# Cold Lightweight Imagers For Europa (C-LIFE)

## Accommodation Study for the ICEE-2 Program

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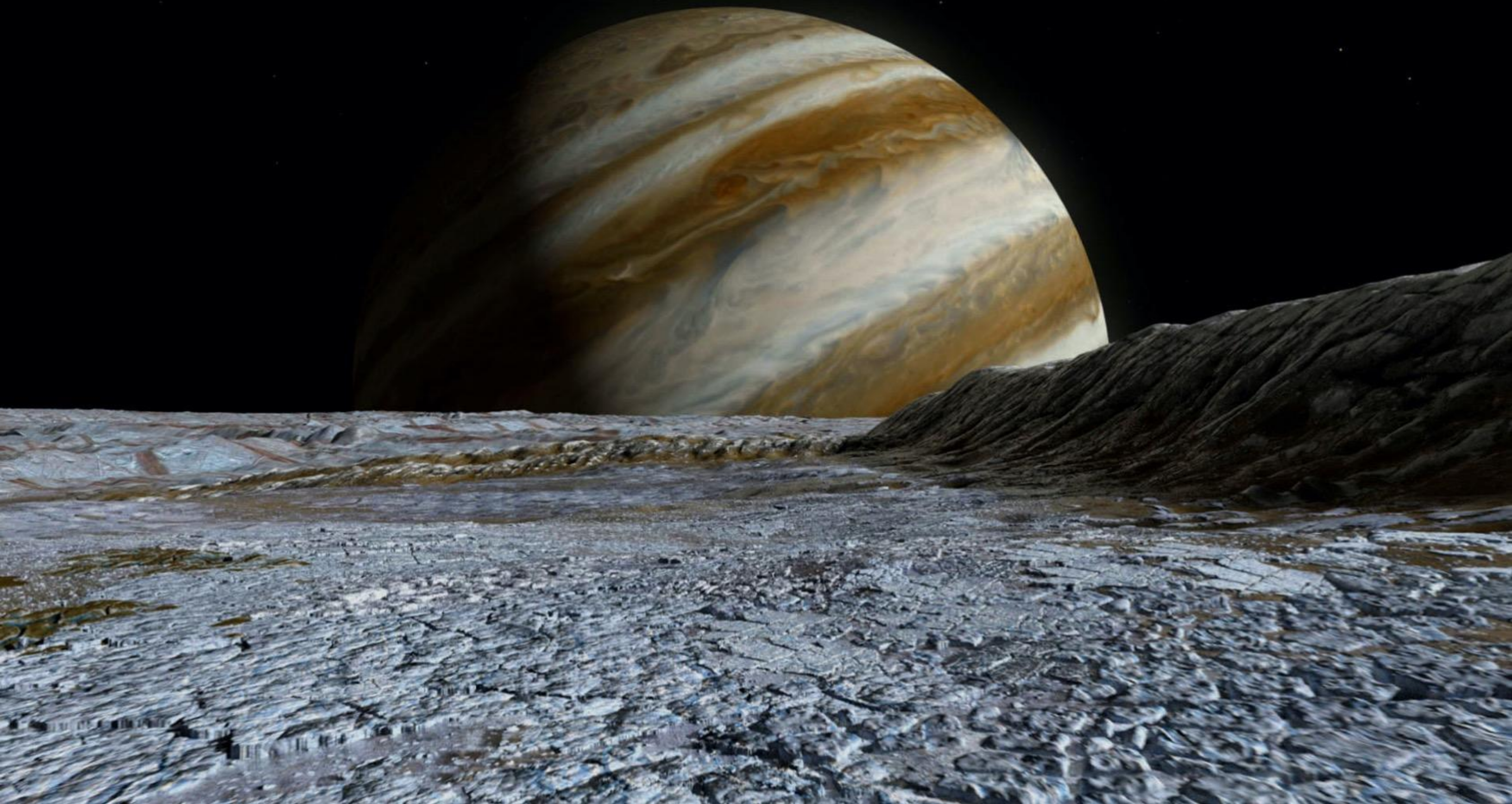

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# Acronyms and Abbreviations

| | |
|---|---|
| C-LIFE | Cold Lightweight Imagers for Europa |
| ConOps | Concept of Operations |
| CSM | Camera Service Module |
| CRSI | Context Remote Sensing Instrument |
| DRM | Detector Readout Module |
| FOV | Field Of View |
| IFOV | Instantaneous Field Of View |
| LED | Light Emitting Diode |
| MEL | Master Equipment List |
| MLI | Multi-layer insulation |
| OCAMS | OSIRIS-REx Camera Suite |
| PAN | Panchromatic filter |
| RSM | Remote Service Module |
| SDL | Space Dynamics Lab |
| SRI | SRI Corporation |
| STM | Science Traceability Matrix |
| UA | The University of Arizona |

# 1. Introduction and Science Goals

C-LIFE is a landed camera suite consisting of a color Context Reconnaissance Stereo Imager and LED flashlights that--on Earth--can also identify biogenic material through fluorescence. The C-LIFE ICEE-2 design leverages past work from our COLDTech award in low-temperature detector qualification and takes advantage of our development work on the Descent Imager for Europa Hazard Avoidance and Radiation Durability (DIEHARD).

The C-LIFE camera head is mounted on the Europa Lander's high gain antenna, which provides tilt and pan capability. Minimal camera head electronics control and read out the detector. Lander vault electronics perform most camera functions, image processing, and LED control. C-LIFE contains no moving parts. In lieu of a focus mechanism, C-LIFE utilizes a field of view elongated in the vertical direction with progressive focus from top (infinity e.g. imaging horizon) to bottom (close e.g. imaging sample delivery port). Vertical stripe filters on the detectors (that match Clipper's EIS) and overlapping images provide color coverage. C-LIFE is warmed for turn-on, but is otherwise unheated to conserve energy. We combine two independent eyes into one mechanical housing (Figure 1) with a dual periscope design, which reduces the mechanical envelope, shielding mass, heating energy and total cabling distance. LEDs are used for illumination and to excite fluorescence in three bands. These three bands can identify the presence of key metabolic biomarkers and discriminate the quantities of live cells, dead cells and spores in a terrestrial setting. During cruise and landing, C-LIFE is stowed in a face-down configuration on the lander deck, which removes the need for deployable covers.

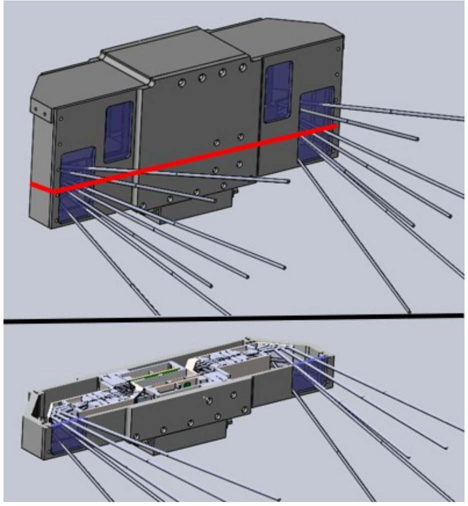


**Figure 1.** A dual-periscope design folds optical trains to mutually shield focal planes (incoming light rays in gray). Fold mirrors locate LEDs inside the camera for shielding.

The Europa Lander Science Definition Team (SDT) identified three goals for the Europa Lander mission (Hand et al. 2017). Goal 1 (later rescoped) pertains to the detection of biosignatures on the Europan surface and near-subsurface. Goal 2 relates to the assessment of habitability and goal 3 aims to support future exploration by characterizing the surface. Of the 8 SDT objectives, C-LIFE addresses six in whole or in part, which we include in our Science Traceability Matrix (STM; see Table 1).

| SDT Goals | SDT Objectives | SDT Investigations | C-LIFE Measurement Requirements | C-LIFE Instrument Requirements | C-LIFE Ops Requirements | Effects of Single-Eye Failure |
|---|---|---|---|---|---|---|
| GOAL 1: Search for evidence of life on Europa<br>**NOTE: GOAL 1 WAS REVISED IN 2018 TO SEARCH FOR BIOSIGNATURES** | 1B. Identify and characterize morphological, textural or other indicators of life. | 1B2: Resolve and characterize the landing site for any macroscale morphological evidence of life | Identify objects as small as 1mm within the lander workspace (~2m), in color. | 0.5mm/pixel at 2m drives 0.25 mrad IFOV<br>Color filters<br>Image SNR of 50 in Pan and 100 in other colors | Color coverage requires first acquiring CLR mosaic with stereo coverage and then an additional 72 exposures recording only the 3 color strips (each color occupies only a quarter of the FOV). | **Degraded** |
| | | 1B3: Detect structural, compositional or functional indicators of life | Search for UV fluorescence of organic material in lander workspace (~2m) | UV flashlight<br>Filters sensitive to fluorescent wavelengths<br>Co-add image frames to boost signal to noise | Nighttime observations | **Potential Total Loss** |
| | 1D. Determine the provenance of sampled material | *(1D1a) Determine geologic history (e.g. tectonism, cryovolcanism, impacts, sublimation, viscous deformation or mass wasting) of the landing zone. | Identify features as small as 1mm in the lander workspace (~2m), and as small as 1cm in the landing zone (~5m), in color. | 0.5mm/pixel at 2m drives 0.25 mrad IFOV<br>Color filters<br>Image SNR of 50 in Pan and 100 in other colors | Panorama in CLR filter requires 48 images from 2m range to horizon and 24 images at closer range (only one side of lander visible) | **None** |
| | | *(1D1b) Determine depth and geologic context within the landing zone of the sampled material | Identify features as small as 1mm at the sampling sites, in color. | | Color coverage requires first acquiring CLR mosaic with stereo coverage and then an additional 54 exposures recording only the 3 color strips. | **Degraded** |
| | | | Determine topography of excavated sites at scales of 5mm. | Second CRSI camera with common filter | | **Total Loss** |
| GOAL 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 | 2A2: Identify patterns of spatial variability (textural, compositional) that may relate to habitability, and inform sample collection | Characterize compositional end-members (through color) and textural (through photometric behavior) differences throughout the landing zone in support of sampling site selection. | Color filters<br>Image SNR of 50 in Pan and 100 in colors | Local time coverage in lander work zone to characterize photometry | **Degraded** |
| | | | Determine distribution of organic material within the landing zone through UV fluorescence. | UV flashlight<br>Filters sensitive to fluorescent wavelengths<br>Co-add image frames to increase SNR | Nighttime observations | **Potential Total Loss** |
| | 2B. Determine the proximity to liquid water and recently erupted materials in the lander's location. | 2B2: Search for evidence of interactions with liquid water on the surface at any scale | Identify any surface morphologies/textures/colors that would indicate recently erupted water in the landing zone (~5m) | 0.5mm/pixel at 2m drives 0.25 mrad IFOV<br>Color filters<br>Image SNR of 50 in Pan and 100 in colors | | **Degraded** |
| | | 2B3: Search for evidence of active plumes and ejected materials on the surface | Search for active plumes with high-phase-angle horizon images | Co-add image frames to increase SNR | Pre-sunrise and post-sunset images. Near-sun pointing. Repeat coverage at similar phases over 3 Europa orbits | **None** |
| | | | Identify fine-grained material in the landing zone (~5m) that may be plume deposits and use thickness variations around obstacles to constrain the direction to source. | 0.5mm/pixel at 2m drives 0.25 mrad IFOV<br>Second CRSI camera for thickness measurements | | **Degraded** |
| GOAL 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. | 3A1: Characterize the physical properties of Europa's surface materials through interaction with the sampling and landing systems | Determine surface compactability and cohesion by observation of lander footpads and the evolving sample trench during the mission.<br>Monitor interaction of sample and sample-delivery port to assess sample delivery problems. | Ability to focus on near-field objects (0.5m).<br>Repeat imaging of sample area during operations. | | **None** |
| | | 3A2: Identify geomorphic features and their quantitative relief (topography) characteristics in the landing zone | Determine centimeter to decimeter slope and elevation distribution of the landing zone (~5m) | Second CRSI camera with common Pan filter | Stereo Panorama requires first acquiring CLR panorama and an additional 64 images with the 2nd CRSI eye | **Total Loss** |
| | | | Observe centimeter- to meter-scale geomorphic features (e.g. boulders, penitentes, frost deposits, sublimation residues, small impact craters, ejecta deposits) in the landing zone (~5m) | 0.5mm/pixel at 2m drives 0.25 mrad IFOV | | **None** |
| | | ***3A5: Place the landing site in global context by acquiring data that allow it to be compared to Europa Clipper datasets. | Acquire stereo imagery of the landing zone that can be reprojected to simulate an overhead view for comparison to EIS and the Europa Lander Descent Imager.<br>Acquire color imagery of the landing zone in filters identical to EIS that can be similarly projected. | Filters on at least one CRSI eye match EIS.<br>Second camera required for stereo data | Color stereo panorama requires equivalent of 180 images (Already acquired under 1D1a+1D1b+3A2 - no additional data requirement) | **Total Loss** |
| | 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. | **(3B1 & 3B2): Characterize the rates of active physical and chemical processes that affect materials on Europa (e.g. gardening or radiolysis) | Test for changes in texture, color or physical distribution of fines and solid ice in the landing zone (~5m) over the course of the mission, especially those areas disturbed by landing and sample acquisition. | Color filters<br>Image SNR of 50 in Pan and 100 in other colors | Repeat color coverage at monitoring sites at several local times near the end of the mission | **Degraded** |
| | | 3B4: Characterize the three-dimensional surface dynamics of Europa and the local dynamic variability (potentially indicative of activity) at the landing site. | Followup imagery over existing stereo pairs with similar illumination to search for surface changes | Second CRSI camera | Repeat coverage of features of interest at similar phases over 2 or more Europa orbits | **Total Loss** |

*SDT investigation 1D1 split into two investigations here **SDT investigations 3B1 and 3B2 combined here ***This investigation was not explicitly included in the SDT STM

**Table 1.** Science Traceability Matrix (STM) mapping six relevant mission objectives (blue) to C-LIFE instrumental and ConOps requirements. Rightmost column indicates consequences of a failure of one eye.

# 2. Concept of Operations

## 2.1 C-LIFE Operations Cycles

C-LIFE conserves energy by operating for short, widely-spaced, intervals and remaining in an unpowered and unheated state between these intervals. In each of these operation cycles, C-LIFE progresses through several steps (Figure 2).

1. C-LIFE camera head heaters turn on to warm the Detector Readout Modules (DRMs) in the camera head to operating temperature before operations. We expect the camera head to be initially close to Europan ambient temperatures at 100 K. To reach an operating temperature of -50° C (223 K) will require ~2 hours at a heating rate of 1K/min. Lower operating temperatures are being investigated to further reduce energy use. Several heater control approaches are possible. The DRM heating can be commanded by:
    a. Lander electronics (current baseline).
    b. C-LIFE vault electronics; however, that would necessitate leaving them powered on and consuming energy.
    c. A separate circuit within C-LIFE could heat the camera head and activate the rest of C-LIFE when the head is warm enough.
2. Once operating temperature at the camera head electronics has been attained, then operations begin, the electronics are activated, and heating is reduced to levels required to maintain -50° C.
3. After required images are acquired (see below for durations) the camera head electronics are powered off. The camera head cools passively to Europan ambient temperatures. In this phase, heaters could be used to limit the cooling rate to <1K/min, but radiative cooling is estimated to be sufficiently slow that heater load will be 0 W.
4. Vault electronics are powered off once data handling tasks are complete. This task duration is determined by the data acquired and the time taken to transfer data to the Lander downlink queue. For the standard operations discussed below, processing is expected to keep up with data acquisition in real time. The vault electronics do not require heating or cooling and will operate in ambient vault conditions.

