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Science Goals and Mission Architecture of the Europa Lander Mission Concept

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Abstract

Europa is a premier target for advancing both planetary science and astrobiology, as well as for opening a new window into the burgeoning field of comparative oceanography. The potentially habitable subsurface ocean of Europa may harbor life, and the globally young and comparatively thin ice shell of Europa may contain biosignatures that are readily accessible to a surface lander. Europa's icy shell also offers the opportunity to study tectonics and geologic cycles across a range of mechanisms and compositions. Here we detail the goals and mission architecture of the Europa Lander mission concept, as developed from 2015 through 2020. The science was developed by the 2016 Europa Lander Science Definition Team (SDT), and the mission architecture was developed by the preproject engineering team, in close collaboration with the SDT. In 2017 and 2018, the mission concept passed its mission concept review and delta-mission concept review, respectively. Since that time, the preproject has been advancing the technologies, and developing the hardware and software, needed to retire risks associated with technology, science, cost, and schedule.

Unified Astronomy Thesaurus concepts: Europa (2189); Ocean planets (1151); Astrobiology (74); Biosignatures (2018)

1. Introduction

Jupiter's moon Europa is a prime target in our exploration of potentially habitable worlds beyond Earth, and of oceans that likely exist beneath the icy shells of numerous worlds in the outer solar system (Figure 1). Europa may hold the clues to one of NASA's long-standing goals: to search for life elsewhere and determine whether or not we are alone in the universe (NASA 2020).

The exploration of Europa presents an important target for both astrobiology and comparative oceanography, i.e., the opportunity to study liquid-water oceans as a planetary process (Hand & German 2018; Hand et al. 2020). Europa's icy shell also offers the opportunity to study tectonics and geologic cycles across a range of mechanisms (e.g., Earth's cooling versus Europa's tidal dissipation) and compositions (silicate in the case of the Earth versus ice in the case of Europa; McKinnon 1998; Nimmo & Gaidos 2002; Doggett et al. 2009; Kattenhorn & Hurford 2009; Kattenhorn & Prockter 2014).

Critically, Europa's subsurface ocean has likely persisted for much of the history of the solar system, potentially providing a long-term, stable environment in which a second, independent origin of life might have arisen (Canup & Ward 2002; Hussmann & Spohn 2004; Moore et al. 2009; Hand et al. 2009; Russell et al. 2017). Observations and models indicate that the ocean is likely in contact with a rocky, silicate seafloor, and the ice shell may have tectonic activity that could allow reductant-oxidant cycling (Kivelson et al. 1997; Anderson et al. 1998; Khurana et al. 1998; Zolotov & Shock 2001). This scenario could lead to an ocean rich in the elements and energy needed for the emergence of life, and for potentially sustaining life through time (Hand et al. 2009, 2007; Vance et al. 2016).

Importantly, the Europa Clipper mission will be able to assess the habitability of Europa via remote-sensing investigations made possible by more than 45 close flybys of Europa. If Clipper reveals that Europa is habitable, then clearly an in-situ investigation with a lander is the next step. But even if the Clipper mission were to reveal that Europa was not habitable, Europa's ice-shell geology, geophysics, and oceanography are in and of themselves worthy of in-situ investigation (National Research Council 1999, 2003b; Hand et al. 2020).

The persistence of Europa's ocean means that life could be alive there today, i.e., signs of extant life could be found within the ice and ocean of Europa. The discovery of signs of extant life is critical if we are to understand biology as a universal process (Lazcano & Hand 2012): does it contain DNA, or does it function on some other large biomolecules for information storage, replication, and repair? Are there many separate "trees of life" within our solar system, or is the tree of life on Earth the only one? The search for past life on worlds like Mars is very important, but the search for extant life is how we will truly revolutionize biology (if life exists beyond Earth).

Lander and melt-probe concepts for Europa have been studied for over two decades (JPL concept studies go back to 1997; Horvath et al. 1997). In 2016 NASA convened a Science Definition Team (SDT) to develop the science and mission concept for a landed spacecraft that could achieve civilization-scale biosignature science, while also answering questions about the surface and subsurface environment (Hand et al. 2017). Figure 2 shows the high-level science goals and objectives of the mission concept. Figure 3 details the model payload, both baseline and threshold versions of potential instruments that could address the measurement requirements. Additional details regarding the model payload are provided in Section 4. With the exception of the Geophysical Sounding System (GSS) all of the instruments work in service to Goal 1, and all five instruments work in service to Goals 2 and 3. Finally, Figure 4 shows four key stages of the mission concept: cruise, deorbit, descent, and surface operations.

The science addressed by the three goals leads to a fully integrated mission concept and model payload that would enable a diverse approach to the search for potential biosignatures, bringing together morphological, organic, chiral, and inorganic indicators of life, all within a well-quantified geologic context.

Chemical analyses of samples collected directly from Europa's near-surface layer would enable detection and characterization of organics at the picomole-per-gram level of sampled material, which is an improvement of approximately nine orders of magnitude over those possible by means of remote-sensing capabilities. High-resolution imaging observations from lander instruments would span scales from nanometers to decameters (0.2 microns to tens of meters) and provide in-situ context for

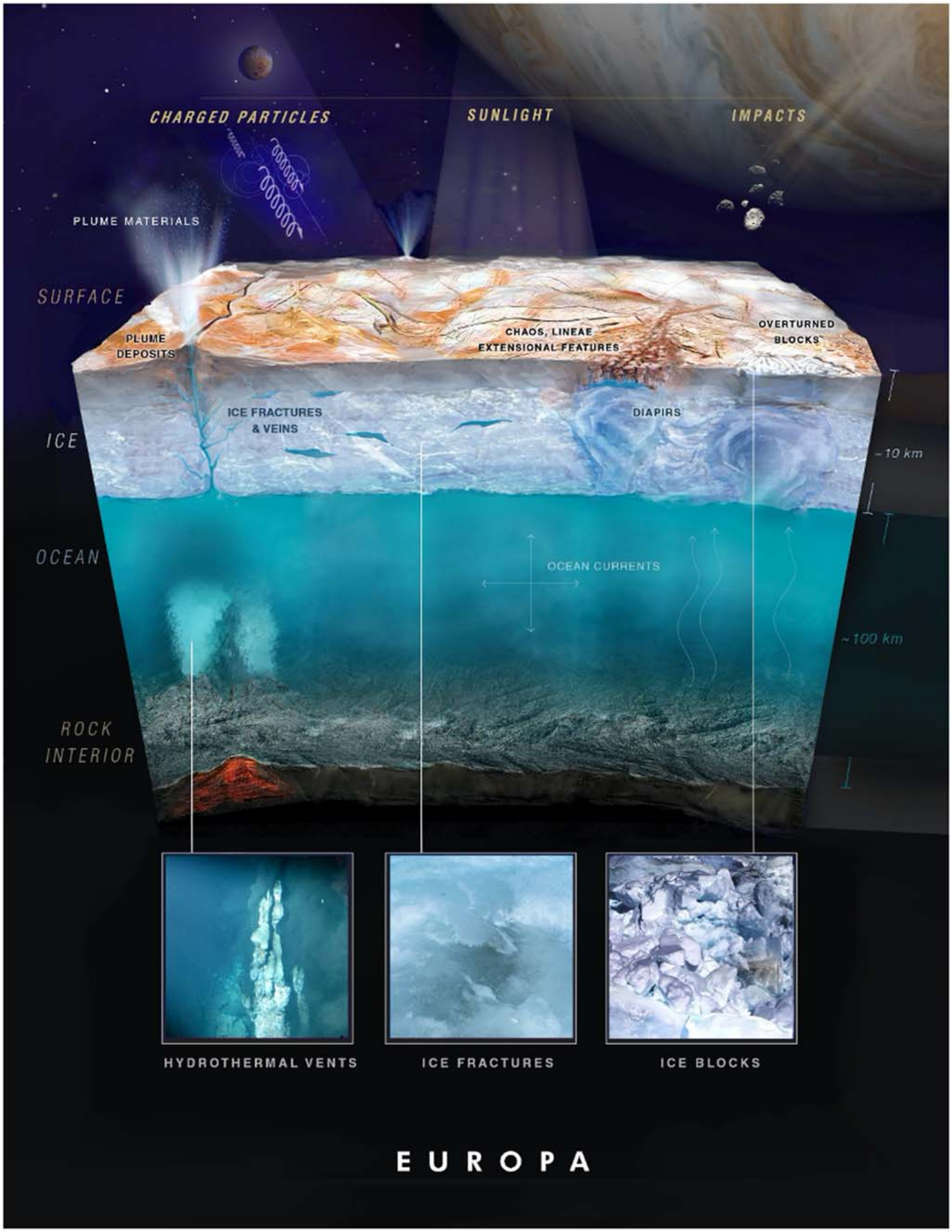


Figure 1. Artistic representation (not to scale) of Europa in cross-section showing processes from the seafloor to the surface. Boxes indicate potentially habitable sites such as hydrothermal vents, as well as regions on and within the ice shell that could harbor biosignatures. This diagram shows an integrated perspective of how the seafloor, ocean, and ice shell could yield biosignatures detectable on the surface by a landed spacecraft.

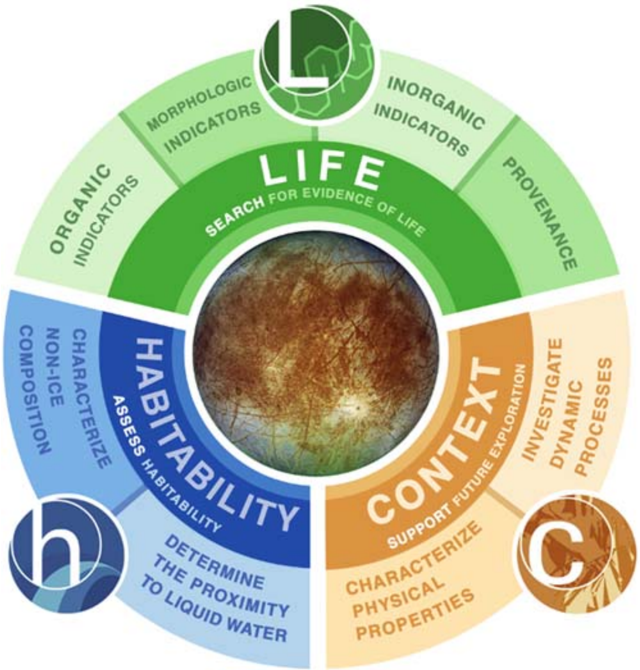


Figure 2. The science goals and objectives of the Europa Lander mission concept. These goals and objectives, as well as much of the technical design of the mission concept, are well suited for landing and conducting science on many of the ocean worlds in our solar system.

Instrument Class [mass allocation, unmargined] Total = 42.5 kg (with margin)	Model Payload: Baseline	Model Payload: Threshold
Context Remote Sensing Instrument (CRSI) [4.3 kg, includes shielding]	Two identical multifilter, focusable, visible to near-infrared, stereo overlapping cameras with narrowband filters comparable to those of the Europa Clipper cameras	Two identical RGB, fixed focus, stereo overlapping cameras
Microscope for Life Detection (MLD) [5.4 kg]	Deep UV resonance Raman and optical microscope with fluorescence spectrometer	Atomic Force Microscope (AFM) with optical context imager
Vibrational Spectrometer (VS) [5.4 kg]		Raman Laser Spectrometer (RLS)
Organic Compositional Analyzer (OCA) [16.4 kg]	Gas Chromatograph Mass Spectrometer (GC-MS) with Stable Isotope Analyzer (SIA)	Gas Chromatograph Mass Spectrometer (GC-MS)
Geophysical Sounding System (GSS) [1.2 kg]	broadband seismometer	3-axis geophone

Figure 3. Baseline and threshold model payloads for the Europa lander. Elements housed within the radiation-protected vault are in white; elements outside of the vault are in orange. Mass allocations are shown in brackets in the left-hand column.

sampled materials, local geology, and surface properties. This roughly seven orders of magnitude enhancement in spatial resolution over the Europa Clipper mission would provide key insights into the properties of Europa's ice shell and any subsurface liquid water. At such high spatial resolution, grain sizes of ice and other materials can be measured and characterized, serving to inform our understanding of Europa's regolith depth, spectral properties, and compositional heterogeneity. These measurements, when coupled with Europa Clipper imagery, spectroscopy, and ice-penetrating radar, could help determine the subsurface ocean chemistry and depth to the ocean. Furthermore, the acoustic sounding measurements would provide unique and complementary measurements to those performed by the radar, magnetometer, and plasma instruments that will be flown on the Europa Clipper mission.

The scientific and technical approach of the Europa Lander mission concept provides a robust strategy for the first landed mission to search for biosignatures on an ocean world. The science return from the model payload is such that if life is present in Europa's ice at a level comparable to one of the most extreme and desolate of environments on Earth (Lake Vostok ice) then this mission could detect signs of life in Europa's icy surface. The combination of detection methods, detection limits, and scales of observations provided by the model payload and mission concept combine to make this possible. In the absence of any signs of life, this mission is also designed to generate an incredibly valuable data set detailing the chemistry of Europa's ice shell, its putative ocean, and the geologic, geophysical, and chemical context for habitability. Either of the above outcomes—biosignatures detected, or not—is of fundamental scientific value to understanding the prospects for life in the solar system, and our place in it.

In 2017 July the mission concept detailed here passed through a Mission Concept Review (MCR), with direction to reformulate the architecture from one in which a communication-relay stage is in orbit around Europa to one in which the communication from the lander occurs direct-to-Earth from the lander, and direct-from-Earth to the lander (DTE and DFE, respectively). In 2018 November, the DTE Europa Lander architecture successfully passed through a delta-Mission Concept Review (dMCR). As a result, this mission is ready to move into Phase A.

In the sections that follow we provide an overview of the mission goals and the architecture of the mission. We also detail the model payload and technology developments that are being pursued to retire the science, technology, cost, and schedule risks associated with the mission concept. For more details on the science objectives and investigations, as well as the full science traceability matrix, we refer the reader to the 2016 Science Definition Team Report (Hand et al. 2017).

2. Science Goals of the Europa Lander Mission Concept

The high-level science goals of the Europa Lander Mission Concept (ELMC) are shown in Figure 2 and listed below:

1. Search for evidence of biosignatures on Europa.
2. Assess the habitability of Europa via in-situ techniques uniquely available to a lander mission.
3. Characterize surface and subsurface properties at the scale of the lander to support future exploration.

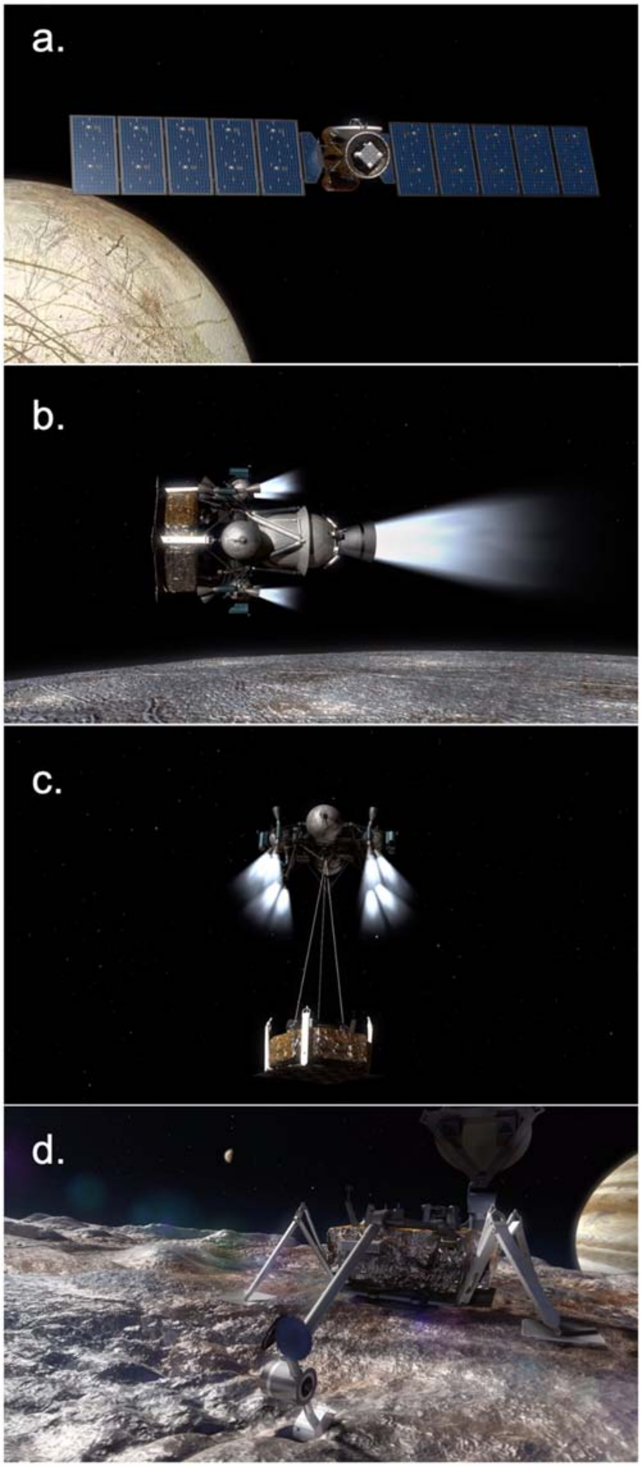


Figure 4. Four key stages of the mission concept are shown here. (a) Cruise to Jupiter, which employs a solar-powered carried stage. The bottom of the lander can be seen at the center of the spacecraft, still encased within the top portion of the biobarrier. (b) Deorbit burn above Europa's surface. The solid rocket motor decelerates the spacecraft, in preparation for descent. (c) The sky-crane architecture is then used, with onboard hazard avoidance, to bring the lander to a safe, low-velocity ($\sim$0.5 m s^{-1}) touchdown. (d) Once on the surface, the science phase begins, and sample collection proceeds with the robotic arm and tools for excavation and sample acquisition.

These goals, and their associated objectives (Figure 5), are achieved by employing a lander on the surface of Europa that collects and processes a minimum of three separate samples, each of at least 7 cm^3 in volume, and acquired from a depth of at least 10 cm. The goals of the mission were developed in ranked priority by the 2016 SDT and lead to a fully integrated mission concept and model payload that would enable a diverse approach to the search for potential biosignatures on an ocean world.

The scientific and technical approach of the ELMC provides a robust, and in many ways conservative, strategy for the first landed mission to the surface of Europa. No high-risk roving or melting capabilities are included in the baseline mission, nor are any radioisotope power sources included that could complicate planetary-protection considerations. Independent of any biosignature results, the scope of the science is such that high science return is nearly guaranteed, by merit of being the first landed mission on the surface of an airless ice-covered ocean world. Finally, we note that many of the technologies employed have high heritage from Mars surface missions, and other in-situ surface science exploration (e.g., the Huygens probe).

