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Sylph: Life Detection Probe for a Europa Plume

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Abstract

Jupiter's Galilean satellite Europa likely contains a vast, global, subsurface salt-water ocean. A singular telescope observation in 2012 indicated possible plume activity, in some ways similar to the continuous plume activity seen at Enceladus. If a Europan plume does expel ocean water into space, its vapor, ice grains, and dust grains could be analyzed by a spacecraft equipped with high-resolution mass spectrometers. Such plume measurements would be sufficient to measure the contextual habitability profile of the ocean, and to detect multiple signatures of life, should it exist in the ocean. Instrumented with MASPEX (Mass Spectrometer for Planetary Exploration) and SUDA (Surface Dust Analyzer), NASA's planned Europa Mission now in development could theoretically conduct this investigation. However, the mission's closest flyby altitude would be 25 km; due to Europa's large gravity, frozen ocean spray containing non-volatile molecular species critical to biosignature detection can be sampled only within 5 km of the surface. The Europa Mission would not fly this low. Sylph is a concept for a complementary, free-flyer smallsat probe, about the same size as an office water-cooler bottle, that could be deployed by the Europa Mission as it conducts a plume fly-through. Sylph would execute a single ~2 km altitude plume pass below the main spacecraft. With a mass of 40 kg and a 24-hr life, the probe would autonomously navigate its low-altitude pass, and carry a dual-channel Mini-SUDA impact ionization mass spectrometer that would measure the composition of large grains, complementing the main spacecraft's measurements of small grains and gas. Sylph is a novel smallsat concept: purpose-built configuration optimized for both the harsh Jovian environment and for Europan planetary-protection requirements, and built with advanced manufacturing methods from both deep space and smallsat components. For $80M (~4% marginal cost), the Europa Mission could buy a Sylph "insurance policy," hedging the possibility that it does discover ocean plumes upon arrival in 2028. At less than 85 kg for probe and accommodations, the mission could carry two or three of the probes.

1. Introduction: Insurance for the Europa Mission

Finding and understanding life off Earth is one of the grand challenges of our time: now coming within our grasp, but certainly not straightforward. Among the central challenges for life-detection missions is determining an intersection between practical robotic missions that could be flown, and measurements that could yield high-confidence inferences.

Europa has emerged as one of the most scientifically compelling locations in our solar system. While its icy surface is heavily irradiated in Jupiter's magnetospheric trapped-particle environment [1], magnetic-field measurements by the Galileo orbiter imply a deep, global, salt-water ocean sheltered beneath its ice shell [2]. That a distant moon contains an ocean more voluminous than Earth's has recast our view of what habitable zones can be, and of the prospects for finding truly alien life in our solar system: life that could not have been seeded from Earth.

From discoveries by Voyager, Galileo, Cassini, Dawn, and a host of Mars missions, we now appreciate that our solar system proffers a range of "ocean worlds" to explore (Figure 1): relict oceans, oceans in contact with silicate rock, oceans with moderate-temperature hydrothermal activity, oceans trapped between shells of ice in different phases, eutectic oceans, and oceans that may experience chemical exchange with oxidants and complex organics. Provocatively, this broader view of our solar system as a potential abode of life is accessible to space missions, and can be investigated using measurement techniques on today's technology frontier. Of the many targets, three top the list: Europa, Enceladus, and Titan. Europa has the best prospects, theoretically. Enceladus is the fastest place to test directly for life. And Titan is a natural laboratory for "cold, weird" life.

NASA is currently developing the flagship-class Europa Mission, which comprises a multi-flyby orbiter for launch in 2022 and possibly a lander for launch in

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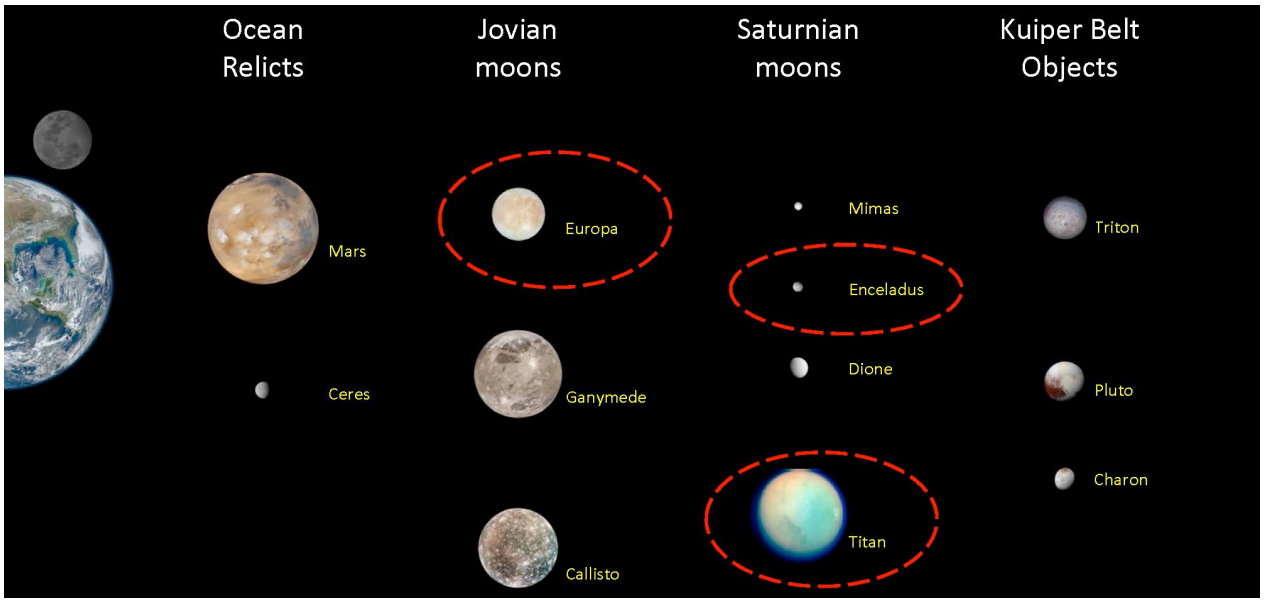

Figure 1. Our solar system contains diverse types of ocean worlds. Of them, Europa, Enceladus, and Titan are the most scientifically compelling places to search for extant life.

2024 [3]. A lander could directly measure seismic activity, and the mechanics and chemical composition of surface ice and salt deposits. The orbiter plans 45 flybys of Europa, some as low as 25 km in altitude, from an elliptical Jupiter orbit that limits its radiation exposure to the brief perijove passes. The orbiter would carry a competitively selected, nine-instrument payload suite to conduct a thorough reconnaissance of the moon, including mapping its magnetic and gravity fields, sounding its icy shell with radar, imaging its surface at high spatial and spectral resolution, and directly sampling its exosphere gas and particle chemistry [4].

NASA selected the orbiter payload in 2016 based on robust findings of Galileo, two decades of subsequent hypothesis crafting, and capabilities of today's mature flight instruments. But in 2012, a surprising detection by the Hubble Space Telescope of excess limb brightening in UV bands sensitive to H+ and OH- implied that there may be episodic plume activity at Europa (Figure 2) [5].

The impressive ocean-world science that arose from Cassini's extensive, repeated in situ measurements of the continuous Enceladus plume (Figure 3) made even this singular detection at Europa highly tantalizing. Indeed, the orbiter is equipped with two advanced mass spectrometers (MASPEX for gas-phase molecules and SUDA for solid grains), that would be capable of detecting life-signs directly in the Enceladus plume if we returned there with a purpose-built Enceladus Life Finder (ELF) mission that replicated Cassini's science mission profile [6].

However, three challenges confound straightforward adaptation of the ELF investigation concept to a Europa plume. First, the original Hubble detection has remained frustratingly unrepeated despite multiple attempts [7]. By contrast, the Enceladus plume is continuous, with average productivity of 200 kg/s of material expelled into space [8], and a flux that cycles by a factor of ~2 with a period matching, and slightly phase lagged from, Enceladus' orbit [9]. The longevity of Saturn's E ring (comprising nanosilica grains from the plume), and the albedo signature (implying plume deposition) directly imply continuous plume activity over at least multi-decade timescales [10]. The Enceladus plume is predictable enough to base a mission on; putative plume activity at Europa is not.