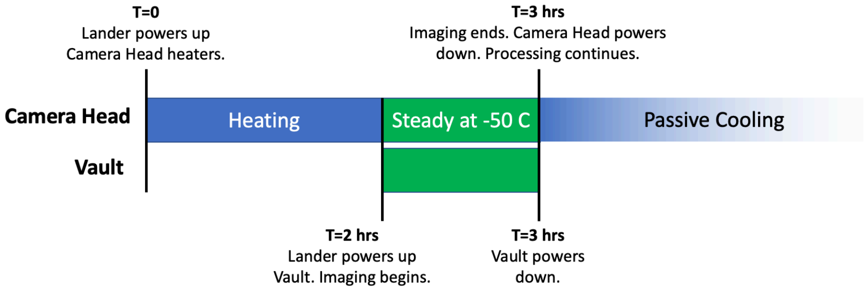


**Figure 2.** Activities for the C-LIFE camera head and vault electronics in a standard operations cycle. Time increases to the right. The operations time of 1 hr is notional, see description of operations cycles below for actual estimates.

During the image acquisition phase, we assume continuous imaging and so a continuous stream of data for the vault electronics to process. LED operation will be required for some observations in this phase and will be controlled by the vault electronics. Vault electronics will discard images taken while the antenna is in motion so that antenna motions could be preprogrammed without control by C-LIFE.

We assume that knowledge of antenna behavior will be available to the C-LIFE vault electronics. Alternatively, C-LIFE could control the antenna during these operations periods or the spacecraft could command C-LIFE to take an image and wait for a C-LIFE flag or product delivery before advancing to the next planned location.

### 2.2 C-LIFE Image Products

C-LIFE builds up spatial coverage of the landing site in each band by having the Lander HGA provide pan and tilt capability. C-LIFE contains no moving parts. In lieu of a focus mechanism, C-LIFE utilizes a Field of View (FOV) elongated in the vertical direction with progressive focus from top (infinity e.g. imaging horizon) to bottom (< 2m e.g. imaging sampled area). Topography within the landing area may require HGA tilts to bring parts of the scene into focus.

C-LIFE uses vertical stripe filters separated by narrow blocking strips on the focal plane (Figure 2) to enable push-frame color imaging, similar to the High-Resolution Camera of PanCam for the ExoMars rover (Coates et al., 2012). C-LIFE uses a 1k x 2k detector (1024 pixels wide, 2028 pixels tall), with 0.25 mrad IFOV, resulting in a ~15° wide, ~30° tall FOV. Half of the lateral field of view (~7.5°) in each eye is dedicated to polychromatic imaging and a quarter on the right and a quarter on the left are used for color imaging.

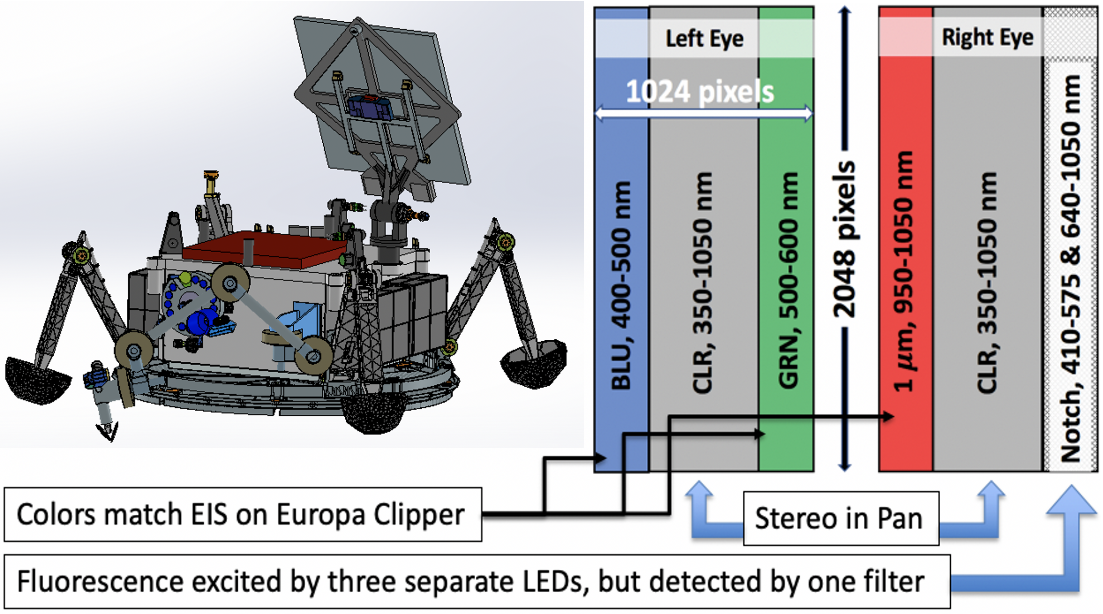


**Figure 2.** (Left) C-LIFE on the Lander's antenna (Right) Focal planes with detector dimensions, filter layout and bandpasses.

Suppressing radiation noise in the images requires using the C-LIFE vault electronics to combine several exposures. C-LIFE acquires three exposures for every image and combines them by selecting the median DN of the three for each pixel. This approach filters out most spurious 'salt-and-pepper' noise. The choice of 3 images in the multi-image median filter and 10× degree of compression were found to be optimal in preserving image information in a trade study described in Appendix A.

The length of C-LIFE operations cycles depends upon the number of images needed, and the time needed to readout the exposures and reposition the antenna. We expect typical exposure times to be ~75ms. We anticipate acquisition and readout of three exposures will take several seconds – conservatively we allocate 10 seconds to acquire and readout three exposures from both eyes. Current settling time for the antenna after repointing the camera (vibrations <0.25 mrad in 75 msec) is unknown, but antenna movement and settling will likely determine the total time needed for any image sequence. We allocate 30s for the small antenna movements (typically a few degrees) needed between images and vibration settling to < 1 mrad/s (0.3 pixel blur). The vault electronics run fast enough to ensure that three exposures from each eye can have the multi-image median filter applied to create one product and be compressed before the next exposures begin.

Some overlap between adjacent frames is required to prevent gaps that would have to be filled later. The pointing accuracy of the antenna is unknown and we assume 10% overlap in the panchromatic filter (20% overlap in the narrower color filters) will be sufficient.

### 2.3 C-LIFE Energy Costs

We list energy costs for each operations cycle below. Each has a duration or image count commensurate with its science goal, giving each operations cycle a unique energy cost.

Each operations cycle requires heating the DRM electronics to -50° C. Thermal simulations involving the whole camera head mass shows that a heater on each DRM would bring the electronics to operating temperature at 1K/min with a 44.3 kJ energy cost (88.6 kJ for both DRMs). After this warming phase we acquire images and pan the camera in 40 s blocks. Acquiring the three component images (for median filtering) from both eyes takes 10 s with each DRM using 2 W each. When panning the camera for the next image, the DRMs remain on in a quiescent mode for 30 s using 1.2 W each. Over these 40 s, the two DRMs use 112 J. The vault electronics processes the acquired images over these 40 s using 9.2W for an energy cost of 368 J. LEDs will only be active for 1s of each of the three exposures and use 15W for each of the two sets. Most images will not require LEDs, for those that do the energy cost is 90 J (an upper limit that assumes all LEDs are used) per image (three exposures from both eyes).

| Activity | Energy Cost |
|---|---|
| Pre-operations camera head heating | 44.3 kJ/operations cycle |
| Camera head image acquisition | 112 J/observation* |
| LED flash operation (used only in some cycles) | 90 J/observation* |
| Vault electronics data processing | 368 J/observation* |
| Camera head heating during operations | ** |
| Camera head heating to limit cooling rate | 0 J/operations cycle |

*An “observation” is three exposures from both eyes combined in a median filter to produce two image products over a total of 40 sec.

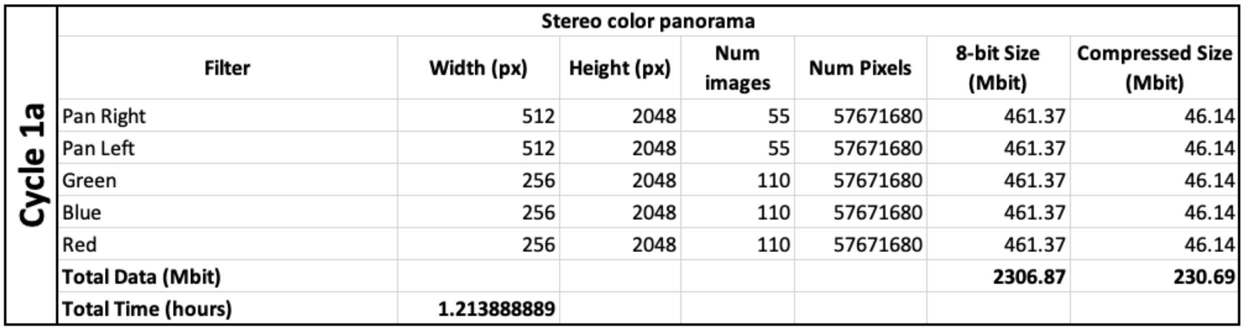
** Varies with time, see section 5.2.

## 2.4 C-LIFE planned operation cycles

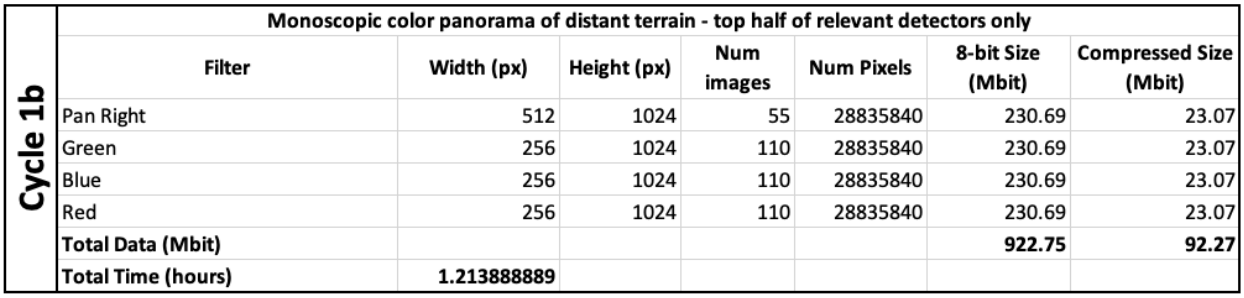
The operation cycles below describe five imaging cycles necessary for C-LIFE to fulfill its science goals. More imaging in support of engineering activities is likely and not included below.

### Cycle 1: Europan day 1, soon after landing

<u>Purpose and Products</u>: Collect data to produce a full color stereo panorama. Data acquired from both stereo eyes and in four filters for the near-field (cycle 1a). Non-stereo color data acquired for mid-field to horizon (cycle 1b).



| | Stereo color panorama | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Filter** | **Width (px)** | **Height (px)** | **Num images** | **Num Pixels** | **8-bit Size (Mbit)** | **Compressed Size (Mbit)** |
| **Cycle 1a** | Pan Right | 512 | 2048 | 55 | 57671680 | 461.37 | 46.14 |
| | Pan Left | 512 | 2048 | 55 | 57671680 | 461.37 | 46.14 |
| | Green | 256 | 2048 | 110 | 57671680 | 461.37 | 46.14 |
| | Blue | 256 | 2048 | 110 | 57671680 | 461.37 | 46.14 |
| | Red | 256 | 2048 | 110 | 57671680 | 461.37 | 46.14 |
| | **Total Data (Mbit)** | | | | | **2306.87** | **230.69** |
| | **Total Time (hours)** | **1.213888889** | | | | | |



| | Monoscopic color panorama of distant terrain - top half of relevant detectors only | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Filter** | **Width (px)** | **Height (px)** | **Num images** | **Num Pixels** | **8-bit Size (Mbit)** | **Compressed Size (Mbit)** |
| **Cycle 1b** | Pan Right | 512 | 1024 | 55 | 28835840 | 230.69 | 23.07 |
| | Green | 256 | 1024 | 110 | 28835840 | 230.69 | 23.07 |
| | Blue | 256 | 1024 | 110 | 28835840 | 230.69 | 23.07 |
| | Red | 256 | 1024 | 110 | 28835840 | 230.69 | 23.07 |
| | **Total Data (Mbit)** | | | | | **922.75** | **92.27** |
| | **Total Time (hours)** | **1.213888889** | | | | | |

### Cycle 2: Europan day 1, sunset and early night

<u>Purpose and Products</u>:

Plume Search by imaging the western sky immediately after sunset, requires monoscopic exposures in PAN (cycle 2a).

Nighttime Fluorescence searches with LEDs. Requires notch filter in right eye only. Mosaic 90° of azimuth in this manner centered on the workspace.

| Cycle 2a | Plume Search from western horizon to 30 degrees above horizon over 90 degrees of azimuth | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Filter** | **Width (px)** | **Height (px)** | **Num images** | **Num Pixels** | **8-bit Size (Mbit)** | **Compressed Size (Mbit)** |
| | Pan Right | 512 | 2048 | 14 | 14680064 | 117.44 | 11.74 |
| | **Total Data (Mbit)** | | | | | **117.44** | **11.74** |
| | **Total Time (hours)** | **0.147222222** | | | | | |

| Cycle 2b | Fluorescence search with three kinds of illumination over 90 degrees of azimuth | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Filter** | **Width (px)** | **Height (px)** | **Num images** | **Num Pixels** | **8-bit Size (Mbit)** | **Compressed Size (Mbit)** |
| | Notch Filter | 256 | 2048 | 84 | 44040192 | 352.32 | 35.23 |
| | **Total Data (Mbit)** | | | | | **352.32** | **35.23** |
| | **Total Time (hours)** | **0.925** | | | | | |

**Cycle 3: Europan day 2, sunrise**

Purpose and Products: Plume Search by imaging the eastern sky immediately before sunrise. Requires monoscopic exposures in PAN.

| Cycle 3 | Plume Search from eastern horizon to 30 degrees above horizon over 90 degrees of azimuth | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Filter** | **Width (px)** | **Height (px)** | **Num images** | **Num Pixels** | **8-bit Size (Mbit)** | **Compressed Size (Mbit)** |
| | Pan Right | 512 | 2048 | 14 | 14680064 | 117.44 | 11.74 |
| | **Total Data (Mbit)** | | | | | **117.44** | **11.74** |
| | **Total Time (hours)** | **0.147222222** | | | | | |

**Note: Lander Sampling activities are assumed to take place early in Europan day two.**

**Cycle 4: Europan day 2**

Purpose and Products: Collect data to produce a full color stereo coverage of the excavation site. Data acquired from both stereo eyes and in four filters. Mosaic 90° of azimuth in this manner centered on the workspace.

| Cycle 4 | Stereo color coverage over 90 degrees of azimuth | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Filter** | **Width (px)** | **Height (px)** | **Num images** | **Num Pixels** | **8-bit Size (Mbit)** | **Compressed Size (Mbit)** |
| | Pan Right | 512 | 2048 | 14 | 14680064 | 117.44 | 11.74 |
| | Pan Left | 512 | 2048 | 14 | 14680064 | 117.44 | 11.74 |
| | Green | 256 | 2048 | 28 | 14680064 | 117.44 | 11.74 |
| | Blue | 256 | 2048 | 28 | 14680064 | 117.44 | 11.74 |
| | Red | 256 | 2048 | 28 | 14680064 | 117.44 | 11.74 |
| | **Total Data (Mbit)** | | | | | **587.20** | **58.72** |
| | **Total Time (hours)** | **0.302777778** | | | | | |

**Cycle 5: Europan day 2, night**

Purpose and Products: Fluorescence searches with LEDs over excavated workspace. Requires notch filter in right eye only. Mosaic 90° of azimuth in this manner centered on the workspace.

| **Cycle 5** | **Fluorescence search with three kinds of illumination over 90 degrees of azimuth** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **Filter** | **Width (px)** | **Height (px)** | **Num images** | **Num Pixels** | **8-bit Size (Mbit)** | **Compressed Size (Mbit)** |
| | Notch Filter | 256 | 2048 | 84 | 44040192 | 352.32 | 35.23 |
| | **Total Data (Mbit)** | | | | | **352.32** | **35.23** |
| | **Total Time (hours)** | **0.925** | | | | | |

### 2.5 C-LIFE Energy and Data Production Summary

**Table 2.5.1.** High-level summary of data and energy used in each operations cycle

| Operations Cycle | Data Produced (Mbit) | Energy Used (kJ) |
|---|---|---|
| 1a+1b | 323 | 215.8 |
| 2a | 11.7 | 50.3 |
| 2b | 35.2 | 48.2 |
| 3 | 11.7 | 52.2 |
| 4 | 58.7 | 109.3 |
| 5 | 35.2 | 91.8 |
| **TOTAL** | **475.5 Mbit** | **567.6 kJ (157.7 W-Hr)** |

If every bit we acquired were to be returned to Earth, then C-LIFE would take most of the anticipated total downlink of 600 Mbit. Some of these images may be considered engineering support e.g. reimaging of excavation site. However, a reduction in C-LIFE's downlink footprint is clearly desirable.