2.1. Goal 1: Search for Evidence of Biosignatures on Europa

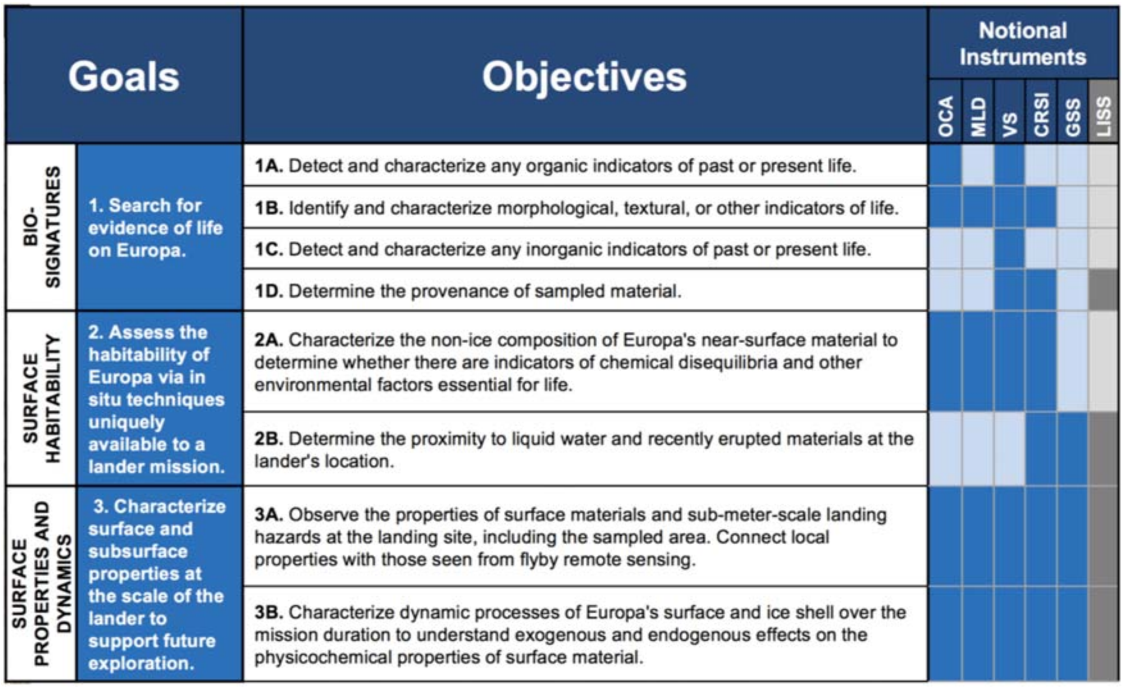
The highest level science goal of the ELMC is to search for evidence of biosignatures on Europa. Biosignatures are defined here as features or measurements interpreted as evidence of life (Hand et al. 2017).

Critically, no single line of evidence—no single biosignature measurement—is likely to be sufficient for concluding that life has been detected. A robust detection of life requires several complementary and redundant biosignatures (Chyba & Phillips 2001). Through nine distinct but related investigations and measurements, each of which represents at least one biosignature, the ELMC would enable the study of Europa such that if biosignatures are present at levels comparable to benchmark environments on Earth, established by the SDT, then life could be detected.

To this end, the SDT leveraged the decades of work and experience from the Mars exploration community, and the biosignature framework that has helped guide the Mars program. Figure 6 shows the array of complementary and redundant biosignature measurements that are incorporated as part of the ELMC measurement framework for biosignatures and life detection. As emphasized in the NASA Astrobiology Strategy (NASA 2015), the fidelity of life detection benefits greatly from strategies that target measurements of multiple, distinct biosignatures. Also of great importance to the mission concept is the fact that the model payload and measurements defined for biosignatures generate highly valuable scientific results even in the absence of any signs of life.

These measurements range from detecting and characterizing organic compounds, to looking for cell-like structures, to determining if the samples originate from within Europa's ocean or other liquid-water environments. The model payload enables detection and characterization of morphologic, chemical, and mineralogical indicators of life, all within a well-characterized geologic and geophysical context.

The organic chemical analyses are specifically targeted to reveal the broadest possible range of signatures produced by life, including analyses of molecular type, abundance, and chirality. Chemical analyses of samples collected directly from Europa's near-surface layer would provide for characterization of organics at the picomole-per-gram level of sampled material, which is an improvement of approximately seven to nine orders



Goals		Objectives	Notional Instruments: OCA	MLD	VS	CRSI	GSS	LISS
BIO-SIGNATURES	1. Search for evidence of life on Europa.	**1A.** Detect and characterize any organic indicators of past or present life.						
		1B. Identify and characterize morphological, textural, or other indicators of life.						
		1C. Detect and characterize any inorganic indicators of past or present life.						
		1D. Determine the provenance of sampled material.						
SURFACE HABITABILITY	2. Assess the habitability of Europa via in situ techniques uniquely available to a lander mission.	**2A.** Characterize the non-ice composition of Europa's near-surface material to determine whether there are indicators of chemical disequilibria and other environmental factors essential for life.						
		2B. Determine the proximity to liquid water and recently erupted materials at the lander's location.						
SURFACE PROPERTIES AND DYNAMICS	3. Characterize surface and subsurface properties at the scale of the lander to support future exploration.	**3A.** Observe the properties of surface materials and sub-meter-scale landing hazards at the landing site, including the sampled area. Connect local properties with those seen from flyby remote sensing.						
		3B. Characterize dynamic processes of Europa's surface and ice shell over the mission duration to understand exogenous and endogenous effects on the physicochemical properties of surface material.						

Figure 5. An abbreviated version of the full Europa Lander science traceability matrix (STM), showing goals and objectives, and traceability to the model payload. Instruments in the model payload are indicated as follows: organic compositional analyzer (OCA), microscope for life detection (MLD), vibrational spectrometer (VS), context remote-sensing imager (CRSI), geophysical sounding system (GSS), and lander infrastructure sensors for science (LISS). The gray-colored LISS instruments are engineering systems on the powered descent vehicle that the SDT have identified as important for the science of the lander mission concept on the basis of their science-relevant measurements (e.g., spacecraft-descent imaging and LIDAR).

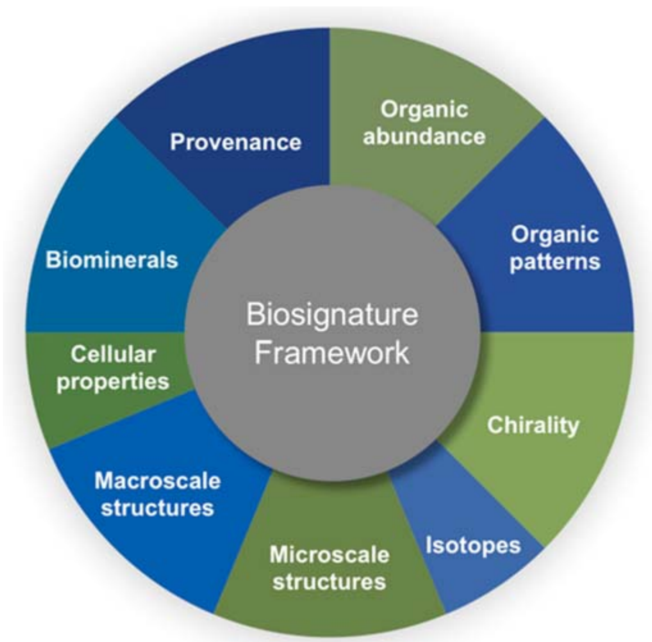


Figure 6. The biosignature framework developed by the Europa Lander Science Definition Team (SDT) leverages the approach of the Mars program, and lessons learned from the Viking missions. Critically, measurements made available by the Europa Lander model payload (shown in the outer ring of this figure) provide a minimum of nine complementary and redundant biosignature measurements that could help reduce the ambiguity associated with assessing biosignatures and confirming, or rejecting, a possible detection of life.

of magnitude over those possible by means of remote-sensing capabilities. Detection limits for measurements targeting evidence of life were established by comparison to several extreme, nutrient-limited environments on Earth.

Spectroscopic analyses of samples provide the inorganic and geochemical context of the samples, and enable differentiation between Europa's endogenous chemistry and exogenous materials that may have been externally delivered (e.g., micrometeorites), or processed by Europa's radiation environment.

Finally, high-resolution imaging from lander instruments could span from microns to decameters, providing imagery for observing potential morphologic biosignatures, as well as in-situ context for sampled materials, local geology, and surface properties.

Within Goal 1, the SDT defined four objectives, each of which carries investigations and example measurements related to the science described above.

The first of the four objectives focuses on the search for and characterization of organic compounds, and emphasizes the importance of a biochemical definition for life. This objective directly addresses the question: are there organic compounds on Europa and, if so, does the population of organic compounds reveal any signs of biological processes? Figure 7 shows the investigations within this objective.

Here we do not detail each investigation and the associated measurements within each objective and goal; instead, we refer the reader to the full SDT report (Hand et al. 2017). As an abbreviated example, however, the following three measurements describe the approach for the detection and characterization of organics as part of the first investigation, within the first objective, of Goal 1:

1. Determine the abundances and patterns (i.e., population distributions) of organic compounds in the sampled material, with an emphasis on identifying potentially biogenic characteristics.
2. Determine the presence, identities, and relative abundances of amino acids, carboxylic acids, lipids, and other

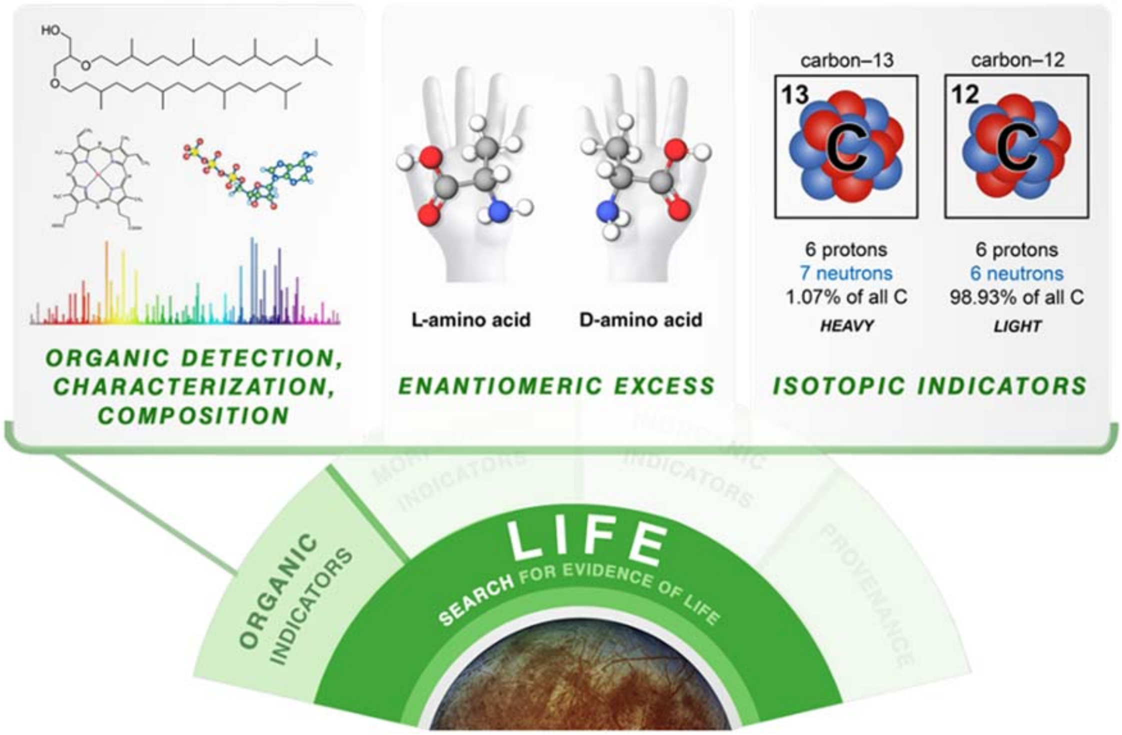


Figure 7. The first objective within Goal 1 centers around the detection and characterization of organic indicators that may serve as potential biosignatures. Within this objective are the three investigations shown here. Measurements of organic abundance, complexity, and specificity lead into measurements of chirality and enantiomeric excesses, followed by isotopic measurements of carbon-12 and carbon-13 as potential chemical biosignatures.

molecules of potential biological origin (biomolecules and metabolic products) at compound concentrations as low as 1 picomole in a 1 gram sample of Europan surface material.

3. Determine the broad molecular weight distribution to at least 500 Da, and bulk structural characteristics of any organics at compound concentrations as low as 1 picomole in a 1 gram sample of Europan surface material.

These requirements target definitive identification of individual compounds, and/or suites of compounds, that could represent biomolecules or metabolic intermediates and end products. The stated detection requirements are set at a level that would allow quantification of free amino acids at the concentrations (low nM) typically observed in Earth reference materials, such as deep ocean water or Lake Vostok accretion ice. The mass range of 500 Da encompasses amino acids, nucleobases, sugars, fatty acids, and other classes of potential molecular biosignatures, as well as oligomers of those compounds and a wide range of (abiotic) compounds found in carbonaceous meteorites.

The second and third objectives of Goal 1 are highly complementary to the organic chemistry biosignature measurements (Figure 5).

The second objective is to identify and characterize morphological, textural, or other indicators of life. The investigations and measurements within this objective work in service to detecting and characterizing microscopic and macroscopic structures that may be evidence of life. Observations of morphology across many spatial scales are highly complementary to the measurements of organic indicators. Direct signs of life can be discerned through observation of active or inactive life forms, deposits, or other biogenic structures (National Research Council 2002). Significantly, morphologic features can be used to recognize both extant and extinct life.

The third objective of Goal 1 is to detect and characterize any inorganic indicators of past or present life. Inorganic compounds and minerals—such as carbonates, silica, reduced and oxidized forms of iron, and various sulfur compounds—can serve as inorganic biosignatures. If found in association with organic and morphologic indicators of life, inorganic biosignatures can serve as a critical, complementary measurements.

The fourth and final objective of Goal 1 addresses the context that is required for interpretation of the physical and chemical data generated in the first three objectives. A critical part of assessing sampled material for potential biosignatures is to determine the place and time of origin of the material, i.e., the provenance. Is the sampled material representative of the subsurface ocean, or other liquid-water environments within the ice? How long has the material been exposed to the surface environment of Europa, and how has surface processing modified the fingerprint of any endogenous chemistry? Ultimately, the purpose of this objective is to determine whether there is a connection between the samples collected and Europa's potentially habitable ocean, or liquid-water environments within the ice shell. By developing an integrated understanding of the chemical, physical, and geological nature of the landing site and samples, the lander could provide a set of complementary investigations capable of detecting signs of life, and which are robust to false positives, false negatives, and potentially ambiguous results. This information would also be closely tethered to the observations and context provided at the global and regional scale by Europa Clipper. Importantly, the Clipper data would guide landing-site selection, helping to establish the larger context of the landing site, both in terms of surface activity (e.g., plumes and fractures) and chemistry (e.g., identification of salts and organics).

There are two investigations within the provenance objective. The first investigation focuses on the geological history, while the second targets the chemical history. Europa's geology and chemistry are closely coupled, and thus each investigation contains aspects of both processes. To accurately assess the specific geological context of the samples, the lander needs images of, and compositional information about, the landing site and sampling workspace at the decimeter to micron scale. Of particular importance for life detection are features indicative of exchange processes with liquid water, be that identification of plumes or detection of salts that are best explained by transfer from the ocean below. Characterizing the chemistry of the sampled materials is critical to determining the endogenous or exogenous origin of the sample, and any surface processing of potential biosignatures. Importantly, measurements as part of this objective would provide substantial overlap with investigations in Goal 2. In Goal 1, the focus on provenance is to improve our understanding of the context of any potential biosignatures, whereas in Goal 2 the focus is on understanding the landscape in the broader context of Europa's habitability. Though similar in implementation, these are two distinctly different questions.

2.2. Goal 2: Assess the Habitability of Europa via In-situ Techniques

Goal 2 for the mission is to assess the habitability of Europa via in-situ techniques uniquely available to a lander mission. Importantly, a habitable environment could well be devoid of life if conditions for the origin of life were not satisfied at some point during the geochemical evolution of that world. In other words, life requires habitability, but habitability does not necessarily imply, or require, life. Understanding Europa's habitability is thus a critical aspect of addressing any ambiguous results that may arise when attempting to detect and characterize biosignatures in Europa's surface material.

If the measurements from Goal 1 do reveal potential biosignatures, then it is important to understand the geochemical context for habitability, and the proximity of the landing site to habitable regions within Europa's ice shell and ocean. If the sampled material is determined to be from a global subsurface ocean, then it may be possible to conclude that Europa's global ocean is inhabited at a global scale, since ocean water would mix and move globally. If, however, the evidence points toward a sample derived from an isolated region within the ice shell, then it would be more challenging to extend habitability to the global scale of a subsurface ocean.

Alternatively, if no biosignatures are identified as part of Goal 1, then it becomes critical that ambiguous or null results are understood in the context of the landing site, and the broader context of Europa's habitability. Did the sampled materials recently originate from Europa's ocean, or other potentially habitable regions? Does a null result at the landing site apply to all of Europa? The SDT defined two objectives within Goal 2 to address the challenges and questions raised above.

The first objective focuses on how Europa's composition informs habitability, and the second focuses on the relationship of the landing site and samples to any subsurface liquid-water environments. Figure 8 shows the two objectives of Goal 2.

Specifically, the first objective is to characterize the non-ice composition of Europa's near-surface material to determine whether there are indicators of chemical disequilibria (see, e.g., Nealson 1997). Investigations within this objective include (1) the requirement to determine the extent to which the habitability of Europa's ocean and liquid-water environments can be inferred from surface materials, as sampled and imaged, and (2) identifying environmental indicators and patterns of spatial variability (textural, compositional) that may relate to habitability. As an example, perhaps the clearest indicator of any past or present oceanic chemistry on Europa would be the definitive determination, by the lander, of the presence or absence of salts, such as chlorides, carbonates, and sulfates in the acquired sample.

Returning to the question raised above, if biosignatures are not detected at the landing site, the environmental and geochemical investigations within this objective would serve to inform our understanding of whether a nondetection of biosignatures is indicative of an ocean devoid of life, or just a localized region devoid of life. In addition, these investigations provide redundancy and robustness for methodological issues and scenarios in which the samples provide false-negative or false-positive results.

