is designed for full-depth penetra- tion up to 30 km into the ice shell and is insensitive to interference from surface roughness compared to the VHF. The shorter VHF wavelength band is optimized to probe structures in the upper 3 km of the ice shell with sufficient resolution to test hypotheses of the presence of near-subsurface liquid water and is less susceptible to Jovian noise and plasma delay effects compared to the HF. In addition, the VHF capability can serve to sound the deeply into the ice shell, potentially sounding its full-depth, to complement observations in the HF band when the latter is exposed to Jovian noise. The VHF band also allows for measurements of surface relief and tidal flexure to detect the subsurface ocean. The combination of longer and shorter wavelengths serves to measure the total electron content of the ionosphere di- rectly beneath the flight system and can detect plumes by local electron enrichment of the ionosphere.

REASON comprises a 60 MHz center frequency (5 m wavelength) band (VHF) with a 10 MHz bandwidth optimized for shallow sounding, and a 9 MHz center frequency (33.3 m wavelength) band (HF) with a 1 MHz bandwidth optimized for full-depth ice shell sounding. Both the VHF and the HF antennas are mounted on the edge of the solar arrays. The HF an- tennas consist of two 17.6-m dipole antennas. The four-element VHF antennas are arranged in a linear array of 2.76 m folded dipole antennas. Both sets of antennas are mounted on and oriented perpendicular to the solar arrays, and they will be deployed soon after launch.

To discriminate clutter along off-nadir portions of the sub-spacecraft swath, the REA- SON 60 MHz band is divided into two receiving channels for interferometry. This technique complements cross-track topographic imaging by EIS. REASON performance capabilities include 30 m vertical resolution depth sounding from 300 m to 3 km, and 300 m vertical resolution from 1 to 30 km.

4.3 In-Situ Instruments

4.3.1 MAss Spectrometer for Planetary EXploration – Europa (MASPEX)

The MAss Spectrometer for Planetary EXploration (MASPEX) – Europa (Fig. 4h; Waite et al. 2024, this collection) is a reflectron-type multi-bounce time-of-flight mass spectrome- ter that will analyze the atomic, molecular, and isotopic composition of neutral volatiles in Europa’s exosphere. MASPEX has a spectral mass range of 2 to 500 u, achieves a spectral mass resolution m/Δm of 4,275 or greater at 50 m/z, and is sensitive to chemical species with relative abundances as low as 1.7 10−4 (in ambient mode). MASPEX will explore the composition of Europa’s exosphere from multiple sources (sputtering, thermal desorption from the surface, and potential active features) to evaluate the habitability potential of Europa’s interior.

The MASPEX functional principle (Brockwell et al. 2016; Waite et al. 2024, this collec- tion) is that neutrals entering the instrument are first ionized by electron ionization inside a closed ion source. The ions are then accelerated into the mass spectrometer, and their mass range and resolution are determined by time of flight. Ions can bounce multiple times be- tween the ion optics (controlled by a time-dependent electric field) to increase path length and travel time. Longer time of flight increases mass resolution as ions with different masses have more time to separate over multiple bounces within the ion optics. Once sufficient bounces have separated (resolved) the ions in time, within the mass range of interest, ions are released for detection on a micro-channel plate electron multiplier. The analog signal from the micro-channel plate detector is then digitized in the MASPEX electronics box, and the mass spectra are packetized for storage and downlink. MASPEX is equipped with a cal- ibration gas system, which delivers controlled amounts of a standard calibrant to routinely calibrate ion mass with respect to time of flight and to determine detector gain for absolute quantification.

During Europa flybys, MASPEX will acquire mass spectra over specific mass ranges of interest with a cadence of 5 s, to measure the atmospheric composition as function of altitude and location. The spatial resolution on the surface is proportional to flyby altitude, allowing MASPEX to achieve a spatial resolution of 35 km or better near closest approach. In addition, MASPEX is equipped with a cryotrap made of sintered stainless steel and cooled by a cryocooler. For nominally four hours around closest approach, the cryotrap will be exposed to the Europa environment inside the mass spectrometer and will adsorb volatiles that will remain trapped inside the instrument until more detailed analysis will occur around apojove, where the radiation environment and associated detector noise are more benign. MASPEX is also able to detect and analyze ice grains if any are encountered during the flybys, and it will measure the composition of Europa torus volatiles at least once over the course of the mission.

4.3.2 SUrface Dust Analyzer (SUDA)

The SUrface Dust Analyzer (SUDA) (Fig. 4i; Kempf et al. 2024, this collection) is a time-of- flight (TOF), reflectron-type, impact ionization mass spectrometer that provides elemental and molecular composition of ice and dust particles present in Europa's exosphere. These dust particles could be either ejected from the surface and/or subsurface of Europa in a ballistic trajectory (endogenic dust particles), or they could come from the Jovian system (exogenic dust particles), such as from the Io torus (as nanograins) or from other Galilean moons (as ring particles). SUDA is an instrument that is open to space all the time after its lid is opened during cruise by a one-time operation. Most of the critical measurements are carried out when the SUDA boresight is aligned with the spacecraft's ram direction, which aligns at the time of Europa close flybys with the Kepler ram direction, i.e., the impact direction of grains moving in circular bound prograde orbits.

Following on the heritage of the Cassini Cosmic Dust Analyzer mass spectrometer, which provided compositional mapping of the surface and plumes of Enceladus, a new method for obtaining the surface composition of airless planetary bodies was developed. The composi- tional mapping technique relies on the fact that impacts of fast, typically 100-μm interplan- etary meteoroids on a moon's surface produce ejecta particles, which populate a tenuous, approximately spherically symmetric cloud around the moon. Information about the geo- logical activity on and below Europa's surface, in particular the material exchange between the interior and the surface, is contained in the types and amounts of inorganic and organic components embedded in the surface. The dust detector onboard the Galileo spacecraft de- tected the ejecta dust clouds around all the icy Galilean moons of Jupiter, including Europa (Krüger et al. 2003), providing preliminary data for developing models and measurement strategies for SUDA.

SUDA will measure the mass, speed, and charge of impacting grains, along with their elemental, molecular, and isotopic composition, with a spectral resolution $m/\Delta m$ 1 u for atomic mass m 200 u. In addition to chemical composition of dust and ice grain particles, SUDA provides information on the location of the source of these grains that are ejected in a parabolic path from Europa's surface by micrometeorite impacts. SUDA data will provide the particle composition if flown through an active plume or over recently active surfaces, producing signatures similar to those of surface ejecta particles.

SUDA works in two polarities (negative and positive ion modes), with one of the po- larities active during any given flyby of Europa. Negative ion mode will be used to identify negative ions in salts contained in ice and dust grains that have been ejected from the surface, while positive ion mode (the default mode) will be used to identify cations in these salts, in- forming the salinity of ejected grains. In addition to characterizing salts, SUDA can detect organic compounds, such as amino acids and fatty acids, at parts per million concentrations, if present in the ejecta dust particles or plumes. In essence, SUDA will provide physical properties and composition of dust particles that help us understand Europa's habitability through informing salinity and detecting organic compounds.

4.3.3 Europa Clipper Magnetometer (ECM)

The Europa Clipper Magnetometer (ECM) (Fig. 4j; Kivelson et al. 2023, this collection) will measure the amplitude of the inductive signature at Europa at multiple natural frequen- cies including those corresponding to the synodic rotation period of Jupiter (11.1 hours), the orbital period of Europa (85.2 hours), and the harmonics and beats of these two fun- damental periods. Knowledge of the induced magnetic field enables retrieval of Europa's ice shell thickness, ocean depth, and ocean conductivity—from which salinity can be esti- mated (Biersteker et al. 2023). As a secondary contribution, magnetic field measurements can be used to characterize aspects of atmospheric composition and loss, and to identify and characterize plumes, if they exist and the spacecraft flies through them.