Second, we do not know that the inferred plume is ocean material. Emissions from airless bodies can be caused in many ways, most of which are not ocean water expressed into space. By contrast, the Enceladus plume is known to comprise both ocean water and condensed

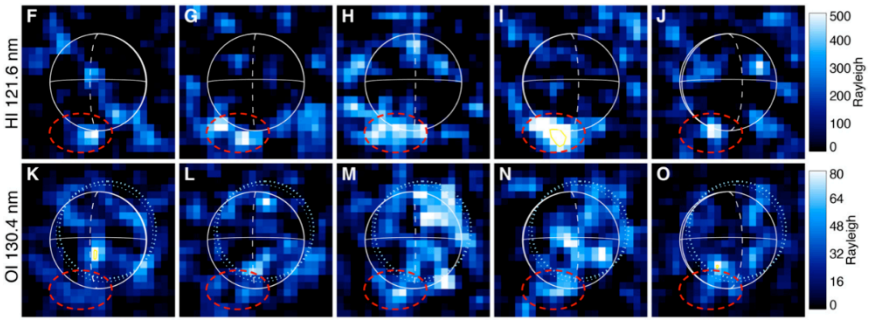

Figure 2. HST observations in 2012 indicated Europa may have episodic water-plume activity. [5]

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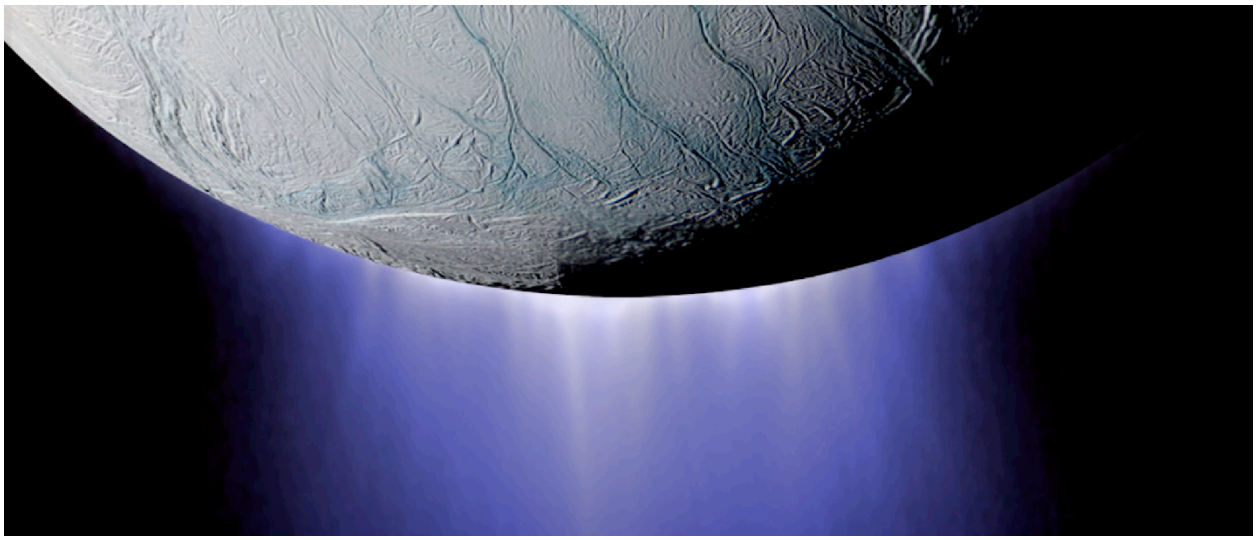

Figure 3. Enceladus is the exemplar of a planetary ocean plume.

vapor. The measured salt content of the solid grains is strongly correlated with grain size, indicating that grains ≥ 5 µm are frozen sea water [11]. Whereas small plume grains (< 1 µm) form when vapor condenses as it streams through the vent, nucleating around nanosilica grains from the ocean [12] or ice crystals in the vapor stream [13], large grains form when ocean spray at the bubbling liquid interface freezes in the vacuum of space [14] (Figure 4). A robust life-sign measurement requires analysis of non-volatile, large organic molecules that can only get into a plume by being transported inside these frozen ocean-spray grains. The Enceladus plume's definitive sourcing is alluring enough to base a mission on; the uncertain source of putative plumes at Europa is not.

Third, if there are large, ocean-spray grains in a Europa plume, they would fall out of the plume from low altitudes, "snowing" back to the surface. At tiny Enceladus, where the surface gravity is about 1/87 g, the plume gas carries such grains very high: Cassini collected and analyzed them on numerous plume passes. But Europa is almost as large as Earth's Moon, with surface gravity about 1/7 g. Any large grains would fall back to the surface at less than about 10 km altitude [16], less than half as high as the Europa Mission orbiter would fly.

Taken together, these uncertainties and challenges pose a programmatic dilemma: the notion that plume science could directly detect life-signs at Europa is enticing, yet we cannot know without a mission whether

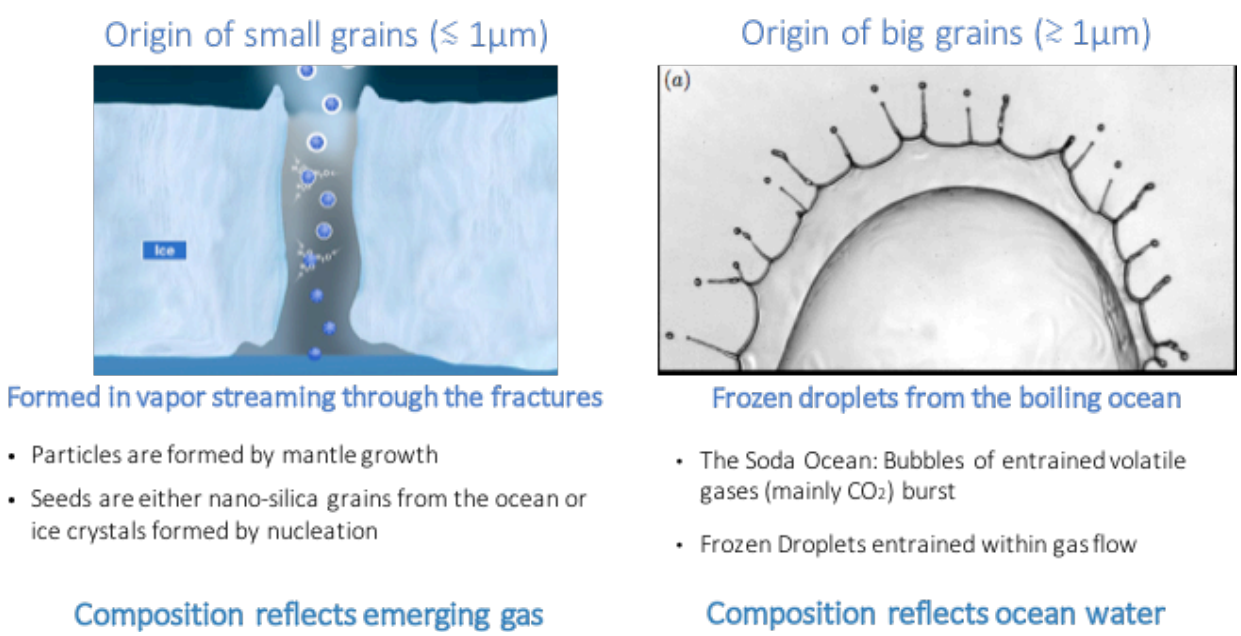

Figure 4. Planetary ocean plumes contain two types of grains: large grains directly sample ocean material. Left image [13]. Right image [15].

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ocean plumes even exist there and the mission being planned cannot do a low-altitude pass in any case.

Sylph is conceived to solve this dilemma. Compared to the flagship mission that would host it, Sylph would be inexpensive and unobtrusive. A sacrificial, short-lived free-flyer probe, it does not purport to be a self-contained mission. Rather, it would obtain only the one critical measurement that the Europa Mission orbiter cannot: mass spectrometry of large plume grains, extremely close to the surface, using a small variant of the orbiter's own SUDA instrument. The Europa PSG (Project Science Group) already includes the Sylph investigation leads: ELF and Sylph PI Jonathan Lunine, ELF DPI and MASPEX-Europa PI Hunter Waite, and SUDA-Europa PI Sascha Kempf. By combining results from the probe with those of MASPEX and SUDA on the orbiter's plume pass, the Sylph investigation would provide a cost-effective, risk-effective "insurance policy" in the event that Europa does have ocean plume activity.

2. Plume science for the detection of life

Cassini created the field of planetary plume science at Enceladus (Figure 5). Plume activity was suspected, based on Enceladus orbiting within the tenuous E ring and displaying a striking hemispheric albedo dichotomy implying surface redeposition of interior material [17]. A slew of Cassini discoveries made the case not only for a sub-ice ocean, but for a very special one:

1. Global in extent and thus geologically long-lived: ice shell librationally decoupled [18] from the silicate core required by the body's density.
2. Astrobiologically compelling: warm temperatures seen by thermal-IR hotspots correlated with ice-fracture features [19]; and water whose salt content is within a factor of ten of our ocean's [11], containing organic molecules [20], with pH ~11 [21] and in direct contact with silicate rock as evidenced by nanosilica grains of a size formed by ~90°C hydrothermal activity [12].
3. Expressed continuously into space for repeated sampling: UV observations of water vapor [22] and visible observations of plume-entrained dust [10]; jets [23]; both frozen ocean spray and condensed vapor grains [11]; extensive, geologically fresh resurfacing of south-polar terrain that is split by parallel fracture networks [24]; direct demonstration that the plume supplies the E ring [25]; predictably cyclic productivity likely due to tidal valving [26].

Enceladus' astrobiological potential is intimately linked to its plume science: Cassini plume measurements stimulated and informed the hypothesis that the Enceladus ocean is habitable; in the future, ELF could determine whether that ocean is inhabited. This Cassini-to-ELF relationship suggests an investigation framework for a purpose-built mission.

High-resolution mass spectrometry, a mainstay of both terrestrial and planetary science, can measure the molecular fingerprints of habitability and life. Relying on only minute quantities of sample, mass spectroscopy is a direct measurement immune to the kind of interpretation uncertainties that have dogged prior astrobiology attempts with Viking (metabolism-dependent chemistry) and Mars meteorites (morphology of microscopic features); it is the most robust, most generally diagnostic technique to detect signatures left by life.

