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Environmental Design Implications for Deep Space SmallSats

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Abstract

The extreme environmental challenges of deep space exploration force unique solutions to small satellite design in order to enable their use as scientifically viable spacecraft. The challenges of implementing small satellites within limited resources can be daunting when faced with radiation effects on delicate electronics that require shielding or unique adaptations for protection, or mass, power and volume limitations due to constraints placed by the carrier spacecraft, or even Planetary Protection compliant design techniques that drive assembly and testing. This paper will explore two concept studies where the environmental constraints and/or planetary protection mitigations drove the design of the Flight System.

The paper will describe the key technical drivers on the Sylph mission concept to explore a plume at Europa as a secondary free-flyer as a part of the planned Europa Mission. Sylph is a radiation-hardened smallsat concept that would utilize terrain relative navigation to fly at low altitudes through a plume, if found, and relay the mass spectra data back through the flyby spacecraft during its 24-hour mission. The second topic to be discussed will be the mission design constraints of the Near Earth Asterioid (NEA) Scout concept. NEAScout is a 6U cubesat that would utilize an 86 sq. m solar sail as propulsion to execute a flyby with a near-Earth asteroid and help retire Strategic Knowledge Gaps for future human exploration. NEAScout would cruise for 24 months to reach and characterize one Near-Earth asteroid that is representative of Human Exploration targets and telemeter that data directly back to Earth at the end of its roughly 2.5 year mission.

1. Introduction

Deep space exploration is a challenging and expensive proposition. To better enhance our understanding of the Solar System, scientists and engineers have been driven to develop new and unique designs that are smaller in size and more focused in their science objectives. The Jet Propulsion Laboratory, along with its partners, is developing a number of new mission concepts and technologies to enable the exploration of deep space using small satellites (SmallSats). The environmental challenges facing these missions and their mitigations remain as daunting to achieve as those faced by existing designs for larger, multiple science objective missions. Space environmental issues such as radiation induced effects or compliance with international planetary protection requirements represent some of the most challenging issues that designers must address. Current mission concepts, such as Near Earth Asteroid (NEA) Scout and Sylph have pioneered the design pathways to achieving world-class science within the constraints of the SmallSat limitations on physical and financial resources. These two missions are proposed missions to respectively: a) explore a near-Earth asteroid and 2) potential plumes on Europa, if found by the planned Europa Mission, in the Jovian system. These mission concepts are enabled by the development of miniaturized yet full performance capable subsystems (i.e. command and data handling, power, instrument interface, software, and communications systems) that are specifically designed for the deep space environments. The electronics and systems need to be specifically and carefully designed to handle harsh radiation and thermal environments as well as support support deep space navigation for long durations to achieve their scientific objectives.

1.1 The Sylph Concept

Sylph is a proposed small spacecraft concept developed by a joint team comprising the Jet Propulsion Laboratory, Cornell University, University of Colorado at Boulder, and the Southwest Research Institute that would fly as a daughter spacecraft on the Europa Mission. The propane tank-sized (40-cm high, 35-cm in diameter), ~40 kg Sylph probe (see Fig. 1) is one of the most unique and capable small spacecraft ever studied by JPL for such a harsh environment. Named after the mythological spirit that inhabits the air and never touches the ground, the mission is proposed as a way to directly sample a presumed plume on Europa, by executing a 2 km altitude flyby above the surface. Carrying a miniaturized version of the Europa mission's SUDA instrument and combined with higher altitude plume measurements made on the main Europa Spacecraft, Sylph's objective would be to provide insight into whether life exists within this icy moon of Jupiter. Sylph is a simple probe designed for a straightforward mission. The spacecraft would be notionally stored on the aft-skirt of the Europa Mission. Upon deployment, its primary batteries power it through its 24-hour life to target the moon, sample the plume, and relay data to the mothership. [1]