The ECM instrument consists of three, three-axis fluxgate sensors distributed along a coilable 8.5-m-long boom that will be deployed soon after launch. In the multi-sensor de- sign, field gradients along the boom are used to identify and remove the contribution of the spacecraft field (Cochrane et al. 2023). Given that ECM does not include an absolute cali- bration reference, intermittent in-flight calibrations will be undertaken approximately once every few encounters with Europa. By spinning the spacecraft multiple times about each of two perpendicular axes, it will be possible to retrieve any change in the relative gains, offsets, and orthogonality of all three sensors. All sensors are controlled and read out by the ECM electronics unit that is installed inside the thick-walled vault that protects it from the intense radiation of plasma trapped in Jupiter's strong magnetic field.

ECM will collect data at 16 vector samples per second for the duration of each Europa encounter. For the remainder of each orbit, background measurements will be made at one vector sample per second. To identify the induced fields with high precision from data col- lected on multiple flybys of Europa, the encounters are positioned across a range of orbital phases (true anomaly) and well-distributed in Jovian System III longitude. The corotating magnetospheric plasma currents interact with Europa and its tenuous atmosphere, creating a magnetic field signature that can perturb the induced field originating from the subsurface ocean. Most of the perturbing effects of the plasma interaction will be characterized and removed using numerical models, guided by plasma properties derived from PIMS observations.

4.3.4 Plasma Instrument for Magnetic Sounding (PIMS)

The Plasma Instrument for Magnetic Sounding (PIMS) (Fig. 4k; Westlake et al. 2023, this collection) is a set of four Faraday cups designed to measure the plasma distributions that perturb the magnetic field near Europa. Accounting for these perturbations in the induction response of Europa is imperative for the success of the induction experiment. The plasma contributions to the magnetic field primarily vary in accordance with the co-rotating Jovian plasma density and flow velocity and are expected to exceed the induction signal in all but a few portions of some flybys. Thus, precise determination of the plasma contributions to the magnetic field is crucial for accurate characterization of the ice shell and the subsurface ocean (Kivelson et al. 2000).

PIMS consists of two separated sensors (PIMS Upper and PIMS Lower), each with two orthogonally oriented Faraday cups of 90° FOV, yielding a contiguous view in the plane perpendicular to the solar array long axis with only minor obstructions. PIMS will measure the ion and electron distributions of the Jovian magnetospheric and the Europa ionospheric plasma utilizing four science modes of operation: 1) "magnetospheric mode," which is opti- mized for measuring the hotter plasma outside Europa's exosphere; 2) "ionospheric mode," which is optimized for the cool dense plasma nearest to Europa; 3) "transition mode," which switches between the ionospheric and magnetospheric modes to ensure coverage of the tran- sition region between Europa's ionosphere and the Jovian plasma; and 4) "survey mode," which is identical to the magnetospheric mode but to be operated far from Europa with a re- duced data rate. In its magnetospheric mode PIMS will measure the Jovian magnetospheric ions between 50 eV and 6 keV, and the magnetospheric electrons between 50 eV and 2 keV with an energy resolution <15%. The ionospheric mode will cover ions and electrons in the energy range from 1 to 70 eV with an energy resolution of 0.3 V, while the transition mode will cover the ions and electrons in the entire PIMS energy range (2 keV to 6 keV, where negative energies apply to electrons). To perform these measurements, PIMS sweeps the voltage applied as a characteristic waveform (DC [V] level with a superimposed sine wave [ΔV]) on either the high- or low-voltage modulator grids. Particles with energy-per-charge (E/q) ratios that fall between the wave height of the wave form $(V\ \Delta V < E/q < V\ \Delta V)$ then produce an AC current on the collector plate, which is measured with a high SNR.

PIMS will also measure the flow direction of the plasma utilizing its segmented col- lector plates located within each of the four Faraday cups to within 5° accuracy. These measurements will be crucial for translating the measured energy to flow velocity of the plasma. Limited compositional measurements of Europa's ionosphere will be obtained by ramming into the cold ionosphere at the high velocity of the spacecraft. This will lead to well-separated peaks in the energy-per-charge of the ions and enable identification of some ion species.

4.4 Investigations Using Engineering Subsystems

4.4.1 Gravity and Radio Science (G/RS)

The Gravity and Radio Science (G/RS) investigation (Mazarico et al. 2023, this collection) utilizes the radio tracking signal between the Earth-based observing stations of NASA's Deep Space Network (DSN, the ground element) and the Europa Clipper spacecraft (the flight element). The Doppler shift of the frequency of the radio signal allows navigators and radio scientists to measure the along-line-of-sight motion of the spacecraft, perturbations to its acceleration, and propagation effects.

The radio tracking measurements are collected in a 2 h window around closest ap- proach during each flyby of Europa. Over the full mission, the spatial coverage is nearly uniform at regional scales (>400 km). The multiple flybys tracked by radio thus provide good observability of key geophysical parameters, notably the degree-2 tidal Love number k2, which relates the gravitational potential resulting from tidal deformation of Europa to the tide-raising potential (i.e., from Jupiter). In the presence of an ocean, k2 is expected to be on the order of 0.25 (Moore and Schubert 2000); however, this parameter is highly sensitive to the rigidity of the ice shell, and to ocean density as well. This ambiguity can be reduced by measuring the amplitude of the surface deformation, which is related to the tidal potential by another Love number h2 that can be obtained through differential range measurements acquired by REASON (Steinbrügge et al. 2018) at ground track intersections (termed crossovers).

In addition to the time-varying potential, Europa Clipper's trajectory is sensitive to the static gravity field parameterized by the Stokes coefficients Clm and Slm (Kaula 1966; Park et al. 2015), where l and m are the spherical harmonic degree and order respectively, a mea- sure of the wavelength of the gravitational perturbation. The degree-2 Stokes coefficients will enable determination of whether Europa is in hydrostatic equilibrium (Verma and Mar- got 2018), a state that has commonly been assumed when inferring moment of inertia from gravity data (Anderson et al. 1998) but is yet to be demonstrated. It is also plausible that there are shorter-wavelength (kilometers-scale height and 10s-kilometers-scale width) grav- ity anomalies related to the ice shell structure (such as upwelling diapirs of warm buoyant ice, or pockets of meltwater or brine) that may be detectable (Roberts et al. 2018; Mazarico et al. 2023, this collection), or similar-scale seafloor topography that could be detectable (Dombard and Sessa 2019; Koh et al. 2022). The reconstructed spacecraft trajectory will provide further constraints on the Europa ephemeris and enable more accurate determina- tion of the Laplace resonance and Jupiter system orbit evolution (Mazarico et al. 2023, this collection).

Beyond the gravity science opportunities, the radio science investigation will conduct radio occultation observations to better characterize the ionosphere of Europa and the plasma environment in the Jupiter system (Withers 2010; Phipps et al. 2020). Distant occultations, in which the radio signal passes through the Io plasma torus, can be performed using the high- gain antenna (HGA) and will lead to development of better plasma models in the Jupiter system. During flybys, this configuration is not available because the narrow HGA FOV will be directed upward, normal to Europa's surface. Thus, during flybys, radio occultation observations to obtain vertical profiles of ionospheric electron density will be conducted in a two-way configuration at X-band only, primarily using a subset of the spacecraft fan-beam and/or low-gain antennas for each flyby (Sect. 5), depending on the Earth direction with respect to the flyby geometry.

4.4.2 Radiation Science

The Radiation Monitor (RadMon) subsystem (Meitzler et al. 2023, this collection) onboard Europa Clipper serves as an engineering resource for the mission, continually measuring the intense radiation environment of the Jovian system near Europa, as well as throughout the orbits to assess health and safety of the spacecraft. The RadMon consists of a charge rate monitor (CRM) mounted on the electronics vault and a distributed set of dosimeters, strate- gically placed around the spacecraft to optimize measurement of the radiation impinging on various instruments and subsystems that may be susceptible to high-energy radiation. The dosimeters will measure the total-ionizing dose (TID) of radiation the spacecraft is exposed to, which can lead to gradual degradation and or failure of semiconductor electronics, es- pecially those which are made of dielectric materials (e.g., SiO2). The dosimeters used for the mission are widely used radiation-sensitive metal-oxide-silicon field-effect transistors (RadFETs), from which TID is extrapolated through measurement of the radiation-induced threshold voltage shift of Si/SiO2 metal-oxide-semiconductor field-effect transistors (MOS- FETs) as a function of time. The CRM will measure the current generated by the incident magnetospheric electrons using a series of bulk charge collection plates and transimpedance amplifiers. Monitoring the incident electron current is important for understanding implica- tions of spacecraft charging and potential internal electrostatic discharge (IESD) effects.