Equipped with high-resolution mass spectrometers, ELF could conduct direct chemical tests of the plume constituents to quantify the Enceladus ocean's habitability and detect bio-signatures in its plume. Based on 1980s flight technology and never anticipating plume fly-throughs, Cassini's mass spectrometers delivered stunning results nonetheless. Now however, by knowing

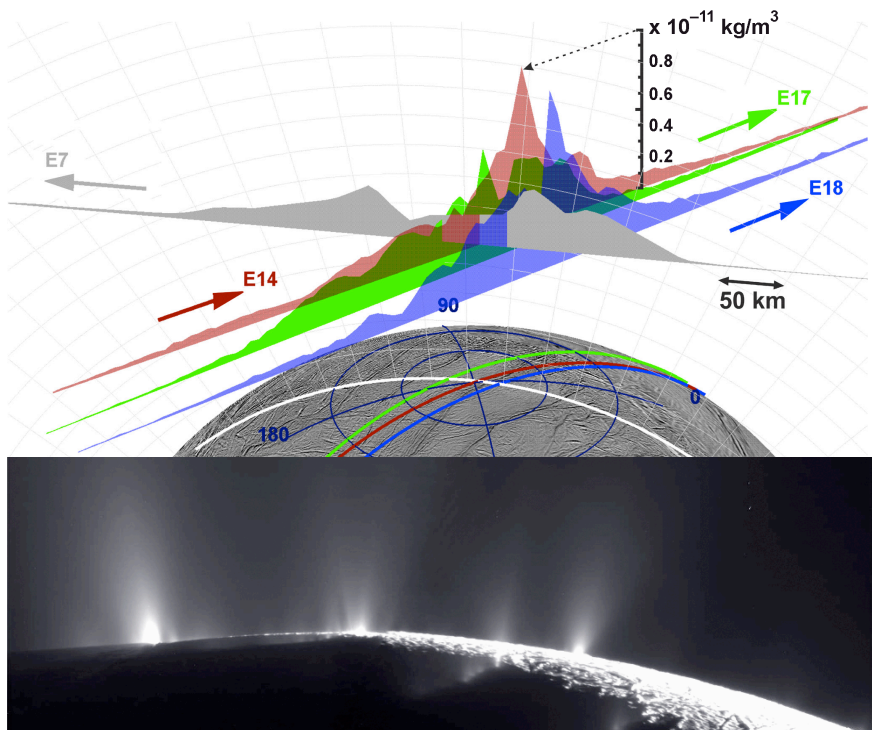

Figure 5. Cassini's seven passes through the Enceladus plume dissected its geophysics and demonstrated how to profile the chemistry of an icy-moon ocean.

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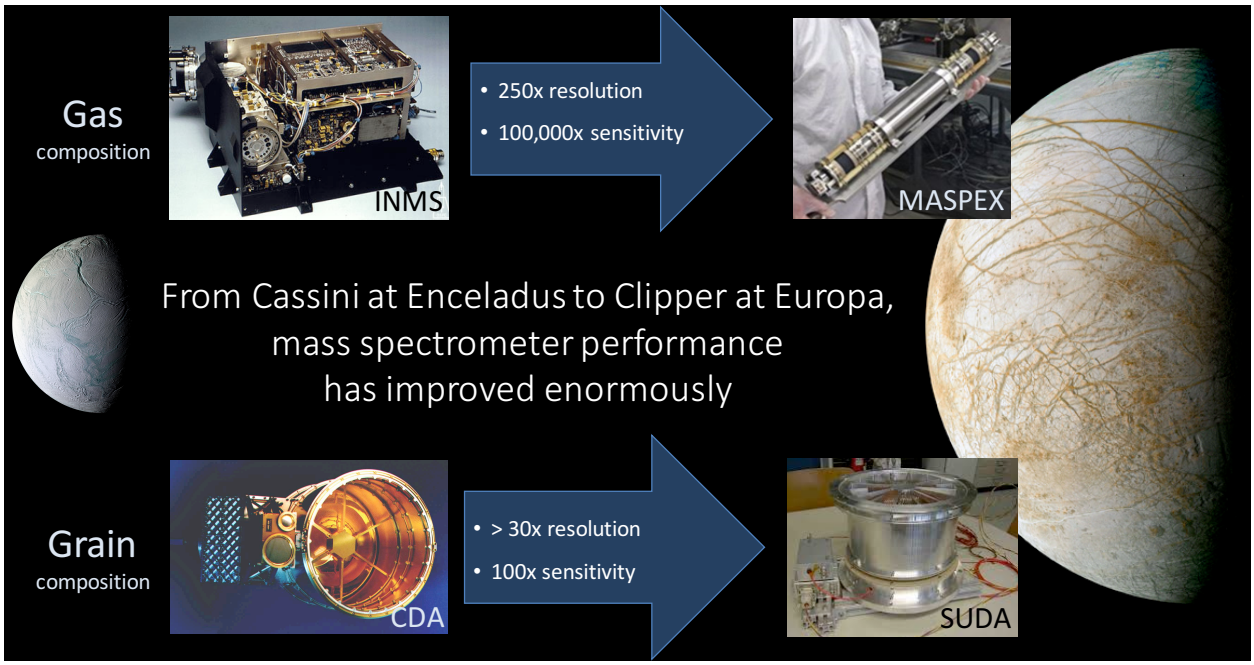

Figure 6. Space-flight mass spectrometers have advanced by orders of magnitude in resolution and sensitivity since Cassini.

what Enceladus has to offer and with the benefit of a quarter-century of technical progress in space-flight mass spectrometers, we can do much better (Figure 6).

And if Europa has ocean plumes also, the ELF investigation framework can be applied there as well. Sylph would profile the chemical context and establish upper bounds on biosignatures. First, measurements of multiple ionic and molecular species can quantify the fundamental habitability of the ocean environment. Working in tandem, MASPEX and Mini-SUDA would: 1) determine the temperature of the ocean and possible hydrothermal systems to within 100 K; 2) quantify the amount of redox energy available; 3) determine the oxidation state of the ocean; and 4) determine the pH of the ocean to within an accuracy of 1 unit. Second, three independent tests would be conducted for the presence of life: 1) MASPEX would determine the hydrocarbon abundance distribution, D/H ratio, and $^{13}C/^{12}C$ distribution in hydrocarbons and CO_2, to look for patterns consistent with biological synthesis; 2) Mini-SUDA would determine the long-chain fatty acid ($C1_2$–C_{30}) distribution to look for patterns such as an even-odd disparity due to modular-C_2 biological synthesis; and 3) both instruments together would search for patterns in the amino acid distribution indicative of biological synthesis, e.g., underrepresentation of glycine relative to other amino acids that are energetically more difficult to form. Together the three tests dissect the "ambiguity space" – from strong negative to strong positive – that might arise on a life-seeking mission.

Table 1 shows the traceability from measurement objectives back to top-priority planetary science. In the complete Sylph STM (science traceability matrix), detection of biosignatures (Objective 3, green) and quantification of contextual habitability (Objective 2, blue) are complemented by determining the primordial sources of volatiles and chemical evolution of organics over geologic time (Objective 1, tan). This science inference framework for exploring a planetary ocean plume is derived directly from the Discovery-class version of ELF first proposed in 2015 [6]. At that time, NASA vetted the STM not just for Enceladus, but as a template for life-seeking investigations generally: "[ELF] may be a pioneering example for future missions to other planetary bodies with known sources of water." (Michael E. New, personal communication, October 11, 2015).

While the specific ratio tests listed are based on structural and functional molecules common to all Earth life, it is important to recognize that high-resolution mass spectra of trace species in a complex environment are also powerfully diagnostic beyond this Earth-centric suite: should Enceladan or Europan life use a different set of molecules, mass spectrometry would still detect them, and patterns among them that would reveal its presence. Discovering clear evidence of alien life would be one of the most momentous discoveries in the history of science, as would determining whether it shares the chemistry of Earth life.

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Table 1. Sylph investigation would quantify habitability and biotic state of a Europa ocean plume.

Decadal Survey	Science Objective	Measurement Objective
What were the primordial sources of organic matter and where does organic synthesis continue today? (Planetary Habitats Question 4). Detailed investigations of the organic chemistry… would be important for any plumes that might be found on Europa (p. 8 23)	1. Determine whether Europa volatiles, including organics, have evolved over time	1a. Determine the original molecular carrier for nitrogen as an indicator of the degree of volatile evolution on Europa.
		1b. Quantify the fraction of the volatile population that has not reacted with liquid water.
		1c. Determine whether the ocean has been, or is, in contact with hydrothermal systems at its base.
Beyond Earth, are there modern habitats elsewhere in the solar system with necessary conditions, organic matter, water, energy, and nutrients to sustain life, and do organisms live there now? (Planetary Habitats Question 6). Does (or did) life exist below the surface of Europa? (p. 8–24). Europa's ocean [is] the highest priority in the outer solar system to explore as a potential habitat for life (p. 3–10).	2. Determine whether Europa ocean satisfies basic requirements of habitability.	2a. Determine the temperature of the ocean and possible hydrothermal systems to within 100 K.
		2b. Quantify the amount of redox energy available.
		2c. Determine the oxidation state of the ocean.
		2d. Determine the pH of the ocean to within an accuracy of 1 unit.
	3. Determine whether Europa plume contains chemical signatures of biology.	3a. Determine amino acid distribution to look for patterns indicative of biological synthesis (e.g., underrepresentation of glycine relative to amino acids more energetically difficult to form).
		3b. Determine long-chain fatty acid ($C1_2$–C_{30}) distribution to look for patterns (e.g., even-odd disparity due to C_2 addition in biological synthesis).
		3c. Determine hydrocarbon abundance distribution, D/H ratio and $^{13}C/^{12}C$ distribution in hydrocarbons and CO_2, to look for patterns consistent with biological synthesis.