With these ConOPs, energy usage is currently expected to be 568 kJ, which is ~10% of the total mission science allocation of 5.76 MJ (1600 W-Hrs). A breakdown of energy allocation per instrument is not available at this time; however, five instruments are expected with an average allocation of 1152 kJ. Thus, C-LIFE is anticipated to use significantly less energy than the average payload element (about half as much) and further energy reduction is not prioritized at this time.

### 2.6 Advanced C-LIFE ConOPs

Several strategies to reduce the data returned to Earth are possible if more onboard processing is available.

- *Automated detection of fluorescence in nighttime images:* This would remove the need for returning data in operation cycles 2b and 5 above. If fluorescence were detected, then only information on which pixels are affected need be returned. Savings of ~70 Mbit.
- *Higher compression of plume search images:* Plumes are expected to be large diffuse structures without pixel-level detail. A compression ratio of 100 would reduce the data volume of cycles 2a and 3 by an order of magnitude. Savings of ~20 Mbit.

### 2.7 Landing Site Limitations

Virtually all Europan landing sites are compatible with C-LIFE operations, which require periods of daylight and darkness. The only pathological exception would be landing exactly at the north or south pole.

C-LIFE utilizes daylight for most observations. Europa has a near-zero obliquity and so all latitudes experience daylight for the same length of time (half a Europan day). Sub-Jovian longitudes experience eclipses at noon as the sun passes behind Jupiter, but these last 2.8 hours at most. These same sub-Jovian longitudes experience significant Jupiter-shine at night that may allow imaging without the use of LED illumination.

The landing site is almost certain to be unshadowed each Europan day. Landing in a permanent shadow is impossible at the equator and extreme topography (inconsistent with our understanding of Europa) is required for permanent shadow at almost all other latitudes.

The north and south poles of Europa are problematic in two ways. At Europa's north and south poles the Sun circles the sky at the horizon and so landing in any topographic depression will result in permanent shadow. Europa's poles lack a day/night cycle so looking for plumes above the horizon just before/after sunrise/sunset cannot be done.

# 3. Architecture

The baseline Architecture for C-LIFE contains components in the camera head and spacecraft vault and is depicted in Figure 3. Within the camera head both eyes have independent optics, detectors, Detector Readout Modules (DRMs), LED modules, and heaters. In the spacecraft vault, there are two redundant Camera Service Modules (CSMs) each of which is independently connected to the spacecraft and both camera-head eyes. The camera head and the vault electronics are connected by two 2-m long cables.

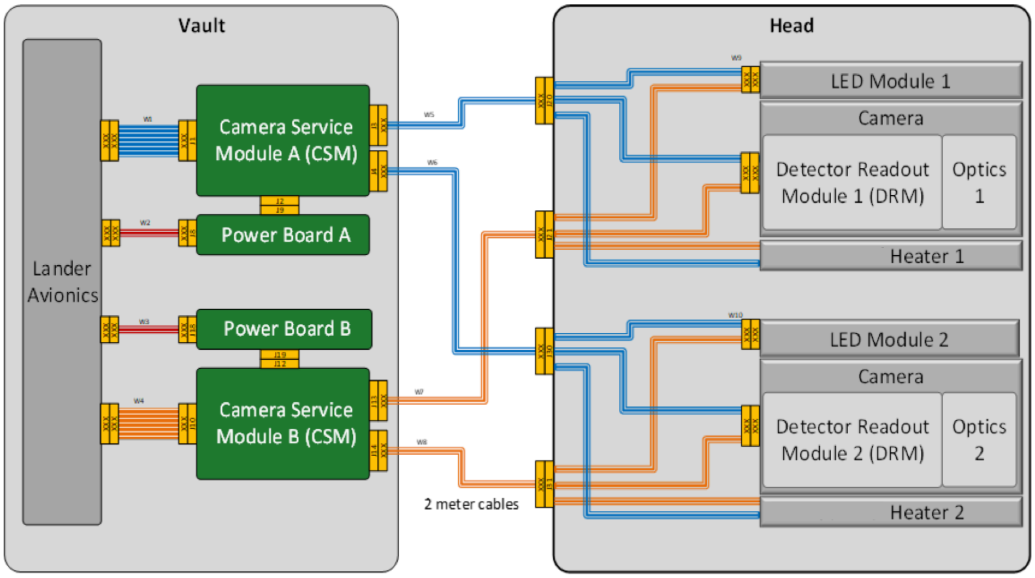


**Figure 3.** C-LIFE architecture.

### 3.1 Camera Head

The camera head utilizes a dual periscope design for both the LEDs and detectors (Figure 4). These LED- and detector-periscopes are offset vertically to enable a slim (6cm in depth) design. The slimline design allows C-LIFE to fit between the HGA and lander deck during cruise to Europa. The benefit of this configuration is that deployable covers are not required to protect the periscope windows.

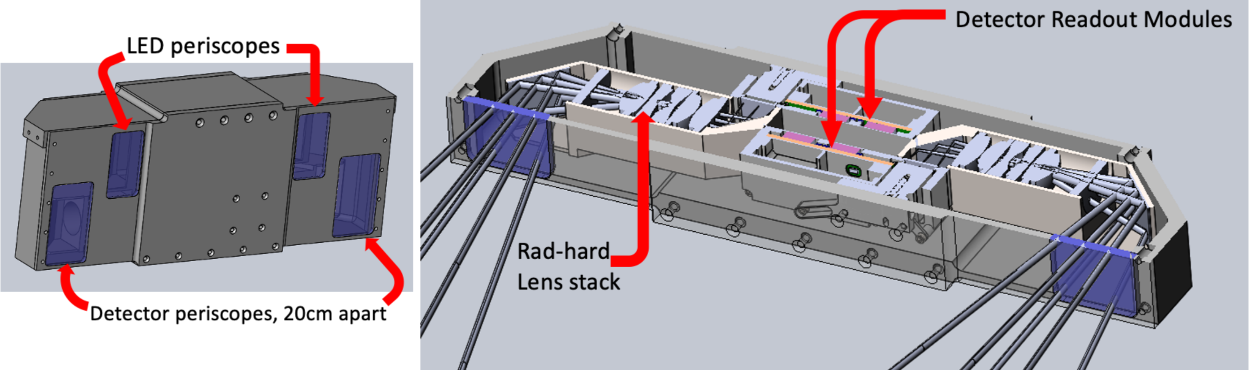


**Figure 4.** C-LIFE camera head utilizing dual-periscope design. Dimensions are 24.5 x 9.5 x 6 cm.

## Optics

The optics relay light through front windows, a series of lenses, and fold mirrors to focus on the CMOS detector that is housed in the DRM. C-LIFE optics (lenses and front window) use only cerium-doped BK7G18 and F2G12 rad-hard glass. At wavelengths longer than 450 nm these have negligible radiation-induced transmission loss up to >100 Mrad (Schott 2018; Henson and Torrington, 2001), so only our BLU filter may be marginally affected. We have tested high-performance Broad Band Anti-Reflection (BBAR) coating up to 2 Mrad for the OSIRIS-REx mission and measured no performance degradation. We anticipate having to use charge dissipative coatings such as ITO on at least some of the optical elements. We have identified a vendor (Research Electro-Optics) who provides high quality BBAR ITO coatings with space flight heritage for our DIEHARD project and will use these same coatings as necessary.

## Detector Readout Modules (DRMs)

Two identical DRMs house the CMOS detectors and readout electronics. The detector used is SRI's Mk x Nk radiation hardened CMOS imager in 1k x 2k format. The DRMs were designed by SRI International and based on the cryogenic detector packages that accommodate their 1k x 1k detector. As part of the C-LIFE program, SRI modified its design to accommodate a 1k x 2k detector, include an FPGA, an analog to digital converter, and all other components needed to run the DRM with minimal input from the vault.

The DRMs (Figure 5) are made up of the detector and two Printed Circuit Boards bonded to a central molybdenum plate. An analog Board to support the imager (Bond Pad connections), provide Analog Signal processing to be sent to the Digital board ADC differentially, and supply I/O connections to the Imager. A digital Board to provide ADC processing, distribute power, supply CMOS timing to the imager I/O (with an RTAX FPGA), receive commands from the CSM, and package parallel pixel data into a single serial stream with clock.

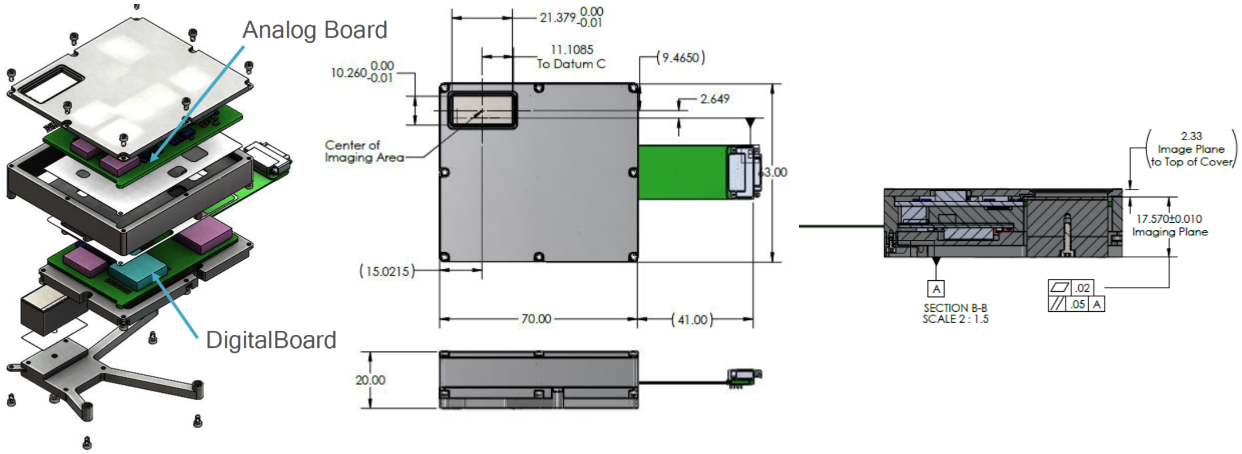


**Figure 5.** Exploded view of one DRM showing both electronics boards, detector pallet, and window. L x W x H: 70mm x 63mm x 20mm.

## LED Modules

Two LED modules are included with four vertical banks of 3 LEDs each. LED placement (Figure 6) mirrors that of filter layout in Figure 2.

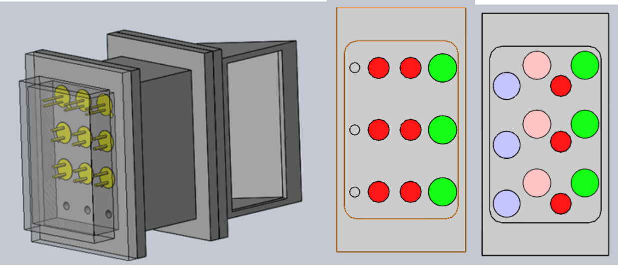


**Figure 6.** (left) LED periscope with fold mirror. LED arrangement on the left and right eye respectively.

Heaters

Each DRM is paired with a heater that warms C-LIFE for initial use and supplies trim heating needed to maintain operating temperatures or control cooling rates after use. The DRMs are thermally coupled passively to the C-LIFE enclosure using a carefully sized copper block that prevents overheating during use.

### 3.2 Vault Electronics

The vault electronics (Figure 7) consist of two identical Camera Service Modules (CSMs) and two identical Power Modules. The CSM commands components in the Camera Head, processes data digitized in the DRM, and transfers data products to the spacecraft. Each CSM and Power Module consist of a PCB with componentry affixed to a mechanical housing. The mechanical housings have identical profiles such that each of these assemblies can be bolted together to form one large housing for the electronics. End plates cap off the assembly to form an enclosure as well as provide radiation shielding. This design is modular and allows for the removal of redundant electronics if so desired.

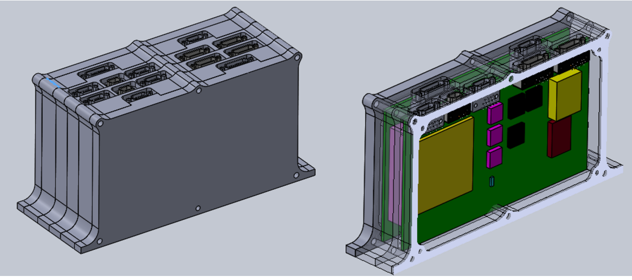


**Figure 7.** Vault electronics box assembly (left) consists of modular Power and CSM modules (right).

The CSM controls the high-level functions of the camera head as directed by the lander avionics. It receives commands from the lander avionics, decodes them and passes them along to the LEDs, heaters or DRMs. It acquires images, and is capable of performing basic image processing operations such as image binning, multi-image median to reduce radiation noise, dark subtraction, flat-fielding, and compression. It transmits packetized images to the avionics in either thumbnail (highly compressed) or full (10x compressed) form. It also packetizes and transmits housekeeping information such as voltages, currents, temperatures and sub-system states to provide an instrument health status. The CSM provides thumbnail versions of all images acquired by C-LIFE to the lander so that full image downloads can be prioritized through the limited available data downlink bandwidth. Additional image processing ability is being considered to further reduce the volume of data that is returned to Earth without diminishing the scientific / operational return of the instrument.

### 3.3 Cables

Two cables (one from each CSM), 2 m in length, connect the vault electronics and camera head and contain 35 wires each. The wires are planned to be 26AWG per M27500. There will be two connectors each at the head and two connectors each in the vault. The connectors will be microminiatures per M83513. Cable workmanship standard NASA-STD 8739.4A will be followed for assembly of the cables. EMI shielding comes from 3M 1811 copper tape wrapped with Kapton XC Black Conductive each with 50% overwrap. Glenair 100-022-016 PTFE-Glass overbraid is used to protect the wire. All electrical interfaces use a Class 1A (250V) minimum Human Body Model (HBM, 1500 Ohm, 100 pF) ESD circuit interface tolerance. We estimate each cable will have a mass of 600g.

### 3.4 Redundancy

The Baseline Architecture of C-LIFE (Figure 3) is designed to minimize the likelihood and consequence of a disruption from either the spacecraft or vault electronics.