While the RadMon is primarily an engineering resource for the spacecraft, it can also pro- vide useful insight for Jupiter system radiation science, and Europa's role therein. The Rad- Mon system will provide low-resolution spectra of Europa's radiation environment in the MeV range, simply due to its construction. More specifically, the variable shielding thick- ness for each plate of the CRM allows four simultaneous current measurements to infer a crude four-band electron energy spectrum. The bands are roughly peaked in energy at 0.5, 2, 10, and 30 MeV. Additionally, the CRM measurements will provide near-instantaneous net charge measurements of the electron radiation environment with a 1-Hz sampling cadence, allowing radiation environment mapping along each flyby of Europa.

Augmenting data from the RadMon system, complementary and opportunistic back- ground radiation data can be acquired by the onboard science instruments. Specifically, the Europa-UVS detector is sensitive to electrons with energy >10–15 MeV; the EIS detector is susceptible to electrons with energy >10 MeV; the MISE shielded Mercury Cadmium Tel- luride detector is sensitive to electrons with energy >50 MeV; and the MASPEX microchan- nel plate is sensitive to electrons with energy >3 MeV. The diverse radiation datasets that will be collected will aid in understanding the role that radiation has on the composition, ori- gin, and evolution of materials on the surface of Europa, while constraining the additional observational data. Thus, the RadMon subsystem and other radiation dataset opportunities provide important engineering context while helping to address the mission's overarching goal of assessing Europa's habitability.

5 Flight System Overview

The spacecraft and the science payload comprise the Europa Clipper flight system, described in detail by Srinivasan et al. (2024, this collection). The flight system is composed of three modules: the propulsion module, the radio frequency (RF) module, and the avionics mod- ule. The flight system and its associated coordinate system are illustrated in Fig. 5. The propulsion module constitutes the core structure of the spacecraft and is composed of the cylindrical structure enclosing the fuel and oxidizer tanks; two solar array wings including their support structure, propulsion lines, and components; redundant sets of engines; and the propulsion module electronics, which provides all electrical interfaces for the propul- sion subsystem, the solar array drive actuators, and deployment hardware. The propulsion module also accommodates the RF module, ECM, the spacecraft thermal radiator, the lower sensor of the PIMS instrument, the REASON VHF and HF antennas including cabling, and the reaction wheel units. The RF module contains most of the communications equipment, including a 3-m diameter dual-band (X and Ka) high-gain antenna (HGA), a medium-gain antenna (MGA), three fan-beam antennas (FBAs), three low-gain antennas (LGAs), and a panel hosting the transponders, amplifiers, and associated equipment. The avionics mod- ule consists of a radiation vault, a nadir-viewing platform, and secondary structures. The vault provides radiation protection and thermal interface control to internal electronics, and it provides mounting support for various external instruments and spacecraft components. It consists of aluminum panels, which reduce the effective radiation dose from Jupiter's harsh environment. Thermal control is achieved by an actively pumped thermal fluid loop, and heat is provided by the instruments and spacecraft subsystem components.

The Europa Clipper flight system is solar powered. The solar array is made up of two wings containing five panels each with a total area of 102 m2 and a power output of 700 W at the end of mission. The solar array can be articulated about its long axis and the angular motion ranges from 185° to 165°. The photovoltaic cells are protected from radiation in the Jovian magnetosphere by a cover glass, which limits the degradation from the beginning to the end of mission to 30%. Power generated by the solar arrays is stored in three lithium-ion batteries, which are connected in parallel and provide a capacity of 365 Ah at the end of mission.

The propulsion subsystem supports attitude control, angular momentum management, and all propulsive maneuvers including trajectory correction maneuvers, Jupiter orbit inser- tion, and orbit trim maneuvers. It is a bipropellant system using monomethylhydrazine fuel and mixed oxides of nitrogen (3%) or nitrogen tetroxide oxidizer. The bipropellant is con- tained in two large, identical tanks—one for fuel and one for oxidizer—and is sized for up to 2750 kg of propellant. Thermal control is provided via a pumped fluid loop to the tanks, components, propellant and pressurant lines, and engines, and through some heaters on the pressurant lines and tanks. There are 24 engines, each capable of delivering 27.5 N of thrust. Sixteen of these engines are pointed in the Z direction, in two sets of eight for redundancy. Maneuvers will utilize up to eight engines to provide a maximum total thrust of approxi- mately 220 N. The thrust vector can be controlled by pulsing any of the eight engines in the primary branch. There are eight more engines (two redundant sets of four) that point in the Y and   Y directions. These engines are configured in coupled pairs and are used for roll control.

The telecommunications system provides the link between the flight system and the ground and provides command reception, science and engineering data downlink, naviga- tion data types including ranging, two-way Doppler, and delta-differential one-way ranging (DDOR). The system includes the 3-m fixed HGA, which supports X-band uplink and both X- and Ka-bands for downlink, with redundant traveling wave tube amplifiers at each fre- quency. Ka-band downlink, the primary data return path for science data, is available only on the HGA. All lower-gain antennas support only X-band communication for uplink and downlink. The three LGAs provide all-sky coverage, but their performance limits their use beyond the near-Earth environment; they will be used for some maneuver attitudes, and two are used for gravity science at Europa. During cruise in the inner solar system, communi- cations will be heavily dependent on the FBAs, with limited use of the LGAs, MGA, and HGA. In the outer solar system, X-band uplink and Ka-band downlink will be the primary links for most of the remainder of the mission. During the Europa flybys, the gravity science experiment is enabled by serially switching between FBAs and LGAs. Downlink data rates from the HGA to a single 34-m DSN station during the tour will be up to 16 kb/s at X-band and up to 500 kb/s at Ka-band. Higher rates are possible by using multiple 34-m DSN sta- tions. The uplink data rate will be up to 2 kb/s with the HGA. Without the HGA, the highest data rate that can be supported at Jupiter is 10 b/s on the MGA.

The science payload consisting of remote sensing and in-situ observing instruments (Sect. 4) is accommodated externally on the vault in nadir and ram-viewing directions, respectively, as shown in Figs. 2 and 5. This configuration allows for simultaneous and synergistic observations of Europa's surface, atmosphere, and space environment. Except for MISE, which is attached directly to the vault, the optical remote sensing instruments are hosted on the nadir deck, which is kinematically mounted to the vault for mechanical isolation. The in-situ instruments affixed to the vault are SUDA and MASPEX, and the Up- per PIMS sensor. The Lower PIMS sensor is mounted at the bottom of the spacecraft, to complete the instrument's total field of view in the YZ plane. The REASON VHF and HF antennas are mounted on the edges of the solar array, and the three sensors of ECM are lo- cated on an 8.5-m-long boom. The REASON antennas and the ECM boom will be deployed soon after launch.

6 Mission Design and Operations

Mission Design includes architecture and implementation of the plan for conducting the mission, starting with the launch, through the interplanetary trajectory and Jovian tour, and ultimately ending with disposal of the flight system. The concept of operations defines how the spacecraft will be flown to achieve the mission's requirements for science and engineer- ing needs. These are more thoroughly documented in Cangahuala et al. (this collection) and are briefly summarized here.

6.1 Mission Phases

The Europa Clipper mission concept was developed through architecture studies to find high science value missions to Europa at realistic cost, as described in Sect. 2. Options were even- tually narrowed to the multiple flyby approach of Europa Clipper. This approach, selected as a low implementation risk that retains high science value, accomplishes the science objec- tives of the mission via a spacecraft in Jupiter orbit carrying science instruments to observe Europa and its environment during an extended series of close Europa flybys (Buffington et al. 2017).