3. Science mission profile, instrumentation, and data sufficiency

The Europa Mission is already instrumented magnificently for plume science: it can image plumes in the visible and UV, and make in situ measurements as well. It is likely to prioritize in situ plume science if it observes plumes at Europa, just as Cassini did at Enceladus. Fly-through maneuvers are quite possible within the constraints of the complex orbital tour design. Figure 7 shows the "Tholian Web" of flyby tracks for a representative mission design. Due to Europa's synchronous rotation, the closest passes cluster over the Jovian and anti-Jovian meridians. The figure also shows the surface source locations mapped for putative plumes responsible for the Roth et al., observation. Figure 8 plots the global flexibility of flyby tracks, given a tour designed before any plume discoveries. The mission design takes about a year to set up the flyby tour once captured at Jupiter; much of this year provides optimal viewing for optical detection of particle-laden plumes.

Should the mission detect plume activity and plan one or more fly-throughs, its lowest nominal pass (and thus its sampling altitude) would be 25 km. Released on approach to such a pass, the Sylph probe would simultaneously fly through the dense, lower part of the plume, 2–5 km above the surface (Figure 9), as though trolled by the orbiter with a tether; Mini-SUDA would measure the composition of large grains while SUDA

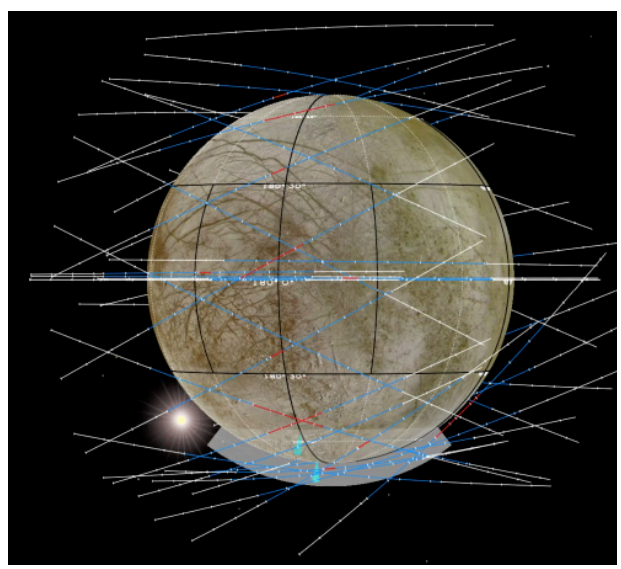

Figure 7. Europa Mission flyby close-pass tracks would be consistent with putative plume source locations. Representative mission design: colors show flyby altitude 50–400 km (blue) and ≤ 50 km (red); cyan cones show source locations corresponding to Roth et al., observations.

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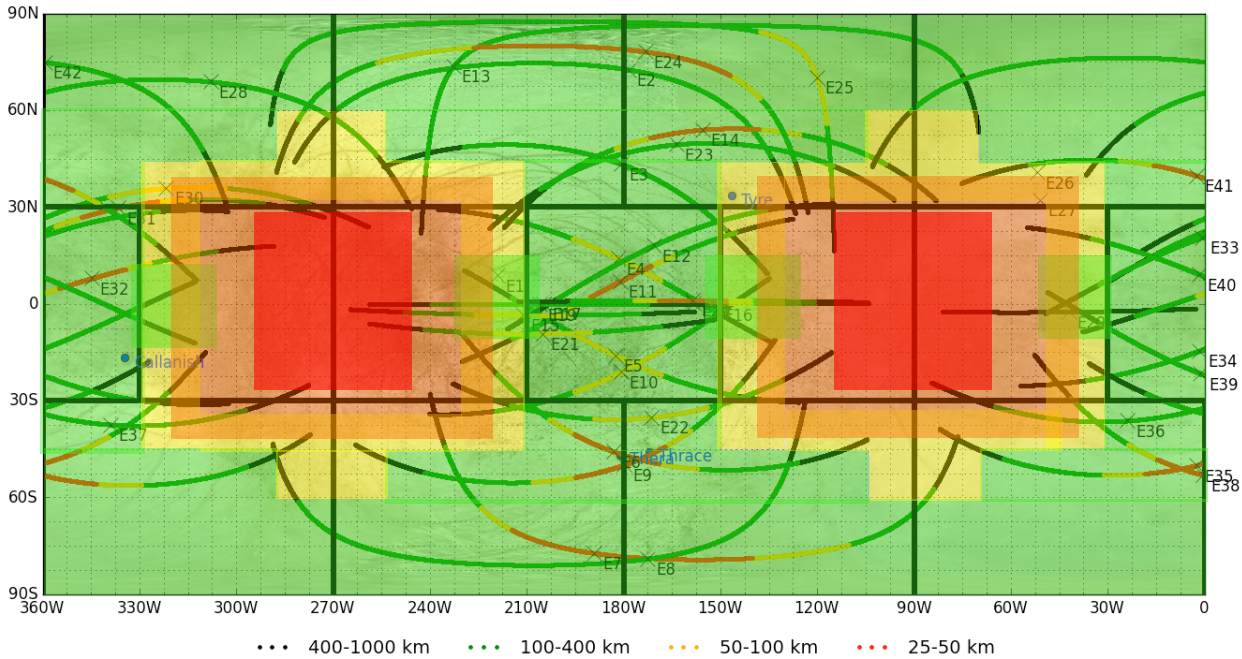

Figure 8. Flyby tour is flexible enough to achieve low-altitude pass through any plumes discovered almost anywhere on Europa, including longitudes most likely to have fissures releasing ocean material. Colored regions show flyby accessibility (green for best); color-coded arcs show nominal tracks (red for lowest altitude segments).

and MASPEX measured the composition of small grains and plume gases ~20 km above it. For the purpose of describing the Sylph concept, the following discussion addresses Mini-SUDA; descriptions of MASPEX measurements are in the literature [27].

Impact-ionization mass spectrometry relies on high-velocity grains impacting a metal foil target, which breaks them apart and ionizes their contents. The fragmentation ions are separated and measured by a time-of-flight mass spectrometer. This technique, inherently immune to terrestrial contamination because it measures only the byproducts of detector impacts in the design range, is perfectly suited for high-speed plume encounters. Particle analyzers have been flown on many missions and have measured the composition of solid-phase material including interplanetary dust and cometary comae [28]. Cassini's CDA (Cosmic Dust Analyzer) has investigated moon exospheres, ring particles, and even interstellar dust grains – and of course ice and refractory grains in the Enceladus plume [29].

While the fundamental technique is common on all these missions, the instrument configuration must be optimized for each application. Cassini's CDA and the Europa orbiter's SUDA have a bucket-shaped first stage, to record the vector velocity of incoming particles. A primary SUDA objective is to perform in situ surface composition measurements from orbit: during the flyby passes it measures the velocity and composition of exospheric dust grains sputtered from the moon's surface by the constant micrometeoroid flux; back-propagating the trajectory of each impact mass spectrum to its source region on the surface allows a map to be integrated.

The Sylph task is much simpler: measure the composition of grains during a single 3-sec plume pass. Measurement impact velocity is dominated by the probe's own tangential orbital speed (~4.5 km/s); only an aperture window is required. Target size is very small, determined by the range of particle column-density expected low in a plume. Figure 10 shows the Mini-SUDA configuration optimized for Sylph: a reflectron with heritage from prior high-flux environments (Stardust at Wild 2 in 2004, and Giotto at Halley in 1986). To avoid signal saturation (i.e.,

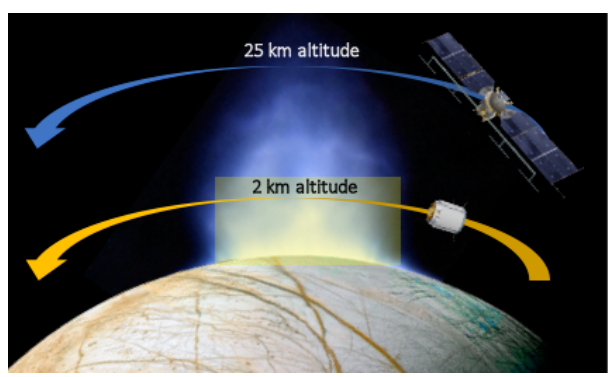

Figure 9. Sylph would fly through a plume in three seconds, 2–5 km above the Europa surface, while the orbiter flies through the same plume at 25 km altitude.