From an engineering perspective, C-LIFE is considered a mission critical component of the Europa Lander. As such, UA looked at the heritage of mission critical camera systems to develop a redundancy plan. OCAMS, the three-camera suite on OSIRIS-REx, was designed and built by UA. As such, there is an in-depth understanding of the system design and motivations. UA has adopted the OCAMS philosophy for redundancy as the lowest risk option for the mission. This philosophy requires redundant electronics within the vault (labeled Primary and Redundant). Each side of the vault electronics (CSM) is connected to both cameras. Additionally, each side of the CSM is connected, via independent power interfaces, to both sides of the spacecraft. This architecture is the baseline architecture for C-LIFE. This section of the accommodation study will identify some of the highlights of the architecture, the consequences in terms of resources and spacecraft needs, and finally discuss other options including the resulting risk posture.

From a science perspective, the loss of a single camera eye affects C-LIFE's science return in several ways (rightmost column of Table 1) and these effects can be weighed when considering the level of instrument redundancy desired. C-LIFE's stereo capability requires two functioning eyes and all investigations that require stereo topography would be a total loss without both. C-LIFE's color capability is spread between both eyes, thus all investigations that require color data will be degraded if some colors are not available. C-LIFE's fluorescence investigation is located in one eye, thus loss of one eye is potentially a total loss of this investigation.

A more risk tolerant posture could be entertained. Without redundant vault electronics, significant savings could be accomplished.

- Cable mass between the vault and the camera head would be halved. We estimate the mass of both cables to be 1.2 kg, thus 600g could be saved.
- C-LIFE vault electronics mass and volume would be halved (or alternatively capability could be increased via a rad-hard compute board). Currently the vault electronics box is over the PIP allocation in mass and volume (see section 5.1).
- Only one power and data link to the spacecraft would be necessary (currently 2 are utilized).
- The spacecraft needn't ensure both sides are not accidently powered up at the same time. Currently the spacecraft must ensure this via run rules or some other means, e.g. run rules were used in OSIRIS-REx.

# 4. Environmental Compatibility

## 4.1 Radiation Simulations

In a collaborative effort, the C-LIFE team (Ball, SDL, SRI & UA), over 3 design iterations, has refined the C-LIFE head and vault mechanical designs in order to effectively shield the electronic components housed within their interiors. The head design currently sits at Version 4 and the vault design at Version 3. From a radiation standpoint, the changes more significant for achieving radiation durability occurred earlier in the design process. The most recent changes have been less dramatic and more motivated by design manufacturability.

Lead mechanical designer Steve Meyer received Version 1 in July of 2019 and refined it over a period of several months until October 29. Version 2 (Oct. 29, 2019→ Jan. 7, 2020) made minimal changes before a Technical Interchange Meeting and the assembled partners made a number of recommendations. The Ball Aerospace radiation effects analysis team analyzed this version and returned the first radiation analysis report on February 7, 2020; this analysis itself went through several iterations with the final version delivered on Mar. 26, 2020. Version 3 of the head's mechanical design (Jan. 7 → May 14, 2020) incorporated these recommendations and made the most significant changes (from a radiation standpoint) of all of the design iterations. The UA handed off this iterated design to Ball on May 14 who returned a report in July 9, 2020. Version 4 covers the period from May 14 until the present.

Ball analyzed the vault mechanical design's radiation disposition and returned that report's first version on May 11, 2020. UA updated the vault design, re-submitted it and Ball re-analyzed it, returning the second vault report on Aug. 11, 2020.

Table 4.1.1 and Figures 8-11 summarize the evolution of the C-LIFE design. Version 1 of the head design separated the distance between the redundant DRM's in order to make space for the Remote Service Modules (RSMs; circuit boards within the head, but outside the DRMs. These boards were removed in later design iterations) (Fig. 8); it moved the LED lamps from being outboard of the optics pass-through windows to being stacked above them; the design also implemented 500 mil of Al thickening in order to establish base shielding and achieve ballpark dosage levels. Version 2 added 5 mm of thickness directly around the equator of both DRM's (Fig. 9). In response to Ball's report and evolution of the electronic design, in Version 3, SRI tripled the DRM top cover thickness in order to reduce dosage by 45% to 80 krad, UA altered the design of the squared-off corners to angled corners in order to save material, added material to the detector front housing, lightened in areas away from DRM's, around the mirrors and windows where there weren't any sensitive electronics, doubled the number of connectors to maintain redundancy and added connectors to the RSM's in response to a changing electronic design (Fig. 10). The revised design was submitted to Ball for a second round of radiation analysis on May 14, 2020 (Fig. 11). Table 4.1.2 presents the results of this analysis.

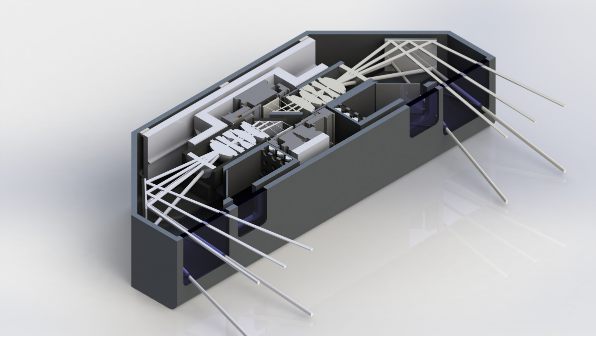


**Figure 8** Version 1 The design inherited from previous programs.

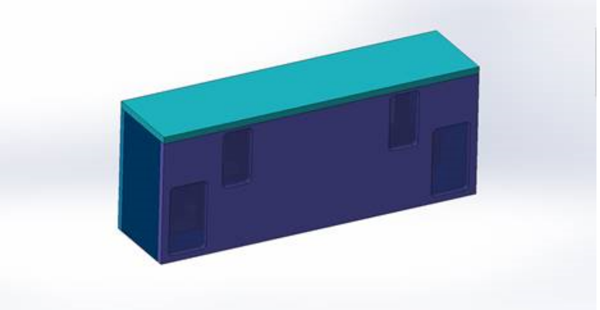


**Figure 9** Version 2 started from scratch in order to make sure that nothing had been missed in previous designs. It had to thin the package to meet the 6cm requirement for mounting on the antenna. This required the eyes to move farther apart. The LEDs were stacked above the lens barrels also to accommodate the new package as well as provide shielding for the RSMs.

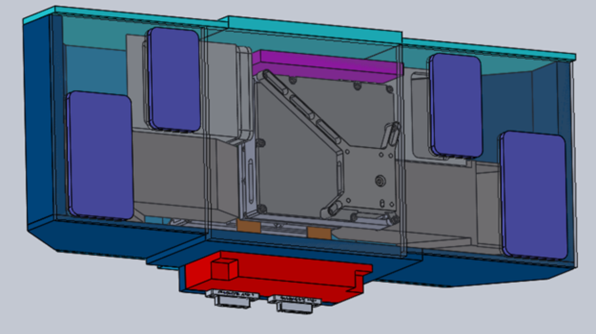


**Figure 10** Version 3 produced the most significant design changes. The design removed material in areas near lenses and mirrors and returned to angled corners to save mass.

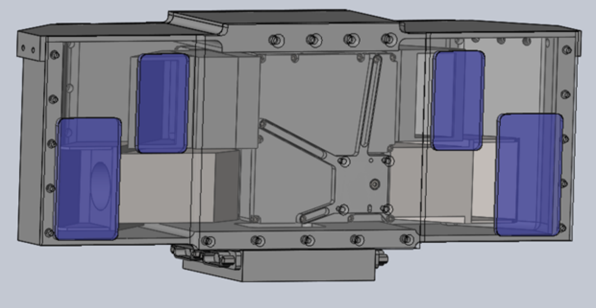


**Figure 11** Version 4 improved manufacturability. Note that new DRMs are taller and provide shielding for previously exposed LEDs. The RSMs have been removed, so the DRMs are no longer sunken into the camera housing.

The results for the camera head are shown in Table 4.1.2. Several components require further testing or analysis, which will be a priority for us in the remaining ICEE-2 timeframe (see Appendix C for radiation test plan). An additional radiation model is being conducted now with the expectation that the most recent design changes will obviate the need for testing some of these components.

**Table 4.1.1.** Changes implemented in each Camera Head Version

| Camera Head Version | Changes |
|---|---|
| 1 | ● UA separated the distance between the redundant DRM's<br>● Moved LED lamps<br>● Implemented 500 mil of Al thickening |
| 2 | ● UA thickened DRM shielding by 5mm around equator<br>● Submitted to Ball for 1st round of radiation analysis |
| 3 | ● SRI tripled DRM top cover thickness<br>● UA altered design of squared-off corners to angled corners<br>● Added shielding to the detector front housing<br>● Lightened assembly in areas away from DRM's<br>● Doubled connector count to maintain redundancy<br>● Added connectors to the RSM's<br>● Submitted to Ball for 2nd round of radiation analysis |
| 4 | ● Design altered to enhance manufacturability |

**Table 4.1.2.** Results of radiation modeling show the radiation ionizing and non-ionizing doses received by the various C-LIFE head sub-assemblies during a single mission lifetime (1X) are well below 300 krad-Si and 5.0E+08 MeV/g-Si, respectively, with the exception of the more extremely mounted LED's which have since been moved into more shielded positions.

| | RSM | Imager | Analog | Digital (Front) | Digital (Back) | LEDs |
|---|---|---|---|---|---|---|
| 1X Ionizing Dose (krad-Si) | 65.6 | 76.4 | 36.8 | 46.6 | 73.3 | 82.2 - 166 |
| 1X Non-Ionizing Dose (MeV/g-Si) | 1.80E+08 | 1.90E+08 (5.11E+10 63 MeV p/cm$^2$) | 1.07E+08 | 1.30E+08 | 2.24E+08 | 2.28E+08 – 4.83E+08 |

The results for the Vault are shown in Table 4.1.3. The shielding provided by the vault itself, the walls of the instrument electronics assembly and the component packaging represents almost a 1 full inch of Al's worth of effective thickness.

**Table 4.1.3.** Results of radiation modeling show the radiation ionizing and non-ionizing doses received by the C-LIFE vault CSM and Power slices during a single mission lifetime (1X) are well below 300 krad-Si and 5.0E+08 MeV/g-Si, respectively.

| | **CSM** | **Power** |
|---|---|---|
| 1X Ionizing Dose (krad-Si) | 58.3 | 59.7 |
| 1X Non-Ionizing Dose (MeV/g-Si) | 1.98E+08 | 2.03E+08 |
| Effective Thickness (mil-Al) | 944 | 932 |

See Appendix C for a list of which components require additional testing or analysis.

## 4.2 Thermal Survival Tests

In order to minimize C-LIFE's energy budget, the antenna-mounted camera head is designed to survive Europan temperatures without requiring spacecraft-provided survival heat. In our CONOPS, the camera will be heated to its operating temperature before being turned on and then left to passively cool down after use. This preheating accounts for a significant part (54%) of C-LIFE's energy budget. So, in addition to verifying that the C-LIFE electronic components are able to survive thermal cycling to and from Europan ambient temperature our testing also aims to find out how low a temperature the system can be run so preheat energy can be minimized.

We prioritized testing based on the programmatic risk of a component failing our thermal requirements. This programmatic risk captures both the technical risk that a particular component may fail, and the availability of alternative components acceptable for our design.

As a result, we started with cold testing of SRI's Mk×Nk detector (performed at SDL, see Figure 12 and 13). This test successfully demonstrated operation (consistent PTC curves and dark current measurements (Table 4.2.1)) of a cryopackaged 1k × 1k detector at temperatures down to -80C (193K) and survival to 100K. The 1k × 1k detector was chosen because it is similar in design, fabrication process, and packaging to the 2k × 1k detector baselined for C-LIFE. Unlike the 2k × 1k detector, 1k × 1k dyes already existed therefore did not require a costly microfabrication fab run.

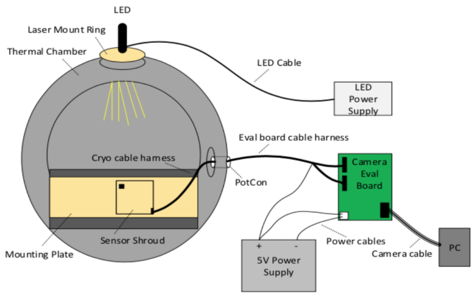
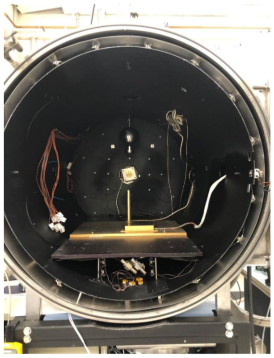


Figure 1: Test Setup



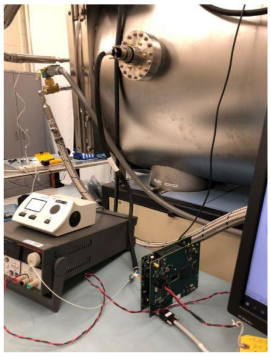


**Figure 12.** SRI's 1kx1k Detector Thermal Cycling Setup Schematic, Inside and outside of thermal vacuum  test chamber at SDL.

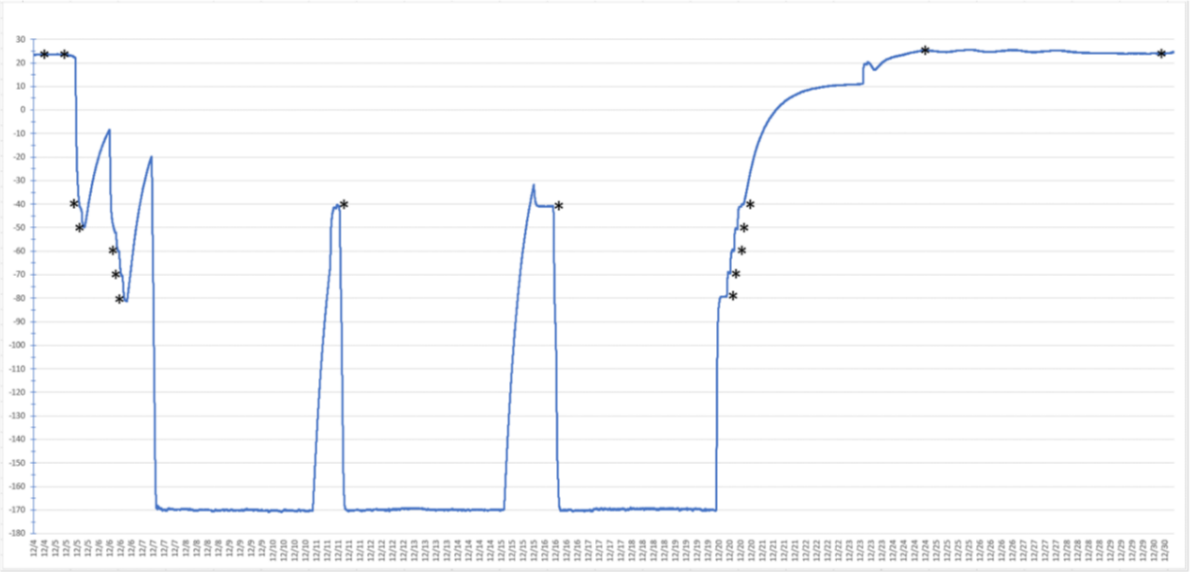


**Figure 13.** SRI 1k×1k Detector Thermal Cycling Temperature Curve

| Parameter[1] | Units | +20C[2,3] | +20C[3] | -40C[3] | -50C | -60C | -70C | -80C | -40C | -40C | -80C | -70C | -60C | -50C | -40C | +20C | +20C[2] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dark Current | e-/pix/s | 1045.70 | 973.91 | 9.78 | 0.48 | 2.136 | 6.63 | 22.56 | -6.40 | -2.98 | 10.79 | 16.69 | 13.26 | 7.50 | -1.29 | 802.17 | 1234.72 |
| Dark Current uncertainty | e-/pix/s | 213.03 | 191.22 | 10.59 | 5.47 | 18.51 | 12.25 | 32.07 | 11.76 | 7.24 | 28.61 | 13.19 | 6.51 | 6.77 | 6.01 | 184.98 | 211.40 |
| DSNU | DN/s | 547.46 | 517.94 | 14.77 | -3.29 | 3.18 | -1.89 | -4.71 | -7.47 | 2.45 | 0.98 | 0.93 | 0.08 | 1.49 | 2.21 | 135.96 | 126.73 |
| PRNU | % | 11.09 | 10.25 | 10.81 | 8.44 | 8.46 | 8.99 | 8.44 | 8.43 | 8.64 | 9.36 | 8.51 | 8.39 | 8.29 | 8.51 | 8.30 | 8.70 |
| Read Noise | e- | 11.78 | 11.73 | 10.63 | 12.50 | 12.10 | 11.10 | 11.97 | 11.93 | 12.26 | 12.05 | 12.02 | 12.02 | 12.73 | 12.19 | 13.28 | 13.19 |
| Read Noise uncertainty | e- | 0.072 | 0.079 | 0.084 | 0.091 | 0.096 | 0.070 | 0.072 | 0.104 | 0.082 | 0.092 | 0.164 | 0.071 | 0.072 | 0.075 | 0.070 | 0.0724 |
| Gain | e-/DN | 0.56 | 0.56 | 0.53 | 0.52 | 0.53 | 0.53 | 0.53 | 0.55 | 0.55 | 0.50 | 0.50 | 0.53 | 0.55 | 0.55 | 0.57 | 0.57 |
| Non-linearity | % | 3.00 | 3.00 | 3.29 | 2.72 | 3.51 | 3.13 | 3.42 | 4.31 | 3.42 | 2.78 | 2.76 | 3.54 | 3.84 | 3.47 | 3.79 | 3.58 |
| Dynamic Range | DN | 1365 | 1379 | 1503 | 1356 | 1441 | 1480 | 1457 | 1508 | 1417 | 1234 | 1351 | 1448 | 1409 | 1456 | 1278 | 1263 |
| Well Depth | e- | 21669 | 21800 | 21749 | 22364 | 23076 | 21658 | 23112 | 23802 | 22922 | 19623 | 21522 | 22920 | 23754 | 23654 | 21622 | 21381 |