6.1.1 Launch and Cruise Phases

The baseline timeline begins with a launch from Cape Canaveral on a Mars–Earth Gravity Assist (MEGA) trajectory in October 2024, using a commercial SpaceX Falcon Heavy vehi- cle in fully expendable configuration. The MEGA interplanetary trajectory has a 5.25-year cruise phase, with a perihelion as low as 0.82 AU. The Mars gravity assist will occur on 28 February 2025, and the Earth Gravity Assist on 2 December 2026 (with dates applicable to a launch at the beginning of the launch period). Jupiter Orbit Insertion (JOI) occurs 11 April 2030. Cruise events are detailed in Cangahuala et al. (this collection).

6.1.2 Tour Phase

The Europa Clipper tour design (Buffington 2014; Buffington et al. 2017; Cangahuala et al. this collection) leverages four gravity assists from Ganymede to set up the first Europa flyby (E01) 11 months after JOI. Following an additional Europa flyby and two additional Ganymede flybys, the first set of resonant Europa flybys, Europa Campaign 1, begins about three months later. Europa Campaign 1 is designed primarily to survey the sun-lit anti-Jovian hemisphere of Europa and is composed of 24 Europa science flybys, most at altitudes at or below 100 km. This campaign is followed by an 8-month period of orbit shaping, utilizing Callisto and Ganymede flybys to set up Europa Campaign 2, with 23 Europa science flybys, to survey the sun-lit sub-Jovian hemisphere of Europa.

Europa Campaign 1 begins with a series of 6:1 resonance Europa-to-Europa transfers, which means Europa orbits Jupiter six times in the same amount of time that Europa Clip- per orbits Jupiter once (about 21.3 days, approximately 3 weeks). The orbit cadence is then increased to 4:1 resonant transfers for Europa Campaign 2 (about 14.2 days apart, approx- imately 2 weeks). Beginning the first campaign with a longer cadence between flybys (6:1 resonant transfers) provides the ground team with a gentler cadence that better allows for anomaly responses in the course of executing science and engineering activities, includ- ing orbit trim maneuvers. In both cases, these highly elliptical orbits afford time for Europa science data playback while outside Jupiter's high radiation environment, extending the life- time of the mission and maximizing the total science return.

The mission's radiation limit utilized for tour design is 3 Mrad total ionizing dose behind 100 mil of aluminum, as modeled from JOI to the final Europa flyby. The Europa Clipper mission concept assures "global-regional" coverage of Europa (i.e., data sets at the regional scale, distributed across Europa globally) via a complex network of flybys from Jupiter orbit. Ground tracks with corresponding altitudes for the nominal 49 planned science flybys of Europa are illustrated in Fig. 6.

6.1.3 Planetary Protection and Disposal Phase

Europa Clipper is a flyby mission to a location of significant interest for the chemical evo- lution or origin of life, with a chance that contamination could compromise future inves- tigations. Thus, the mission is deemed Category III from the planetary protection perspec- tive, limiting the probability of contamination Europa's ocean with a single organism to 1 x 10−4, over a 1000 year period of concern for biological contamination (National Research National Research Council 2012). To address this limitation, the Europa Clipper mission adopts a probabilistic model (McCoy et al. 2021) that considers:

spacecraft failure scenar- ios and the associated potential for impact onto Europa; expected geological resurfacing timescales that could carry terrestrial biological contamination to Europa's liquid water; and assessment of biological mortality from Earth to Europa. Instead of demonstrating that the spacecraft hardware would be fully sterile, the project shows that the probability is suffi- ciently small that Europa Clipper inadvertently impacts Europa and delivers hardware onto a piece of the surface that resurfaces within the 1000-year period of biological exploration (McCoy et al. 2021; DiNicola et al. 2022).

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 with Europa. The disposal phase of the mission ensures the permanent avoidance of Europa impact by deliberately impacting another Jovian body, nominally Ganymede. The currently planned disposal phase is the period between the End-of-Prime-Mission (EOPM) on 23 June 2034 and End-of-Mission (EOM) on 03 Septem- ber 2034, where EOPM is defined as 30 days after the last targeted Europa closest approach, and EOM is defined to be the time of impact. If the science mission were to be extended through agreement with NASA, the disposal phase would be delayed.

6.2 Concept of Operations

6.2.1 Templatized Repeatable Science Observations

A key factor in the observing strategy is the unavoidable coincidence of science observations and high radiation in the vicinity of Europa. Acquiring all the observations needed to fulfill science objectives requires several total weeks within this challenging environment, where a safe limit on total time is imposed by flight system tolerance to the accumulating radiation dose. The advantage of the multiple-flyby approach is the ability to divide this necessary exposure into many short intervals of a day or two each. These periods are then separated by 2–3 weeks on average, as determined by Europa Clipper's orbit period around Jupiter. Routine activities such as data return, energy renewal, orbit maintenance, and calibrations may then be conducted at a more leisurely pace and without the added complication of an intense radiation environment.

Naming conventions for a typical orbit and encounter are provided in Fig. 7. The repet- itive nature of both science observations and engineering support activities is efficiently accommodated by use of templates, repeatable observations that cover specific time periods within each orbit. Observations may be coordinated among instruments, and calibrations, rolls to obtain data on fields and particles, maintenance activities, and downlink can all be accommodated with minimal uplink process iteration and risk. An example of a templatized approach to orbital activities is illustrated and described in Cangahuala et al. (this collection).

Trajectory options for Europa Clipper are designated by the year of the tour's development (here, 2021), an indication that the tour is for a multiple flyby mission (F), the sequential number of the developed tour family (here, 31), and the specific version of the tour (here, version 6).

6.2.2 Data Downlink Plan

Compared to historical deep space missions, the Europa Clipper mission will carry a sub- stantial amount of non-volatile data storage capability to meet its unique science and engi- neering data storage needs: each Europa Clipper flight computer, or Europa Compute El- ement (ECE), will have a redundant Bulk Data Storage (BDS) device designed to hold at least 512 Gibibits (where 1 Gibibit 1030 bit), or 550 Gb, of payload data. This is the volume required through the end of mission, after accounting for memory degradation due to radiation and other environmental factors over the expected life of the mission. Following data collection, the scheduled communication links to Earth may not support the downlink of all the collected data before the subsequent Europa flyby or flybys. As such, the BDS contains sufficient capacity to allow storage of those carryover data, until those data can be downlinked. Instrument data will be sorted into priority bins so they can be placed in the data product catalog for eventual downlink. The total data volume expected to be returned during the Jovian tour is >6 Tb.

6.3 Science Planning Process

Science planning lessons from the Cassini mission (Paczkowski et al. 2009) have guided the science planning strategy for Europa Clipper. The Europa Clipper Science System is respon- sible for developing the science strategic plan to document the high-level science objectives and priorities used by the Mission Operations System (MOS) to refine the science observa- tion timeline. The key product of the science strategic planning process will be the Science Strategic Planning Guide (SSPG), which will document the integrated cross-discipline sci- ence priorities for each orbit throughout the mission. The SSPG will be developed prior to JOI via discipline-focused discussions and negotiations held within the Thematic Working Groups (TWGs, Sect. 7.2.1). Key content of the SSPG includes: science priorities for the non-nadir period of each orbit, inclusive of the period before Europa Campaign 1; science data playback priorities per encounter; integrated observation strategies; and target selection strategies and priorities. The leadership of the TWGs and the Habitability Advisory Board (HAB) will be responsible for synthesizing each TWG's priorities into the SSPG, to develop an integrated science product. This integrated SSPG will be reviewed and concurred by the Science Leadership (Principal Investigators, Team Leaders, and TWG co-chairs; Sect. 7.2) prior to delivering it to the MOS. The general process flow is given in Fig. 8a.

During Europa Tour Operations, the SSPG may need to be updated based on new Europa discoveries, lessons-learned from science data collection and analysis or from instrument- related performance changes that may require re-thinking the science strategies or the science data playback priorities. Given the latency in downlinking and interpreting science data to inform changes, the expectation is that (nominally) during this process, the science team will not be making significant changes to the overall strategic plan, and will only adjust the plan to best achieve the science requirements. The SSPG updates will likely occur once dur- ing Europa Campaign 1, once during the transition to Europa Campaign 2, and once during Europa Campaign 2.