Such analyses would also benefit greatly from the coupled approach of Europa Clipper global and regional mapping, and landing-site selection based on several years of analyses of the habitability of Europa. Using Clipper data, geologically young landing sites rich in salts and organics could be detected and mapped. If we then land at such a site and find organics, but no morphologic or other chemical biosignatures, would that imply that Europa does not harbor life? Perhaps. But as with our approach to Mars exploration, even in the absence of any direct signs of life, it is critical to employ a suite of measurements that advance our understanding of past or present habitability and geochemistry. The Europa Lander model payload works in service to this goal (Hand et al. 2017).

For example, iron and phosphorous could be limiting elements for life, and while Clipper may be able to detect them remotely, in-situ analyses with a lander provide a much more comprehensive measurement capability. As part of Goal 2, these elements, and their associated compounds and minerals, would be searched for and characterized on Europa (Hand et al. 2017). The in-situ capabilities of the lander could improve the detection limits of the Clipper remote-sensing mission by many orders of magnitude, thereby significantly advancing our assessment of habitability, and informing the results of measurements made in service to Goal 1.

The second objective of Goal 2 is to determine the proximity to liquid water, and recently erupted materials, at the lander's location. Investigations and measurements within this objective focus largely on geologic and geophysical indicators of any connection between the landing site and the subsurface ocean (or liquid water within the ice shell).

The investigations within this objective include searching for any subsurface liquid water within 30 km of the lander, as well as searching for any evidence of interactions with liquid water on the surface, including the search for active plumes and ejected materials. Lastly, if the ice shell is active and provides a sufficiently strong sounding source (i.e., large Europa "quakes") the final investigation within this objective includes an effort to determine the depth of Europa's ocean. By constraining the depth of the ocean and the thickness of the ice

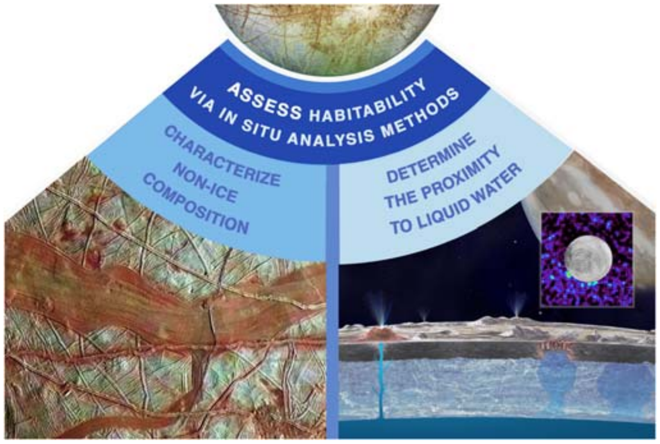


Figure 8. Goal 2 of the Europa Lander is focused on assessing the habitability of Europa through in-situ analyses uniquely available to an in-situ lander. This includes investigating whether sampled materials were derived from an ocean, and also determining the proximity of the lander to any subsurface liquid water.

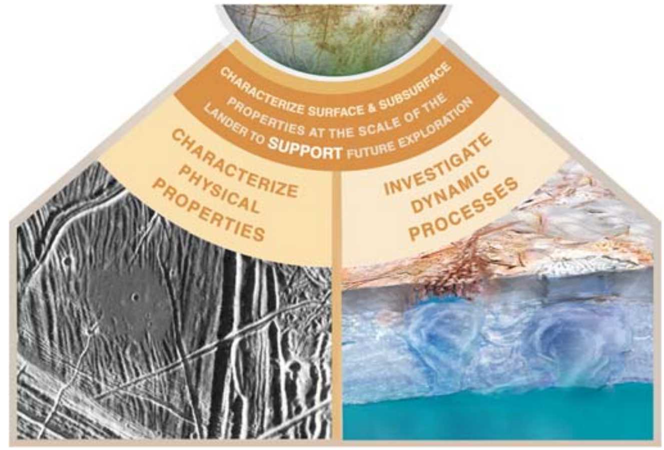


Figure 9. The two objectives within Goal 3 focus on the physical properties of the landing site, and the dynamic processes occurring in the region around the lander.

shell, measurements from the lander would provide data needed to model exchange processes extending from the seafloor up to the surface.

Critically, as part of Goal 2, the ELMC would advance our scientific understanding of fundamental oceanographic processes in the solar system, independent of whether or not signs of life are discovered on Europa. Through this goal, measurements would be conducted that could (1) answer fundamental questions about the chemistry and geology of Europa's ice shell and ocean, and (2) provide ground truth for Europa Clipper measurements.

All of the regional and global measurements from Clipper, be they of Europa's composition or geology, would have ground-truth measurements and observations that are essential to better understand remote-sensing observations. In other words, by conducting in-situ chemical and geophysical measurements, the lander would help resolve uncertainties in the interpretation of spectral measurements, uniqueness fits, and unmixing algorithms associated with, e.g., infrared, UV, gravity, and radar measurements made during Clipper flybys. Acoustic sounding measurements, for example, would provide unique and highly complementary measurements to those performed by the radar, magnetometer, and plasma instruments that will be flown on Europa Clipper.

The lander offers a highly complementary approach to assessing Europa's habitability, one in which a specific region of Europa could be monitored for activity over several tidal cycles with surface observations. These measurements could then be coupled with Clipper data to extend our understanding of Europa at the regional and global scale.

2.3. Goal 3: Characterize Surface and Subsurface Properties at the Scale of the Lander to Support Future Exploration

Goal 3 of the ELMC is to characterize surface and subsurface properties of Europa at the scale of the lander to provide geologic and geophysical context, and to support future exploration. The lander could be a "pathfinder" for the exploration of Europa (National Research Council 1999, 2003a), and possibly for many other ocean worlds of the outer solar system. The measurements made by the lander could feed forward into designs of future robotic vehicles that would explore across the surface or down into the subsurface (Hand et al. 2020). The nature of the landing environment, mobility hazards, and surface physical properties are all key characteristics to observe and directly quantify as part of Goal 3. This same strategic approach to science and exploration has proven highly successful in the systematic exploration of Mars (McCleese et al. 2001; Hubbard et al. 2002).

Two overarching objectives were defined by the SDT to address Goal 3. The first focuses on the surface properties of Europa, and the second focuses on dynamic processes. Figure 9 shows the objectives of Goal 3.

Objective 1 is to observe the properties of surface materials and submeter-scale landing hazards at the landing site, including the sampled area, and to connect local properties with those seen from flyby remote sensing. Investigations within this objective include characterizing textural, structural, and compositional heterogeneities in surface and near-surface materials through measurements of the samples and through observations of the terrain, from the lander workspace to the horizon, and into the ice shell.

Coupled with this is the second objective, which is to characterize any dynamic processes of Europa's surface and ice shell, over the mission duration, to understand exogenous and endogenous effects on the physicochemical properties of surface material. The investigations within this objective are focused on the surface properties and dynamic processes at Europa's surface, all of which would provide context for understanding the results from Goals 1 and 2, and feed forward into future exploration.

Significant crossover exists between Goal 3 and measurements defined in Goals 1 and 2, especially as they relate to chemistry and seismic measurements. The scientific utility of each measurement is, however, in service of a distinctly different goal. Regardless of whether biosignatures are detected, Goal 3 would help characterize the surface properties and processes on Europa to provide geologic context.

All five of the model payload instruments work in service to both objectives of Goal 3. Here, again, the connection with the global and regional mapping efforts of the Clipper mission are important: together with a lander that provides geologic and geophysical ground truth for remote-sensing measurements, all of the data from Clipper becomes more valuable and less uncertain: regolith properties are determined in situ, ice-shell deformation is measured acoustically, and surface properties are observed directly by the lander.

Importantly, Goal 3 leverages crossover with the engineering subsystems of the Europa Lander project, utilizing engineering-critical measurements to support science investigations. The deorbit, descent and landing (DDL) system, for example, provides high-resolution nadir-viewing descent imaging, fine-scale digital terrain models (DTMs), and other measurements of the landing site during the lower altitude descent phase. As another example, the lander's robotic arm and sample-acquisition device—which would allow the engineering team to precisely control arm motion and positioning, as well as excavation operations—would also enable quantitative feedback to be gathered on the physical parameters of Europa's surface, such as the mechanical strength and compressibility of the surface materials. Furthermore, the thermal-management system of the lander could also characterize and quantify temperature changes on the surface, and help determine the thermal properties of Europa's surface regolith and subsurface materials. Such an approach has been employed on Mars missions dating back to Viking in the 1970s.

3. Framework for Life Detection

Ask detailed in the SDT report (Hand et al. 2017), the ELMC is not specifically tasked with the goal of life detection. Rather, the framework for multiple redundant and complementary biosignature measurements is such that were a suite of robust biosignature results to be returned from multiple samples, then the claim of life detection might be possible. In other words, the mission and model payload has the capacity for life detection, based on biosignature inventories and concentrations in analog environments here on Earth. Simply put, life detection is a *capability*, not a *requirement*. Levying a life-detection requirement on any mission, or planetary target, is a misplaced interpretation of the goals of astrobiology, as life may or may not arise on any number of habitable worlds.

To aid in the operational assessment of biosignature measurements, the SDT developed the "biosignature bingo" template for concatenation of multiple positive and negative individual biosignature results. Included in these discussion was the recognition that false positives and false negatives may be likely, and that any singular measurement may be ambiguous, thus necessitating a gradation of interpretation as opposed to a simple "yes/no" result for a specific biosignature measurement.

For a given payload suite, many permutations exist that could help refine and reduce the risk of false-positive and false-negative results. Ongoing work in the development of instrument candidates, and detection limits for specific types of biosignatures (e.g., chemical or morphologic), will help reduce risks associated with the identification of potential biosignatures on Europa, or any in-situ ocean world mission.

4. Model Payload and Instrument Development

For each science objective, model payload instruments are described in detail in the SDT report. To demonstrate the overall scientific and technical viability of the mission concept, the SDT defined two example payload configurations, baseline and threshold (Figure 3), based on flight-proven technologies that could be adapted to Europa conditions. These example model payloads fit within the currently established engineering constraints of the ELMC, and achieve the baseline- and threshold-level science requirements defined in the SDT. All model payload instruments work in service to numerous goals, objectives, and investigations. With the exception of the context remote-sensing instrument (CRSI), all instruments are held within the main body of the lander, which also serves as a vault that provides radiation shielding.

The mass allocation on the lander for the payload is 42.5 kgs. As a point of reference with other in-situ landed missions, the Mars Exploration Rovers (MERs) carried an instrument payload of <8 kg, while that of the Mars Curiosity rover is $\sim$65 kgs.

The SDT report identified five instrument types to support the ELMC goals, objectives, and investigations:

1. A context remote-sensing instrument (CRSI) would capture stereo color imagery to recognize objects, materials, and morphological details as small as 1 mm within the 2 m radius workspace that the sampling system can reach, and 1 cm within a 5 m range. In addition, the CRSI would potentially collect spectral information between 350 and 1050 nm to aid material identification and compositional analyses.
2. A microscope for life detection (MLD) would provide the capability to search for structures, such as microbial cells, as small as 0.2 microns in diameter. The MLD would have a field of view of at least 100 μm by 100 μm.
3. A vibrational spectrometer (VS), which in the baseline model payload is a Raman and deep-UV fluorescence spectrometer. The VS would be boresighted with the MLD, and would serve to characterize both organic and inorganic compounds down to a level of parts per thousand by mass, with a Raman shift of 150–3800 cm^{-1} and a resolution of better than 6 cm^{-1}.
4. An organic compositional analyzer (OCA), which in the SDT baseline model payload is a gas chromatograph–mass spectrometer (GC–MS) capable of achieving 1 picomole-per-gram of sample limit of detection for organics. The OCA would enable the search for biochemical and molecular biosignatures.
5. A geophysical sounding system (GSS) would utilize acoustic waves generated in the ice shell to measure the thickness of the ice, and potentially the depth of the ocean. The GSS would help identify deformation mechanisms within the ice, and address the presence or absence of liquid-water lenses within the ice near the lander. The SDT baseline model payload included a three-axis seismometer, covering the frequency range 0.1 to $>$100 Hz.

Though numerous instruments with flight heritage were available and used as points of reference for the SDT report, payloads always require considerable work to adapt instruments to new planetary conditions and to the specific accommodation constraints of a given mission architecture. With such challenges in mind, NASA released a competed call for instrument and technology developments, described in the next section, that could retire risks associated with the payload and sample handling.

4.1. Instrument Concepts for Europa Exploration (ICEE-2)

Based on the instrument types called out in the SDT, in 2019, NASA selected 13 instrument teams, plus one team working on a sample-handling system, for development relevant to the Europa Lander model payload (Table 1). These efforts were funded under the NASA Research Opportunities in

Table 1
Europa Lander Instrument Classes as Defined in the Science Definition Team Report and the Relation with the ICEE-2 Instruments

SDT Instrument Class	———————SDT Model payload————————-		ICEE-2 Instrument
	Baseline	Threshold	
Context remote-sensing instrument (CSRI)	Focusable visible to near-IR stereo camera with narrowband filters equivalent to the Europa Clipper EIS camera	RGB fixed-focus stereo camera	**C-LIFE:** Cold Lightweight Imagers for Europa, is a landed camera suite consisting of a color context-reconnaissance stereo imager (CRSI) and an LED flashlight that can also identify biogenic material through fluorescence. P.I.: Shane Byrne, U AZ **ELSSIE:** Europa Lander Stereo Spectral Imaging Experiment, is a landed camera with 20 filters in four thematic sets: (E) Match EIS to extrapolate to surface; (S) discriminate ice and hydrated salts; (I) discriminate crystalline from amorphous ice; (O) detect organics. P.I.: Scott Murchie, APL-JHU
Microscope for life detection (MLD)	Deep-UV resonance Raman and optical microscope with fluorescence spectrometer	Atomic force microscope (AFM) with optical context imager	**ELM:** Europa Luminescence Microscope uses visible light to image organic and inorganic structures with submicron resolution and excitation of native fluorescence, using UV and visible light, for characterization of sample organic and mineral content. P.I.: Richard Quinn, ARC
Vibrational spectrometer (VS)	Deep-UV resonance Raman and optical microscope with fluorescence spectrometer	Raman laser spectrometer (RLS)	**CIRS:** Compact Integrated Raman Spectrometer acquires high-S/N Raman spectra of diagnostic biomolecules and salts. P.I.: James Lambert, JPL
Organic compositional analyzer (OCA) / chemical analyzer	Gas chromatograph–mass spectrometer (GC–MS) with chirality analysis and stable isotope analyzer (SIA)	Gas chromatograph–mass spectrometer (GC–MS) with chirality analysis	**MASPEX-ORCA:** Mass Spectrometer for Planetary Exploration—Organic Composition Analyzer for Europa Lander combines the maturity of MASPEX development for Europa Clipper with a novel microdevice gas chromatograph and sample preparation systems. P.I.: Christopher Glein, SWRI-San Antonio **MOAB:** Microfluidic Organic Analyzer for Biosignatures is a microchip analyzer capable of determining the identity, abundance, and patters of amines, amino acids, and carboxylic acids. P.I.: Richard Mathies, UC-Berkeley **EMILI:** Europan Molecular Indicators of Life Investigation merges liquid-based capillary electrophoresis with laser-induced fluorescence and conductivity detection, and gas-based pyrolysis/derivatiztion gas chromatography as a front-end to an ion trap mass spectrometer. P.I.: William Brinckerhoff, GSFC **CORALS:** Characterization of Ocean Residues and Life Signatures, a UV-laser-based mass spectrometer. Ricardo Arevalo, U MD **MICA:** Microfluidic Icy-World Chemistry Analyzer. P.I.: Antonio Ricco, ARC & Stanford U
Geophysical sounding system (GSS)	Broadband seismometer	Three-axis geophone	**SIIOS:** Seismometer to Investigate Ice and Ocean Structure. P.I.: Samuel Bailey U AZ **ESP:** Europa Seismic Package. P.I.: Mark Panning, JPL **EMS:** Europa Magnetotelluric Sounder. P.I.: Robert Grimm, SWRI-Boulder **MAGNET:** MAgnetometer for Geophysical and Noise-Reduction ExperimenT. P.I.: Mark Moldwin, U MI

Space and Earth Sciences (ROSES) "Instrument Concepts for Europa Exploration 2" (ICEE-2) program.

Six additional instrument teams asked to participate on a no-funding basis. These six comprise an atomic force microscope, a holographic microscope, a laser absorption spectrometer, a mass sSpectrometer, a hyperspectral microscope, and an X-ray spectrometer.

In addition, the NASA Concepts for Ocean worlds Life Detection Technology (COLDTech), Scientific Exploration Subsurface Access Mechanism for Europa (SESAME), Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO), and the Maturation of Instruments for Solar System Exploration (MatISSE) programs within ROSES have also funded numerous technology and instrument

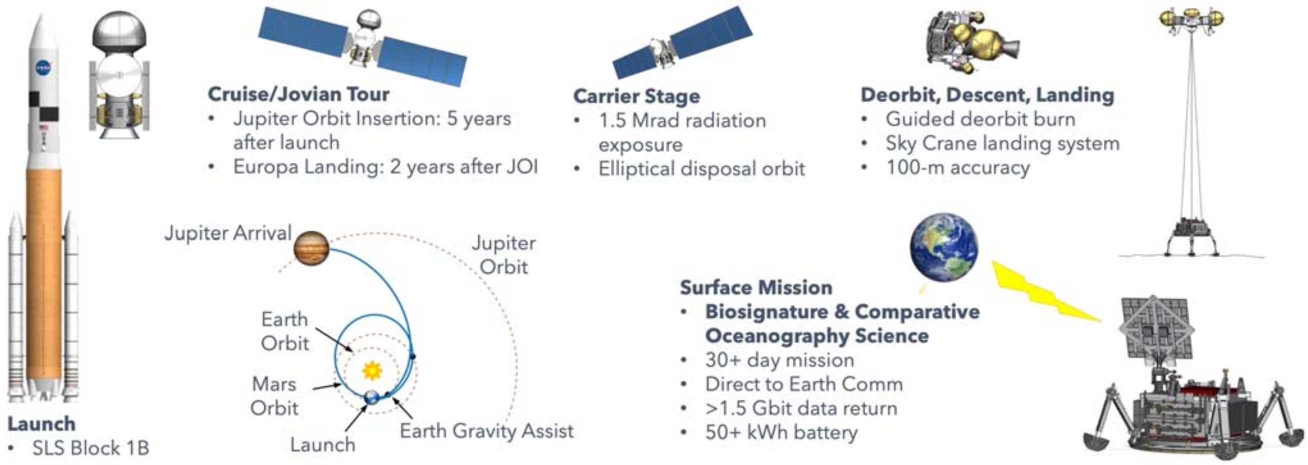


Figure 10. Overview of the Europa Lander mission concept architecture. (1) The baseline mission would launch on a Space Launch System (SLS) rocket, followed by (2) a ∼5 yr cruise to Jupiter orbit insertion (JOI), after which (3) the carrier stage then conducts flybys of Ganymede and Callisto to position the spacecraft for (4) deorbit, descent, and landing on Europa, using terrain-relative navigation and the sky-crane landing system, followed by (5) the surface science mission, which lasts for at least 30 days and is focused on the search for biosignatures and the science of comparative oceanography.

developments to build a strong foundation for ocean-worlds science investigations.