[1] *DSNU* *Dark Signal Non-Uniformity*
*PRNU* *Photon Response Non-Uniformity (gain uniformity) @ 50ms*

[2] *These tests were taken while the chamber was not under vacuum.*

[3] *The four video offsets on these tests were slightly lower than the following tests resulting in numerous pixels reading zero DN at dark. The remainder of the tests had higher offsets to bring it above zero.*

**Table 4.2.1** SRI MkxNk Detector Performance during TVAC test

With the detector test complete and satisfactory we proceeded to test the ST RHF1401 Analog to Digital Converter (ADC), RTAX 250SL Field Programmable Gate Array (FPGA) and the Vorago VA10820 microcontroller. Two boards were designed, fabricated and programmed. A small printed circuit  board that includes the only the ADC, FPGA and Microcontroller and can be installed in our thermal vacuum chamber was designed and built (Figure 14). A second printed circuit board to provide power, reference signals, as well as inputs and outputs necessary to test the ADC, FPGA and microcontroller was also designed and built at SDL. An electronic test procedure was developed and validated at SDL and a TVAC test plan was developed, proven without the test hardware and finally executed at UA (see figure 14).

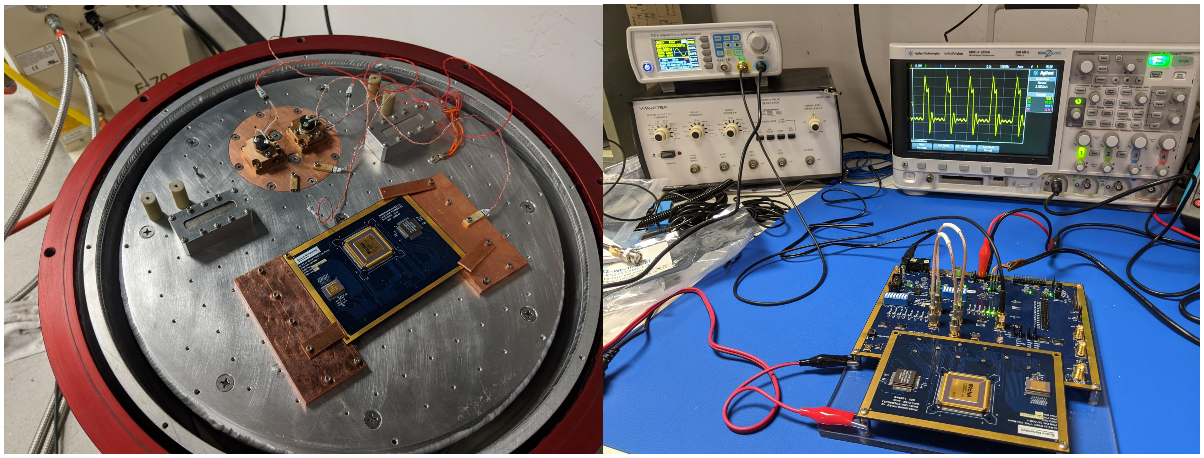


**Figure 14** Test board equipped with ADC, FPGA and Microcontroller mounted to the cold plate of cryostat at UA (left). Test board connected to Board connected to custom-designed interface board to verify performance after a cold run (RIGHT).

We tested the function and performance of the components before and after each of a series of cold soaks (Figure 15) at decreasing temperatures all the way to 100K without seeing any measurable effect on function or performance.

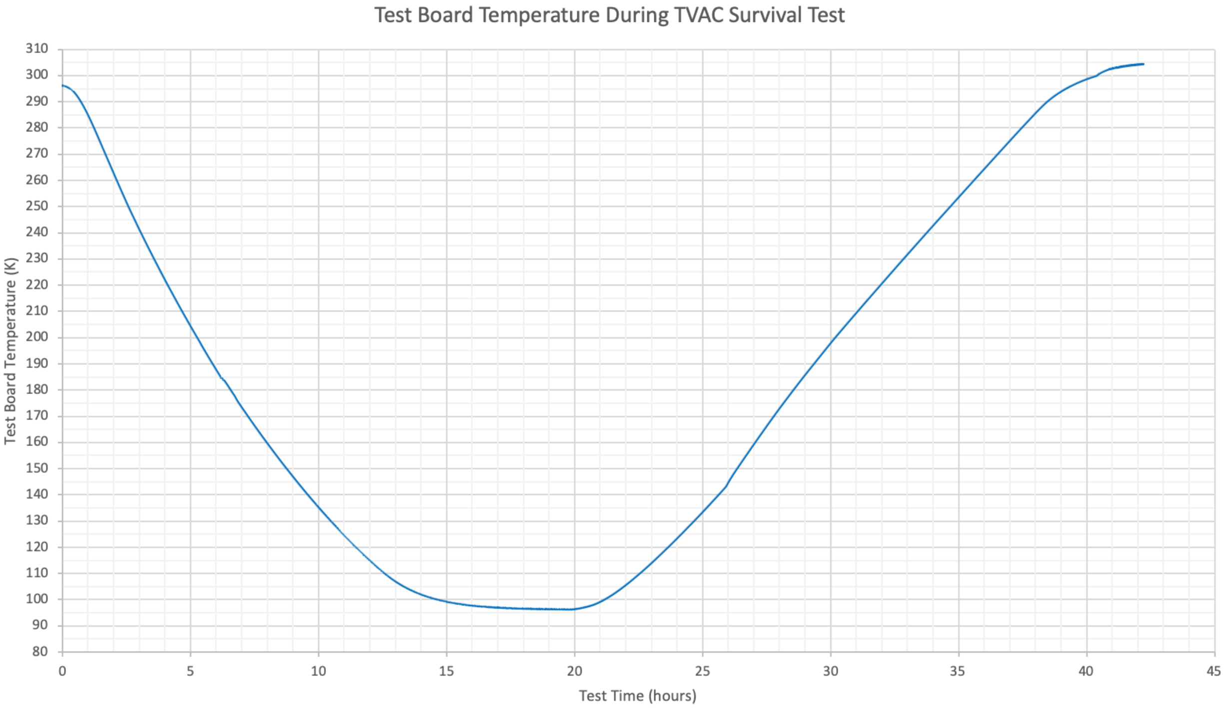
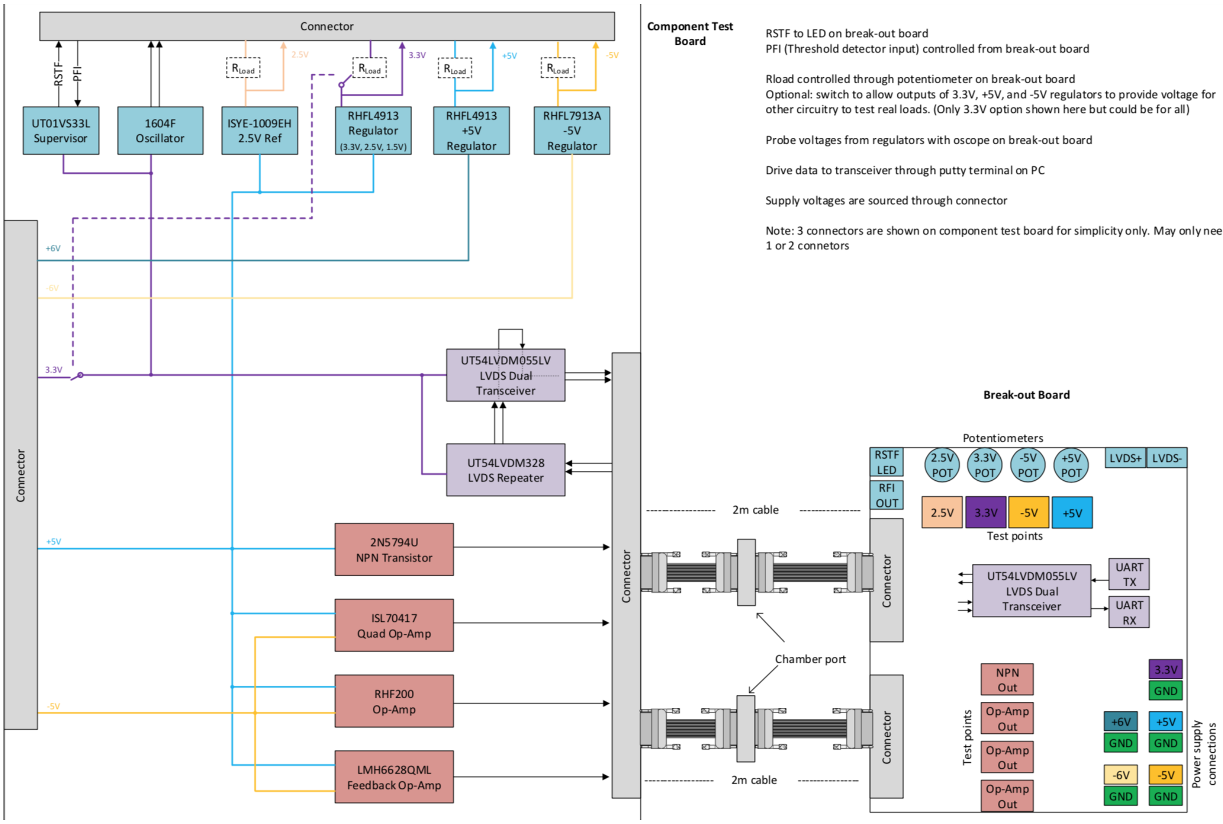


**Figure 15** Test board temperature during 100K survival test. The board was cooled and held at or below 100K for approximately 6 hours.

To minimize setup cost this test was only designed to verify survival to low temperature. Part performance was evaluated at room temperature before and after cold testing and showed no degradation for any of the parts. The test was performed at UA in a thermal vacuum cryostat procured under COLDTech. Having demonstrated survival to Europan ambient for all three parts, we are now planning to test their performance at temperatures in the -50 to -100C range in a liquid nitrogen cooled Sun temperature chamber purged with dry nitrogen gas, which is setup at UA.

Our next step is to test the survival of the remaining lower-risk electronic components in the imager head. This test is being planned for 2021 at UA. As in the previous test SDL has been contracted with the design and fabrication of a component test board and a break-out board interface board (figure 16). The test will address survivability and minimum operating temperatures the necessary op-amps, transistors, LVDS communication modules, oscillator, reference voltage supplies and regulators. Passive components such as resistors, capacitors and LEDs will be tested separately.



RSTF to LED on break-out board

PFI (Threshold detector input) controlled from break-out board

Rload controlled through potentiometer on break-out board

Optional: switch to allow outputs of 3.3V, +5V, and -5V regulators to provide voltage for other circuitry to test real loads. (Only 3.3V option shown here but could be for all)

Probe voltages from regulators with oscope on break-out board

Drive data to transceiver through putty terminal on PC

Supply voltages are sourced through connector

Note: 3 connectors are shown on component test board for simplicity only. May only need 1 or 2 connetors

**Figure 16** Cold test boards on order for TVAC test at UA in 2021. Together these two boards allow the testing of all the electronic components baselined for the imaging head that have not yet been tested.

### 4.3 Planetary Protection Assessment

NASA has designed the Europa Lander mission a Category IV planetary protection mission per JPL D-TBD (Categorization Letter and JPL Lander PPP), which flows requirements from NPR 8020.12D. Per NPR 8020.12D. Category IV planetary protection missions are lander/probe missions with the following planetary target priority: *of significant interest relative to the process of chemical evolution and/or the origin of life and for which scientific opinion provides a significant chance that contamination by spacecraft could compromise future investigations*. The C-LIFE portion of the Europa Lander mission is baselined to land on the surface of the body. As such, protection of Europa from terrestrial organisms is of concern. C-LIFE will meet the requirements for Category IV Planetary Protection mission designation per NPR 8020.12D and JPL D-TBD (JPL Lander PPP).

The current baseline approach to satisfy planetary protection requirements for microbial reduction includes a final Dry Heat Microbial Reduction (DHMR) bakeout of the deliverable hardware at 126°C for 207 hours. This will result in a 6-log microbial reduction for mated surfaces provided that the initial bioburden load meets the requirement.

As shown in Table 4.3.1, all C-LIFE parts, for which maximum storage or survival temperature information is available, are survival-rated to temperatures higher than 126 C. They will be able to withstand the planned microbial reduction operation with no degradation or loss of performance.

Other C-LIFE parts classes (adhesives used for optical mounting and/or mechanical stabilization and conformal coats, glass and metal materials) suffer zero degradation from the DHMR heating event.