Members of the science team also participate in tactical decision-making processes (oc- curring on a 4-week cadence) via the

Tactical Science Group (TSG). The TSG includes representatives from the science investigation teams, TWGs, mission operations, and sci- ence team leadership, ensuring a broad range of experience and perspectives. This group is empowered to make operational decisions on behalf of the broader science team. It also advocates for science during tactical planning and serves as the primary personnel inter- face between the science team and the mission operations team. Each role in this group has unique responsibilities, and because most of the individuals serving on this team have external obligations, each role will have a defined rotation cadence to allow for transitions and workload balancing. Activities that require the support of the TSG (training, operational readiness tests, activity timeline updates, and tour operations) will begin approximately one year before JOI. As shown in Fig. 8b, the main interface functions of the TSG include: reviewing and assessing all proposed science intent changes during each uplink process, providing the agreed-upon changes to MOS, and providing an out-brief of those changes to the science leadership, which will include a summary of potential implications for future flybys.

6.4 Geospatial Analysis Software

For the science team to be full participants in Europa Clipper's concept of operations, soft- ware tools are required to conduct integrative science analysis, to permit science observation and data visualization, and to support science observation planning. Such tools will be essen- tial interfaces to facilitate well-informed communication between the MOS and the science team. Two such tools, Cadmus and iDigit, are currently in use to aid planning. Another such tool, the Europa Geospatial Analysis Software (EGAS), will support a broad range of science data to enable integration across the investigations. Built on the framework of the Java Mission-planning and Analysis for Remote Sensing (JMARS; Christensen et al. 2009), EGAS will display science data, enabling multiple data sets to be analyzed together at high fidelity and promoting cross-instrument scientific analyses. It will also ingest and display select mission data such as a basic activity timeline; instrument pointing, FOVs, FORs, and footprints; geometric characteristics of the trajectory; and locations of nearby planetary bodies. EGAS will provide critical contextual information to the science team members as they are supporting and participating in mission operations, enabling strategic and tactical science decision-making and efficient communication across the science team.

6.5 Data Products and Archiving

The Europa Clipper mission will generate an abundance of scientific data products, and it is the science team's policy that all data products be freely shared among science team members. Raw data products will be archived at the Planetary Data System (PDS) within six months, and derived products by the end of mission, for public use. The generation and validation of data products and archives, and the delivery of archives to the PDS, is overseen by the Data Archive Working Group (DAWG). Data products are categorized by processing level and comprise telemetry, raw, partially processed, calibrated, and derived data products. Telemetry and raw data contain the original data received from the instrument, whereas calibrated data products have been converted to physical units, and derived data products include processing beyond the calibrated level. Each archival data product will be defined in a software interface specification document.

The science operations will be geographically distributed, with a common data reposi- tory referred to as the Mission Data Store. The high-level flow of data through the stages of archive generation, validation, and transfer to the PDS for distribution to the science community is illustrated in Fig. 9 and is described as follows. Upon receipt of telemetry from the DSN, the MOS will generate data products up to the raw level within the mission Science Data System (mSDS) and provide these data, along with trajectory and relevant ancillary data, to the science team for scientific analyses. These data are also delivered to each inves- tigation team's home SDS for generation of higher-level calibrated and derived data prod- ucts, and the resulting products will be returned to the Mission Data Store and forwarded as archive bundles to the PDS after they have been fully validated. The archival data products associated with instrument data will be in PDS standard version 4 (PDS4) data format and include metadata in the form of PDS4 labels (Planetary Data System 2021). Archival data products produced by the MOS, specifically raw data products, trajectory and engineering data, and any other relevant information, will follow the same procedures as data products designated for the science archives. All levels of data products from all investigations will be available to anyone on the science team.

Validation of science, engineering, and trajectory data follows the generation of data products and will be carried out by the generating entity. Validation of the data archive is a key requirement for the mission to ensure the integrity of scientific content. Scientific analysis of the derived products constitutes an important form of validation, as problems can be uncovered during the work. During the validation period, the data suppliers will check for and correct obvious errors in processing and missing files. Secondary validation using PDS-provided software will check for missing files, defects in the file and directory structures, compliance with PDS4 standards, and integrity of the electronic transfer of the data products. Generation and validation of products will occur within a period of six months between receipt of data and delivery to the PDS. Content validation will rely on scientists of the relevant investigation teams who will ensure integrity of the data product archives. Upon delivery of data, the PDS will conduct additional validation of the data archives and will iterate with the investigation teams to resolve issues prior to public release.

To support cooperative and synergistic science along with adaptive and efficient mission planning, collaborative data products will be shared within the full science team as they become available and will include "quick-look" products, which will be made available to the science team within two weeks. Collaborative data products are not expected to be archive-ready, but they will be suitable for the purposes of aiding scientific investigations and enabling preliminary discussion among the science team, and some (as appropriate) will ultimately be archived with the PDS. The scientific use of these data is integral to data validation and ensures that high-quality products will be delivered to the public.

In coordination with cognizant science team members, some communications data prod- ucts will be derived from collaborative data products for purposes of public outreach and media releases. These products are intended for rapid dissemination of new and significant information by the project’s communication team to the public, and they include images, derived data products, and other forms of data that illustrate new results that are likely to be of high public interest. Public distribution of data includes news media events, digital and social media dissemination, and distribution of written materials concerning mission operations and/or scientific analyses.

Standard data products form the core of the archives that will be produced by the Europa Clipper project, investigation teams, and participating scientists, and they will be delivered to the PDS for distribution to the science community. These products and related documen- tation (software interface specification, user guides, and tutorials) will be validated prior to transfer to the PDS. Engineering data relevant to the interpretation of science data and required for processing raw data into higher-level data products will also be archived. In some cases, these data may be aggregated with science data products rather than forming dedicated products on their own. The generated archive bundles will be delivered by the re- spective producers to the Mission Data Store and the PDS. Once transferred to the PDS, the Europa Clipper archives will be available online through the PDS archive interface. Newer versions of products may replace older versions over time. The PDS will provide a capabil- ity for the user to be able to search for and retrieve digital data that meet criteria requested by the user, such as specific target body, location on the body, instrument, and times of coordinated observations; map-based searches will also be supported.

7 Science Team Structure and Philosophy

7.1 “One Team” Philosophy

To understand whether Europa is habitable, we need to disentangle the complex and interre- lated processes that reveal whether this moon possesses the “ingredients” for life. We need to know the location and properties of liquid water, including its relationship to tidal heat- ing, the movement of melt, and the composition of brines. Information on whether Europa’s chemical-physical environments are suitable for life can be inferred from detailed measure- ments of the surface and tenuous atmosphere, including remote and in-situ measurements of the surface, gases, particles, and plasma. To understand whether Europa’s ocean has the chemical sources of energy to support life requires knowledge of the geological, geochem- ical, and radiolytic processes that affect composition and abundance of oxidants and reduc- tants in potentially habitable niches. To discern Europa’s secrets, synthesis of phenomena and processes is key.

Each of Europa Clipper’s instruments will be used to interrogate Europa and its environs, and with each we will find critical clues about how that planetary body works. However, it is in combining and assessing the details, limitations, and datasets from each instrument that we can gain collective clarity into the multi-disciplinary mysteries of Europa. To achieve the mission’s goal of exploring Europa to understand its habitability, then, we must step beyond the comfort zone of our own specific scientific disciplines and work across instru- ment realms, to celebrate and engage the expertise of the full Europa Clipper science team, and beyond. As is common in science, it is at the overlapping boundaries of sub-fields that the greatest insights and discoveries are derived: diverse and interdependent teams result in innovative and groundbreaking science (Balakrishnan et al. 2011; Uzzi et al. 2013; Foster et al. 2015).