The instrument development efforts funded under ICEE-2 have been working closely with the Europa Lander preproject efforts to ensure that the mission concept is

1. undergoing iterations on accommodation trades associated with instrument needs and constraints (e.g., volume, mass, power, and thermal environment);
2. capable of supporting an integrated instrument suite for sample analyses;
3. addressing sample handling and delivery issues related to the needs of instruments that process samples;
4. assessing lander system issues that could affect instrument performance (e.g., vibrations that interfere with seismic monitoring); and
5. addressing data volume and ground-in-the-loop constraints associated with instrument performance and operations.

The ICEE-2 efforts are intended to enhance the effectiveness of a potential future proposal opportunity for instrument providers, and help the preproject team retire technical, cost, and schedule risks associated with payload accommodation and performance issues typically encountered later in the mission life cycle.

5. Mission Architecture

5.1. Overview

The Europa Lander mission concept, as presented here (Figure 10), has been under development for much of the past decade.

Over the past two decades, JPL and APL have examined a range of mission architectures, from minimal-science ballistic probes and impactors to highly capable melt probes. Ballistic probes initially appear simple, but detailed analyses reveal significant complexity for comparatively low science return. Melt probes and deep drills, meanwhile, achieve high-value science but require too many miracles, leading to high technical and cost risk. In addition, we have also examined options for lander missions that might fit into a Discovery or New Frontiers budget, but no viable options emerged.

The original configuration for the architecture presented here consisted of a comanifest and launch, with the Europa Multiple Flyby Mission, which has now been officially renamed Europa Clipper. Complexity, schedule, and cost resulted in a decoupling of the two spacecraft in 2015, and a formal science definition team was convened in early 2016 to establish the science goals, objectives, and investigations for a stand-alone mission.

The architecture of the 2016 Europa Lander mission concept included a CS that delivered the lander to Europa, and which subsequently served as a communications-relay stage in orbit around Europa. The communications-relay stage operated with a period around Europa of approximately 24 hr and enabled frequent ground-in-the-loop (GITL) decision making for engineering and science operations. This architecture passed its MCR in 2017 June, but key feedback from the MCR board and NASA Headquarters was to reduce the mission cost by removing the carrier-relay stage, and instead use a direct-to-Earth (DTE) communications link from the surface of Europa.

The DTE mission concept followed much of the same flight-system architecture as the MCR version; however, without the 24 hr cadence for GITL, an additional effort was made in the DTE system to include autonomy and autonomous functions, as an enabling capability that could increase mission robustness and science return (see Section 5.9).

Figure 10 provides an overview of the Europa Lander as configured for the 2018 dMCR. Various advancements, technology developments, and systems trades have been conducted since that time, many of which are described in the sections that follow. The overarching architecture, however, remains the same and follows the following sequence: (1) launch on a Space Launch System (SLS) rocket, followed by (2) a ∼5 yr cruise to Jupiter orbit insertion (JOI), after which (3) the CS conducts flybys of Ganymede and Callisto over ∼2 yr to position the spacecraft for (4) DDL on Europa, using terrain-relative navigation (TRN) and the sky-crane landing system, followed by (5) the surface science mission, which lasts for at least 30 days and is focused on the search for biosignatures and the science of comparative oceanography.

Significantly, the dMCR mission concept was designed to achieve high-value science without requiring an excessive number of engineering miracles; this mission aims to be the right first mission to the surface of Europa and balances technical risk with science return and cost (National Research Council 1999, 2003a).

The ELMC uses primary batteries and is designed to survive, with margin, for ∼30 days on the surface; it could survive for ∼60 days or more with a number of low-risk modifications to the power subsystem (see Section 5.7). The choice of primary batteries was, in part, to save on cost and complexity. A longer lived mission concept with a radioisotope power system was studied, but planetary protection, thermal management, and increases in mass all contributed to increased cost and technical risk. The MCR and dMCR review boards both determined that the surface lifetime from primary batteries was acceptable, and helped to limit planetary protection and cost risks.

The dMCR DTE concept was costed at \$2.8B, in real-year dollars, for phases A–D. This includes 32% for unallocated future expenses (UFEs), which is in addition to reserves held by the preproject at the subsystem level. The \$2.8B estimate is from an independent cost estimate (ICE) at the 50% confidence level in the S-curve, compliant with a NASA headquarters level 7 120.5E requirement. We note that the cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

Importantly, the ELMC builds on the investment in Europa Clipper, using data from that mission for landing-site selection. There would be at least 5 yr of time between the end of Clipper's prime mission and the landing-site selection date. Also significant, data from Clipper would be unlikely to dramatically change our approach to deorbit, descent, and landing: the mission concept team examined a variety of mechanical configurations and concluded that even after the acquisition of the Clipper data, the DDL and mechanical architectures would not significantly change. Uncertainty about parameters such as porosity and structure at the submeter scale would still require the intelligent landing system, with TRN and hazard avoidance. Furthermore, the lander would still need to employ the "snowshoe belly-pan" and "grasshopper" adaptive stabilizer legs (Section 5.5) to accommodate soft and variable surfaces at the submeter scale.

The technology and instrumentation investments made to date (which exceed \$300M) could enable a new era of planetary exploration. Many of the technologies that have or are being developed for the Europa Lander mission concept could be utilized for landing on the unknown surfaces of many ocean worlds and other airless bodies in our solar system.

5.2. Trajectory Options

The ELMC has trajectory options that are compatible with multiple launch vehicles, and there are launch opportunities every year or two. At the time of the dMCR, the team baselined launch on a SLS Block-1B, in 2026 (with a backup opportunity in 2028). Both of these trajectories used Earth and Mars gravity assists to reach Jupiter approximately 5 yr after launch.

The 2026 trajectory achieved landing on Europa approximately 2 yr after Jupiter orbit insertion (JOI), while the less favorable 2028 trajectory required about 3 yr until landing.

After 2028, there is no convenient Mars gravity assist for a decade, but there are many other viable trajectories that trade flight time, ΔV, and launch-vehicle performance. With a SLS Block-1b (or Block-1 with minimal launch-vehicle margin), ELMC could launch every 13 months on a 4.5 yr ΔV-EGA (Earth gravity assist) trajectory to Jupiter, using a retrograde "Cloudtops" JOI to save ΔV. Landing would be about 3 yr after JOI with this arrival strategy.

The final Europa Landing sequence is constrained to be during the period when Jupiter is within a distance of 5 au to the Earth, which lasts about 6 to 7 months out of every 13 months (the Earth–Jupiter synodic period). Some trajectories produce a Jupiter arrival time that does not match well with the landing constraint, thus requiring an additional 6 months in Jupiter orbit.

5.3. Flight System

The launch flight-system configuration is shown in Figure 11. The launch stack consists of the launch-vehicle adapter, with a system for spacecraft separation after a successful injection orbit is achieved. Above the launch-vehicle adapter is the CS, which hosts the cruise-propulsion system, power system, and communication system. Above the CS is the Europa Deorbit Vehicle (DOV), which provides the DDL system.

The DOV consists of a solid rocket motor (SRM)-based deorbit stage (DOS) and the powered descent vehicle (PDV). The PDV consists of two elements, the descent stage (DS) and the Europa Lander. The DOV is encapsulated in a biobarrier to maintain our planetary-protection cleanliness from encapsulation through launch. The mass equipment list breakdown of the entire flight system is shown in Figure 12.

5.3.1. Carrier Stage

The carrier stage (CS), shown in Figure 13, consists of a bipropellant propulsion system using heritage components to provide ΔV for the cruise portion of the mission, from launch-vehicle separation to DOV separation. The propellant tanks are sized for 1875 m s^{-1} of ΔV, plus additional margin. In addition to ΔV engines, there are attitude-control thrusters.

The CS provides power to the entire flight system during the cruise by deploying two solar-array wings with 127 square meters of surface area. The solar arrays must be low-light, low-temperature capable, and meet the end-of-mission power requirements after exposure to Europa's radiation environment. Arrays with this capability have been demonstrated by the Juno mission and upcoming Europa Clipper and JUpiter ICy moons Explorer missions. For the small eclipses during the mission, a heritage lithium-ion battery is provided.

To enable continuous communication during the mission, the CS hosts multiple antennas (low and medium gain) including a high-gain antenna (HGA) for communications while at Jupiter. The telecom system has solid-state amplifiers that are driven by the mission radio, hosted on the lander.

The CS structure hosts a launch-separation system at the bottom and a DOV adapter at the top of the stage. It is sized to support the launch loads while supporting the mass and inertia of the DOV.

Thermal control of the CS uses heaters, louvers, and heat pipes to maintain all equipment within their allowable flight temperatures. The flight software and computers are hosted on the lander; these provide the control of the entire flight system during the cruise.

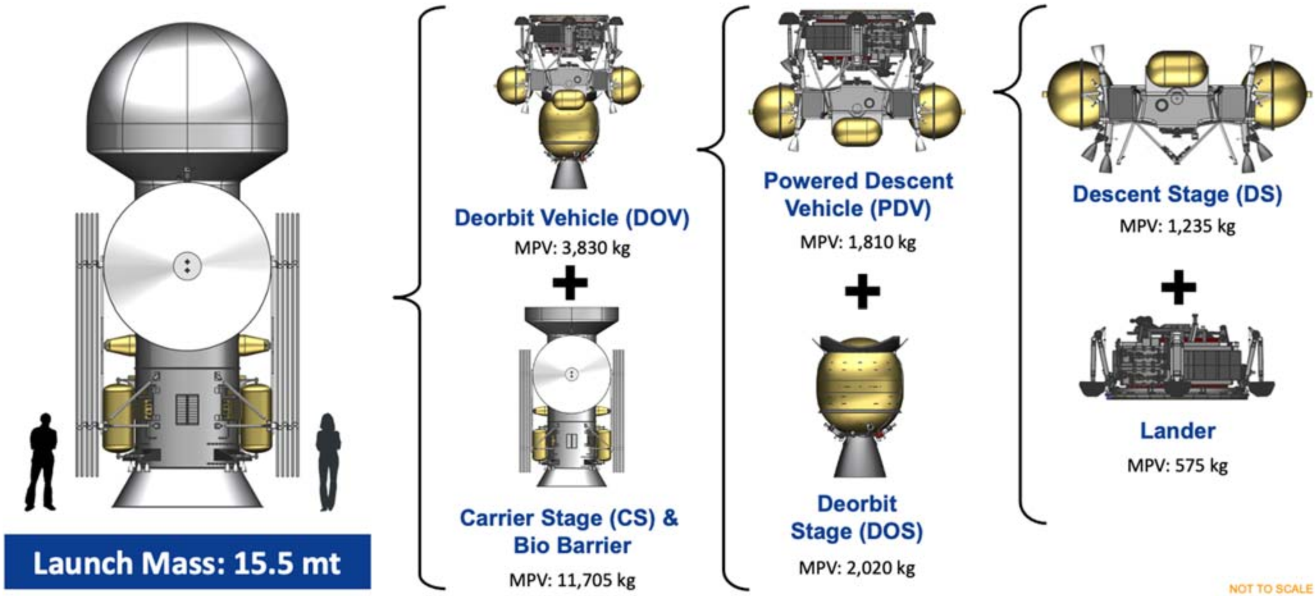


Figure 11. Overview of the Europa Lander flight system, showing the full, integrated system to scale with humans on the left, and the full, wet launch mass in metric tons. The components of the full flight system are sequentially detailed at right, with the maximum predicted values (MPVs) for mass shown beneath each subsystem. The launch stack consists of a launch-vehicle adapter (with a system for spacecraft separation after a successful injection orbit is achieved.) Above the launch-vehicle adapter is the carrier stage (CS), which hosts the cruise-propulsion system, the power system, and the communication system for cruise and prior to final separation of the lander system. Above the CS is the Europa Deorbit Vehicle (DOV), which provides the deorbit, descent, and landing system that ultimately places the lander and payload onto Europa's surface.

The inertial measurement unit and stellar-reference hardware are located on the descent vehicle and used during cruise (and DDL). Digital Sun sensors are hosted on the CS to provide a safe-mode attitude reference during the cruise. The CS has power distribution and control electronics for the CS hardware. Onboard electronics control the propulsion system valves and articulate the solar arrays.

After DOV separation, the cruise stage is no longer utilized and enters a stable orbit around Jupiter (meeting planetary-protection requirements).

5.3.2. Deorbit Stage

The deorbit stage (DOS) attaches to the CS and interfaces with the PDV. The primary function of the DOS is to reduce the spacecraft's velocity at Europa during the deorbit burn from 2000 m s^{-1} to below 100 m s^{-1}. The flight system provides heating power to maintain the SRM within its allowable flight temperatures during cruise. The SRM is based on heritage designs. Recent advanced development work has demonstrated the ability to perform its function after a long cruise, and exposure to the Europa radiation environment. After the SRM completes its burn, the DOS is disposed of on the surface of Europa down-track from the landing region in a way that limits the amount of the Europan surface that could potentially be contaminated by debris.

5.3.3. Descent Stage

Figure 14 shows the descent stage (DS), with numerous components and subsystems labeled. The DS performs the sky crane DDL and interfaces to the DOS and the lander. The lander is hard mounted during the cruise, deorbit, and descent, and then suspended by a bridle system on the DS during the sky-crane landing.

The DS has a monopropellant propulsion system that provides thrust vector control (TVC) during the SRM burn. It also provides ΔV and attitude control during powered descent and landing. The guidance, navigation, and control (GNC) electronics provide an inertial measure and stellar reference during cruise, and provide the functions detailed in Section 5.4.

After separation from the lander, the DS performs a fly-away maneuver to dispose of itself away from the landing site in a way that limits the amount of the Europan surface that could potentially be contaminated by debris.

5.3.4. Lander

Figure 15 shows the configuration of the Europa Lander, with many subsystems labeled, both pre- and postdeployment of the HGA. The four landing stabilizers (legs), along with the belly-pan, provide surface stability during touchdown and after landing.

Primary communication DTE/DFE is through the gimballed HGA; a backup low-gain antenna (LGA) can be used for commanding only. The communication system has a radio and 100 W traveling wave tube amplifiers (TWTAs) to meet our mission science downlink needs.

To provide landing context and generate maps for sampling, a stereo camera system is hosted on the HGA. The robotic arm and sampling system would gather samples and transfer them to the instruments via the collection dock.

The lander is powered by at least four primary battery assemblies mounted on the exterior of the lander body (vault), providing added radiation shielding for instruments and systems within the vault. The onboard computer contained within the vault carries the flight software that controls lander sequencing for sampling and communication.

Mass Table							Margin Table	
Name	Stage	CBE Dry (kg)	MPV Dry (kg)	Total Consumables (kg)	MPV Wet (kg)		Stacked Margin MPV-CBE / CBE (%)	JPL Margin MPV-CBE / MPV (%)
Carrier Stage (CS)	CS	**3160**	**4510**	**6895**	**11405**		**43%**	**30%**
Bio-Barrier (BB)	BB	**210**	**300**	**-**	**300**		**43%**	**30%**
DeOrbit Stage (DOS)	DOS	**195**	**280**	**1740**	**2020**		**43%**	**30%**
Descent Stage (DS)	PDV	580	830	410	1240		43%	30%
Lander Flight System	PDV	310	530	-	530		43%	30%
Lander Payload System	PDV	32	43	-	43		-	-
Powered Descent Vehicle (PDV)		**1010**	**1400**	**410**	**1810**		**43%**	**30%**
DeOrbit Vehicle (DOV)	DOS + PDV	**1205**	**1680**	**2150**	**3830**		**43%**	**30%**
Total Launch Mass (incl. LVA)		**4575**	**6490**	**9045**	**15535**		**43%**	**30%**

SLS Block 1b capability to C3 of 36 km^2/s^2: ~18,500 kg → ~3,000 kg of Launch Vehicle Margin

All stages meet JPL Design Principle Mass Margins

Figure 12. The mass equipment list for the Europa Lander mission concept is shown above for each stage and component of the flight system detailed in Figure 11. Current best estimates (CBEs) and maximum predicted values (MPVs) are shown for the "dry" (no fuel) and "wet" (with fuel) stack. Margins are shown at right, and Space Launch System capabilities are shown at bottom. Importantly, all stages meet JPL design principle mass margin requirements.

For protection from the radiation environment, and to maintain allowable flight temperatures, most equipment would be hosted within the vault.

At the end of the mission, the terminal sterilization system (TSS), which carries its own power source and command logic, would activate to increase the internal vault temperature to provide added assurance and adherence to planetary-protection requirements.

5.4. Deorbit, Descent, and Landing

Since the 1970s, NASA's exploration of Mars has largely driven the development of landing technologies and innovative concepts, the results of which have been eight successful landings and one failed landing on the planet.

Compared to landing on Mars, the challenges of landing on Europa are in some respects lower and more deterministic, in the sense that for Europa, by merit of being an airless body, a landing system does not have to deal with the complexities of aeroshells, heat shields, parachutes, and atmospheric uncertainties such as density, winds, and dust storms.

On the other hand, landing on Europa presents a bigger challenge—at least when compared to the most recent Mars missions—due to the comparably low knowledge we have of the Europan surface at the scale of a lander. Only a few high-resolution images of Europa exist, and those are ∼6 m per pixel.

However, it is worth noting that the Mars Viking engineers and scientists found themselves in a similar situation during the Viking design phase as the ELMC team now faces. As detailed below, however, many innovations, improvements, and successful landings have been made over the decades, all of which have informed the design and architecture of the ELMC.

The DDL architecture for the Europa Lander incorporates elements from previous successful landers, including the Lunar Surveyor and Apollo in the 60s, Viking in the 70s, and the Mars Exploration Rovers and Curiosity rover in the first decades of this century. In particular, the ELMC incorporates the sky-crane landing technique, successfully demonstrated by Curiosity in 2012 and Perseverance in 2020. This landing system enabled the rovers to be softly placed onto the surface, while also minimizing contamination of the surface by thrusters on their DS.