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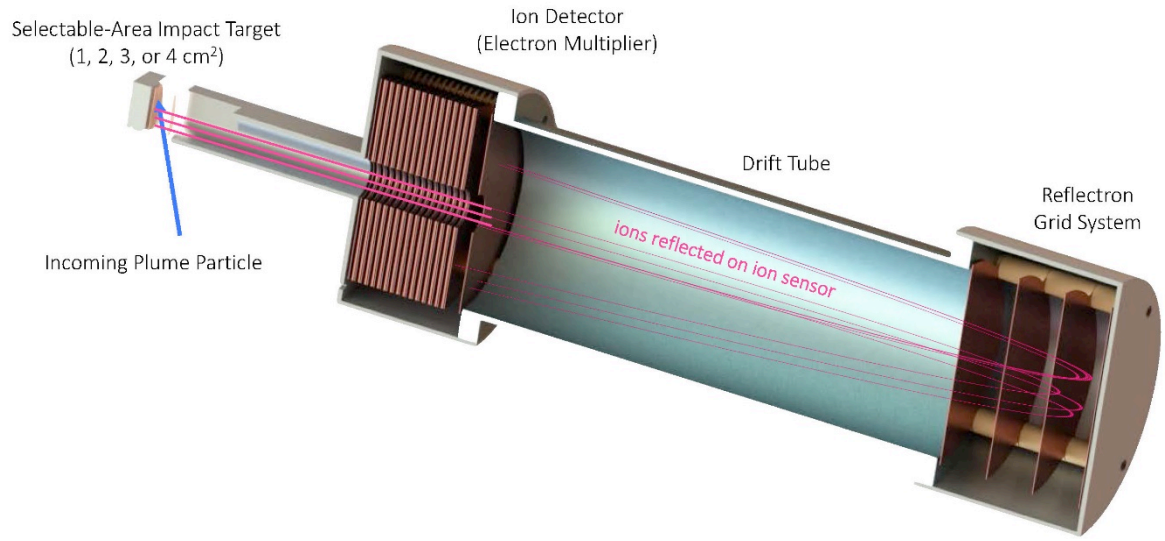

Figure 10. Mini-SUDA shares ion detector and electronics design with SUDA, but ion optics are optimized for high-flux plume conditions at low altitude.

overlapping spectral peaks) from measuring too many particles at once, the detector area is selected in flight (1, 2, 3, or 4 cm^2) when the probe is initialized, once the chosen plume is characterized and the plume pass planned. Because the experiment is done in a single quick run, measuring both anions and cations requires two channels: two identical detector tubes operate simultaneously, one biased positive and one negative.

Table 2 demonstrates Mini-SUDA measurement sufficiency for Sylph. The table shows only the species of interest for the volatiles and organics, habitability, and life-detection objectives of the Sylph STM. However, even if the mission finds no suitable plumes, deployment of Sylph would significantly enhance the baseline SUDA objective, by measuring Europa surface composition along the ground track with very high (~2–5 km) spatial resolution.

4. Mission Design

In folklore, a sylph is a supernatural being who inhabits the air, never touching the ground.

The Sylph probe is designed for the single task of flying through a Europa plume once: small, light, inexpensive, and expendable; with just one robust, high-heritage, two-channel instrument; rad-hard and capable of being brutally sterilized for planetary protection; and unobtrusively housed asleep in a shielded biobarrier hangar until needed. The orbiter could easily take two or three of them.

The driving architectural conceits of the design are: 1) add the minimum possible mission enhancement, given the stacked and irreducible uncertainties regarding Europa plumes' existence and utility; therefore 2) leverage what the Europa Mission already carries and already will plan to do, to the maximum possible degree;

Table 2. Mini-SUDA completes Sylph science measurements deep in the plume (potential other measurements not shown).

	Physical Parameter	Sensitivity	Uncertainty relative to measurement requirement
Amino acids	Relative abundance of glycine, alanine, aspartic acid, glutamic acid, lysine, arginine, phenylalanine	$< 10^{-5}$ relative to H_2O	< 100×
Fatty acids	Relative abundance of molecules with carbon number 12–30	$< 10^{-6}$ relative to H_2O	< 10×
Salts	Concentration of Na, K	$< 10^{-5}$ relative to H_2O	< 100×
	Na/K abundance ratio	< 28%	< 10×
	Concentration of SO_4^-	$< 10^{-7}$ relative to H_2O	< 10×
	Concentration of NO_3^-, H_2S	$< 10^{-6}$ relative to H_2O	< 10×
	Concentration of $Na(Na_2CO_3)_n$ in clusters up to n = 3	$< 10^{-6}$ relative to H_2O	< 10×
	Concentration of $Na(NaOH))_n$ and $Na(NaCl)_n$ in clusters up to n = 4	$< 10^{-6}$ relative to H_2O	< 10×

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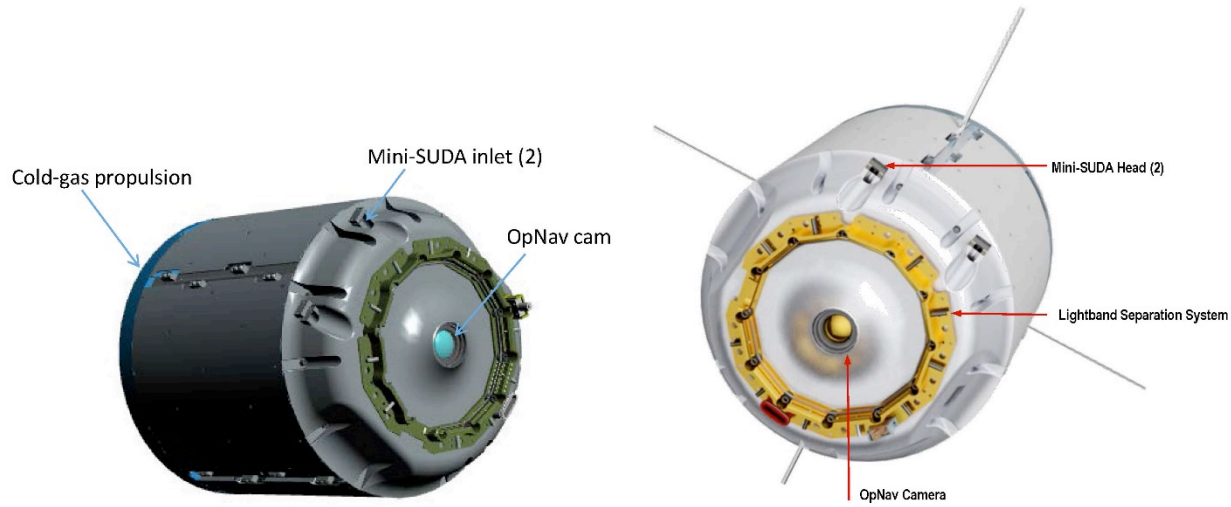

Figure 11. Sylph free flyer, the size of a water-cooler bottle, would make the one measurement needed to augment the Europa Mission's own ability to measure plume composition.

then 3) realize that the compositional measurement of large grains at low altitude is the only additional measurement to be made; and thus finally 4) emulate the effect of simply lowering SUDA on a 20 km tether, and towing it through the plume to make measurements simultaneous with the orbiter.

This concept is implemented most easily with a small free-flyer (Figure 11). Terrain-guided auto-navigation would guide it to a keyhole 2–5 km above a designated surface point on a map uploaded prior to deployment. AutoNav is required because Sylph must aim much much more accurately than the dispersion of the Europa Mission's moon-relative ephemeris allows. Figure 12 shows the navigation improvement required to hit the plume target point (and not hit the surface). AutoNav is implemented at a system level by software built on the Deep Impact heritage; guidance sensors are a JPL OpNav camera at the forward end of the probe system, and a Honeywell MIMU (Miniature Inertial Measurement Unit); the attitude actuator is an integral cold-gas thruster module at the aft end. The Honeywell MIMU is flight-mature and uniquely meets Sylph's drift-rate and radiation-tolerance requirements; its size and power consumption are key system drivers for the probe. The AutoNav algorithms use limb shape and previously mapped surface features to aim for a cross-track coordinate above the limb, and thus do not depend on imaging or targeting the plume itself. Sylph would execute one main (7 m/s) targeting maneuver, but has provisions for up to three additional adjustment maneuvers before T–30 min.

Figure 13 summarizes the mission operations sequence. Required lifetime is very short: the probe completes its mission from deployment to final data retrieval in less than 15 hours.

In this concept, after months of plume-pass science-observation planning, development, simulation, and verification, the Europa Mission's encounter command sequence is uploaded from Earth. Seven days before the encounter (T = 0), Sylph is activated and undergoes final system checks. After the final Mission' cleanup maneuver, just nine hours before the encounter, it uploads into Sylph the aim point, based on observed plume density, and corresponding surface-feature map, and releases the probe one hour later.

After ejection by the hangar, the MIMU cancels angular rates imparted by the separation spring and roller guides. The OpNav camera images a star field to gain an attitude fix; zeroing the MIMU rates then sets initial state. 1.5-hr after separation the probe thrusts away from the mother ship, downward toward Europa where it continues on almost the same trajectory, 20–25 km displaced. Throughout approach, the camera passes recurring images of the moon to the AutoNav

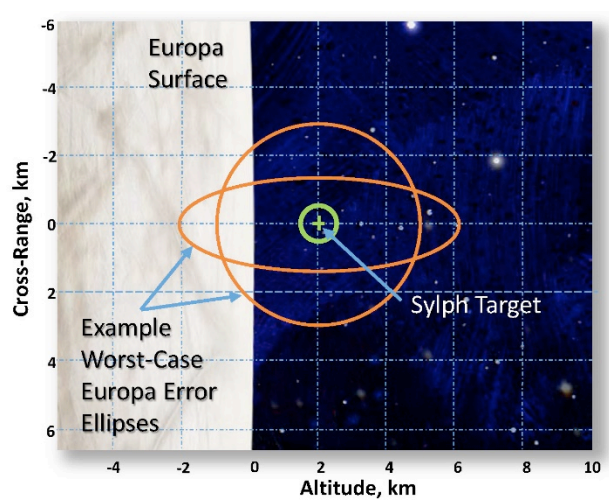

Figure 12. Terrain-relative AutoNav compensates (green) for the mother ship's orbital dispersion (orange), allowing a plume pass very close to the surface.