Integrated science cannot be achieved post hoc, as an afterthought, but instead requires forethought and planning as to how the science team itself is organized and interacts. Syner- gies among instrumentation and investigators must be built into the organization and social fabric of the team, to best enable multi-disciplinary investigations (Vertesi 2020a). Balakr- ishnan et al. (2011) describe that teams may be co-acting, coordinating, or integrated, with such integration best beginning at a project’s inception. Therefore, from the start, the Europa Clipper science team has adopted a “one team” philosophy, promoting visibility and interde- pendence across the science team, regardless of members’ instrumental or disciplinary affil- iation. This requires understanding and sharing each other’s processes, techniques, data sets, analyses, caveats, and results (Shrum et al. 2007; Vertesi and Dourish 2011; Vertesi 2020a). Visibility and interdependence bring trust, promote partnerships, inspire group identity, and enhance the interpersonal relationships essential to team support (Durkheim 1893; Vertesi 2020a). Visibility and interdependence provide fertile ground for the development of joint investigations, data-sharing arrangements, and interdisciplinary science. These values also provide holistic solutions to problems that could arise; for example, if a Europa Clipper in- vestigation is at risk of not achieving its contribution to a science objective, the science team (e.g., via the TSG) will be readily motivated to provide resources to ensure success for the at-risk technique’s contribution to the science objective.

Promoting visibility and interdependence across the Europa Clipper science team is ac- complished in many ways, including:

Working and focus groups that are open to all science team members, and which are fluid in membership and participation; Mailing lists and newsletters shared across the science team; Meeting formats that promote sharing of information, ideas, and plans; Shared software that displays observation plans and what-if “sandbox” scenarios; Shared software that promotes comparative analysis and synthesis of datasets; Team collaboration websites that provide for information sharing;

Strategic planning that involves the whole science team via the TWGs in developing initial estimates of how spacecraft resources (observation time, BDS space, and downlink) will be utilized; thereafter, the TSG (which includes representatives of each Investigation team and each TWG) will decide how to use resources tactically, instead of instrument teams being assigned individual allocations a priori;

“Quick-look” and other collaborative datasets shared across the full science team; Common “data store” where any team member can access any raw or processed dataset; Shared analysis tools to view collaborative and integrated science datasets;

Shared measures of forecasted performance against science requirements and flight sys- tem consumables;

Publication policies that promote sharing of paper outlines and drafts across the science team, along with calls for contributions from potential co-authors;

Meeting rituals such as social events, journal clubs, award ceremonies, informal gather- ings, and a monolith mascot, that connect scientists across sub-teams.

The Europa Clipper science team's Rules of the Road (Europa Clipper Science Team 2022) provides team policies on data sharing, publications, professional code of conduct, and science team responsibilities. This document is intended to provide open, transparent, and equitable operating rules for the Europa Clipper science team for the duration of the project, to enable strong working relationships and to ensure that the highest quality science is delivered from the project. All Europa Clipper science team members are required to abide by and uphold the policies and practices described in that document.

7.2 Science Team Structure

The foundational membership of the science team was established with NASA's selection of the nine individual investigation teams, upon instrument selection in May 2015. The Gravity and Radio Science team members were selected later, in July 2020. Science team onramps include nomination and approval of team affiliates (professional, post-doctorate, and grad- uate student—the latter two categories during the limited time of their related work), and limited nomination of new Co-Investigators, generally replacing Co-Investigators who have left the team or those who have entered Emeritus Co-Investigator status with a relatively low level of activity. Furthermore, it is anticipated that NASA Headquarters will add participat- ing scientists for the mission near the time of Jupiter Orbit Insertion, permitting them to be trained and ready in time for the first Europa encounter. Onramps and offramps for partici- pation are extremely valuable to ensuring a vibrant and active science team, with ability to evolve over the long timescale of the mission.

The Europa Clipper science team adopts a hybrid flat-hierarchical organizational struc- ture (Fig. 10), to promote team integration and for broad participation with a variety of voices heard (Turco 2016; Vertesi 2020a). At the same time, an embedded hierarchical structure facilitates management and communication pathways. Examples of hierarchical structure within the team are the structure of the Project Science Group (PSG), chaired by the Project Scientist and with the NASA Program Scientist as vice-chair; a Science Manager, who manages contracts and logistics associated with the PIs and other science investigators, and facilitates training and programmatic logistics for the PSG; investigation teams, man- aged by a Principal Investigator (PI) for the competitively selected science investigation teams or by a Team Leader (TL) for scientists working with facility-provided hardware; and Thematic Working Groups and Focus Groups, described next. While these groups are hier- archical in having distinct leadership, they are also relatively flat in promoting broad science team participation and interdependence, and the Working and Focus Groups feature rotating leadership positions.

7.2.1 Thematic Working Groups (TWGs)

Under the one team philosophy, the Europa Clipper science team members work together to address the goal and objectives of the Europa Clipper mission through TWGs covering the areas of habitability, interior, composition, and geology. The TWGs are designed to provide high-level, cross-instrument and cross-discipline science objective-driven perspectives that ensure the goal and objectives of the Europa Clipper mission are met, and that the highest quality integrated science is achieved. The TWGs include one goal-focused group, and three science objective groups.

The Habitability Assessment Board (HAB) considers the primary mission goal: explore Europa to investigate its habitability. The HAB is a plenary body, with a rotating leader- ship composed of three co-chairs with broad expertise nominated by the full science team, and each member of the Europa Clipper science team is considered a member of the HAB group given that each individual team member contributes to the habitability goal. The HAB group considers how each of the individual investigations contribute to our understanding of Europa's habitability, as well as how meeting each of the science objectives will cre- ate an integrated understanding of the body as a potentially habitable system. The HAB is additionally responsible for mediating inter-objective discussions, and synthesizing reports and recommendations across the objective TWGs. During the prime mission, HAB will be responsible for considering and adjudicating interests among the objective TWGs.

Each objective TWG is charged with providing a broadly integrated science perspec- tive to help ensure that the Europa Clipper mission can meet its objectives, and that the highest quality integrated science is achieved. Objective TWGs have two rotating co-chairs nominated by the groups and one facilitator provided by the project. The Interior Work- ing Group considers the mission objective to characterize the ice shell and any subsurface water, including their heterogeneity, ocean properties, and the nature of surface–ice–ocean exchange. The Composition Working Group considers the mission objective to understand Europa's ocean through composition and chemistry. Finally, the Geology Working Group considers the mission objective to understand the formation of surface features, including sites of recent or current activity, and to characterize high science interest localities.

7.2.2 Focus Groups (FGs)

In addition to the TWGs, Focus Groups (FGs) are periodically formed to gather information on specific cross-cutting topics, and to study and discuss science guidelines, policies, and trades as they affect the scientific success of the mission. Each FG must establish a specific task requiring expertise from multiple TWGs and is supported by the Project Scientist and TWG co-chairs. Each FG advocates for its specific charter through the relevant TWGs. In mission phases A–D, the FGs considered the interdisciplinary science related to plumes, radiation, geodesy, and reconnaissance. FGs have a rotating leadership consisting of one or two co-chairs nominated by the individual FGs, as well as a facilitator provided by the project.

7.3 Efforts Toward Equity, Diversity, Inclusivity, and Accessibility

The Europa Clipper science team is committed to improving equity, diversity, inclusion, and accessibility (EDIA), and is encouraging of team cohesion in scope, priorities, and contri- butions within the "one team" philosophy (Sect. 7.1). It is well recognized in social science literature that the sciences have a poor track record when it comes to the representation of women, minorities, and marginalized groups (Smith-Doerr et al. 2017; Nielsen et al. 2018). Central to Europa Clipper's science team efforts is an understanding that the team needs to look critically at EDIA best practices and outcomes, and to continually improve, in areas where most needed. To improve the working environment, engage with a broader swath of the community, and maximize the mission's overall science return, the Europa Clipper science team pursues ways to provide a diverse and equitable environment. Ultimately, an important aspirational goal for Europa Clipper is a more inclusive team that looks like the United States as a whole. Toward this end, we recognize a need to continually strive to include voices from members of traditionally underrecognized groups (Rathbun et al. 2020).