Fig. 1. The Sylph probe concept

1.2 NEAScout Concept

Propelled to Earth escape by the SLS EM-1 launch, the NEAScout smallsat as shown in Figure 2. would, using a solar sail for propulsion, image and characterize a Near-Earth Asteroid during a slow flyby, thereby demonstrating a low cost reconnaissance capability for deep space in a 6U form factor. Key mission objectives would be to conduct target imaging and close proximity operations to gather high resolution pictures (~ 10 cm / pixel). The slow flyby (<20m/s) would be controlled using a large 86 sq. meter solar sail propulsion system that fits in a third of the spacecraft's volume. In just two years, the sail can propel the smallsat nearly 1 AU in distance from Earth. NEAScout is a led by the Marshall Space Flight Center, with the flight system being developed at JPL, and science and analysis support from GSFC, JSC and LaRC.

Fig. 2. The NEAScout smallsat concept

1.3 SmallSat Size Constraints

The challenges of implementing small satellites within limited resources can be daunting when faced with the inescapable effects of deep space radiation. These effects are detrimental to COTS electronics, requiring heavy shielding or unique adaptations for protection, impacting the system's limited mass, power and volume constraints due to the carrier spacecraft. This paper will explore the development of the Sylph and NEAScout concept flight systems, focusing on the environmental constraints and/or planetary protection mitigations drove innovations and adaptations required for small spacecraft to conduct unique science observations on the small satellite platform in deep space environments.

2. Driving Design Requirements

Environmental constraints and/or planetary protection mitigations have been two of the most critical technical challenges in designing the flight systems of deep space Smallsats. Unlike the larger, more complex spacecraft that have been the staple of deep space exploration for the last 30 or more years, these smaller, single-string satellites embracing the CubeSat paradigm have evolved, along with the requisite philosophy of lower cost at a higher risk. These Smallsats have to be fully capable of completing their mission objectives yet fit within the limited mass and volume allocations provided by either the host spacecraft (mothership) or the limitations placed upon them by the launch vehicle.

2.1 Radiation Challenges at Europa

Sylph would be subjected to a diverse set of constraints and requirements, radically different than what is common on Earth-orbiting small satellites or even the most advanced CubeSats planned for venturing to the moon, deep space, Mars, or near Earth asteroids. The probe must survive nearly a decade of storage onboard the Europa spacecraft and is designed to handle the highest expected, life-limiting radiation environment approaching 150 KRad behind centimeters of shielding aluminum. The expected total dose begins with the multi-year cruise piggybacking in a sealed deployment dispenser on the Europa mission to get to the Jovian system. Once in orbit around Jupiter, the Europa Mission executes multiple flybys of the icy moon rather than entering a Europan orbit so as to limit the dose seen by the spacecraft. Sylph would not be deployed until after the Europa primary mission flybys are completed. Upon ejection from the host spacecraft Sylph, now in operational mode, will no longer be protected by the thick walls of its deployment dispenser and would accumulate a final, large radiation dose as it approaches its target plume. In all, the Sylph system is designed to an expected total mission dose of about 103 krad based upon models of Jupiter's radiation that are being used for the Europa mission. Using established design principles, a radiation design factor of two is applied so that internal components are chosen to meet a radiation hardness level of up to 300 krad.

Sylph's total ionizing dose is over four orders of magnitude more than a LEO Cubesat, where a mission would expect no more than 10 rads of ionizing radiation per year behind 4 mm of aluminium. The probe was designed for a worst-case scenario in which it is deployed at the end of the Europa clipper's primary mission. Sylph's small size and short mission operations allow an efficient approach to mitigation that minimizes excess "dumb mass"; the shielding requirement is intelligently suballocated between the probe and its biobarrier deployer. If mass is kept on the probe itself, more propellant is needed for targeting maneuvers. However, mass left in the deployer may burden the mothership, thus providing for a separate systems trade study on mass-optimized allocations. On Sylph itself, the structure and power components are designed to be intertwined so as to also provide radiation shielding while supporting the mounting of components. In the end, Sylph is subjected to 91 krad before deployment from the deployer and 13 krad during its brief 24-hour operation. This is achieved through a simple design; the deployer has a 17-mm aluminium 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. [2] The design balances the shielding and mass optimally between the deployer and the Sylph flight system in an optimal way.