**Table 4.3.1.** C-LIFE Parts List Planetary Protection Disposition

| Generic Part Number | Manufacturer | Description | On PPCL/PPSL? | Max. Operating/Storage Temp. from Tech. Data Sheet (°C) | Location |
|---|---|---|---|---|---|
| UT54LVDM055LV | Cobham | LVDS Dual Driver/Receiver | Yes | 125/150 | CSM/Vault |
| 69F192G24RPFE | DDC | NAND Flash, 192Gbit | No | 125/150 | CSM/Vault |
| ISL71590SEHVF | Intersil | Temperature Transducer | Yes | 125/150 | CSM/Vault |
| RT4G150-CG1657V<br>RT4G150-1CG1657V | Microsemi | FPGA | Yes | 125/150 | CSM/Vault |
| RHFL4913S33-03V | STMicro | 3.3 V rad-hard positive fixed voltage regulator | Yes | 150 | CSM/Vault |
| RHFL4913A | STMicro | MICROCIRCUIT, LINEAR, POSITIVE, ADJUSTABLE, LOW DROPOUT, VOLTAGE REGULATOR, MONOLITHIC SILICON | Yes | 150 | CSM/Vault |
| RHFAD128 | STMicro | 8 CH, 50ksps- 1Msps, 12 bit | No | 125/150 | CSM/Vault |
| 1604F100M0000BF (TBR) | Vectron | 100 MHz oscillator | No | 125 (24 hrs at 150) | CSM/Vault |
| UT01VS33L | Cobham | Voltage Supervisor | Yes | 125/150 | DRM/Head |
| ISYE-1009EH | Intersil | Reference 2.5V | IS-1009EH on list | 125/150 | DRM/Head |
| ISL71590SEH | Intersil | 2-termianl Temperature Transducer (AD590) | Yes | 125/150 | DRM/Head |
| ISL70419 | Intersil | IC, QUAD Precision Op Amp | ISL70419SEH on list | 125/150 | DRM/Head |
| RTAX250S | Microsemi | Radiation-Tolerant FPGA | RTAX250SL-CG624V on list | 125/150 | DRM/Head |
| 2N5794UC | Semicoa | Dual Matched NPN switching transistor | Yes | 200 | DRM/Head |
| RHFL4913S25-03V | STMicro | 2.5 V rad-hard positive fixed voltage regulator | Yes | 150 | DRM/Head |
| RHFL4913S33-03V | STMicro | 3.3 V rad-hard positive fixed voltage regulator | Yes | 150 | DRM/Head |
| RHF1401 | STMicro | Rad-hard 14-bit 20 Msps A/D converter | Yes | 125/150 | DRM/Head |
| RHFL4913S15-03V | STMicro | 1.5 V rad-hard positive fixed voltage regulator | Yes | 150 | DRM/Head |
| RHF200 | STMicro | Diff Amp | Other RHF parts on list | 125/150 | DRM/Head |
| LMH6628QML | TI | Dual Wideband, Low Noise, Voltage Feedback Op Amp | LMH6628 on list | 125/150 | DRM/Head |
| 1604F040M0000BF | Vectron | Oscillator 40MHz Single Pair LVDS | No | 125 (24 hrs at 150) | DRM/Head |
| M3GB2803R305T | IR |  | Yes | 125 | PWR/Vault |
| UT54LVDM055LV | Cobham | LVDS Dual Driver/Receiver | Yes | 125/150 | CSM/Vault |
| ISL70061SEH or<br>ISL70062SEH 10A | Intersil |  | No | 125/150 | CSM/Vault |
| RHRPMPOL01 | STMicro | Rad-hard 7 A point-of-load synchronous step-down regulator | No | 125 | CSM/Vault |
| 1604F20M0000BF (TBR) | Vectron | 20 MHz oscillator | No | 125 (24hrs at 150C) | DRM/Head |
| RHFL7913A | STMicro | Rad-hard adjustable negative voltage regulator | Yes | 125/150 | CSM/Vault |

# 5. Requirements

## 5.1 Physical

Volume

C-LIFE’s design philosophy involves no moving parts, including the elimination of deployable lens covers. We therefore desire the camera head to be stowed facedown on the lander deck to protect the optics from debris mobilized during the landing. There is only 6cm between the stowed HGA and lander deck and this dimension drives the C-LIFE mechanical design. Another potential solution is to stow the HGA at an angle so this constraint can be relaxed; however, our current design meets the 6cm requirement.

The C-LIFE camera head meets the 6cm critical dimension and is 60mm x 245mm x 107 mm with a mounting hole pattern (easily changed) of 70mm x 80mm as represented in Figure 17 below. The camera head design meets the PIP allocated volume in all dimensions.

The C-LIFE Vault electronics do not currently meet the PIP allocation in all dimensions. The vault electronics volume allocation is defined in the PIP to be 48mm x 216mm x 120mm. We assume that the connectors to the lander are within this volume. In the development and layout of the baseline design, the redundant nature of the vault electronics required a total of 4 boards to be housed within the vault and connectors from each side of the vault electronics to each of the cameras. Given those interfaces, the total expected volume of the baseline vault electronics is 78mm x 200mm x 103mm (Figure 17) with a mounting hole pattern of 45mm x 185mm. C-LIFE’s vault electronics exceed the PIP volume expectation, in one dimension (78mm vs 48mm allocated). Removing the redundant electronics would allow us to meet the volume constraint. However, this strategy increases risk in a mission-critical capability. Discussion between the C-LIFE and Lander teams is needed to resolve this issue.

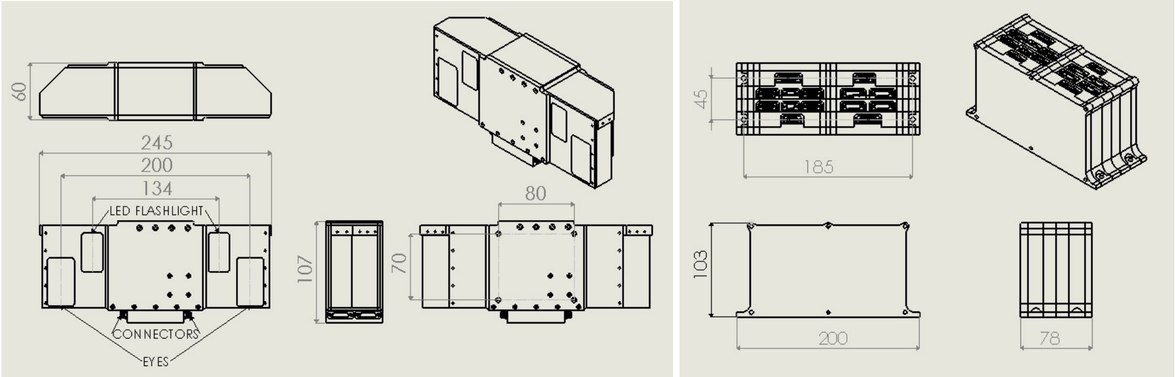


**Figure 17.** Schematics of C-LIFE camera head (left) and vault electronics (right).

Mass

The Mass of the Camera Head (breakdown in Table 5.1.1) totals 2.6 kg. This is less than the PIP allocation of 3.1 kg; however, the C-LIFE mass does not include the cables to the vault. Discussion between the C-LIFE and Lander teams is needed to resolve who is responsible for the cable mass and readjust the Camera Head mass allocation if necessary.

**Table 5.1.1.** Mass Breakdown of C-LIFE camera head.

| Part | Wt ea (g) | Qty | Total Wt (g) |
|---|---|---|---|
| Cover, Camera, Top | 181 | 1 | 181 |
| Cover, Camera, Front | 176 | 1 | 176 |
| Main Chassis, Camera | 275 | 1 | 275 |
| Cover, Camera, Rear | 176 | 1 | 176 |
| Lens Barrel, Left | 107 | 1 | 107 |
| Lens Stack | 18 | 2 | 37 |
| Lens Barrel, Right | 104 | 1 | 104 |
| Pass Through Cover | 54 | 1 | 54 |
| Optics Window | 28 | 2 | 56 |
| LED Window | 19 | 2 | 38 |
| LED Assembly | 46 | 2 | 92 |
| Connectors | 12 | 8 | 96 |
| Internal Wiring | 50 | 4 | 200 |
| Detector Assembly | 450 | 2 | 900 |
| Misc Fasteners | 100 | - | 100 |
|  |  | **Total** | **2592** |

The mass of the C-LIFE vault electronics is estimated at 2.2 kg. This exceeds the PIP allocation for the camera vault electronics of 1.2 kg. The total mass of the C-LIFE instrument (head+vault, but not including cables) is 4.8 kg, which is more than the 4.3 kg total allocated in the PIP. Again, the elimination of the redundant electronics would bring C-LIFE under the PIP allocation, but is a significant sacrifice.

**Table 5.1.2.** Mass Breakdown of C-LIFE Vault Electronics.

| Component | Material | Mass (g) | Qty | Line Total |
|---|---|---|---|---|
| Housing, Power Slice | Aluminum | 92 | 2 | 184 |
| Housing, Control Slice | Aluminum | 122 | 2 | 244 |
| Housing, Cover | Aluminum | 373 | 2 | 746 |
| Power Board | Electronic Board | 238 | 2 | 476 |
| Control Board | Electronic Board | 78 | 2 | 156 |
| Connectors | Stainless Steel | 216 | net | 216 |
| Fasteners | Alloy Steel | 150 | net | 150 |
|  |  |  | **Total:** | **2172** |

### 5.2 Power

C-LIFE power needs are divided between heat to the imaging head and power required to run the vault electronics and the DRM electronics. In order to minimize heat energy needs, the head is left unheated when not in operation. Even so, heat to the DRM makes up most of the energy used by C-LIFE. In our current CONOPS, the DRM is heated to its operating temperature (-50C) starting approximately two hours before use. As the DRM reaches its operating temperature, the DRM is turned ON and the heater power is decreased as needed to maintain constant DRM temperature. In this approach, the cold biased DRM uses the mass of the enclosure as a heat sink allowing the DRM to maintain the desired operating temperature by cycling its heater as needed. Our simulations demonstrate that the heavy enclosure needed to provide radiation shielding has enough thermal mass to support the longest imaging campaign planned. Additionally, the amount of power needed to warm the DRM up to its operating temperature and run it is only a relatively small portion of the power allocated to the Europa Lander instruments. The initial results of our modelling are provided below. They are encouraging, but more work is needed to improve the fidelity of our model and optimize C-LIFE's heat management strategy.

C-LIFE power needs can be divided into several categories (see also ConOPs in Section 2). Note we do not include the energy required to move the HGA for our imaging.

- Heaters raise the camera head electronics to -50C for operation at a rate of 1K/minute (work is ongoing to lower the operating temperature and thereby minimize power needed. We expect operating temperatures lower than -80C may be possible). Power can be adjusted by controlling heater duty cycle over this warming period and for each camera eye needed starts near zero, ends at a maximum of 7.8 W and averages 6W.
- The vault electronics use 9.2 W and operate during C-LIFE's five operations cycles that range in duration from 0.15 to 2.43 hours.
- During operations cycles, heating persists to maintain detector temperature (Figure 18). Heat is also created by detector operation and lost to the C-LIFE enclosure. As the enclosure warms and accepts less heat from the electronics then the heaters are reduced. When the heaters reach zero power after ~2.5 hours then C-LIFE can no longer operate without the camera head electronics warming above -50C. We do not anticipate operating C-LIFE at warmer temperatures.
- C-LIFE consumes power to operate each DRM (2W for 10s of imaging, 1.2 W for 30s of panning to new image location).
- C-LIFE consumes power to operate the LEDs (15W over 1s for each exposure; 3 exposures per image).

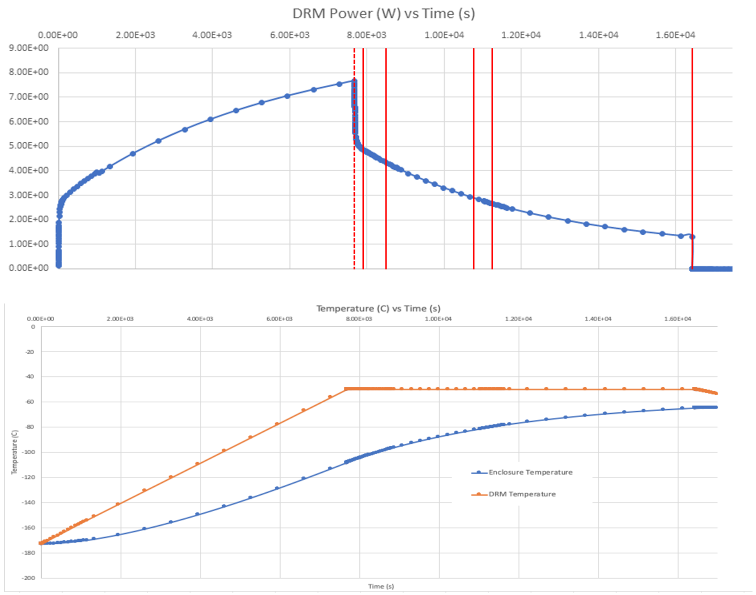


**Figure 18.** (Top) Total heating of one DRM vs time (from heaters and operations). Initial heating occurs until 7380s (red dashed line). Imaging stops at one of the solid red lines (depending on which operations cycle is executing). (Bottom) C-LIFE enclosure and DRM temperature vs time. When the temperature of the enclosure gets too close to that of the DRM then it can no longer absorb waste heat from the electronics and imaging stops.

Peak power (Figure 19)needs occur at the start of imaging in each operations cycle and in short peaks due to LED use in some operations cycles. At the beginning of each cycle, the vault electronics are running and heating is being completed to two DRMs for a total of 24.8 W. Power to the heaters is quickly reduced to ~5W and operating power to the DRMs and LEDs is supplied. Operating power to DRMs and LEDs depend on which operations cycle is executing, but averages range from 1.4 to 3.7 W. Short-lived (1s) peaks occur during cycles 2b and 5 when using LEDs to search for fluorescence - these peaks can reach 31.2 W near the beginning of these cycles.

Total power profile for all five operations cycles are shown in Figure 19. Total energy broken down by operation cycle and activity is shown in Table 5.2.1.

**Table 5.2.1.** Energy costs for C-LIFE operation broken down by activity and cycle. Note that the ‘keep warm’ costs for the DRMs are combined for cycles 1a+1b and 2a+2b. Percentages (bottom row) clearly show energy costs are dominated (80% of total) by initial warmup of the DRMs and the running of the vault electronics.

| Op Cycle | Warmup DRM 1 | Warmup DRM 2 | Vault | Keep Warm DRM 1 | Keep Warm DRM 2 | Image Energy DRM 1 | Image Energy DRM 2 | LED Energy | Energy cost (J) |
|---|---|---|---|---|---|---|---|---|---|
| Cycle 1a | 44300 | 44300 | 40480 | | | 6160 | 6160 | | 141620 |
| Cycle 1b | | | 40480 | 10600 | 10600 | 6160 | 6160 | | 74220 |
| Cycle 2a | | 44300 | 5152 | | | 0 | 784 | | 50250 |
| Cycle 2b | | | 30912 | | 8730 | 0 | 4704 | 3780 | 48210 |
| Cycle 3 | | 44300 | 5152 | | 1930 | 0 | 784 | | 52180 |
| Cycle 4 | 44300 | 44300 | 10304 | 3610 | 3610 | 1568 | 1568 | | 109316 |
| Cycle 5 | | 44300 | 30912 | | 8010 | 0 | 4704 | 3780 | 91790 |
| **TOTALS** | **88600** | **221500** | **163392** | **14210** | **32880** | **13888** | **24864** | **7560** | **567586** |
| **TOTAL %** | **15.6** | **39** | **28.8** | **2.5** | **5.8** | **2.4** | **4.4** | **1.3** | **100** |