For the Mars 2020 Perseverance rover, the sky-crane heritage has been augmented with TRN, an autonomous navigation technology that uses an imaging camera and an onboard map of the landing area to precisely locate and determine the landing site on the Martian surface.

When applied to the airless surface and low gravity of Europa, the sky crane, coupled with TRN, would enable landing on the surface of Europa within 50 m of the designated landing site selected for science value and engineering safety. In other words, the landing ellipse would have a diameter of ∼100 m and it remains close to circular, again due to the lack of an atmosphere.

Finally, the Europa Lander's DDL architecture incorporates two new landing technologies that are being developed for this mission to handle the challenges of unknown and potentially dangerous terrain: (1) hazard detection and avoidance (HD&A), which uses a LIDAR-based sensor to map a 100 m diameter area in 3D with 5 cm resolution to detect and avoid lander-scale terrain hazards that are beyond the resolution of Clipper's high-resolution images; and (2) adaptable stabilizers that would enable the lander to achieve a stable and robust landing configuration for science and ground operations, even in the presence of very rough terrain, resulting from a failure of the HD&A system to find a more benign place to land, or just as a complement to it. The hazard-detection sensor being developed for the ELMC also performs the altimetry function, and is capable of generating a low-resolution (2 to 5 m) 3D terrain map of a 1 by 1 km area from a 5 km altitude.

The landing sequence for Europa would start with the delivery of the DOV by the carrier spacecraft, to a point at 5 to 8 km altitude, and 80 km up-track from the selected landing site, traveling at a surface relative speed close to 2 km s^{-1}. At this point the DOV performs a deorbit burn using a SRM to

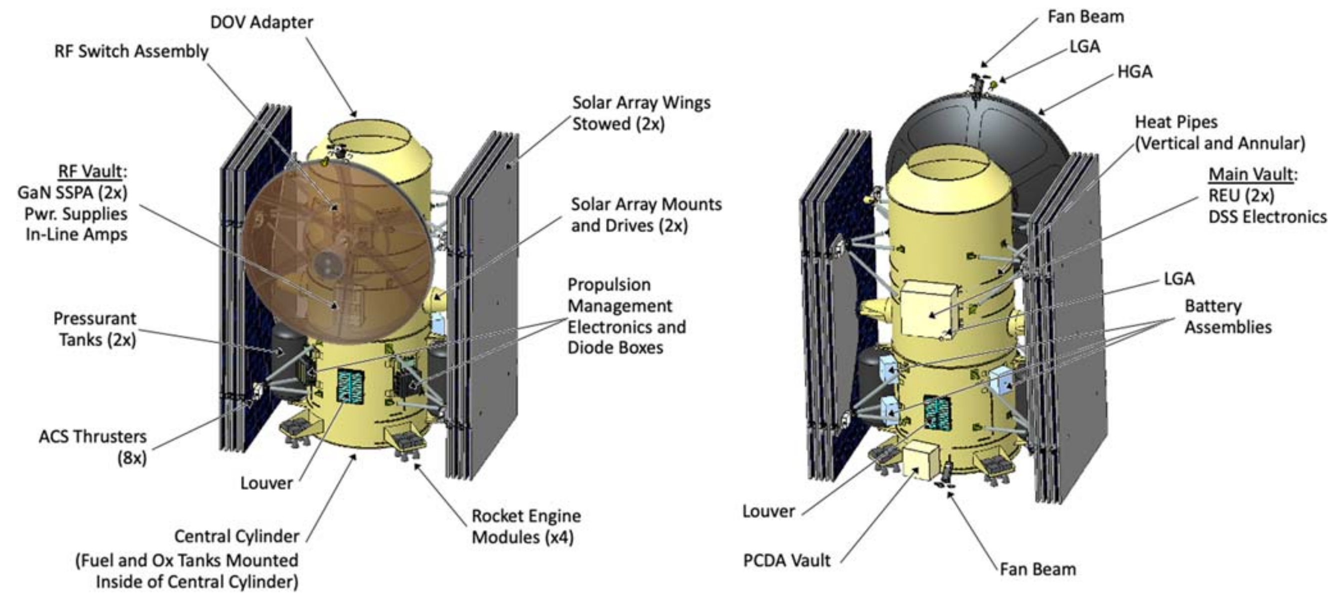


Figure 13. The full, integrated carrier stage (CS) configuration for the Europa Lander mission concept. Solar arrays are showed in stowed configuration. The high- and low-gain antennas (HGA and LGA) for the CS are shown for the two perspectives shown at left and right. Also shown are the adaptor for the Deorbit Vehicle (DOV), the vaults that protect the avionics and power from radiation, and the attitude-control (ACS) thrusters.

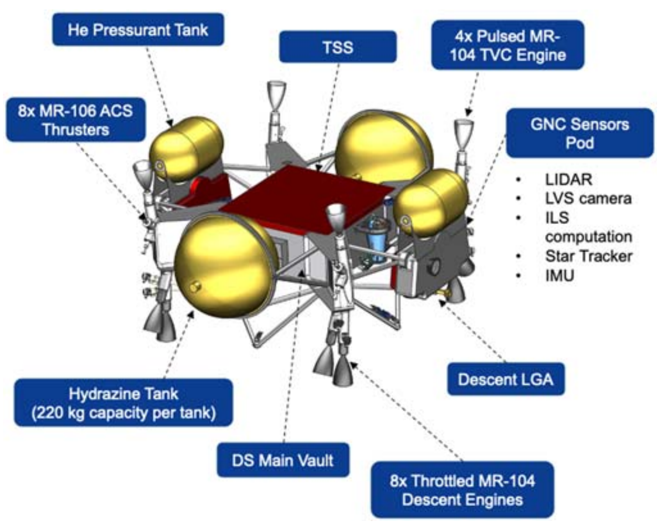


Figure 14. The descent stage (DS) of the spacecraft is responsible for the sky-crane maneuvers and setting the lander safely down on the surface of Europa. Once the DS has completed its task and fired the pyros to release the bridal tethers, it powers itself away from the landing site and impacts the surface. The DS also initiates its own terminal sterilization system (TSS), which heats the vehicle to >500 °C to further sterilize the spacecraft, working in service to planetary-protection requirements.

bring the lander velocity to below 100 m s^{-1}. Upon SRM burnout, the spacecraft is 6 km up-track from the landing site, at which point a maneuver is initiated to separate the SRM from the PDV.

The PDV then determines its position relative to the Europan surface using the hazard-detection LIDAR to measure its altitude and the TRN to measure its horizontal location. The PDV then initializes the powered approach phase, which uses the PDV throttleable engines to bring the lander to an altitude of 700 m and within 50 m of the landing site. At this point the

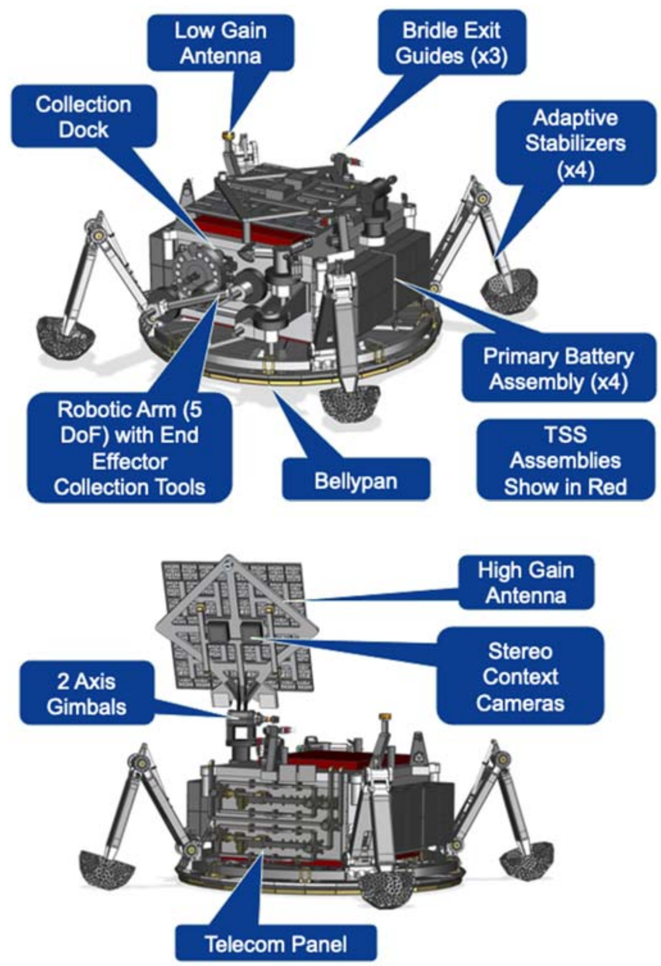


Figure 15. Shown here is the configuration of the Europa Lander—with many subsystems labeled—both pre- and postdeployment of the high-gain antenna.

landing system has zero horizontal velocity and is descending vertically with a velocity of 30 m s^{-1}.

After compensating for altitude variations, and upon reaching 500 m altitude, the hazard-detection sensor is commanded to map the landing area in 3D, resulting in a digital elevation map (DEM) covering a 100 m diameter area with 5 cm resolution. The DEM is processed onboard to identify safe landing areas, according to lander-scale relief flatness criteria.

Subsequently, the PDV selects the closest safe landing site and performs a divert maneuver to that site, after which the PDV initiates vertical descent over the site. When the PDV reaches 23 m, now traveling with a constant descent speed of 0.5 m s^{-1}, the sky-crane maneuver commences, separating the lander from the DS, which hosts the landing engines and navigation sensors.

Once the lander is totally deployed from the sky crane, the landing logic enables the touchdown trigger: upon contact, the four landing stabilizers (i.e., adaptable legs) passively retract to conform to the terrain, thus keeping the lander top deck level. Once mechanical switches in the lander belly-pan indicate that the belly-pan has contacted the surface, pyros are fired to rigidize the landing stabilizers, thus freezing the pose of the lander relative to the surface (see Section 5.5).

As with Mars sky-crane landings, when the touchdown trigger in the DS senses the loss of the weight of the lander, the landing logic commands the DS to stop its vertical motion, followed by severing of the four bridles connecting it to the lander, and finally initiating a fly-away maneuver that disposes of the DS at a safe distance from the lander.

5.5. Lander Mechanical Configuration

The ELMC landing system is an evolution of proven landing systems incorporated on other planetary landers (Figure 16). As mentioned in the previous section, one of the key features of the landing system is the sky-crane architecture, which provides the lander with stability needed during landing as well as mitigating surface contamination from the landing engines.

Four bridles maintain a level lander body as the four passively conforming legs adjust to the terrain encountered during touchdown. Each leg is comprised of a four-bar linkage that controls its pose prior and during the landing event. One of the bar/links in the leg is compliant to ensure the leg mechanism avoids kinematic lockup during its landing articulation. The legs are also preloaded downward with a constant force to aid in surface accommodation and compression prior to touchdown, which provides additional landed stability.

The legs maintain contact with the surface as the lander continues to be lowered onto the surface and each leg passively accommodates surface topography in its region. The lander feet are designed to aggressively interact with the surface to provide stable traction and to prevent sliding of the lander on an icy surface.

The belly-pan beneath the main body of the lander provides the vault with protection from the potentially harmful terrain by acting like a skid plate. However, unlike a skid plate, the belly-pan acts as a fifth leg, with traction that resists shear motion on the terrain with which it interacts. Once the belly-pan contacts the surface, sensors trigger touchdown logic that locks the legs in position, providing a stable outrigger table-like stance.

Figure 16. One of our full-scale Europa Lander mechanical test-bed vehicles is shown here with its stabilizer legs configured to show adaptation to hazardous terrain with significant relief. Importantly, such a landing would only occur if the hazard-avoidance system failed. Even in that scenario, the lander system is designed to adapt and conform to the surface morphology. Once the belly-pan contacts the surface with sufficient force, the legs are locked into place so as to position the lander perpendicular to the surface normal and prepare the vehicle for sampling and surface operations. Shown atop the test bed is a high-gain antenna prototype.

Leg locking is done by locking up the “hip” and “knee” rotary joints, which lock out all degrees of freedom the leg once had. Up to this point in the DDL sequence, the bridles were responsible for keeping the lander level, but now the bridles transfer this responsibility to the legs. Once the bridles have been adequately off-loaded, ensuring the stability forces have been transferred from the bridles to the legs and belly-pan, touchdown is declared and the bridles are pyrotechnically cut. The hovering propulsive stage is then commanded to fly away, leaving the lander in a stable landed stance on the surface.

5.6. Direct-to-Earth Communications

The ELMC is baselining DTE communications for all telemetry, command, and science data return. The telecom subsystem is designed to support tone transmission during DDL, to return a minimum of 1.5 Gbits of data during surface operations, and to communicate either with the deep space network (DSN) or with spacecraft in Europa’s vicinity.

These requirements, along with the need to minimize power consumption and to operate reliably in the high-radiation environment of Europa, drove the Europa Lander telecom system design to a redundant X-band telecom system using the highest power commercially available, flight-qualified TWTAs; compact, low-power consumption radios; a series of LGAs; and to the design of a new high-efficiency, compact HGA capable of closing the DTE link at a nominal distance of 5 au. The requirements for this HGA antenna are challenging: it must be dual band, circularly polarized, have high gain (>35 dBi), high efficiency (>75%), a low profile (<5 cm height when folded onto lander deck), be able to handle an RF input signal of 100 watts, and survive the high-radiation and low-temperature environment.

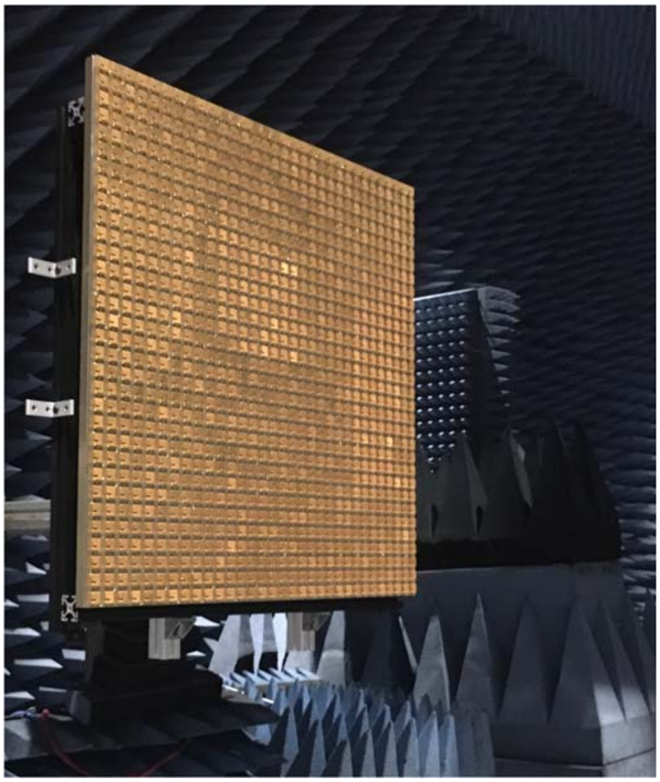


Figure 17. The 32 × 32 element high-gain antenna in the test range at JPL.

Despite these challenges, the ELMC team has built and tested brassboard versions of the HGA that meet or exceed the performance requirements (Figure 17). The Europa Lander HGA is a 32 × 32 patch array based on a newly patented and tested design (Chahat et al. 2020). Using incrementally larger prototype antennas, the telecom team has finalized the design for the 32 × 32 element HGA and is bringing the antenna to Technology Readiness Level 6 (TRL-6).

An 8 × 8 subarray was irradiated with the expected mission total ionizing dose (TID) and internal electrostatic discharge (iESD) of 2.8 Mrad (Si), radiation design factor (RDF) = 2. No performance change was measured after radiation, thus confirming the robustness of the design to radiation (Chinn & Martinez Sierra 2019).

A 16 × 16 subarray was built to verify manufacturability, assembly techniques, and waveguide power-divider design. The array performance was measured to have excellent agreement with predictions, resulting in antenna efficiencies at both 7.19 and 8.45 GHz of 75% or greater.

Both prototypes were temperature cycled from −170 °C to 110 °C. Postcycling performance revealed no changes, thereby validating the antenna's thermal design (Chahat et al. 2018).

Finally, a full-size 32 × 32 element HGA prototype has been assembled and found to meet expected RF performance of 35 dBi or greater. Figure 17 shows the 32 × 32 element antenna in JPL's indoor test range. The antenna successfully underwent random-vibration testing and was successfully thermal tested in 2021 March.

To simplify antenna assembly and reduce antenna mass, a second-generation prototype of the HGA has been designed using a thinner and stiffer front plate and an ultrasonic additively manufactured (UAM) backplate. The UAM process holds the promise that true metallurgical bonds can be created between two similar metals, thus allowing waveguide cavities to be formed within a single part rather than requiring fasteners to hold two half-height waveguide cavities together. A UAM backplate was manufactured for the 8 × 8 subarray and the antenna was found to perform identically to the conventionally manufactured waveguide subarray. The prototype UAM backplate made for the 8 × 8 subarray is shown in Figure 18.

Figure 18. An 8 × 8 element subarray of the high-gain antenna with the ultrasonic additively manufactured backplate.

5.7. Power and Lander Lifetime

The ELMC power subsystem team examined numerous options for powering the lander, including radioisotope thermoelectric generators (RTGs) and solar power, both of which must be coupled with rechargeable batteries.

Due to limitations imposed by the distance from the Sun, the 85.2 hr diurnal cycle of Europa (∼43 hr of darkness), and the mass of solar panels and associated rechargeable batteries, solar power was determined to be a strong risk for accommodation.

RTGs are attractive due to their utility in deep space and in the absence of solar insolation. However, on an ocean world such as Europa, the young surface age of the ice and potential connection to a habitable subsurface ocean present numerous known, and unknown, challenges related to planetary protection (National Research Council 2012). In addition, RTG designs for the lander revealed accommodation (e.g., instruments), mass, and thermal design challenges that added significant complexity, cost, and risk to the mission concept.

Table 2
Summary of Key Battery Cell Testing (10 Mrad Total Ionizing Dose for all Irradiated Cells)

Test	Discharge Temperatures (C)	Discharge Rates (mA)	Test Conditions
Electrical performance	−20, 0, 20, 40, 60	50, 250, 500	Capacity and energy delivered for pristine and irradiated cells
Capacity dispersion	20	250	Evaluate mean capacity delivered for pristine and irradiated cells
Storage	20	250	Storage at 20, 30, 40, 60 °C for 6, 12, and 18 months of pristine and irradiated cells
Microcalorimetry	No load	No load	Evaluate heat output under OCV conditions at 6, 12, and 18 months of pristine and irradiated cells
Heat evolution	20	20, 250, 500	Evaluate heat generated for both pristine and irradiated cells

The final option considered was primary batteries, which typically offer an energy density >2× rechargeable batteries. Primary batteries have the drawback of a predefined and finite mission power availability, but present the advantage of a simpler power subsystem that can be readily adjusted, for example, by adding or subtracting power in units of D-cells. Given the mass and accommodation advantages, primary batteries were selected for the ELMC. Primary batteries also have the advantage of low planetary-protection risk compared to RTG systems.