2.2 Planetary Protection Considerations in an Ocean Worlds Environment

In addition to the damaging radiation issues that must be factored in to the design and lifetime requirements, planetary protection drivers place an overarching burden on the development of the flight system. Because Europa is considered to be an ocean world that could harbour life, the mission must guarantee that no terrestrial life is inadvertently transported from Earth to Europa aboard the probe. Because of this, Sylph was designed on the assumption that it would be subject to the Category IV planetary protection requirements. These requirements are strict and challenging, requiring a mission to guarantee that the probability of inadvertent contamination of a liquid water body by a single viable terrestrial microorganism is less than 1×10^{-4}. Planetary protection requirements can be met either by assuring that the spacecraft's control and orbital errors are sufficient to prevent impact, or by sterilizing the spacecraft. Sylph's straight-forward design includes limited propulsive capability and is dependent on a close approach of a potentially geologically active region of Europa, so the probability of impact (either from a failed flyby or subsequent entrapment in the Jovian system) is assumed to be guaranteed. Currently there are four accepted methods that could be used to sterilize the flight system: irradiation, dry heat microbial reduction (DHMR), filtering (for fluids like propellants), and/or vapor hydrogen peroxide (VHP). The DHMR process involves extended bake periods at high temperatures (>125 °C) and is used on components that can withstand high temperatures. For external surfaces, VHP can be used to sterilize surfaces, but is unable to penetrate packaging, like batteries or integrated circuits. To sterilize the inside of components, irradiation can be used on components that do not degrade under megarads of radiation or cannot be sterilized by other methods. As a further burden, compliance with planetary protection requirements must be met before the mission is launched, so the spacecraft assumes no microbial reduction credit for radiation exposure after launch and throughout the Cruise phase. For this reason, Sylph would use a combination of all four above methods of microbial sterilization in the integration of the flight system.

2.3 Radiation Design for Long-duration Smallsat Missions

While Sylph faces a short life in a harsh environment, the NEAScout project has its own set of constraints and requirements stemming from its 2.5 year mission duration. Over this long cruise, rendezvous, and downlink of science data, the integrated radiation effects are the most driving. While the environmental radiation background drives the design to be tolerant to both Total Ionizing Dose (TID) as well as Single Event Effects (SEE), all this must be developed within a CubeSat form factor the size of a shoebox with a mass of 14 kg and entirely comprised of single-string electronics; there is simply no extra volume or mass available for redundancy. This limits the inherent robustness of the system. The driving challenge for NEAScout is that low-thrust solar sail mission design requires that the system perform for ~ 2 years' duration in the space environment to reach its target destination. The constant bombardment of space radiation degrades all electronic parts on the avionics and payload electronics while induced sensor noise degrades performance and sensitivity of the camera payload and star tracker. Because of this, there is a push on the design to use existing rad-hard or tolerant technologies where possible (or implement the first use of newer technologies along with their associated risks). However, many of these potential solutions do not yet exist that support the CubeSat or SmallSat form factors. Therefore, there is a fundamental constraint that requires the use of existing commercial components designed for low Earth orbit wherever possible augmented as needed, with specialty deep space designs. The critical risk management tool for this total dose issue is the calculation of a dose-depth curve using mission specific trajectory information. This curve is shown in figure 3. Figure 3 shows four different mission lifetime options as a function of equivalent aluminium shield thickness in units of mils. A Radiation Design Factor (RDF) is listed as 1 for this particular analysis. This implies there is no additional margin added on to radiation requirements. This helps mission designers determine electronic part selection. Smallsat mechanical and volume requirements are severe and provide limited margin options for radiation shielding design.