7.3.1 Code of Conduct

The Europa Clipper science team is the first NASA planetary mission team to have a code of conduct (Diniega et al. 2020)—a statement written with an aim to foster a safer and more equitable environment by protecting the physical, mental, and emotional safety of all participants. Inclusion of this policy within its Rules of the Road is important for transparency, across the breadth of the Europa Clipper team and the mission's long lifetime of more than a decade, with many changes to team membership anticipated. A key focus of the code of conduct is to emphasize not only respectful behavior across all team interactions, but also active work toward an equitable culture.

This code of conduct has been evaluated, discussed, and revised several times since formation of the Europa Clipper science team. As the team's explicit and implicit norms, demographics, and experience change, it is important that this policy be updated to reflect current best practices and enable effective and fair interactions throughout the team. It is expected that this document will continue to be revised throughout the mission's lifetime.

7.3.2 Science Team Meeting Initiatives

The Europa Clipper science team, like most modern large planetary mission teams, is widely distributed; thus, many communications and decisions need to be made via remote interactions (commonly with distributed groups collocated). Meeting types include regular seminars, status updates, and discussion meetings on weekly and monthly cadences. The Europa Clipper's Project Science Group (PSG) meeting is the largest meeting type, where the full science team meets at least annually for several days to come to a common level of understanding on topics including project development status and mission science options. These PSG meetings encourage networking within the team and across investigations.

Each PSG meeting agenda includes time to develop group and individual practices leading to better team connection and interaction. At several PSG meetings, bystander intervention training has been offered to all team members and required of PIs and TLs. Bystander intervention training encourages all participants to be proactive about noticing potential or actual harm and, when able, to intervene during or after such an event (Bennett et al. 2023). At each PSG meeting, the team strives to invite one or more social science experts to speak with the team on topics relevant to diversity, equity, and inclusion.

To facilitate discussion and engagement while broadening access, the science team has worked on normalizing practices to help people with a wide range of communication and thinking styles to contribute. This includes advanced posting of agendas so people can take the time they need to prepare for discussion and having multiple platforms for contribution (speaking aloud, writing into chat, and posting questions anonymously). Accessibility initiatives include use of color schemes that are distinguishable to those with color disability, and early adoption of auto-generated captioning for remote meetings.

Given the broad physical distribution of the science team, Europa Clipper project was an early adopter of remote technologies, including the use of cameras and remote audio at meetings. During 2017 and 2018, given limited funding for standalone meetings, the science team experimented with hybrid-format meetings appended to scientific conferences, allowing the team to practice remote meeting strategies, ahead of the unanticipated COVID-19 lockdown. In response to COVID-19 protocols, the Europa Clipper science team further invested in creating effective and remote experiences. Notable efforts include the use of software for gathering questions anonymously and with up-voting capabilities and for pursuing synchronous or asynchronous "side" conversations within meetings. Key to these efforts was incorporation of explicit statements and practices that emphasize deliberate consideration of team structure and interactions, to promote equity and inclusion. New meeting social norms include methods to help team members break into discussions, and employing a dedicated moderator to help with communication issues and guide discussion (Diniega et al. 2019).

A common issue with long-duration flagship missions is the immobility of the science team: once selected, newcomers to the field have limited opportunities for career mobility. Therefore, Europa Clipper inaugurated a team affiliate member status for graduate student and postdoctoral researchers for the duration of their mentorship, to formalize their association with the mission and promote potential future mission participation. These and other affiliation statuses are indicated in the Rules of the Road document, each supporting full team membership in the "one team," with associated rights and responsibilities.

To reach beyond current team members and build toward a more equitable community in general, the Europa Clipper science team was an early adopter of the NASA Here-to-Observe (H2O) program, to provide undergraduates at minority-serving institutions the opportunity to attend a mission science team meeting (Smith 2022). This has the benefit of introducing these undergraduate "Observers" to mission development and operation and make them aware of possible associated career paths. Observers chosen by NASA were paired with mentors from the science team who served as their primary point of contact for questions during PSG meetings. The program has been very well-received by both program participants and PSG members and has served to improve and augment the NASA H2O program.

Following each PSG meeting, anonymous surveys solicit feedback on meeting engagement and productivity. These surveys also assess whether meeting structure and content helped generate the desired "one team" aim, and lessons learned are applied to future Europa Clipper meetings. As PSG meetings transitioned back from fully remote to including a substantial in-person component, organizers have maintained the accessibility improvements brought by strong remote participation (Persaud and Armstrong 2020) by conducting meetings in hybrid mode.

7.3.3 Grassroots Team Initiatives

While engagement and direction from Europa Clipper project science leadership has been fundamental in keeping EDIA considerations at the forefront of team activities, work and organization within the team also has been critical for gathering a diversity of ideas, perspectives, concerns, and solution options. Through grassroots efforts, the Europa Clipper team has initiated three groups for focused EDIA and team dynamics discussions: (1) a traditional journal club focused on social science literature (Diniega et al. 2019); (2) a “sunrise group” for discussions among members who self-identify to be in the sunrise years of their careers (Leonard et al. 2024); and (3) an EDIA-focused mailing list for sharing concerns, ideas for team action, and gathering of suggestions for information sources or new practices. These groups are each opt-in, with clearly defined goals, and organized by a few team members. Ideas from these groups provide potential topics for discussion within the full science team, for example elevating a speaker to the Europa Clipper seminar series or for discussion at a PSG meeting. Many Europa Clipper science team members have also been heavily involved in community EDIA efforts, for example leading white papers and professional meetings on relevant topics.

7.3.4 Leadership Opportunities

Rotation of leadership within the Europa Clipper science team is a key means of growing and strengthening the team through its full lifetime, enabling a mix of building from experience, bringing in fresh ideas, and providing training opportunities. Additionally, as one of only a few large, strategic NASA missions, Europa Clipper team membership presents a unique opportunity for career and science leadership growth. In particular, the TWG and FG co-chairs serve for limited terms (2–3 years and/or through 4 PSG meetings). TWG co-chairs rotate every several years to enable “role distance”: the separation of a position from person who inhabits it (Goffman 1961). These positions are open to anyone on the science team, including early career scientists. As practical, TWG co-chairs include a senior scientist and an early career scientist, providing opportunities for emerging scientists to take on a mission leadership role and to work with a mentor, while supporting mobility in their career path. These leadership roles can include coordinating science efforts, leading trajectory assessments, and evaluating and participating in observation planning. These co-chairs also participate in science leadership discussions with the Project Scientist, Project Manager, investigation PIs, and NASA Headquarters representatives. Nominations for these positions are made by the science team, and selection of these chairs is made by the Project Scientist in consultation with science leadership. The selection process considers individual expertise and diversity of demographics, institutions, and career levels across the science leadership group.

7.3.5 Mission Sociologist

Beginning in 2009 during the science definition phase, the Europa Clipper team has engaged a mission sociologist, Dr. Janet Vertesi of Princeton University—expert in the interrelation between science, technology, and society—who provided valuable perspectives on human factors that affect mission teams. Vertesi had previously performed embedded ethnographic studies of the Mars Exploration Rover and Cassini mission teams. While simultaneously studying the Europa mission in its early stages (Vertesi 2019, 2020b), Vertesi provided mission leaders and team members with observations from other missions and sociological literature as context for shaping the Europa Clipper team structure. This included emphasis on data production context as influencing how data are ultimately valued and shared (Vertesi and Dourish 2011), technologies and best practices for communication and collaboration among members of a distributed team (Swezey and Vertesi 2019), and how the degree of team integration affects scientific outcomes (Balakrishnan et al. 2011). Notably, Vertesi provided perspectives on how team structure and desired science outcome are related, given the premises that team “personality” is established early in mission development and team structure is critical in shaping scientific outcomes (Vertesi 2020a).

8 Coordination with Earth-Based Telescopes and Other Missions

Europa Clipper builds on a foundation of past observations and missions (Sect. 1.1) as well as ongoing and future observations and missions. Here we briefly note coordination with ground-based and space-based telescopes, NASA’s Jupiter-orbiting Juno mission, and the ESA JUICE mission.