To provide sufficient energy and stay within an acceptable battery mass envelope, the specific energy for the primary battery cells is targeted at >700 Wh kg^{-1}. The power modes of the lander require only low-to-moderate discharge currents (<C/50 rates), with the current battery thermal design targeting operation over the range of 0 to 60 °C. Evaluation of various primary battery chemistries (e.g., Li/SO_2, $Li/SOCl_2$, Li/MnO_2, Li/CF_x-MnO_2) at JPL has indicated the Li/CF_x primary battery chemistry can meet these operational requirements (Jones et al. 2017; Krause et al. 2018).

To evaluate battery cell options for the mission, a comprehensive test matrix has been established (Table 2). D-sized cells from several vendors are currently being tested. The most critical aspect of this testing is electrical performance testing over a range of anticipated operational temperatures and discharge rates, which helps to establish the ability of the cell chemistry to meet different mission power profile scenarios.

Since the total delivered energy is critical to mission success, extensive testing to establish the mean and standard deviation of delivered energy, and the capacity of cells from a single manufacturing lot are also being performed. From this testing, a statistical model that bounds the maximum and minimum energy delivered is being developed. Testing is being performed in the ESPEC Platinous Environmental Chambers using Maccor 4000 Battery Cyclers at JPL. This testing will also be accompanied by evaluation of cells in a vacuum environment (Figure 19).

Depending on the final mission profile and cruise time, the duration from manufacture of the cells (i.e., electrolyte filling and cell conditioning) to the end of mission could be as long as 10 yr. Therefore, a clear understanding of the self-discharge and calendar-life characteristics under long-term storage conditions is required. Storage testing is currently being performed under real-time (20 °C) and accelerated (30, 40, 60 °C) conditions, to support extrapolation to 10 yr of storage time. Although the predicted cruise temperature is ∼0 °C, initial test results at even 20 °C have indicated a barely discernable loss in capacity after 6 months. Based on this observation, storage testing has been executed at 20 °C temperature or above.

One key objective of the test campaign is to evaluate the potential for identifying cells with enhanced self-discharge, prior to cell selection for the flight battery. Toward this goal, initial microcalorimetry data are being collected using a TA Instruments TAM IV Micro-calorimeter, which is capable of measuring heat output at the microwatt level. The 18 month storage cells are being evaluated using this technique at each of the four storage temperatures, and at the 6, 12, and 18 month time points, to correlate observations with the full discharge data.

To support operation at the very low temperatures of Europa (−180 °C or ∼100 K), an adequate battery thermal design will be critical. At present, the baseline battery thermal design does not utilize electrical heaters but waste heat from the avionics, combined with heat generated by the discharge of the Li/CFx cells, which serve to keep the cells in the 0 °C to 60 °C range. Therefore, it is critical to understand the ratio of thermal-to-electrical power generated under different load conditions. To accommodate this testing, isothermal calorimetry is being conducted using a Calarus IBC Calorimeter under different load conditions.

An important aspect of testing is evaluation of cells that have experienced high doses of ionizing radiation. There are two elements of radiation exposure that factor into cell testing: planetary protection and environmental. Since one of the goals of the ELMC is to investigate biosignatures, implementing strict planetary-protection protocols to avoid contamination from Earth organisms is vital. Since primary cells cannot undergo dry-heat microbial-reduction treatments, treatment with gamma radiation (5 to 10 Mrad total ionizing dose) is currently being investigated. This could require irradiating individuals cells, or the full battery pack, with gamma rays

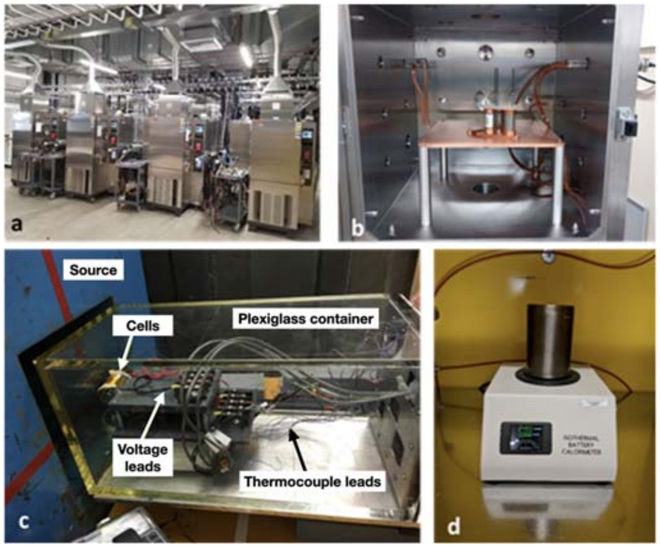


Figure 19. Facilities and equipment used for evaluation of Li/CFx cells including (a) convectively controlled environmental chambers for wide-temperature cell testing, (b) vacuum chamber for evaluating cell thermal response under flight-like external pressure, (c) chamber used for containing and monitoring cells during radiation dosing, and (d) isothermal calorimeter for evaluating heat output of cells during discharge.

prior to flight. Once at Europa, the cells and battery modules would receive further radiation exposure, due to the radiation environment created by Jupiter's magnetosphere.

Initial testing to date has indicated that the Li/CFx chemistry can support the load profiles and targeted mission duration for the ELMC (Jones et al. 2020). A specific energy of >700 Wh kg^{-1} at relevant rates has been demonstrated, with minimal impact from 10 Mrad doses of gamma radiation on delivered capacity.

Ongoing work is focused on long-duration storage testing, evaluation of heat output versus load, safety and abuse testing, and improved state-of-charge monitoring. Alternative approaches to meeting planetary-protection requirements that do not require heat treatment or radiation doses are also underway. Finally, further cell-design improvements are underway to improve specific energy and increase mission duration.

The design for the lander primary battery subsystem provides for ∼60 kWh of energy. This allocation includes and exceeds seven full Earth days of ongoing energy consumption for sample acquisition of three samples from at least 10 cm depth, sample processing of three samples, instrument analyses of the three sample, and data return for the samples, as well as data from the context-imaging systems and seismic monitoring system.

Important to the surface lifetime of the ELMC, design trades show that with little added risk the surface lifetime of the mission could be augmented to exceed 60 Earth days on the surface of Europa. The subsequent addition of more D-cells to the lander further increases the mission lifetime but requires refinements on the flight-system margins. A 90 day surface mission may be possible, and is being studied as part of the development of the power subsystem.

5.8. Sampling System

The surface sampling operation of the lander is designed to have four high-level functions: (1) identify a location, or locations, to sample; (2) excavate a trench into the surface of at least 10 cm depth (if needed) to mitigate the effects of radiolytic processing of the collected sample; (3) collect and retain on the order of 10 cm^3 of surface material from the bottom of the trench; and (4) deliver the collected sample to the science payload while maintaining the sample's scientific integrity, which includes, but is not limited to, keeping the sample's temperature below 150 K or at the surface temperature of the landing site.

During the initial stages of the ELMC development the sampling subsystem team examined a wide range of possible modes and mechanisms for sampling Europa's surface. As shown in Figure 20, drills, scoops, saws, and other means of excavating the surface and collecting a sample were considered. Based on the SDT report and requirements for sampling, useful but risky mechanisms such as drilling could be eliminated, as the SDT report does not set a science requirement on preserving the stratigraphy of the acquired sample. For reasons such as these, many of the sampling tool development efforts have focused on prototypes that saw or grind into the surface to excavate to at least 10 cm depth, and then utilize a scoop or rasp to acquire the sample.

5.8.1. Sampling Depth

The design requirement of the sampling system for the lander is such that a sample be acquired at a minimum 10 cm depth from anywhere in the arm workspace, i.e., at full extension of the arm reaching out from the lander. Importantly, the robotic arm is about 1.2 m in length; the closer the sampling region is to the lander, the deeper the sampling system can go, just by merit of the length of the robotic arm. The 10 cm requirement for sampling depth is for unit-density cryogenic water ice.

Though the 10 cm depth was defined by surface-radiation processing (see, e.g., Nordheim et al. 2018, 2019), operationally the depth factors into the mission design as a way to parameterize energy consumption. When formulating operational scenarios, the ELMC has allocated (with at least 30% margin) enough energy to excavate to at least 10 cm depth in unit-density ice. Importantly, because the energy-expenditure allocation is a design parameter (with margin), the energy allocation could be used for a variety of different surface conditions, for example to get through >50 cm of porous, low-density snow on Europa's surface.

Related to the above, landing-site selection could well target salts and other indicators of endogenous oceanic materials. Such compositional considerations are also important for preservation of organics and biosignatures, as dense materials, such as salts, do not permit radiation processing to the depth that occurs in water ice (Johnson 1990).

Significantly, not all sites on Europa are equal in terms of radiation exposure. Surface age, geography, total dose, and sampling depth are all critical considerations; and somewhat serendipitously the reconnaissance data from the closest approaches of the Europa Clipper mission will occur over the sub- and anti-Jovian hemispheres, which experience lower radiation fluxes than the trailing and leading hemispheres of Europa (Paranicas et al. 2001; Nordheim et al. 2018).

Finally, while radiation is obviously deleterious to sample integrity, it is important to emphasize that "pristine" samples have never actually been sampled on any planetary surface. Even here on Earth rocks from the Archean have undergone significant diagenetic modification and radiolysis from long-

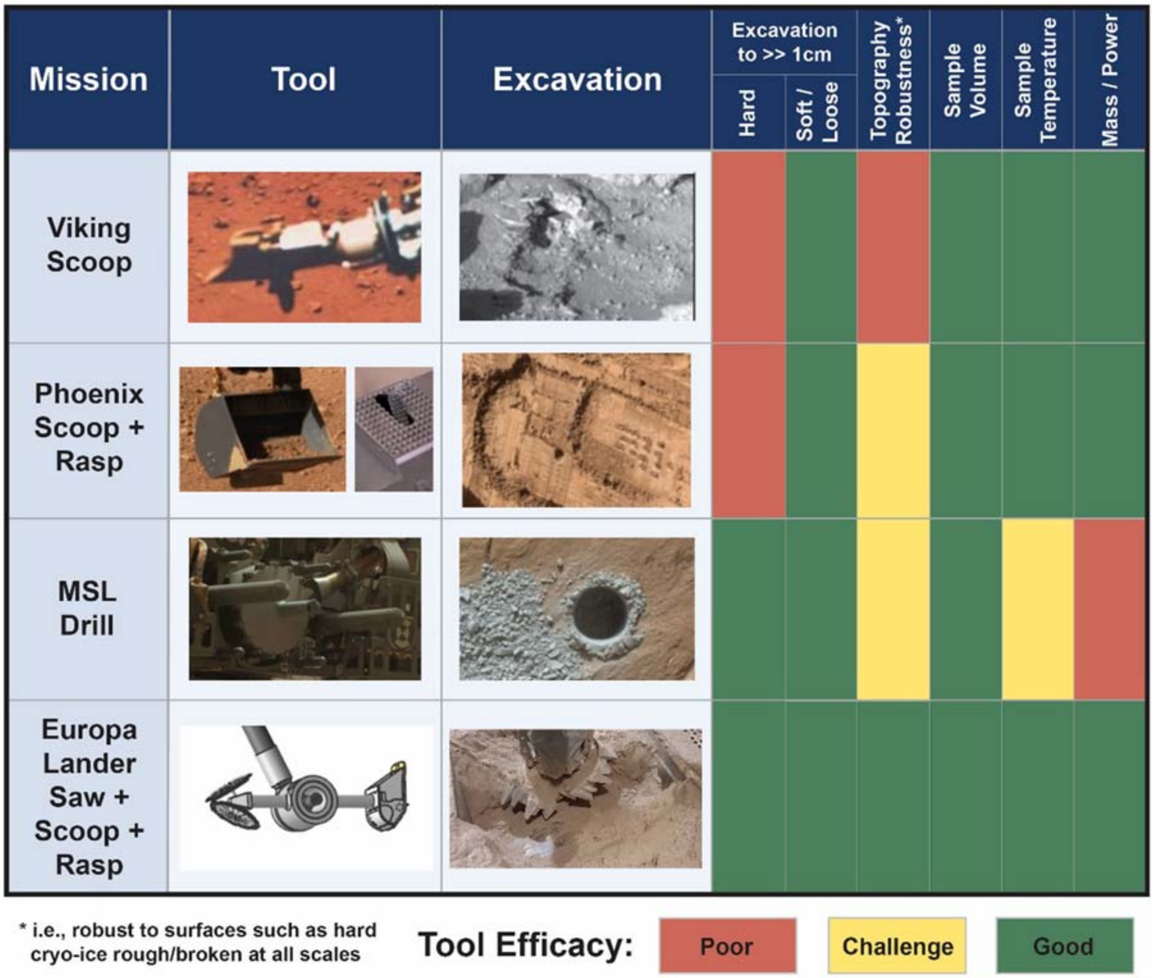


Figure 20. The ELMC team conducted many sampling system and tool design trades and examined a variety of sampling systems used on prior in-situ missions that sampled the Martian surface and other planetary bodies. Shown here is a qualitative comparison of various sampling systems used on Mars, and how each system addresses the requirements from the Europa Lander SDT report, and various engineering challenges associated with sampling Europa's surface.

lived radionuclides. On Mars we have never sampled deeper than 10 cm, and the Martian near surface is old and accumulates a significant radiation dose from galactic cosmic rays (GCRs). Interestingly, GCRs are not a very significant contribution to total dose on Europa because of the young surface age and the shielding that Jupiter's magnetosphere supplies (Nordheim et al. 2019). Related to this, even with radiolytic modification organics and other chemical and morphologic biosignatures persist under Europan surface conditions (Hand et al. 2009; Hand & Carlson 2012).

5.8.2. Sampling System Design, Testing, and Prototyping

The lack of data on the centimeter-to-meter scale surface topography and composition (at the scale relevant to the sampling subsystem) creates high uncertainty about the conditions the lander will encounter and the operations it must implement for mission success. These are challenges that any "first" mission to a new world faces, be it Mars (e.g., as with the Viking landers and subsequent missions with new sampling targets) or the surface of a low-gravity asteroid (e.g., as with asteroid Bennu and the sampling conducted by the OSIRIS-REx mission).

Aside from the operational challenges of collecting and delivering a sample, the Europa environment also poses challenges unique to most of today's landed sampling missions. The low temperature and high radiation on the surface of Europa create unique design drivers, material limitations, and operational considerations—all of which must be understood early to inform adequate and robust design solutions. For these reasons, the engineering task of understanding how to design and validate a robotic system robust to these challenges is paramount in the sampling system development effort.

Throughout the pre-Phase A development, the ELMC sampling team has implemented and maintained a strategy to better understand the fundamental physics behind subsystem performance, while developing hardware, test beds, and infrastructure to explore promising concepts. Figures 21 and 22 show several examples of the tools and the test beds.

Promising hardware concepts developed run the range from ice-fracturing saw blades to percussive instruments and simple scoops for excavation, to coring-drill-inspired centrifugal collection tools, to pneumatic-based sample transfer mechanisms.

The team has also developed a number of subsystem test beds, most notably a one-of-a-kind cryo-vacuum chamber, named the Cryogenic Ice Transfer, Acquisition Development, and Excavation Laboratory (CITADEL). As shown in Figure 21, CITADEL allows for testing all elements of the subsystem at roughly 70 K and 10^{-6} torr, which enables the engineering and science team to understand tool performance

Figure 21. Technology development associated with the sampling system includes the construction of the Cryogenic Ice Transfer, Acquisition Development, and Excavation Laboratory (CITADEL) thermal vacuum chamber (a), which is approximately 1.7 m in height and enables full-scale testing of sampling tools and procedures for a variety of Europa surface simulants. CITADEL can simultaneously accommodate up to six test material blocks ∼30 cm × 10 cm × 8 cm in volume. Shown in (b) and (c) are the interior of the chamber with cryogenic ice prior to and during cutting and excavation. In (d–g) are shown numerous prototype tools and end-effectors for excavation and sampling, many of which have been tested in cryogenic ice and with other Europa surface simulants. The lander team has considered over 200 tool concepts and continues to evaluate saws, drum cutters, rotary drills/cutting tools, reciprocating axial tools, augers, and scoops/scrapers. The work of the sampling team builds on decades of hard-earned experience testing and operating sampling systems for Mars.

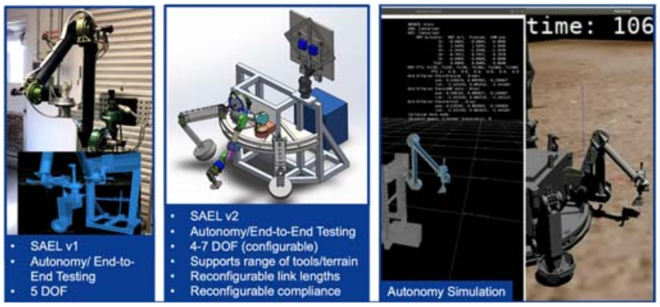


Figure 22. Physical and virtual test beds are being used for development and validation of sampling autonomy for the Europa Lander. The physical test bed, with a five degree-of-freedom (DoF) robotic arm, and referred to as the Sampling Autonomy for Europa Lander (SAEL) test bed, is shown in the left panel. Sampling tools, such as excavation saws and acquisition scoops, have been used with this arm to investigate autonomy aspects of the sampling process, including surface preparation, excavation, and sampling. The five DoF arm is kinematically similar to the robotic arms that flew on the Mars Phoenix, MSL, and Mars 2020 missions. A seven DoF robotic arm is being built that will be used in the test bed to investigate the benefits of different numbers of DoFs in a robotic arm; a CAD diagram of the arm in the test bed is shown in the center panel. The seven DoF arm will be reconfigurable to be used as a five, six, or seven DoF arm and with varying link lengths. Stereo cameras in the test bed acquire images that are used to generate digital elevation maps for automated terrain analysis and target selection. An autonomy visualization system, shown in the panel at right, visualizes the current estimated state of the physical system, such as joint angles and terrain mechanical properties, and visualizes autonomy planning information such as planned trajectories. An environment simulator, using the Dynamics and Real-Time Simulation system (DARTS; Biesiadecki et al. 1997; Jain 2019), represents a physical system, as shown at far right. DARTS provides tool–soil interaction forces based on specified terrain mechanical properties that can vary across the volumetric workspace.

and ice behavior at flight-like temperature and pressure. Additionally, CITADEL has four large gate valve-isolated load locks that allow for cycling surface simulants into the chamber, significantly increasing test throughput without breaking the chamber vacuum.