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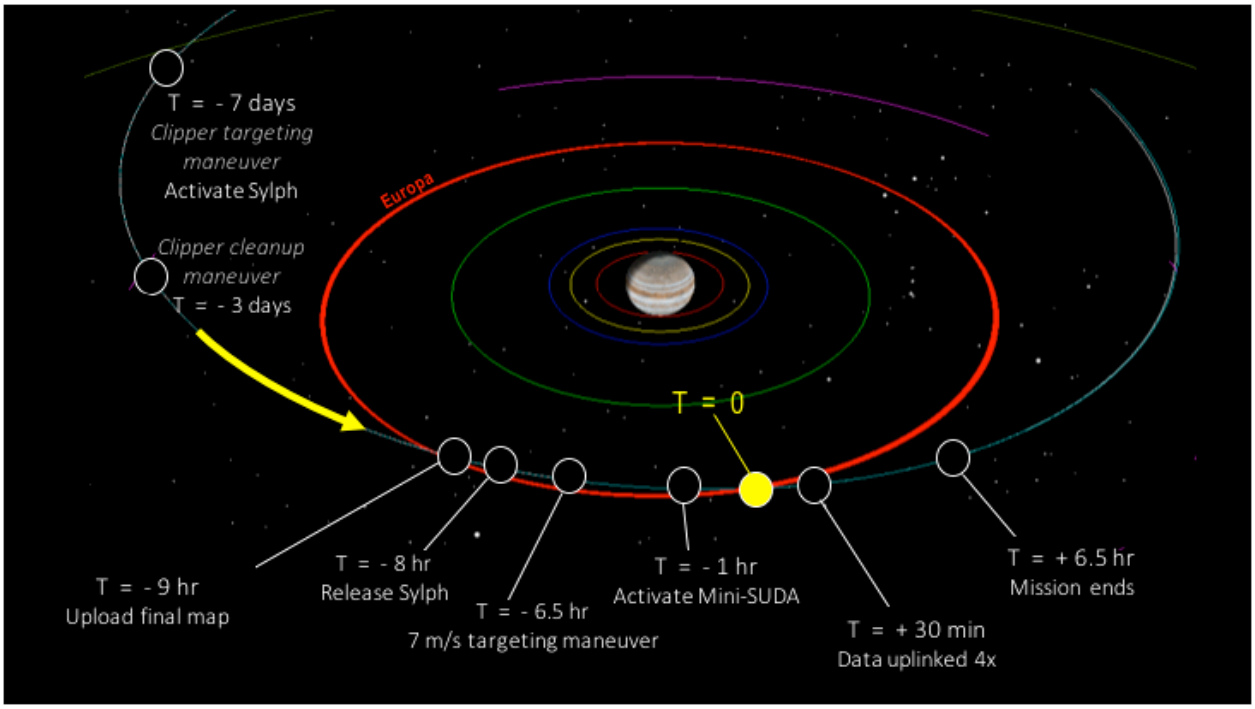

Figure 13. From deployment to final data retrieval, the operations sequence takes only 15 hours.

software, which correlates the captured scene with the onboard terrain map, pulsing cold-gas thrusters to aim for the target keyhole. Mini-SUDA is activated at T−1 hr.

The plume pass occurs in just 3 sec. The OpNav camera needs no protection from particle impingement because its task is complete by that point. By T+30 min, all the mass spectra, and enough camera images for trajectory reconstruction, are transmitted by UHF to the mother ship four times over. Within 6 hr, the probe is over 700 km away from the Europa Mission spacecraft; end-of-mission is declared at 6.5 hr post-encounter. Its batteries expire; Sylph coasts derelict in an orbit similar to the Europa Mission until the mother ship makes its next close-pass targeting maneuver. The mission design assumes that at some indefinite future time, Sylph impacts the Europa surface.

5. System and Subsystem Baseline Design

Free-flying probe

The active components are: Mini-SUDA payload (twin sensor heads and shared electronics); guidance and propulsion (MIMU, OpNav camera, cold-gas propulsion module); power (primary batteries); telecom (UHF antennas and radio); and avionics [30].

Sylph is similar in size to an office water-cooler bottle: 40 cm high, 35 cm in diameter. Additive manufacturing of both structure and propulsion subsystems avoids the mass and volume penalty of discrete functional parts. The structure is aluminum, allowing intricate optimized shapes to minimize mass where appropriate. The main structure comprises a modular stack of segments that contain the active components. After parallel integration, these segments are stacked together for final assembly (Figure 14). The

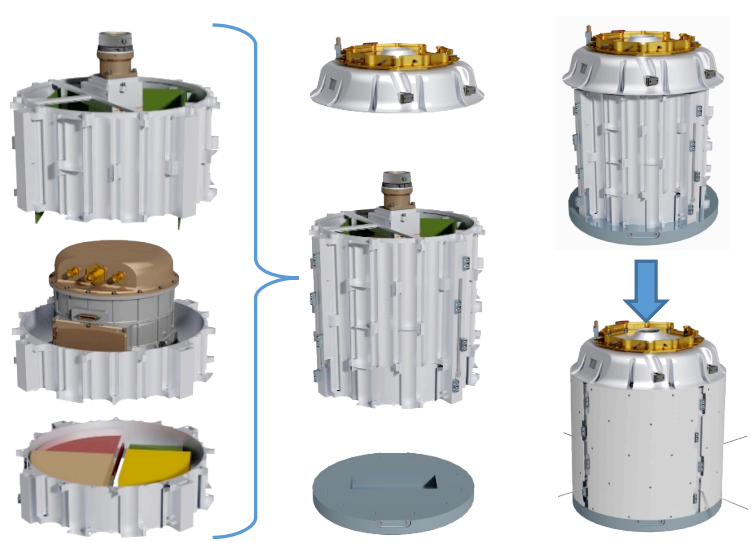

Figure 14. Modular structure segments allow parallel integration and test flow, and together with the batteries provide the radiation shielding required for the 15-hr design life.

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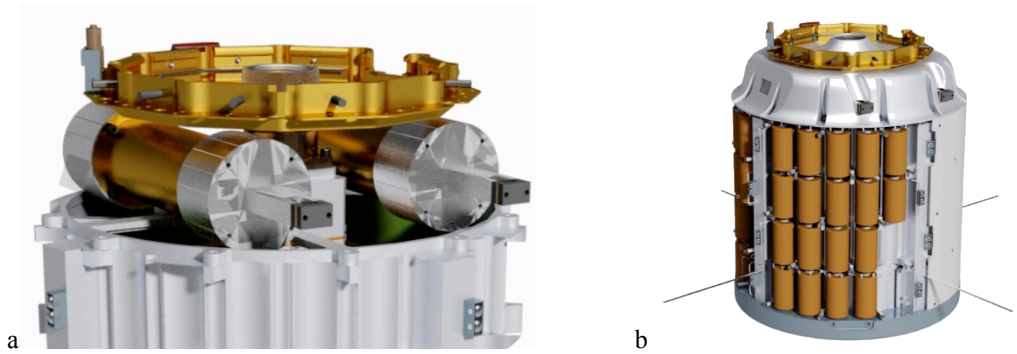

a b

Figure 15. (a) Top segment holds twin Mini-SUDA instrument heads. (b) Batteries line perimeter inside closeout panels.

aft segment contains avionics and instrument electronics. The middle segment both contains the MIMU (the largest single component in the system, which drives system size and power) and mounts the camera, to control alignment tolerance for these two guidance sensors. The top segment holds the instruments (Figure 15a). The segments are scalloped into battery trays around the perimeter (Figure 15b). The stack is closed out on the aft end with the integrated (3D-manufactured) propulsion module, on the forward end by a shielded lid supporting the Lightband separation ring and electrical interface, and around the side by panels over the batteries.

Only the Mini-SUDA apertures, opening to the impact targets, are exposed to space. Minutes before the plume encounter, the probe reorients to a 45° incidence angle so the impact targets are normal to the velocity vector.

Table 3. Mass summary includes significant contingency for non-catalog items.

Subsystem	CBE	Cont. %	MEV
Mechanical	8.9 kg	29%	11.5 kg
Harness	0.5 kg	30%	0.7 kg
GNC	4.9 kg	8%	5.3 kg
Power	7.3 kg	6%	7.7 kg
Telecom	0.6 kg	35%	0.8 kg
C&DH	0.4 kg	39%	0.5 kg
Instrument	4.6 kg	43%	6.5 kg
Propulsion	3.0 kg	43%	4.7 kg
Propellant	2.9 kg	5%	3.0 kg
Sylph Total	**33.1 kg**	**22%**	**40.4 kg**
Hangar and Door	31 kg	30%	40.2 kg
MLI	2.9 kg	30%	3.8 kg
Hangar Total	**33.9 kg**	**30%**	**44.0 kg**
Sylph Mission Total	**67 kg**	**26%**	**84.4 kg**

Figure 16 diagrams the complete system, which leverages JPL's deep-space smallsat avionics: Sphinx architecture built around a Leon processor, with custom memory storage and interface cards. The transmit-only UHF radio leverages JPL's Iris smallsat product. Four dipole antennas, held by burn wires until after ejection from the biobarrier hangar, provide omnidirectional coverage. The bus operates at 28 V. The power source, sized for a margined lifetime of 24 hrs, comprises 72 D-cell size Li-Ion primary batteries.