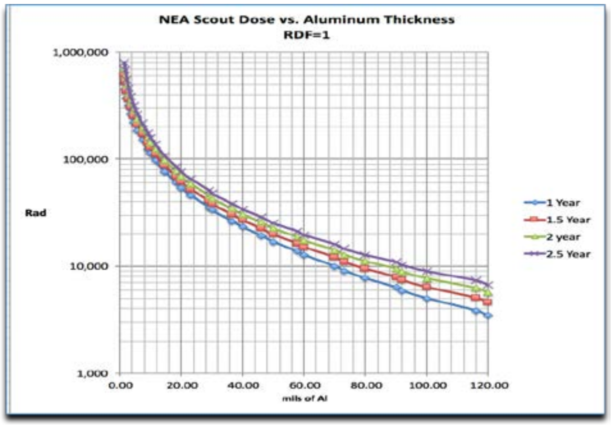

Fig. 3. Radiation dose curves for the NEAScout concept

3. Space Radiation Drivers on the Design

To perform a mission in the harsh radiation environment of the Jovian system, the Sylph probe design focused on radiation tolerance as well as a short operational lifetime requirement. The Sylph spacecraft design is enabled by the infusion of JPL's deep space small satellite technologies currently being developed for CubeSats such as Lunar Flashlight and NEAScout. Some technologies don't exist yet or have a low Technology Readiness level (TRL) in the SmallSat domain, so the Sylph design is augmented by traditional 'large spacecraft' components. For example, the spacecraft uses a deep space "conventional" Inertial Measurement Unit. This unit, the Honeywell MIMU (Miniature Inertial Measurement Unit), was selected as the only available solution for meeting the stringent radiation tolerance requirements, pointing accuracy, and drift characteristics required for Sylph to complete its mission. All other IMUs were either too rad-soft, have too low a TRL classification, or had a detrimental drift rate. Selection of the MIMU ultimately drove the overall spacecraft configuration (see Fig. 4). Sylph depends on an accurate IMU to be able to target itself to the plume, using cold gas thrusters, as well as to measure dispenser ejection rates and monitor propulsion system performance and errors. Lack of existence of a smaller, rad-tolerant IMU forced not only the configuration of the system but, ultimately drove many mass and volume aspects of the design. The Honeywell MIMU is flight-mature and uniquely meets Sylph's drift-rate and radiation-tolerance requirements; its size and power consumption being key drivers in the design accommodation. However, it is the largest single assembly of the system, driving both the power consumption as well as the volume and mass envelop.

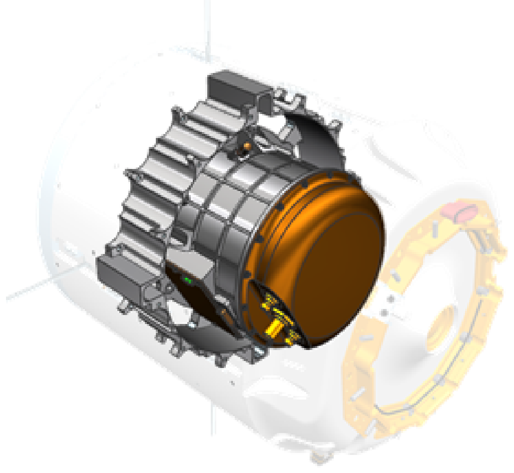

Fig. 4. MIMU inside the Sylph concept

3.1 Avionics

The avionics of the Sylph spacecraft are built on the rad-hard, deep-space small satellite hardware under development at JPL for future deep-space SmallSat missions. Power, attitude control and computational command and data handling are the prime areas that require radiation tolerant designs to enable this mission. The command and data handling system is the next evolution in architecture of JPL's deep space SmallSat C&DH design called Sphinx. This subsystem is built around a LEON3 architecture, with a custom memory implementation specifically modified with SRAM memory chips. While these memory modules are much less “dense”, they enable the flight system with a higher radiation tolerance required for the Jovian environment. Because Sylph only performs a single fly-through of the plume, all of the mission’s data is rapidly collected. The mini SUDA instrument collects 215 Mb of data during this encounter. To supplement the limited amount of on-board memory storage available on Sphinx, custom memory storage and interface cards are included to interface between the C&DH and the other avionics and the instrument. With more memory limitations for on-board storage, software designs were planned that will help condense and prioritize the science data collected for telemetering back to the planned Europa Mission and, ultimately, to Earth.