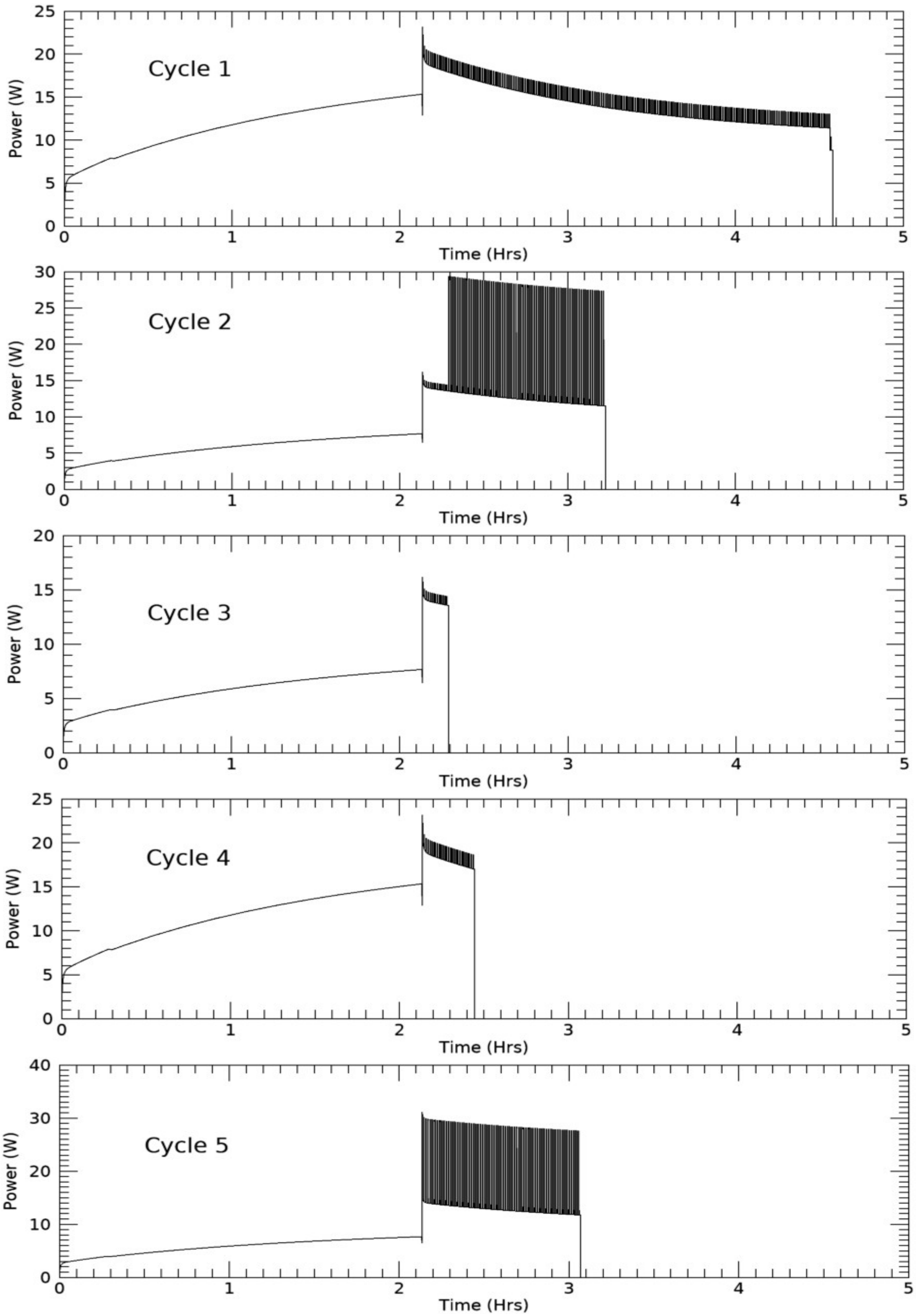


**Figure 19.** Power profiles for five C-LIFE operations cycles.

## 5.3 Spacecraft Interfaces

The two redundant CSMs are identical and connect to different sides of the Lander Avionics using Micro-D right-angle connectors with 25 pins. Table 5.3.1 shows the details of the connection scheme. The serial data interface between the Lander Avionics and C-LIFE for commands and data comply with a full duplex SpaceWire interface based on standard ECSS-E-ST-50-12C.

**Table 5.3.1** Lander Avionics Data Interface to CSM

| Conn | Pin | Signal Name | From | To | Description | Voltage Level (V) | Type | Current (A) | Rate |
|---|---|---|---|---|---|---|---|---|---|
| J10 | | TEMP_PRT_DRM1_P* | DRM1 | LA | Temperature to Lander Avionics | TBD | Analog | | NA |
| J10 | | TEMP_PRT_DRM1_N* | DRM1 | LA | Temperature to Lander Avionics | TBD | Analog | | NA |
| J10 | | TEMP_PRT_DRM2_P* | DRM2 | LA | Temperature to Lander Avionics | TBD | Analog | | NA |
| J10 | | TEMP_PRT_DRM2_N* | DRM2 | LA | Temperature to Lander Avionics | TBD | Analog | | NA |
| J10 | | HEATER_SURV_DRM1_1* | LA | DRM1_1 | Heater placeholder for DRM1 | TBD | TBD | TBD | NA |
| J10 | | HEATER_SURV_DRM1_2* | LA | DRM1_2 | Heater placeholder for DRM1 | TBD | TBD | TBD | NA |
| J10 | | HEATER_SURV_DRM2_1* | LA | DRM2_1 | Heater placeholder for DRM2 | TBD | TBD | TBD | NA |
| J10 | | HEATER_SURV_DRM2_2* | LA | DRM2_2 | Heater placeholder for DRM2 | TBD | TBD | TBD | NA |
| J10 | | TEMP_PRT_CSM_P | CSMB | LA | Temperature to Lander Avionics | TBD | Analog | | NA |
| J10 | | TEMP_PRT_CSM_N | CSMB | LA | Temperature to Lander Avionics | TBD | Analog | | NA |
| J10 | | SPW_DATA_LA_TO_CSM_P | LA | CSMB | Lander Avionics interface | LVDS | Digital | | 20Mbps (TBR) |
| J10 | | SPW_DATA_LA_TO_CSM_N | LA | CSMB | Lander Avionics interface | LVDS | Digital | | 20Mbps (TBR) |
| J10 | | SPW_DATA_CSM_TO_LA_P | CSMB | LA | Lander Avionics interface | LVDS | Digital | | 20Mbps (TBR) |
| J10 | | SPW_DATA_CSM_TO_LA_N | CSMB | LA | Lander Avionics interface | LVDS | Digital | | 20Mbps (TBR) |
| J10 | | SPW_STROBE_LA_TO_CSM_P | LA | CSMB | Lander Avionics interface | LVDS | Digital | | 20Mbps (TBR) |
| J10 | | SPW_STROBE_LA_TO_CSM_N | LA | CSMB | Lander Avionics interface | LVDS | Digital | | 20Mbps (TBR) |
| J10 | | SPW_STROBE_CSM_TO_LA_P | CSMB | LA | Lander Avionics interface | LVDS | Digital | | 20Mbps (TBR) |
| J10 | | SPW_STROBE_CSM_TO_LA_N | CSMB | LA | Lander Avionics interface | LVDS | Digital | | 20Mbps (TBR) |

*Note: These signals pass through the CSM boards only

The two redundant CSM power boards are identical and connect to different sides of the Lander Avionics. Table 5.3.2 shows the details of the connection scheme.

**Table 5.3.2** Lander Avionics Power Interface

| Pin | Signal Name | From | To | Description | Voltage | Type | Current (A) |
|---|---|---|---|---|---|---|---|
| 1 | 28V | LA | PWR | 28V Power | 28 | Power | 2 (TBR) |
| 2 | GND | LA | PWR | GND | GND | Power | 2 (TBR) |

## 5.4 Thermal Dissipation in the Vault

The CSM electronics operate at ambient vault conditions and do not require heating. They are also unpowered while the DRMs in the camera head are being pre-heated. During imaging, the CSM commands the LEDs, DRMs and camera-head heaters and processes data returned into individual compressed products ready for download. This processing generates 9.2W. In the current ConOPs (Section 2), the total energy deposited into the vault over the mission can be summarized as:

**Table 5.4.1.** Timing and amount of energy deposited into the vault

| Observation Cycle | Timing | Duration (hours) | Total Heat (kJ) |
|---|---|---|---|
| 1a+1b | Europan Day 1 | 2.43 | 81 |
| 2a+2b | Europan Night 1 | 1.07 | 36 |
| 3 | Europan Night 1 | 0.15 | 5.2 |
| 4 | Europan Day 2 | 0.3 | 10.3 |
| 5 | Europan Night 2 | 0.93 | 30.9 |
| **Total** | | | **163.4** |

## 5.5 In-flight Calibration

Several forms of calibration data will be acquired:

- C-LIFE's face-down stowage during cruise facilitates the collection of dark exposures. We plan to collect dark exposure data at several temperatures and times throughout the cruise. This will require exercising the CSM, DRMs and heaters. Each calibration exercise will necessitate power supplied at approximately 12-20W for 2-3 hours (exact power and time depend on the thermal state of the surrounding spacecraft).
- The Europa Lander's prolonged tour of the Jupiter system facilitates the collection of data that can further characterize the effects of the radiation environment on images. We plan to collect dark exposure data at several times during the Jupiter tour (power requirements similar to dark current calibration above).
- Should we land on the Jupiter-facing side of Europa, then C-LIFE will acquire images of Jupiter in all color bands during each operations cycle. With such a landing site, Jupiter will always be visible (~830 C-LIFE pixels across) albeit at different phases. Jupiter has a well-understood absolute brightness that will allow us to check for drift in the pre-flight calibration.
- A deck-mounted calibration target is desired that C-LIFE will utilize during each operations cycle. Dark exposures during the surface mission can be accomplished by restowing C-LIFE face down on the lander deck.

## 5.6 Spacecraft Storage

The C-LIFE CSM processes data into individual compressed products ready for download. These products are transferred to the spacecraft for storage and not held in C-LIFE memory. In the current ConOPs (Section 2), the total size of these data products and the timescales over which they are transferred can be summarized as:

**Table 5.5.1.** Timing and amount of data deposited into Lander storage

| **Observation Cycle** | **Timing** | **Duration (hours)** | **Product Size (Mbit)** | **Transfer Rate (kb/s)** |
|---|---|---|---|---|
| 1a+1b | Europan Day 1 | 2.43 | 323 | 37.8 |
| 2a+2b | Europan Night 1 | 1.07 | 46.9 | 12.5 |
| 3 | Europan Night 1 | 0.15 | 11.7 | 22.2 |
| 4 | Europan Day 2 | 0.3 | 58.7 | 55.7 |
| 5 | Europan Night 2 | 0.93 | 35.2 | 10.8 |
| **Total** | | | **475.5** | |

# 6. Future Work

Several issues require discussion with the JPL project group to resolve:

1. The C-LIFE vault electronics box is outside the volume and mass envelope specified in the PIP. This could be fixed by removing redundancy; but, given the mission-critical nature of imaging, it is not our preferred solution.
2. To facilitate redundancy, two connections to the spacecraft are needed. Currently the PIP specifies one connection per instrument.
3. The mass of the cables between the vault and camera head (CBE 1.2 kg total for 2 redundant cables and connectors) is currently not being budgeted by C-LIFE and the PIP is ambiguous about who is responsible for this. Although we have endeavored to reduce the number of wires per cable to a minimum, two meters of heavily shielded cable could still use a significant part of the current camera head mass allocation. Adjustments to that allocation will be needed if the cable mass becomes the instrument's responsibility.
4. C-LIFE's current ConOPs uses most of the anticipated science downlink. This could be reduced to about half the science downlink with some straightforward onboard analysis. More-complex processing techniques are being investigated to reduce this further. We need a target allocation to aim for - at present instrument-specific downlink allocations are not available.
5. A deck-mounted calibration target is desired.
6. We assume here that the Lander can switch on heaters two hours in advance of imaging and thermostatically control C-LIFE's temperature. If it's necessary for C-LIFE electronics to do this instead of the lander, the C-LIFE vault electronics will have to be turned on two hours prior to imaging. The extra two hours of ON time prior to each observing campaign will increase C-LIFE's total energy cost by ~95 W-hr, so that our total mission energy budget will rise from 160 to 254 W-hr. Alternatively a dedicated thermostatic control and timer system could be added to C-LIFE that would be responsible for pre-heating the imaging head and only commanding the rest of the C-LIFE vault electronics when the head has reached operating temperature. Mass and volume for this additional circuitry is not currently budgeted in C-LIFE.

Further work by the C-LIFE team is planned in several areas:

1. SDL will deliver component test boards that we will use at UA to thermally qualify the remaining untested components. We will also investigate lower operating temperatures for the camera head electronics in order to reduce energy costs.
2. Further optimization of our thermal management strategy and refinements to our model will yield a higher-fidelity energy budget. Adjustments to the emissivity of the camera head enclosure and size of the thermal link between the enclosure and electronics will be made to lower C-LIFE's energy budget.
3. Ball aerospace will deliver final radiation modeling results that will improve on what is presented here. We anticipate lower TIDs and so fewer components will require future testing.

4. The C-LIFE optical design is based on a scaled version of the OSIRIS-REx sampling camera (SamCam), but further work is needed to include a progressive focus. A progressive focus can be implemented in several different ways. The focal plane can be tilted with respect to the optical axis to meet the Scheimpflug condition, guaranteeing that any object in a given plane in object space will be imaged in focus. Alternatively, a progressive diopter lens can focus different parts of the image at arbitrary distances. A third possibility is to use glass plates of different thickness introduced between lens 5 and the detector resulting in a bifocal or multifocal arrangement. Heritage for these optical solutions stems from SamCam and MapCam on OSIRIS-REx respectively. We will trade the benefits of these different approaches, downselect the one best suited for C-LIFE and complete its optical design
5. Further design work on the power and optical design for the LEDs is required. Although a minor part of the energy budget, we anticipate some additional savings from this optimization. LED usage drives short-lived peaks in power usage (Section 5.2) so this task may lead to lowering peak power requirements.

# Appendix A: Image compression trade study

The C-LIFE ConOps (Section 2) leverages the stationary nature of the typical Europan landing site scene by acquiring several images and median filtering them at each pixel in order to exclude radiation events. After this prelude, the control electronics divides the images into different products by filter and compresses them.

The C-LIFE ICEE2 image compression study's goal was to find the parameters that achieved the best image quality for compressed and downlinked C-LIFE images with the lowest downlink size, subject to the radiation noise that will be experienced at Europa. In addition, it explored whether altering operating temperature and exposure time ranges could mitigate the effects of radiation exposure, allowing better definition of the ConOps.

The radiation noise's histogram was modeled from images and signal data recorded from pre- and post-radiation-exposed detectors gathered by UA and SDL in preparation for the OSIRIS-REx mission, but never published. The hot spots and traps created within the detector silicon during these tests were very similar, statistically, to those expected for Europa-like radiation noise. In particular, the long tail, or skirt, visible in the dark histogram of these images (Figure A1) was a characteristic of RTS noise, the dominant source of radiation-induced noise observed within the Mk × Nk detector and its predecessors (e.g., see Janesick et al, 2009, 2010, 2013 in their descriptions of RTS noise; Fig. 40b of part III; Figs. 19, 24, 25 of part IV; Figs. 47a, b & 103a, b of Part V).