Tests with ice under Europan conditions show that while ice is harder at cryogenic temperatures, it can be readily drilled, excavated, and sampled. Decades of work on drilling, excavating, and sampling basalt, granite, and other hard rocks on Earth and on Mars have helped inform the sampling team's approach to this challenge.

Along with hardware design, a dedicated surface simulants team has been making ongoing efforts to understand how to create Europa on Earth, in both ambient and cryo-vacuum conditions. The team's charter is to define and engineer the surface of Europa, based on available spacecraft and ground-based observations, for the purposes of hardware and software development, testing, and validation. To enable this, the ELMC team is investing heavily in research and development tasks and infrastructure to develop the knowledge, capabilities, and logistical operations vital for any in-situ ice-covered ocean-world flight project.

Simulants to date span the range from pure water ice at ∼100 K to various salt-dominated mixtures at cryogenic temperatures, to sulfuric acid solutions frozen to cryogenic temperatures. Basic cryogenic drilling, excavation, and sampling experiments have also been conducted successfully with Crisco© shortening (an accessible and inexpensive endmember for an organic-dominated cryogenic sample) and large, hard, horse-lick salt blocks (an accessible and inexpensive endmember for consolidated, endogenous, salt-rich deposits on Europa.) Along with testing a wide variety of compositional permutations and mixtures, the team is also conducting tests on different physical parameters for various samples, such as porosity and surface hardness.

5.9. Autonomy and Autonomous Operations

Autonomy can enable increased science return per unit time, and dollars, spent on a mission. As just one example, the autonavigation system on the Mars Perserverance rover has completed autonomous drives up to 167 m in distance, allowing the science team to reach sites of interest for sampling in fewer martian days (sols). For the specific case of the ELMC, autonomy is an important component of enabling more science with the DTE mission architecture. Without a communication-relay orbiter, the lander experiences DTE/DFE blackout periods during the Europan night (approximately 43 hr). Autonomy, as detailed below, permits the lander to conduct a variety of operations during such periods, serving to minimize idle time on the surface. Autonomy can also ensure that the primary batteries are utilized efficiently and effectively for a given sequence of operations, and for data downlink prioritization.

The challenges of autonomy are numerous and require early attention, exploration, trade studies, and experimentation to determine the right baseline for the eventual mission. The use of autonomy is a natural architectural solution to many of the challenges, but autonomy on the ELMC is not a simple reapplication of prior techniques, nor is it sufficient to assume that there is a direct relationship to strategies used in other in-situ missions. Autonomy design and development spans hardware, algorithms, functions, ground operations, and mission activities in an end-to-end manner. This development is already in progress with the ELMC and such work could help pioneer new technologies, techniques, and operations that are applicable to the exploration of many bodies throughout the solar system.

Our baseline concept employs onboard autonomy to efficiently collect and analyze samples, and then transmit prioritized information to Earth. Figure 22 shows some examples of the specific systems under development for surface operations. Importantly, operational efficiency and urgency is only one of a number of challenges that an in-situ mission at Europa, or any ocean world, must address.

Here we provide a brief overview of challenges that have been identified, and the current approach to advanced developments for autonomy and the specific application to the lander mission.

5.9.1. Surface Uncertainty

The lander spacecraft would set down on the surface of Europa with surface knowledge at a scale larger than what would be needed for sample acquisition; the Clipper high-resolution imagery will be at the scale of fractions of a meter, whereas the sampling system would require imagery at the centimeter scale. Since the surface topography and the specific material properties of the surface material will have a significant measurement uncertainty prior to landing, the spacecraft must be designed for a range of possible scenarios, and the system must be able to autonomously adapt as required.

The advanced developments and future work underway to address this challenge are as follows. First, the surface uncertainty requires the onboard system to be perceptive enough (e.g., stereo imagery for mesh generation, sufficient dynamic range, and color filters to be robust to variations in solar illumination and reflectance) to refine the measurements sufficiently in order to identify the proper action (e.g., excavate a trench, acquire a sample, and deliver the sample to the lander vault). Second, there must be a diversity in the methods and mechanisms such that the proper action is available. Since sample acquisition is a critical function, multiple methods are being developed for achieving the surface-sample-acquisition requirements (excavation to >10 cm, collection, processing, and delivery of the sample material to the instruments).

The construction of both a hardware-in-the-loop (HITL) test bed and a software-plus-simulation ("SoftSim") test-bed environment enable the implementation of multiple prototype systems. The HITL test bed is being be used to compare and contrast different end-effector and sampling tool choices with manipulators that vary from low to high dexterity (e.g., three to six+ degrees of freedom). The HITL test bed has representative control and kinematics allowing for the development of dynamic and adaptive control strategies for excavation, collection, and tool exchange. The SoftSim environment enables the investigation and experimentation of the other behaviors of the surface vehicle including planner/executive/learning agents, energy conservation, fault/failure/interruption recovery, and instrument data assessment. The test bed environments are designed to have both the fidelity and flexibility to represent the trade space for the most challenging tasks related to autonomous functionality.

5.9.2. Europa's Distance and Orbit

Europa's ∼4.2 au distance from Earth during opposition, and its 3.55 day orbit around Jupiter, constrain the timing and frequency of communication with Earth. Europa will be approximately 4.2 au from Earth during the surface mission phase. At this distance, data rates are significantly less than Mars missions enjoy, and the light time introduces additional latency. Furthermore, Europa is tidally locked to Jupiter with an orbital period of ∼85.2 hr. This means that Earth is only visible to the lander for approximately 40 hr per orbit.

As part of the initial mission architecture, presented during the 2017 MCR, the mission included a communications-relay stage in orbit around Europa, with a 24 hr period. This relay stage simplified data transmission and GITL surface operations, but came at great cost and complexity to the mission; the guidance received by the team post-MCR was to develop an architecture without the relay stage, and a lander that employs DTE communication. Without autonomy, the DTE constraints would lead to significant idle time on the surface of Europa, during which energy for heating and spacecraft maintenance would be consumed without yielding any science return.

As part of the advanced development and future work for this challenge, lander autonomy is being developed for communications DTE/DFE. Critical to this effort is the efficiency inherent in a well-designed autonomous system: when the Earth is in view the lander must have the capability to know when to expend the energy to be ready to receive, when to transmit, and for how long to transmit. These are essential considerations for allocating resources such as heat and power. In addition, any additional urgency due to GITL involvement in operations could introduce a desire for "spontaneous" downlink to convey to ground operators the data they need to make decisions affecting subsequent sampling and mission activities.

5.9.3. Fault/Fail, Recover, Continue

Autonomy has served an important role in mission efficiency for fault identification and recovery in past missions (Reeves & Snyder 2005; Maimone et al. 2007) and will be important for future missions (Ono et al. 2020). For the ELMC, the system should not be dependent on GITL intervention to recover from interruptions, faults, or failures. For instance, the system needs to detect, recover, and continue the mission without ground intervention if faced with a radiation-induced single-event effect (SEE) that manifests as an interruption in the electronics. Developments in this area include the identification of detection methodologies that expose SEEs, understanding the necessary state and information needed to permit recovery, and identifying the techniques and behaviors necessary to orchestrate recovery autonomously.

5.9.4. Balancing Autonomous Operation and GITL

The use and implementation of onboard autonomy must balance the advantages of autonomy for efficient operation of the mission with the need for a GITL decision process that incorporates concerns of the human stakeholders (e.g., the science team). While a fully autonomous vehicle could be constructed and could execute without GITL, the concept for operations (and a far more likely scenario) is that there will be a carefully orchestrated coordination of flight and ground behaviors and responsibilities to allow for surface operations to change once the vehicle is on the surface.

Exploring where the possible boundaries for autonomous flight vehicle responsibility versus ground operations team responsibility is part of the trade and exploration space. The advanced development work has included the examination of the flight versus ground responsibilities, and the decision processes required by human operators. Premier among these trades and the optimization process for GITL and autonomy is identifying decisions and operations that work in direct service to the high-level science goals and investigations.

By systematically evaluating the information required in order to make key decisions, the migration of such decisions from ground to the spacecraft can be assessed. The assessment includes the viability of any required sensing, constructing the information set, assessing the complexity of the algorithmic decision logic, and assessing the presumed variations in the resulting onboard behavior. All of these are scrutinized with a focus on being able to demonstrate, test, and certify/trust the autonomous behavior. The end goal is an adaptive autonomous system that works in service to the science team and maximizes the science return of the mission.

5.9.5. Energy Storage and Management

For the dMCR baseline design of the Europa Lander, the energy density of the primary batteries, plus the mass of the batteries themselves, yielded a predicted lifetime of at least 30 to possibly more than 60 Earth days of operation on the surface of Europa. The hardware design and onboard software would need to autonomously modify energy consumption rates as a function of the mission activities. In addition, the system would need to predict energy expenditure and remaining energy in order to maintain sufficient capacity to return all required science and instrument data before the end of the mission. Maximizing the surface lifetime is critical to lowering overall mission risk.

Early development work includes battery lifetime and capacity testing, and battery chemistry tuning with industry partners (e.g., Eagle Picher). In addition, the exploration of lower power electronics is an ongoing activity. The end goal is a system that autonomously adjusts energy consumption as a function of activities, and that autonomously allocates resources for mission-critical activities, such as transmission of data back to Earth.

5.9.6. Information Flow to Earth

As detailed above, the baseline mission uses a DTE/DFE communication architecture with a highly efficient HGA design, a high-power radio/amplifier, and an arrayed set of DSN antennas. The effective downlink rate is expected to be approximately 48 kbps. This bandwidth is a significant driver on battery capacity (and thus mission life) as it couples the radio/amplifier on-time with the quantity of data transmitted.

Ideally, the spacecraft uses its last Joule of energy transmitting science data. It is conceivable that the system may switch to exclusively transmitting data if the already collected high-value data reaches a threshold where further activities become of low predicted utility.

Increasing the total data volume and the information density of the data that must be returned requires a combination of approaches. For example, as detailed previously, JPL has developed and patented a HGA design that has unprecedented performance (Chahat et al. 2018, 2020). This is a critical step toward increasing the information-return capability. Complementary to this are the strategies and techniques to increase the science and engineering value of the information that is transmitted. This includes the traditional strategies of decimation and compression, as well as investigating onboard instrument data assessment and prioritization. It is possible that autonomy and machine-learning techniques could be applied to allow the onboard system to replan communications activity, based on assessment of instrument data and priority measurements. As one example, the "biosignature bingo" concept for life detection, as detailed in the SDT report (Hand et al. 2017), could be used to inform autonomous prioritization of data downlink that best informs the team about biosignature measurements. The ELMC project engineering team is currently investigating such capabilities and developing autonomy tools that can address the optimization challenges.

5.9.7. Building Hardware to Enable Autonomy

Autonomy cannot be viewed as an addition to the system: it must be developed, designed, and incorporated in the early iterations of the architecture, and the design of the overall vehicle.

A surface mission with significant autonomy goals would require expanded resiliency by design. Advanced development work is being conducted to identify sensors and measurements that could improve resiliency. Most notably, perception methods—both in the form of robust sensing and the algorithms needed to interpret the sensed scene/situation—require investigation and development. Almost equally important are literal and functionally overlapping methods to achieve the critical mission objectives: sample acquisition, sample transport, sample processing, and sample analysis. Less visible, but still critical, to autonomous behaviors are sufficient computational resources, sufficient memory and storage, and effective fault/interruption detection.

5.9.8. Synergistic Instrument Design

Historically, instruments have been treated as "payload" on the spacecraft to be operated and managed in coordination with the "spacecraft", with the payload loosely coupled with spacecraft design and operations. Of course, architectural decisions like interface definitions, power requirements, and mechanical patterns are precise and impact the overall system. There are also coupled onboard operations, like sample handoff, that drive interoperability, but these two areas envelop the scale of the onboard interdesign complexity for, e.g., Mars surface missions. Similarly, vehicle and instrument operations teams intentionally operate semi-independently to the level reasonable for planning, and coordinate at the highest level reasonable to check for known conflicts and overuse of resources, as this provides greater flexibility and autonomy for the ground team during operations.

Moving forward with autonomy and developing autonomous operations will foster a closer coupling between the payload system and the spacecraft system, ensuring that one system "knows" what the other is doing and how best to prioritize actions and manage resources.

The ELMC employs a close coupling between instrument and spacecraft to optimize resource utilization and to enable uncertainty handling autonomously. Understanding how instruments and their operation can be accommodated is one of the thematic purposes of the ICEE-2 instrument development effort. The development in this area is intended to identify instrument and surface vehicle requirements that enable an autonomous system to operate cohesively.

In many cases, the instruments themselves would need to provide the autonomous behaviors that traditionally might have required a GITL cycle to effect operations. This includes not just the instruments but also the sample-acquisition and sample-delivery mechanisms. Development of these enabling capabilities for autonomy are being pursued directly through the preproject and through the ICEE-2 program.

5.10. Planetary Protection

Forward planetary protection (i.e., delivery of Earth organisms to another world) is a key driver in the architectural development of the lander. Given that Europa is an ocean world with a geologically young, dynamic ice crust, it is imperative to demonstrate that any subsurface liquid water will neither be directly contacted by Earth organisms nor contaminated through transport vectors (e.g., organism proliferation or ice-crust resurfacing).

Through contamination-control requirements, planetary protection (PP) also plays an important supporting role in enabling the science team to achieve the goal of biosignature detection with a high degree of confidence, minimizing both false positives and false negatives.

The PP approach is driven by the following documents:

1. NPD 8 020.7G, Biological Contamination Control for Outbound and Inbound Planetary Spacecraft (NASA 1999–2022).

2. NID 8 020.109A (formerly NPR 8 020.12D), Planetary Protection Provisions for Robotic Extraterrestrial Missions (NASA 2017).
3. Committee on Space Research (COSPAR) Policy on Planetary Protection (approved by the COSPAR Bureau on 2020 June 17; COSPAR 2020).

The ELMC team has adopted a conservative and stringent approach to PP. The mission design must be compliant with the Planetary Protection Category IV requirements for Europa, per the COSPAR and NASA Policy (NID 8 020.109A). Unlike previous missions, the worst-case scenario was selected as the design driver for initial lander architecture and proces-flow decisions, e.g., biobarriers, system-level vapor hydrogen peroxide (VHP) sterilization, and inclusion of a TSS.

PP policy currently requires that the probability of inadvertent contamination of an ocean or other liquid-water body must be less than 110^{-4} per mission (NPR 8 020.12D). In this context, contamination is defined as the introduction of a single viable terrestrial microorganism into a liquid-water environment within the roughly thousand year period of biological exploration (PoBE), ending in the year 3000. The PoBE refers to the time necessary for robotic missions to determine whether biological systems occur on a potentially habitable planetary body (National Research Council 2012). This was enacted by the NASA Office of Planetary Protection (OPP) in 2019 via a Memorandum of Understanding between the Jet Propulsion Laboratory and NASA OPP.

The ELMC team is currently developing a probabilistic risk assessment (PRA) model to assess compliance with this requirement. This model includes an assessment of the end-to-end sequence of events that could lead to contamination, from both a successful nominal mission that intentionally contacts the surface of Europa via landing, sampling, and disposal of hardware on the Europa surface, and potential off-nominal events that could lead to contamination via failure of the spacecraft, potential impact trajectories, and scattering of debris over the Europa surface.

For both nominal and off-nominal scenarios, geological-resurfacing timescales that may introduce transported Earth organisms to interstitial liquid water, and an assessment of biological mortality throughout the journey from Earth to the subsurface ocean of Europa, are considered.

The mission and flight-system design, together with the year 3000 PoBE, enable the current estimate of the probability of contamination underlying the nominal Europa Lander mission to be less than 110^{-4}. This is for two reasons:

1. the nominal mission places the CS into a stable orbit, precluding Europa contact; and
2. All other hardware (Lander, DS, and DOS) contacts the surface of Europa in very a controlled, deterministic, and precise manner such that landing-site selection can serve to avoid geologically active areas on Europa that could risk delivering a microorganism to a subsurface-habitable region within the PoBE.

However, off-nominal events leading to Europa contamination may occur with sufficient probability that warrants further analysis to demonstrate compliance with the PP requirement. Therefore, mitigating the PP risk associated with off-nominal scenarios and quantifying the probability of such events is a primary focus of the PRA effort at this time.

The PP strategy implemented for the lander leverages the evolving PP state of understanding through its investment in building capabilities and data to fully assess the contamination risk. Quantitative metagenomics will be utilized to provide a clearer picture of the biological contamination at launch, and ultimately allow the project to demonstrate an understanding of spacecraft cleanliness.

Experiments are also underway to better understand the role radiation and space environments play in the mortality of Earth microorganisms. The harsh radiation environments of Jupiter and Europa's surface are currently in the process of being factored into the PP bioburden and assessment of the probability of contamination; clearly, including both the flux and total accumulated dose can serve to further sterilize the spacecraft.

The project has taken a conservative approach with the design, implementation, and risk assessment. As the knowledge and models continue to evolve, hardware simplifications and reduction of mass required by PP accommodation may occur. The ELMC has demonstrated that PP is not only prioritized, but that the constraints and requirements can also be feasibly achieved.

6. Technology Development Efforts

Since the dMCR, the pre-Phase A ELMC team has continued a targeted and strategic plan to mature the advanced technologies needed to implement the mission. In keeping with the tremendous potential science returns, there are several significant engineering developments. The preproject team ranked all of the mission risk-mitigation actions and selected the following 11 items for NASA's advanced development funding. Work on these tasks began soon after the dMCR and will continue through at least 2023. We detail some of these developments below and illustrate the work done by the team to reduce the risk of these challenges, particularly for DDL on Europa (Table 3) and the surface phase of the mission (Table 4).

6.1. Deorbit Stage Design for the Mission Environment

Background and rationale. The DOS of the Europa Lander uses a SRM to provide braking before achieving a safe, accurate landing. Three unknown design factors for the DOS are radiation, long-duration cold temperature, and PP controls. Characterization of these environmental effects is a critical step toward validating or updating the DOS design.

Development approach and results. The team has engaged two suppliers, as well as analysis and testing at the Marshall Space Flight Center (MSFC). MSFC developed a test plan to irradiate various SRM materials and perform complete postirradiation evaluations of mechanical properties and ballistic performance. To date, these materials have included inert propellant, as well as propellant-liner-insulation (PLI) samples and live propellant. Radiation-exposed samples showed an increase in hardening and a decrease in strain capability based on initial tests. The irradiated PLI bond line samples showed no significant degradation in bond strength. The results enabled the industry suppliers to select the best-performing formulation to continue testing and analysis.