The NEAScout avionics are also built upon both JPL custom and commercial CubeSat/SmallSat hardware under design for current and future deep space SmallSat missions. The JPL-designed Sphinx C&DH based upon the dual core LEON 3FT processor and 8Gb of Non-volatile flash memory storage coupled with JPL specialized software make up the core of the flight computer. This single board flight computer with a 1U form factor, draws 3 Watts of power and is designed to withstand and perform at up to 30 krad. The design has heritage from GRACE Follow-On and the Electra Lite radio developments. It also supports spacecraft timing requirements with it’s A 50 MHz on-board oscillator acting as the master clock.

3.2 Sylph Power System Drivers

Power electronics are particularly sensitive to deep space radiation effects. Sylph’s power system architecture consists of an unregulated spacecraft bus operating at around 30V, and three regulated buses at 28V, 12V, and 5V. Power storage is comprised of 72 Dcell sized Li-Ion primary batteries, sized to enable a 24 hour lifetime requirement including degradation for the 10 year cruise and design margin. Sylph used a battery only architecture because solar panels generate 1/25th the power at Europa compared to an equivalent panel at Earth; to meet the power requirements of the MIMU and instrument, Sylph would need solar panels much larger than the spacecraft itself. Therefore, primary batteries were selected via a detailed trade study as being a better solution than secondary (rechargeable) batteries for this short duration mission application because of their higher energy density as well as their ability to handle required sterilization techniques. Primary batteries also degrade less than secondary cells when taking into account the multi-year cruise, storage and ultimate energy needs of the mission after accounting for losses and depth-of-discharge constraints. An additional benefit is that these Li-Ion cells when incorporated in the configuration of the multifunctional structure, provide additional radiation protection for the sensitive internal electronics (see Fig. 5).

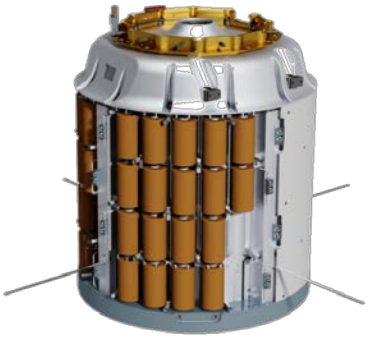

Fig. 5. Sylph concept - multifunctional structure and batteries

3.3 NEAScout Power System Drivers

The NEAScout’s power architecture is driven by a different set of constraints, namely the ability maintain power storage capability over the 2-year lifetime of operations. Like most spacecraft, the system uses high-density secondary re-chargeable lithium ion batteries. The driving design requirement for the power subsystem comes from the frequent, deep cycling of the batteries driven by the overall mission design. JPL design practices only allow the NEAScout mission to drain the batteries to a 40% state of charge. Because of the solar sail on the spacecraft, the flight system must slew to point the medium gain antenna towards Earth and establish a link to the ground. Because of this, the solar panels, which are in a parallel plane to the solar sail, are also rotated off sun and incur a cosine loss; the flight system is able to go 70 degrees off sun to point the antenna, meaning that the solar panels only generate 34% of the power they would if they were pointed flat at the sun during this time. This reduced generation leads to increased discharge rates and short downlink times for the flight system. With discharge rates sometimes reaching 3x flight practices (and subsequent heat generation), a custom battery housing has been developed to dissipate the heat generated. NEAScout has also designed in a removable battery pack, so qualification batteries can be tested through the rigorous environmental tests meant to stress the system. Then, before final flight qualification, the unstressed batteries can be re-incorporated.