8.1 Ground-Based and Space-Based Telescopes

Ground-based and Earth-orbiting spacecraft will provide valuable observations of Europa to enhance and extend the data from Europa Clipper’s flybys. Extended temporal coverage, the acquisition of data at additional wavelengths and at multiple locations in the solar wind or in Jupiter’s magnetosphere, expanded viewing geometries, spatial context for Europa and its environment, monitoring, and follow-up of activity or of specific regions of interest all represent beneficial augmentations to the scientific value of the mission. Other missions, including Rosetta and Juno, have effectively managed ground-based observing teams to provide increased scientific value (Snodgrass et al. 2017; Orton et al. 2021). Finally, the mining of historical data can extend the temporal baseline of observations substantially, especially for the outer planets where seasonal changes may take place over decades (e.g., Hickes et al. 2022). Moreover, extended temporal depictions of possible geologic changes can provide insights into geophysical processes.

Historical observations of Europa have already yielded tantalizing evidence of possible plume activity on its surface even earlier than those detected by the space-based Hubble Space Telescope (HST). Observing at NASA’s Infrared Telescope Facility on Mauna Kea, Tittemore and Sinton (1989) found that a definite measurement in the M filter (4.7 μm) was anomalous:

> “[T]his measurement, which yields a fourfold increase in the observed flux over any other measurement, is unassailable [T]here seems no possibility of misidentification. A total of 25 pairs of integrations were made that were mutually consistent ...
>
> and there seems no possibility of error in these parameters.”

HST continues to provide important data on Europa, from compositional mapping of its surface in the visible and ultraviolet wavelengths (e.g., Trumbo et al. 2019), to the detection of water vapor in the space environment near Europa (Roth et al. 2014; Sparks et al. 2016, 2017). Continued Earth-based observations of the moon prior to, during, and following the Europa Clipper mission will provide a broader context in which to interpret data returned by the spacecraft. Remote observations will provide greater temporal, spatial, and multi- wavelength coverage of Europa during the mission lifetime.

The James Webb Space Telescope (JWST) has great sensitivity in the mid-infrared wave- lengths between 5–15 µm (Norwood et al. 2016). Early results revealing concentrations of carbon dioxide on Europa but no currently detectable plumes (Trumbo and Brown 2023; Villanueva et al. 2023) demonstrates the great potential of JWST for monitoring Europa. The Atacama Large Millimeter Array, with its continued upgrades, can provide thermal emis- sion maps at radio wavelengths (Trumbo et al. 2018). Other extremely large ground-based telescopes, notably the Giant Magellan Telescope (Fanson et al. 2020) and the European Extremely Large Telescope (Ramsay et al. 2020), are due to become operational by Europa Clipper's JOI and will have several times higher sensitivity and greater spatial resolution than currently operating 8–10-m-class telescopes. Simultaneous observing of Europa by these facilities and Europa Clipper will enhance the science return of the mission.

The Europa Clipper mission has also established a ground-based observing team to work closely with the science team on follow-up and contextual observations with Earth-based assets. This team will be especially important in providing extended temporal coverage if telescopic observations are able to confirm current activity on Europa.

8.2 Juno Mission

NASA's New Frontiers class Juno mission entered a polar orbit around Jupiter in July 2016, from which it has characterized the giant planet's composition, gravitational field, mag- netic field, and polar magnetosphere (Bolton et al. 2017). While in the Jupiter system, Juno executed multiple serendipitous observations of Europa, including infrared observations of composition and temperature by the Jovian InfraRed Auroral Mapper (JIRAM) (Filacchione et al. 2019) and the first in-situ measurements of electrons in Europa's auroral footprint us- ing a multi-instrument approach (Allegrini et al. 2020). In its extended mission, the Juno mission adopted three satellite science objectives relevant to Europa that include investigations of satellite-magnetosphere interactions, characterizing the upper 10 km of planetary ice shells, and surface sputtering effects and atmosphere interactions. Beginning with a flyby of Ganymede in June 2021, Juno's extended mission included a single 355 km altitude flyby of Europa in September of 2022. Juno observations of Europa included 1.2 km per pixel visible images of the equatorial leading hemisphere, sparse thermal and compositional spec- trometry, passive microwave radiometry, and measurements of the magnetic field and space environment (NASA 2021). The ground tracks of this flyby transect several of those of Eu- ropa Clipper's planned flybys, enabling additional opportunities to seek evidence for change on the surface of Europa over decade-timescales.

8.3 JUpiter ICy Moons Explorer (JUICE) Mission

The ESA JUICE spacecraft launched in April 2023 and it will arrive in Jupiter orbit in 2031. JUICE will examine the Jupiter system and the icy Galilean satellites with emphasis on Ganymede and its habitability (Grasset et al. 2013). JUICE will make 35 total flybys of Ganymede, Europa, and Callisto before entering into orbit about Ganymede for at least one year. As a comparable flagship mission, JUICE hosts an array of investigations that are highly complementary to those of Europa Clipper. JUICE's two flybys of Europa will be over the antijovian hemisphere, with closest approaches of altitudes 400 km (Grasset et al. 2013; Witasse and The JUICE Teams 2020). These encounters will provide added data along ground tracks from the equator to about 50° north and south for the two respective flybys.

The two missions' science teams have partnered to form a JUICE–Clipper Steering Com- mittee (Bunce et al. 2023), which is composed of a diverse group of scientists from both the JUICE and Europa Clipper science teams. This committee is tasked to identify scientific experiments that could be uniquely accomplished or significantly enhanced by having two spacecraft in the Jupiter system simultaneously. For example, there currently exist two op- portunities where the spacecraft are near Europa within 0.5 RJ of one another and only a few hours apart. Scientific opportunities may fall into one or more categories: (1) time depen- dent, in which both spacecraft would need to acquire data at same time or one spacecraft's observations would inform the other's; (2) geometry dependent, in which each spacecraft acquires data from different parts of the Jovian system, or both observe the same target with similar or different viewing geometries; and (3) an increase in science data return, e.g., extending temporal, spatial, or wavelength coverage made possible by the availability of different instrument types or data collection opportunities on the two spacecraft, as well as cross-calibration between comparable instruments of the Europa Clipper and JUICE pay- loads.

9 Conclusions and Outlook

The Europa Clipper mission promises paradigm-altering science. As the first mission fully dedicated to an outer planet satellite, it will acquire unprecedented knowledge of icy satel- lite physical processes such as: electromagnetic induction, tidal heating, convection, cryovolcanism, tectonism, mass wasting, impact cratering, sublimation, radiolysis, sputtering, ionization, and airglow. Even more significant, Europa Clipper will assess Europa's habit- ability through interrogation of the satellite's interior, composition, and geology, including any current activity. Its objectives and scope are directly responsive to the 2011 planetary science decadal survey (National Research Council 2011), building on decades of iterative refinement. The instrument suite is extremely capable, poised for both hypothesis testing and discovery. The flight system is designed for synergistic science, enabling nominal ob- servations by all instruments simultaneously. From Jupiter orbit, Europa Clipper will swoop past Europa nearly 50 times at altitudes typically 25–100 km, achieving regional coverage that is near-globally distributed, along with high-resolution sampling.

Human factors have been considered concurrently with designs of the flight system and mission system, promoting observational synergies. A "one team" philosophy pro- motes visibility across the full science team, and corresponding cross-instrument and cross- disciplinary interdependence to best understand Europa's interrelated physical phenomena and fully address Europa Clipper's top-level science objectives. Such interdependence will bring great opportunity for scientific advancement and discovery.

The Europa Clipper science team strives to achieve a standard of excellence on issues of EDIA, with acknowledgement of goals that are aspirational. The team's Rules of the Road can serve as a model that could be tailored for other large missions with objectives that call for interdependent interactions. Europa Clipper's organizational structure can feed forward to future outer solar system missions, and its scientific results are expected to form the basis for further spacecraft exploration, such as a mission to search for biosignatures via a potential future Europa lander.

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