Equipment list and margins

Figure 17 shows the parts list graphically. Small parts count, catalog components, integrated solid modeling, and additive manufacturing make the system mass highly predictable (Table 3); significant contingencies are allocated to non-catalog hardware. Table 4 shows the key resource margins for the pre-Phase A design.

Shielded biobarrier hangar

Until its deployment, Sylph hibernates in a canister mounted unobtrusively on the mother ship, likely on the aft skirt (Figure 18). The 44 kg canister provides multiple functions: 1) contains the Lightband ring that holds and deploys the probe and provides its electrical interface until deployment; 2) provides radiation shielding until the deployment; 3) acts as a HEPA-vented biobarrier for handling, integration, and launch operations; 4) allows late integration onto the mother

Table 4. Flight system margins allow ample maneuvering room for concept maturation.

Spacecraft Functional Requirement	Driving Requirement	Proposed Design Value	Margin
Hangar + Probe Launch Mass (kg)	250	84.4	165.6 (196%)
Stored Energy (Whr)	1265	1810	545 (43%)
Science + Eng. Data Storage (Mb)	215	1024	809 (376%)
Data Transmit Time (min)	3.5	30	26.5 (757%)
DeltaV and Attitude Control (m/s)	12.3	23.3	11 (89%)

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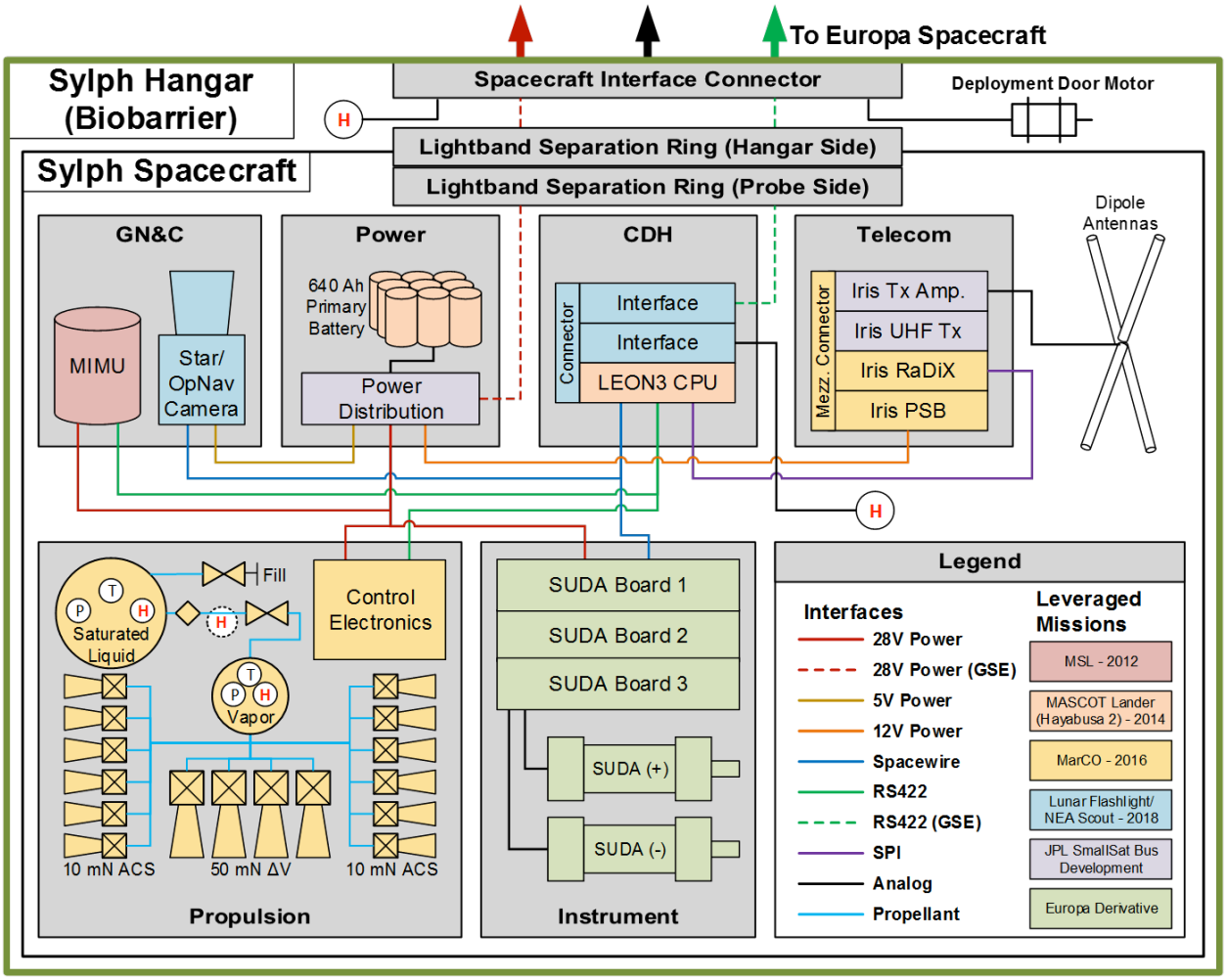

Figure 16. Flight system combines heritage components with smallsat hardware being developed now for other missions, the SUDA instrument being developed for the Europa Mission, and a few items tailored for Sylph.

ship, to keep Sylph well off the Phase D critical path; 5) manages thermal leak from the mother ship with insulation, heaters, and a motor-driven door that re-closes after deploying the probe.

Radiation tolerance

The harsh Jovian radiation environment severely limits practical system life. This challenge led directly to the highly elliptical, looping orbital tours of both Juno and the Europa Mission, which spend only a short fraction of their respective orbit periods in high-flux conditions where they conduct their primary science.

Total ionizing dose to internal components is limited to <150 krad over the total mission life, defined as the worst-case scenario in which Sylph is deployed at the end of the primary mission. Sylph's small size and short mission operations allow an efficient approach to mitigation that minimizes excess "dumb mass": 1) the shielding requirement is suballocated between the probe and its biobarrier hangar; and structure and power components are configured so as to also provide radiation shielding. The components are selected for hardness to 300 krad; the integrated system admits 104 krad (effective RDF 2.9): 91 krad before deployment from the hangar, and 13 krad during Sylph operations. The hangar has a 17 mm aluminum wall; the probe has a 3 mm (minimum) wall; and the wrap-around batteries (themselves radiation-tolerant) provide 9 mm equivalent thickness assuming 20% shielding effectiveness.

Integration and Planetary Protection

The planetary-protection design assumes that Sylph would eventually impact the Europa surface. This makes it a Category IV investigation: one in an environment capable of hosting life. The driving requirement is to limit the probability of inadvertent contamination of a liquid-water body by a single viable terrestrial microorganism to $< 1\times10^{-4}$. Current NASA policy for interpreting the requirement takes no account of geophysics: the probability of survival on the Europan surface until transport into the interior, and the probability of transport through the Europan ice to the

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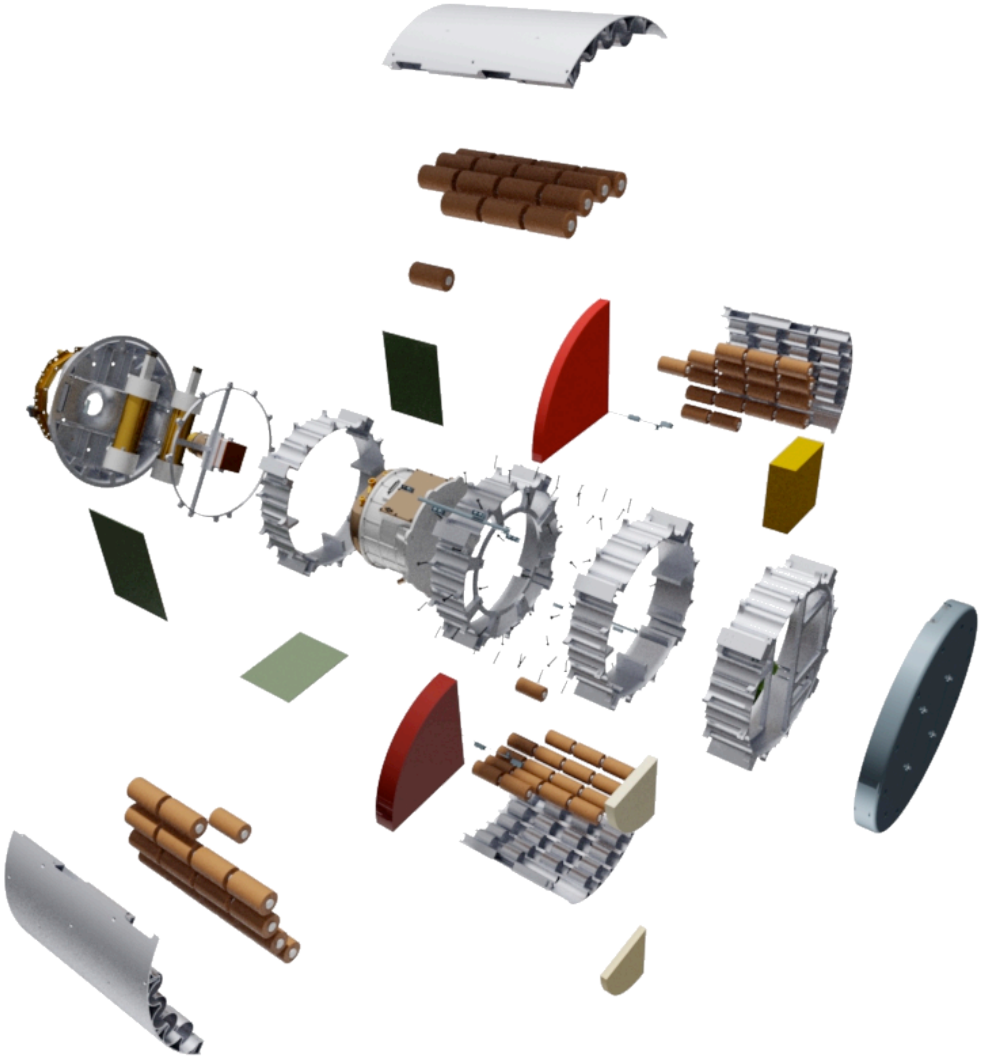

Figure 17. Sylph flight system baseline design has a simple architecture with few parts.

ocean, are both conservatively taken as unity. Sylph's small size, simple instrument, materials list, and modular configuration allow it to be brutally sterilized during assembly to meet this requirement. Also conservatively, Sylph assumes no credit for post-launch microbial reduction due to radiation exposure, even though it receives ~100 krad in flight.