3.4 Sensor Noise Implications and Mitigations

Both Sylph and NEAScout use optical sensor systems for science imaging and/or navigation. NEAScout also makes use of a star tracker for attitude control. These optical sensors have to be designed to handle the anticipated duration in the deep space environment as well. Radiation induces sensor noise that can degrade imaging quality and in the case of the star trackers, provide spurious inputs into the control system leading to poor pointing control and knowledge. These effects can be so severe to even cause the spacecraft to have off-nominal entry into safe mode. NEAScout is implementing a JPL-designed imaging camera currently under production for the OCO-3 mission (see Fig. 6) as well as the Blue Canyon Technologies (BCT) star tracker. Internal configuration and layout of the electronics and sensor shielding take advantage of the primary structure and other internal elements that are evaluated as a system in reducing overall radiation susceptibility. Additionally, a separate circuit was added to the camera to mitigate single event latchup risks. Both of these systems are designed and qualified to meet the TID requirement of 20 krad or greater environment with a radiation design margin of 1, though many of the components are designed to be greater than 100 krad tolerant. The Blue Canyon Nano Star Tracker has been subjected to a complete board level system radiation characterization campaign with protons, heavy ions, and total dose [3]

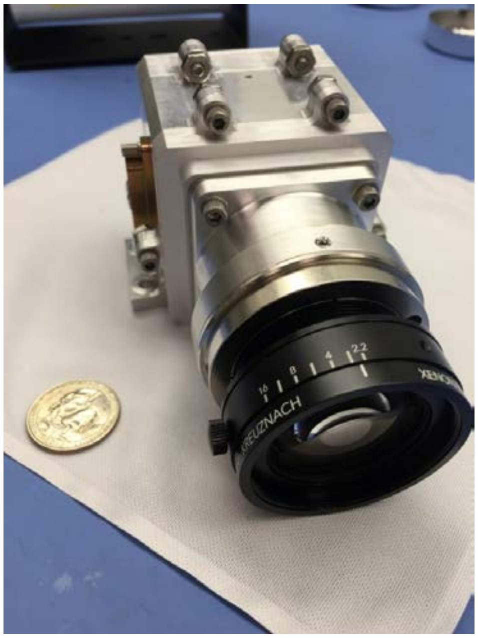

Fig. 6: JPL CAM used for NEAScout

4. Planetary Protection Requirements and Sterilization Processes on Integration and Test

Meeting internationally-agreed upon planetary protection sterilization requirements is a significant driver for mission destined to planetary surfaces that potentially harbor ice and water. As noted earlier, planetary protection requirements and compliant design techniques will drive the assembly and testing, and handling plans for Sylph as well as those of the host spacecraft, the planned Europa Misison mothership.

Sylph uses all currently accepted methods for sterilizing flight system hardware which include: heat microbial reduction (HMR), vapor hydrogen peroxide bath (VHP), filtration, and irradiation. HMR is a bulk-sterilization technique that involves subjecting flight hardware to 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 (i.e. propellants and thermal loops) to remove cells and spores. Irradiation can be used for components that do not degrade under radiation but conversely, cannot tolerate the extended heating resulting from the HMR process. The Sylph assembly sequence (See Fig. 7) is designed around the four microbial-control techniques, and the constituent parts are selected accordingly.

HMR is the primary sterilization technique to meet the allowable microbial spore count. The system would be subjected to 12.5 weeks of bake-out to reduce the microbial count to acceptable levels. All components except the batteries would undergo a dry heat microbial reduction bake-out for 10 weeks at up to 128 °C. After this, all components would would be assembled in cleanroom conditions and then baked for an an additional 2.5 weeks. Separately, the batteries are irradiated with up to 10 Mrad of radiation (note: not all battery chemistries can withstand high temperatures and maintain charge after being baked). Then the batteries are installed and closed out, the propellant is filtered and aseptically loaded, and the complete flight system is integrated into the biobarrier deployer aseptically in a VHP (vaper H2O2) atmosphere. Sylph's small size requires only a VHP glovebox to be used for assembly during these final steps. Finally, the sterile flight system is delivered to the Europa Mission to be encapsulated inside the biobarrier deployer. This biobarrier is important because Sylph will be more sterile than the Europa spacecraft and cannot be contaminated during cruise to the Jovian system