In the next phase, testing will focus on evaluating the effects of combined environments on propellant, the PLI bond line, and the ballistic performance of the DOS SRM. Radiation will

Table 3
Deorbit, Descent, and Landing Risk Areas Addressed with Advanced Development

Risk	Advanced Development	Outcome	Current Progress
Unique environment for SRM	Combined environment testing of SRM material	SRM materials selected and demonstrated	Two contractors completed Phase 2; proposal for Phase 3
Mass growth of descent stage	Passive visual odometry (VO) for DDL to eliminate need for radar hardware	Flight test of VO algorithms	Algorithms developed; field-test planning and RFP
Sky-crane adaption for Europa	Develop 800 N throttled engine	Hot fire test of prototype engine	Moog TVA design complete; Aerojet on contract for engine
Landing on unknown surface	Robust landing system to maintain horizontal vault for 1 m surface relief	Prototype tested in Europa landing system test bed	Iteration 1 HW tested; iteration 2 HW built
Landing on unknown surface	Onboard hazard detection and avoidance for DDL	Flight test of prototype LIDAR	Two LIDAR contracts; prototypes in design and HW rad test

Table 4
Major Lander Risk Areas Addressed with Advanced Development

Risk	Advanced Development	Outcome	Current Progress
Data rate to achieve science	Direct-to-Earth high-gain antenna	Prototype environmentally tested.	32×32 meets RF performance; ready for env. testing
Energy margin to achieve science	Characterize and improve primary battery for Europa environment	Environment, abuse, and life testing on primary battery	Tested Build 1 cells, in test of Build 2 cells, proc. improve Build 3
Mass growth of lander	Motor control with 3× reduction of mass and 4× reduction of vol over MSL	Prototype testing completed	Current sensor and Motor control card 1 complete
Planetary protection of Europa	Terminal sterilization system for relevant components and env	Energetic material tested on e-box for proper time and temp	Selected two energetic materials; testing to validate models
Contamination of samples	Plume contamination test	Validate model of surface contamination	Contract with DLR, test plan complete

be applied to samples along with cold and vacuum, which represent the interplanetary transit and Jovian environments. The effects of these environments will be tested on a subset of inert SRM materials. At the end of the development, we will have a mature concept design for the DOS from two suppliers with materials demonstrated to perform in the flight environments.

6.2. Throttleable Landing Engine Hot Fire Testing

Background and rationale. A throttleable engine is necessary to provide the control authority needed for the descent profile demanded by the Europa Lander. The Mars Science Laboratory (MSL) 3300 N Mars Lander Engine (MLE) is too large to meet the requirements for the lander mission. This development will modify the throttle valve of the MSL MLE for an 800 N engine.

Development approach and results. The first step of this development will modify the throttle valve assembly (TVA) by changing the cavitating venturi and pintle geometry to meet the smaller 800 N engine flow rate ($\sim$0.38 kg s^{-1}). Water-flow testing will demonstrate that the modified TVA can achieve the required response time, throttle setting resolution, and flow rates, while maintaining cavitation over a full-throttle range of 100% to 1%.

The TVA will then be integrated with the engine and hot-fire tested to mimic the MSL MLE qualification test. These tests will demonstrate that the engine can achieve the quick response that GNC needs, and "deep throttle" from 100% down to $\sim$15%, with acceptable catalyst bed degradation (engine life verification). The ELMC team is on contract with Moog; their TVA design is complete and the TVA material is ordered. The engine contract with Aerojet Rocketdyne has begun.

6.3. Dual-mode LIDAR for Landing Altimetry and Hazard Avoidance

Background and rationale. Even after the Europa Clipper mission, the lack of high-resolution (10's cm), lander-scale compatible 3D terrain maps requires that the lander perform altimetry, real-time 3D mapping, hazard detection, and safe site selection during DDL (a similar technique was used by Mars 2020). The short timeline for mapping and safe site detection over a 100 by 100 m region at 5 cm ground sample distance requires a LIDAR that is capable of 4M samples per second. The LIDAR must be low mass and survive the radiation environment.

Development approach and results. We have established a LIDAR development plan with two contractors followed by field tests to verify performance. The objectives of this plan are to (1) identify optimal LIDAR modality; (2) develop designs and assess via component testing, analysis, and simulation; (3) identify critical technology enabling components of the LIDAR; (4) design, develop, and fabricate such components (e.g., large-format focal plane arrays, ROICS and ASICS); (5) perform radiation testing on the critical components; and (6) demonstrate ranging and mapping performance over the DDL operational envelop of the flight-like LIDARs via field tests.

The result of this development effort will be a LIDAR design that is space qualifiable. We are currently in the second phase of the technology maturation with two vendors: Hexagon-Sigma Space and MIT Lincoln Labs. After the delivery of the two brassboards, we will conduct field tests over Europan analogs for rough terrain and icy surfaces. These tests will use a helicopter-based platform for hazard mapping, mimicking the descent profile at 500 m altitudes, and land vehicles for long-range (5–8 km) range acquisitions. The LIDAR-acquired digital terrain maps will then be compared against the truth map and the truth sensor suite on the test platform.

6.4. Optical Velocimetry Eliminating the Need for a Landing Radar

Background and rationale. Prior landing systems have used onboard radar to obtain velocity measurements. To eliminate the mass of this radar, the lander would be the first interplanetary spacecraft to utilize a TRN camera and software to meet the <0.1 m s^{-1} velocity knowledge requirements. We will conduct a field test to prove out optical velocimetry.

Development approach and results. The team has developed an optical velocimetry software prototype, including image processing for feature tracking and state estimation, based on the Mars 2020 Lander Vision System. The Mars 2020 team conducted simulations for performance prediction and error analysis to quantify the effects of terrain relief, feature-tracking errors, calibration errors, and inertial measurement unit (IMU) errors. For the Europa Lander field test, the team has developed a sensor payload, comprised of an IMU, a 1 megapixel camera, a laser rangefinder, and a GPS-based inertial navigation system for ground truth.

The payload will repeatedly execute terminal descents from 150 m altitude to soft touchdown, at vertical velocities of 5–10 m s^{-1}, over different terrain and under different lighting conditions. The data will be postprocessed through the software prototype. Verifying that the test is consistent with the model predictions will allow the team to extrapolate to flight performance on Europa and inform algorithm refinements.

6.5. Landing System for up to 1 m Surface Relief

Background and rationale. The ELMC architecture utilizes the heritage MSL/M2020 sky-crane landing system. It can support a touchdown of 0.5 m s^{-1} vertical velocity. The four-legged landing gear provides adaptability to unknown 1 m surface reliefs with locking joints in the "hips" and "knees", which are commanded upon surface contact with the belly-pan. Feet at the ends of the legs provide lateral grip and vertical reaction between the lander and the surface. Four bridles provide stability during initial terrain interactions to keep the vault level. Locking the leg joints results in a level and stable lander, transferring lander stability from the bridles to the landing gear. Once this transfer is complete, the DS flies away from the lander.

Development approach and results. Landing-system elements are being developed to demonstrate the performance of the landing system. This includes foot-pad selection, landing-system prototypes, a landing-system test bed, and a landing-gear test bed.

The testing will show the impact and sensitivity of the landing-system elements to a simulated surface. The test data will be used to validate analytical models so that extreme cases can be evaluated with analysis. To date, a prototype landing system has been designed and tested utilizing a full-weight lander simulator. The lander was successful at the full vertical landing speeds of 0.5 m s^{-1}. The overall landing system performed as expected with no unexpected dynamics or fatal approach flaws. The landing legs demonstrated conformance with the relief and slope requirements. The lander prototype demonstrated the robustness of leg locking, triggered by the belly-pan contact with the surface. The prototype also demonstrated postlanding lander deck angles of fewer than the 10° requirement. Multiple foot designs have been developed and some have been tested to simulate landing dynamics. The second prototype leg configuration has been designed and is in assembly. The second prototype belly-pan is being designed and will enter fabrication in the near future.

6.6. High-efficiency, High-gain Antenna

Background and rationale. The Europa Lander mission must support DTE communications and transmit at least 1.5 Gbit to Earth during surface operations. While most of the communications link can be supported with space-qualified hardware, the requirements on the HGA drive a new design. The antenna must have high gain (>36 dBi), high efficiency (>75%), a low profile, be able to handle a 100 watt transmitter, and survive the high radiation and low temperature. The HGA developed by the ELMC team is a 32×32 patch array based on a newly patented high-efficiency, dual-band circular-polarized antenna for harsh environments.

Development approach and results. Using incrementally larger prototype antennas, the ELMC team developed a plan to finalize the design for the 32×32 HGA and bring it to TRL-6. The test plan uses 8×8, 16×16, and 32×32 element HGAs as test articles to verify requirements. An 8×8 array (with coax interface) verified performance within electrical and radiation requirements, and its mechanical design was validated at –170 °C.

The 16×16 HGA gain was measured to be 31.3 dBi at 8.425 GHz. To date, the 32×32 HGA has been designed, its parts fabricated, and the HGA assembled. Preliminary radiation patterns show excellent agreement with predictions, with gains of greater than 35.5 dBi achieved.

Once assembly is complete on the 32 × 32 HGA, the antenna's electrical performance will be measured and it will be tested in relevant mechanical environments, including pattern and gain measurements at −170 °C. Another 8 × 8 subarray prototype will be used to verify radiation susceptibility and dielectrics performance in the antenna.

6.7. Miniature Motor Controller

Background and rationale. To allow more resources for lander instruments, we are reducing the volume, mass, and power of the lander motor controller. To achieve this reduction, we are developing modular standardized multi-chip modules, utilizing advanced substrate and system-in-package technologies that can be configured into a compact topology.

Development approach and results. The motor controller consists of a computer card, a power supply card, and enough motor control cards to control 12 motors. Many functions common to our previous motor controller designs implemented on Mars 2020 have been packaged into multi-chip modules. These functions include motor-drive electronics, resolver electronics, power regulation, current sense, and telemetry electronics. These modules allow for considerable miniaturization of the electronics without losing functionality.

The goal of this work is to design, build, and test a prototype motor control box that can be integrated into a field-test demonstration. We have completed the requirements development and passed key milestone reviews. All modules have been designed and tested individually except the 10 A version of the motor driver module, which has not yet been tested. We have completed the fabrication of the first motor control card, and it is now being tested. The power conversion card is now in fabrication. The processor card is in design.

6.8. High-specific-energy Primary Batteries

Background and rationale. Primary batteries have been baselined as the sole power source for the surface mission. The specific energy of cells of >700 Wh kg^{-1} provides sufficient energy and results in a total mass within our battery mass envelope.

The power modes of the lander would require only low discharge currents with the battery thermal design targeting operation over the range of 0 °C to 60 °C. Evaluation of various primary battery chemistries indicates that the Li/CFx is the only chemistry that would meet or exceed the lander requirements. Development is required since there is no flight heritage for Li/CFx.

Development approach and results. We established a test matrix for evaluating D-sized cells from several vendors. This testing included evaluations of cells exposed to twice the mission radiation dose. The most critical aspect of this testing is electrical performance testing over a range of operational temperatures and rates to establish the ability of this cell chemistry to meet different mission power profile scenarios.

Total delivered energy is critical; we are testing to establish the mean and standard deviation of delivered energy and capacity of cells from different manufacturing lots. We are developing a statistical model that bounds the maximum and minimum energy delivered. We are characterizing the self-discharge and calendar-life characteristics under long-term storage conditions. Storage testing is currently being performed under real-time (20 °C) and accelerated (30 °C, 40 °C, 60 °C) conditions to extrapolate to 10 yr of storage time.

Waste heat from the battery discharge is used for lander heating; we are testing to determine the ratio of thermal-to-electrical power generated under different load conditions. Testing to date has indicated the Li/CFx chemistry meets or exceeds the load profiles and targeted mission duration for the lander. A specific energy of >700 Wh kg^{-1} at relevant rates has been demonstrated with minimal impact at a 10 Mrad radiation level. Ongoing work is focused on long-duration storage testing, evaluation of heat output versus load, safety, abuse testing, and improved state-of-charge monitoring. Further cell-design improvements are underway to improve specific energy. Based on the results so far, we expect to be able to significantly increase the surface life of the lander mission.

6.9. Sampling and Sample Transfer

Background and rationale. We are exploring capabilities for autonomous excavation, collection, and transfer of the sample from an icy surface to the lander. The primary challenges associated with the sampling subsystem are (1) uncertain terrain topography at the sampling scale, (2) uncertain material properties, (3) maintaining sample integrity throughout the sample acquisition and transfer process, and (4) developing a system compatible with the harsh environment. Development work is underway to reduce these risks.

Development approach and results. A state-of-the-art cryogenic vacuum test bed (capabilities: 50 K, $< 10^{-6}$ Torr) has been built, commissioned, and has demonstrated ice cutting in a cryo-vac environment. An extensive test campaign is underway to observe and characterize the behavior of cryogenic cuttings and to test end-to-end sample integrity for all sampling processes (including mechanical and pneumatic solutions).

In addition to the cryo-vac test bed, six ambient test beds support sampling autonomy development, effects of system compliance, sampling robotic arm development, and initial tool investigations. Over 300 ambient tests have been completed to date, with significant long-term ambient test programs currently coming online.

An initial cold actuator demonstration was successfully completed at 100 K and vacuum. We are evaluating a range of tool options for excavation, collection, and testing those tools across a range of challenging surface simulants (varying both topography and material properties) to stress the capabilities of the sampling subsystem.

Simulant compositions for cryogenic and ambient testing are being developed to identify key material properties that drive design and performance. At the task's end, we will demonstrate the capabilities of the sampling subsystem through a field test, create a terrain specification document, which outlines the range of simulant characteristics required for testing (mechanical properties, terrains, boundaries), and map sensitivities between surface properties, autonomy, and sampling hardware.

6.10. Planetary Protection Using a Terminal Sterilization System

Background and rationale. PP requirements for icy-moon and ocean-world landers may necessitate a hardware sterility level that could be challenging to achieve solely using ground bioburden reduction before launch. Radiation exposure during the mission (a unique benefit of the Jovian environment), would perform much of the additional bioburden reduction.

At the mission's end, the ELMC also employs a TSS, which would sterilize the hardware in the vault that is shielded from radiation. On command, energetic material would be ignited and raise the temperature of the components to achieve sterility within 14 s. Energetic-material development is required.

Development approach and results. The technical challenges to develop the TSS are being lead by ELMC team members at Sandia National Laboratories and include (1) development of a new rapid-heating energetic-material formulation, (2) materials tests in the relevant environments, (3) development and validation of a model for the thermal response of electronics exposed to this energetic material, and (4) testing of the packaged energetic material in a realistic configuration.

The outcome of the current development work is a demonstration of a prototype that is at TRL-6. To date the team has (1) performed feasibility testing using commercially available energetic material, (2) developed models to estimate the behavior and size of the system, (3) performed a material screening and down-selected the energetic material for the baseline design, (4) performed initial safety and sensitivity analysis on top energetic-material candidates, (5) designed and procured hardware for tests to verify the energetic-material function, and to provide model validation data, and, (6) developed a fluid dynamics model to predict the thermal response of sterilized materials.

6.11. Contamination Control from Engines

Background and rationale. Europa's surface would be impinged upon by the plumes of the sky-crane engines that suspend the lander during its soft delivery to the surface. This plume impingement could potentially contaminate or deform the surface. For this reason, we need to understand the physical and chemical effects on the Europan surface of impinging combusted-plume products, by-products, and unreacted precursor material. Creating and identifying the plume-impingement products is essential to understanding the science returns from the lander mission.

Development approach and results. We are modeling engine plume expansion into vacuum during sky-crane touchdown. We use a modeling methodology of one-way coupling between computational fluid dynamics and direct simulation Monte Carlo solutions that accurately represents both high-density, continuum plume flow at the exit of the engine nozzle, and low-density, rarefied plume flow at the landing surface tens of meters away. This has been extended to incorporate realistic plume–-plume and plume–vehicle interactions, with boundary conditions representative of those anticipated for the lander.

To validate the models, we are experimentally testing analog monopropellant engine plumes with witness samples and surface simulants to characterize the interaction properties. These properties include position-dependent impingement velocities, droplet sizes, chemical compositions, and chemical reactions.

To date, we have developed simulations, obtained hydrazine thrusters, and have completed several plume tests in partnership with the German Aerospace Center (DLR).

7. Ongoing Trade Studies

As part of the development effort, we are continuing numerous trade studies to mitigate development risks, mission risks, cost and schedule risks, and to mature more areas of the mission concept design.

In addition to the previously mentioned battery trade study for surface-life extension, and the refinement of the model payload accommodation and sampling system as informed by the ICEE-2 efforts, the project has been pursuing the following trade studies:

1. Investigate DDL navigation robustness improvements through changes to the DDL timeline.
2. Examine possible benefits and risks of active-lander load-leveling to assure a stable platform for sampling and science.
3. Improving margin for the DDL and surface telecom links.
4. Increasing the heat-rejection capability of the lander.
5. Capabilities for providing reliable and clear engineering imaging for sampling.
6. Simplifying postmission sterilization.
7. Examining hardware and voting algorithms within avionics architectures to tolerate radiation-upset events, on top of any single random hardware failure during the time-critical DDL window.

Lastly, one of the more sweeping trade studies has been examining options for flight-system compatibility with a variety of launch vehicles.

These trades, along with any significant outcomes from the risk-reduction studies, will feed into the ongoing evolution of the pre-Phase A baseline mission concept.

8. Conclusion

The science return possible from the Europa Lander mission concept is such that if life, or its biosignatures, are present in Europa's surface ice at a level comparable to one of the most extreme and desolate of environments on Earth (Lake Vostok ice and/or deep polar ocean water) then this mission could detect such biosignatures in Europa's icy surface. The combination of detection methods, detection limits, and scales of observations provided by the model payload and mission concept combine to make this civilization-scale science mission possible.

Furthermore, this mission is designed to work in concert with the detailed global and regional mapping efforts that will be pursued by the Europa Clipper mission, which has as its goal to investigate the habitability of Europa via remote-sensing capabilities. The lander investigations provide critical ground truth for Clipper measurements and greatly enhanced detection limits that complement the global- and regional-scale observations of Clipper.

Significantly, even in the absence of any signs of life, this mission is also designed to generate an incredibly valuable data set about the chemistry of Europa's ice shell, its putative ocean, and the geologic, geophysical, and chemical context of this ocean world. Either of the above outcomes is of fundamental scientific value to understanding the prospects for life in the solar system, and our place in it.

The Europa Lander mission concept is mature, technologically well developed, and ready to proceed to Phase A.

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