Instead, Sylph uses all four of the currently accepted methods for sterilizing flight system hardware: dry heat microbial reduction (DHMR), vapor-phase hydrogen peroxide bath (VHP), filtration, and irradiation. DHMR is a bulk-sterilization technique that involves high-temperature (>125°C) baking over extended times. VHP can be used for mating surfaces but cannot penetrate packaged items like integrated circuits. Filtration can be used for fluids, to remove cells and spores. Irradiation can be used for components that do not degrade under radiation but cannot tolerate extended bake. The Sylph assembly sequence (Figure 19) is designed around the four microbial-control techniques, and the parts are selected accordingly.

The principal sterilization technique is DHMR. Accepted practice recognizes that 12.5 weeks at 128°C reduces contained microbial count by six orders of magnitude. The core subsystems, including Mini-SUDA with the inlets protectively capped, are baked for 10 weeks and then assembled in cleanroom conditions. That integrated assembly is then baked for another 2.5 weeks. In parallel, the batteries are irradiation-sterilized with up to 10 Mrad (some battery chemistries can withstand high temperatures, but suffer from severely reduced discharge capacity after being baked and then stored for years). The propellant is filtered at 0.2 µm to meet the spore limit. Then the batteries are installed and closed out, the propellant is loaded, and the complete flight system is integrated into the biobarrier canister aseptically in a VHP (vapor H_2O_2) atmosphere. Sylph's small size requires only a VHP glovebox for these final steps; the Mini-SUDA inlet caps are removed just prior

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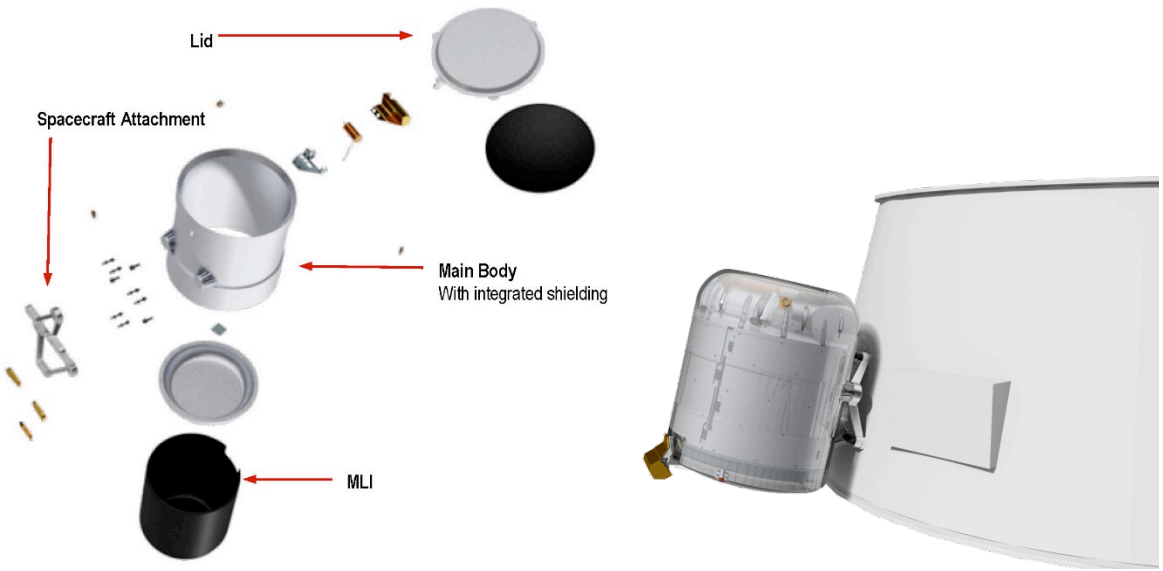

Figure 18. Biobarrier canister shields and deploys probe.

to sealing in the biobarrier. Finally, the sterile flight system is delivered to the Europa Mission orbiter encapsulated inside the biobarrier.

Because Sylph is so physically small and simple, implementing rigorous planetary protection for it is both straightforward and a valuable process pathfinder for Category-IV integration jobs to follow (e.g., a potential Europa Lander two years later).

6. Programmatics

The Sylph schedule proposed to support the Europa Mission Flagship project included: 18 month Phase A, 11 month Phase B, 28 month Phase C, 12 month Phase D, and 80 days of funded critical-path schedule margin for delivery to the project at Cape Canaveral in November 2021.

The cost basis of estimate is: discrete costs for catalog hardware; model-based estimates for structure and the biobarrier canister; actuals experienced on the MarCO smallsat development; and wrap rates for radiation-environment engineering and project management, systems engineering, and mission assurance. $28M is allocated specifically for integration of this Class C/D payload into a Class A flagship project and for planetary-protection planning, oversight, implementation and test activities plus Engineering Model and pathfinder hardware. No new facilities would be needed.

Three system-level cost methods (Price TP, SEER, and PCEC/NICM) bounded the cost. At 50% confidence

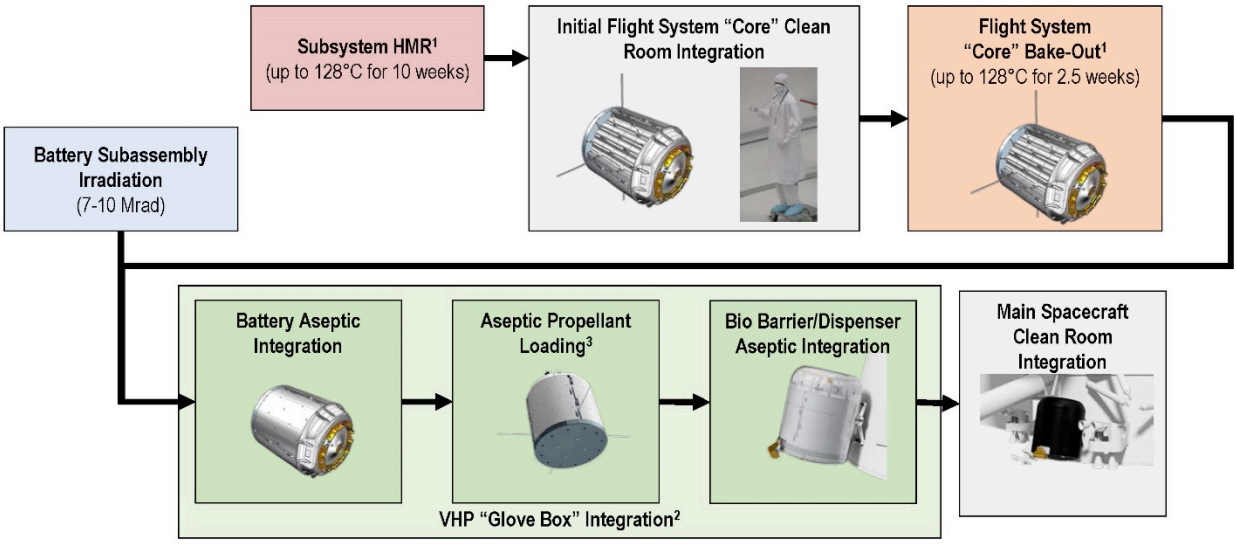

Figure 19. Assembly flow accommodates all four approved sterilization techniques: component baking, battery irradiation, propellant filtration, and aseptic assembly in vapor hydrogen peroxide.

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level, the first unit would cost less than $80M, FY15; copies would cost less, and The Europa Mission orbiter could carry two or three within its 250 kg mission-enhancement mass allocation.

7. Conclusions

The Sylph concept solves the impracticality of committing a mission based on the many uncertainties associated with putative Europan plumes. Rather than a standalone mission, it suggests a small, low-cost, no-frills, minimum-impact free flyer that the Europa Mission Flagship could deploy to make the one critical measurement that it cannot: composition of large ice grains at low altitude in an ocean plume. Together with measurements by the primary mission's mass spectrometers, Sylph would enable definitive detection of biosignatures, if an ocean plume is found in 2028.

All probe components directly leverage subsystems that exist or are in development now. At less than $80M for the first copy, and with minimal accommodations impact, the payoff from this "insurance policy" could be very high. In any case, it would obtain high-resolution composition measurements of the Europa surface. Sterilization for planetary protection is straightforward for such a small system, and would pave the way for sterilizing more complex ocean-world flight systems including a possible Europa Lander.

8. Acknowledgments

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