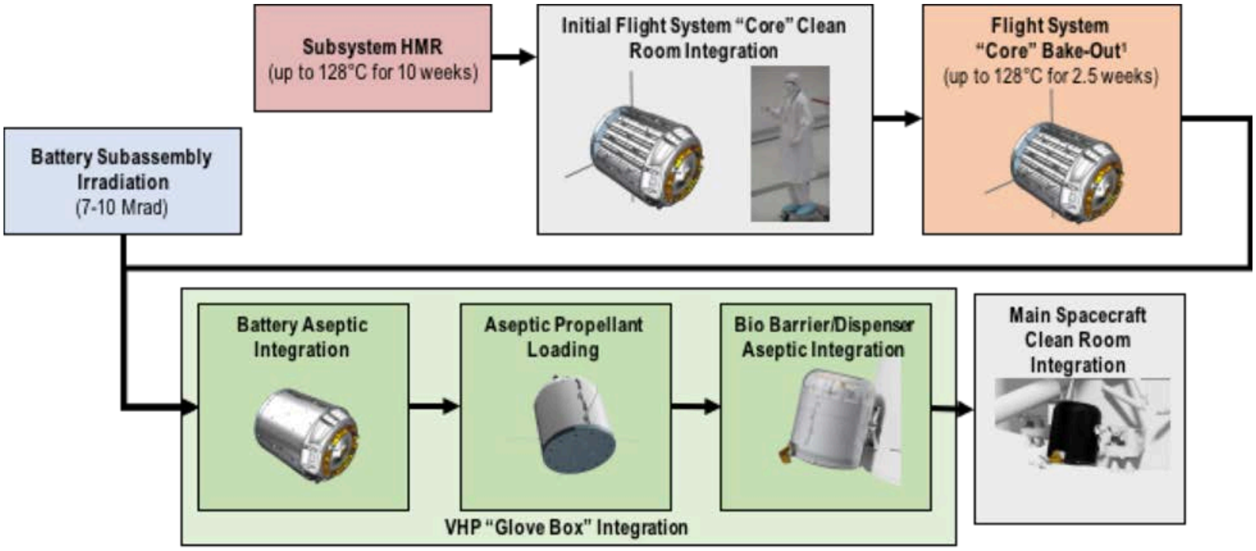

Fig. 7. Assembly flow accommodates all four approved sterilization techniques: component baking, battery irradiation, propellant filtration, and aseptic assembly

NEAScout has no planetary protection requirements due to its target objectives. Solar system small bodies are not covered by international treaties on bioburden and planetary protection that have otherwise been established for planets and other objects.

4.1 SmallSat Deployment

An integral part of the Sylph flight system design is the custom deployer, similar to the secondary dispensers used to launch and deploy CubeSats (such as PPODs). Potentially mounted to the aft skirt of the Europa spacecraft, Sylph's 44 kg deployer is a key functional element that includes a biobarrier to prevent contamination throughout the launch preparation processing. The walls of the deployer seal the probe behind nearly 2 cm of aluminium to reduce the radiation dose until deployment at Europa. A motorized door seals the spacecraft until ejection; after Sylph leaves the deployer, the door closes to minimize heat loss that would impact the Europa spacecraft.

NEAScout is launched in a deployment system as a secondary payload on the first launch of the SLS. While the launch and dispensing functions are equivalent to that of the Sylph deployer, the design-related drivers to support radiation protection and containment of biohazards are not required. NEAScout is deployed a few hours after the SLS EM-1 mission deploys the Orion spacecraft. After executing lunar flybys, NEAScout free-flys to its target using the solar sail as propulsion instead of being carried by a mothership to a target destination for many years.

5. Conclusions

As shown, new deep space mission concepts and technologies to enable the exploration of deep space using SmallSats face unique challenges driven by the space environmental issues such as radiation induced effects, and mitigation of bioburden to comply with international requirements on planetary protection. The NEAScout and Sylph mission concepts have explored and architected design options within the tight constraints of mass, power and volume as well as SmallSat limitations on physical and financial resources. These missions are establishing an approach to enable new frontiers of exploration and space science to be conducted at a fraction of the cost. JPL is at the forefront of these exciting new disruptive advances in the pursuit of obtaining more scientific understanding of our solar system.

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