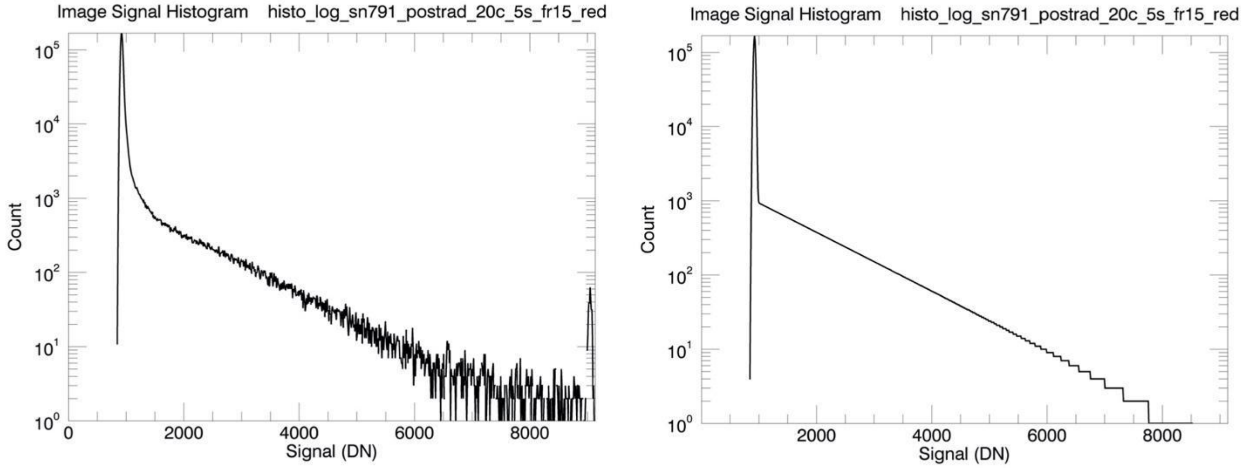


**Figure A1.** (Left) OCAMS Detector Radiation Exposure created a population of hot pixels that showed up as a distinctive and characteristic tail skirt in the histogram, very similar to the RTS pixel population that is expected to manifest as Europan radiation noise. We recruited these data and the resulting radiation noise model with dosage, temperature and exposure time as a more useful simulated description of Europan radiation noise than typical models (Right).

The creation of a long tail is a general characteristic of radiation-induced noise and modeling it in a fundamental way allows the creation of selectable parameters corresponding to dosage, temperature and exposure time that can potentially alter, or tune, the values describing the shape of the noise's histogram appropriately for the Europan environment. Using these values, we can better simulate radiation-exposed C-LIFE images and use them to test the compression algorithm, the multi-image median filtering scheme contemplated for C-LIFE ConOps, and other image-based studies.

By gauging the electron noise loading expected at Europa and comparing it to the evident loading recorded in the radiation-exposed images, we identified images in which the noise load, measured in terms of electrons (or Data Number, DN) of signal, was comparable to the expected impingement levels, as well as several times what would be expected for the expected exposure times and operating temperatures.

The full test implementation (Figure A2) added simulated radiation whose noise was described by a histogram with a long-tailed skirt similar to Figure A1. For a given trial, we generated several simulated images (whose number was an input that ranged from 1-10) by adding a randomly-determined (and different) noise population to each image and then applied a median filter before sending it through the compression algorithm on the RTG4 development board. This matched the proposed ConOps and allowed us to vary both number of images contributing to the filter and compression ratio in a way that would reveal the optimum values of both. We then used TER software to decompress the image.

For compression, we anticipate using an algorithm from Alma Technologies, embedded with an RTG4 FPGA, that is a self-contained implementation of the CCSDS 122.0-B-1 image compression standard. It uses a two-dimensional 9/7 Discrete Wavelet Transform (DWT), similar to the irreversible wavelet transform used in JPEG2000, followed by a bit-plane encoder (rather than the reversible 5/3 wavelet transform used in JPEG2000).

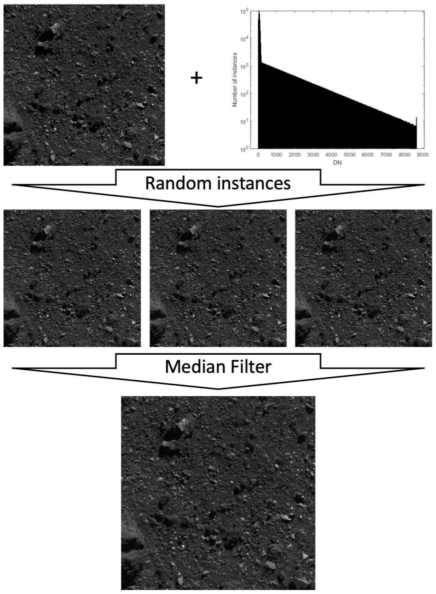
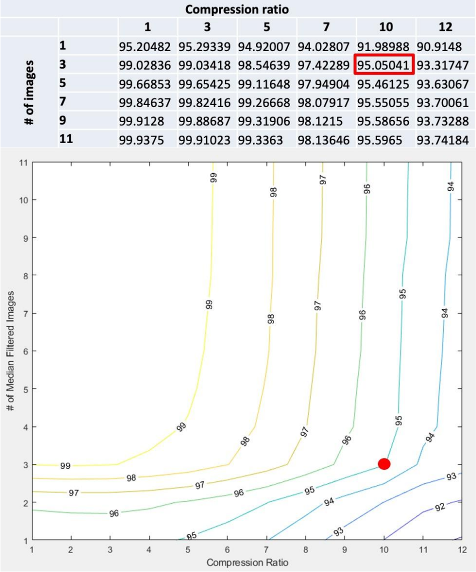


**Figure A2.** Cartoon illustrating trade study workflow. Original data (top left; from the surface of Bennu) was combined with simulated random radiation noise to produce simulated exposures (middle row). These exposures were combined in our median filter and the final image was compressed and then decompressed with the C-LIFE flight software (bottom image). The top left and bottom images were compared using the SSIM.

Testing showed that most of the settings of the Alma core used to tune the compression algorithm have little to no effect when changed. The parameter providing the most flexibility is the register controlling the size of the segment byte-stream which correlates to the compression ratio used in the process. This means a specific compression ratio can be determined (for a specific image) and the algorithm will run until that ratio is reached no matter what the resultant outcome is. Therefore a balance must be maintained to use a compression ratio that meets the mission storage and downlink objectives but also has an acceptable image quality.



| | Compression ratio | | | | | |
|---|---|---|---|---|---|---|
| **# of images** | **1** | **3** | **5** | **7** | **10** | **12** |
| **1** | 95.20482 | 95.29339 | 94.92007 | 94.02807 | 91.98988 | 90.9148 |
| **3** | 99.02836 | 99.03418 | 98.54639 | 97.42289 | 95.05041 | 93.31747 |
| **5** | 99.66853 | 99.65425 | 99.11648 | 97.94904 | 95.46125 | 93.63067 |
| **7** | 99.84637 | 99.82416 | 99.26668 | 98.07917 | 95.55055 | 93.70061 |
| **9** | 99.9128 | 99.88687 | 99.31906 | 98.1215 | 95.58656 | 93.73288 |
| **11** | 99.9375 | 99.91023 | 99.3363 | 98.13646 | 95.5965 | 93.74184 |

**Figure A3.** SSIM (structural similarity index measure) as a function of compression ratio and number of images that contributed to the median filter. Moving from one to three images acquired of each scene produces marked improvement in the quality of the final product. Further images produce only a slight improvement. Compression ratios as high as 10, or even higher, produce acceptable SSIM results (≥95%). Red point on plot and outline in table show our baseline choice of 10:1 compression and a three-image median filter.

We compared the processed images to the original image (Figure A3) using the structural similarity index measure (SSIM). SSIM is a method for expressing the fidelity of one image to another; in this case, it compares the compressed/uncompressed image to the original. The similarity is expressed as a percentage; the closer to 100%, the more faithful the reproduction. Figure A3 shows clear benefits to the median filter that largely max out at N=3, while compression ratios up to 10:1 still deliver high fidelity results. We select 10:1 compression as our baseline ConOPs. Figure A4 shows a full-resolution example.

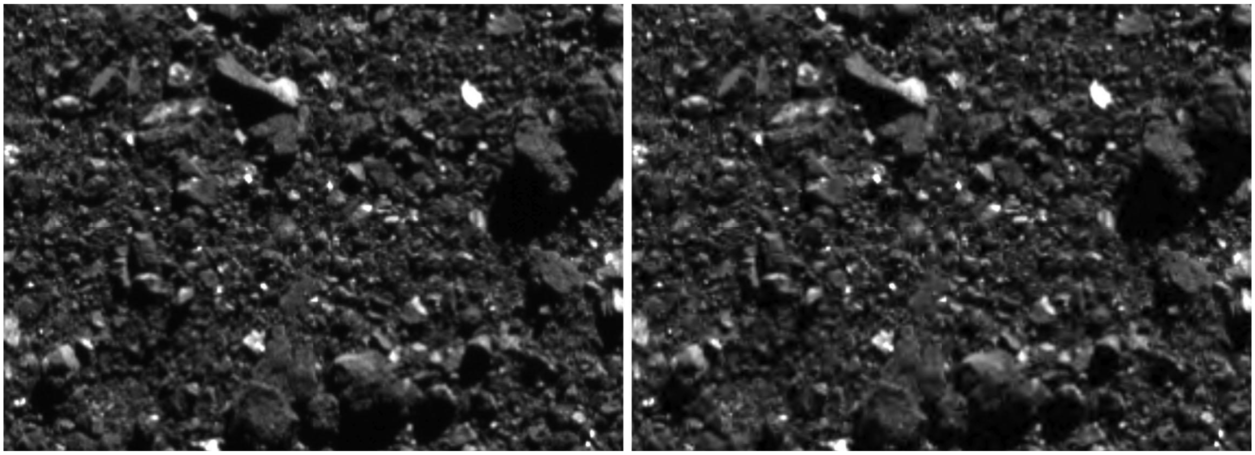


**Figure A4.** Full resolution view of Bennu’s surface showing original data (left) and our expected product from our baseline procedure (10:1 compression with three-image median filtering) after adding Europan radiation noise, median filtering, compression, and decompression. SSIM of the right image is 95%, few differences from the original can be discerned by eye.

# Appendix B: MEL

<table>
<tr><th colspan="4">Camera Head</th></tr>
<tr><th>Part Number</th><th>Manufacturer</th><th>Description</th><th>Qty</th></tr>
<tr><td>TBD</td><td>TBD</td><td>Cover, Camera, Top</td><td>1</td></tr>
<tr><td>TBD</td><td>TBD</td><td>Cover, Camera, Front</td><td>1</td></tr>
<tr><td>TBD</td><td>TBD</td><td>Main Chassis, Camera</td><td>1</td></tr>
<tr><td>TBD</td><td>TBD</td><td>Cover, Camera, Rear</td><td>1</td></tr>
<tr><td>TBD</td><td>TBD</td><td>Lens Barrel, Right</td><td>1</td></tr>
<tr><td>TBD</td><td>TBD</td><td>Lens Barrel, Left</td><td>1</td></tr>
<tr><td>TBD</td><td>TBD</td><td>Lens Stack</td><td>2</td></tr>
<tr><td>TBD</td><td>TBD</td><td>Pass Thru Cover, Camera</td><td>1</td></tr>
<tr><td>TBD</td><td>TBD</td><td>Internal Wiring Harness</td><td>4</td></tr>
<tr><td>TBD</td><td>TBD</td><td>Window, LED</td><td>2</td></tr>
<tr><td>TBD</td><td>TBD</td><td>Window, Optical</td><td>2</td></tr>
<tr><td>TBD</td><td>TBD</td><td>Detector Assembly</td><td>2</td></tr>
<tr><td>TBD</td><td>TBD</td><td>LED Assembly</td><td>2</td></tr>
<tr><td>TBD</td><td>TBD</td><td>Microminiature connector, 21 pin</td><td>4</td></tr>
<tr><th colspan="4">Vault</th></tr>
<tr><th>Part Number</th><th>Manufacturer</th><th>Description</th><th>Qty</th></tr>
<tr><td>TBD</td><td>TBD</td><td>Housing, Power Slice</td><td>2</td></tr>
<tr><td>TBD</td><td>TBD</td><td>Housing, Control Slice</td><td>2</td></tr>
<tr><td>TBD</td><td>TBD</td><td>Housing, Cover</td><td>2</td></tr>
<tr><td>TBD</td><td>TBD</td><td>Power Board Assy</td><td>2</td></tr>
<tr><td>TBD</td><td>TBD</td><td>Control Board Assy</td><td>2</td></tr>
</table>

**Table B.1** Mechanical equipment list

**DRM Electronics (2X)**

| Part Number | Manufacturer | Description | QTY |
|---|---|---|---|
| UT54LVDM055LV | Cobham | LVDS Dual Driver/Receiver | 1 |
| RHFL4913A | STMicro | MICROCIRCUIT, LINEAR, POSITIVE, ADJUSTABLE, LOW DROPOUT, VOLTAGE REGULATOR, MONOLITHIC SILICON | 1 |
| UT01VS33L | Cobham | Voltage Supervisor | 1 |
| ISYE-1009EH | Intersil | Reference 2.5V | 1 |
| ISL71590SEH | Intersil | 2-terminal Temperature Transducer (AD590) | 1 |
| ISL70419 | Intersil | IC, QUAD Precision Op Amp | 1 |
| RTAX250S | Microsemi | Radiation-Tolerant FPGA | 1 |
| 2N5794UC | Semicoa | Dual Matched NPN switching transistor | 1 |
| RHFL4913S25-03V | STMicro | 2.5 V rad-hard positive fixed voltage regulator | 1 |
| RHFL4913S33-03V | STMicro | 3.3 V rad-hard positive fixed voltage regulator | 1 |
| RHF1401 | STMicro | Rad-hard 14-bit 20 Msps A/D converter | 1 |
| RHFL4913S15-03V | STMicro | 1.5 V rad-hard positive fixed voltage regulator | 1 |
| RHF200 | STMicro | Diff Amp | 1 |
| LMH6628QML | TI | Dual Wideband, Low Noise, Voltage Feedback Op Amp | 1 |
| 1604F040M0000BF | Vectron | Oscillator 40MHz Single Pair LVDS | 1 |
| RHFL7913A | STMicro | Rad-hard adjustable negative voltage regulator | 1 |

**Table B.2** DRM electronical components

| CSM Electronics (2X) | | | |
|---|---|---|---|
| **Part Number** | **Manufacturer** | **Desc** | **QTY** |
| TBD | TBD | CSM Board | 1 |
| UT54LVDM228 | Cobham | Driver/Receiver | 1 |
| UT54LVDM055LV | Cobham | LVDS Dual Driver/Receiver | 4 |
| 1604F100M0000BF (TBR) | Vectron | 100 MHz oscillator | 1 |
| ISL71590SEHVF | Intersil | Temperature Transducer | 1 |
| RHFAD128 | STMicro | 8 CH, 50ksps- 1Msps, 12 bit A/D Converter | 1 |
| 69F192G24RPFE | DDC | NAND Flash, 192Gbit | 1 |
| RT4G150-CG1657V | Microsemi | FPGA | 1 |
| RT4G150-1CG1657V | | | |
| RHRPMPOL01 | STMicro | Rad-hard 7 A point-of-load synchronous step-down regulator | 1 |
| RH3845 | Analog | High-Voltage Synchronous Current Mode Step-Down Controller | 1 |
| RH1086 | Analog | Low Dropout Positive Adjustable Regulator | 1 |
| TPS50601-SP | TI | 6A Synchronous Step-Down Converter | 1 |
| IRHNM53110 | Infineon | Power MOSFET | 1 |
| TBD | TBD | Microminiature Connector, 22 pin | 2 |
| TBD | TBD | Microminiature Connector, 15 pin | 2 |
| TBD | TBD | Microminiature Connector, 9 pin | 1 |

| Power Electronics (2X) | | | |
|---|---|---|---|
| **Part Number** | **Manufacturer** | **Desc** | **Qty** |
| TBD | TBD | Power Board | 1 |
| M3GB2815S | IR | DC/DC Single Converter | 1 |
| IRHLNM73110 | Infineon | Logic Level Power MOSFET | 1 |
| TBD | TBD | Microminature Connector, 21 pin | 1 |
| TBD | TBD | Microminature Connector, 15 pin | 1 |

**Table B.3** Vault electrical components

# Appendix C: Radiation Test Plan

## Summary

Table C.1 lists the main EEE parts in the C-LIFE preliminary electronics design, listed alongside manufacturer, part designation and location in either Sensor Head or Vault Electronics Controller. Table C.2 lists the status of these parts vis-à-vis the various categories of potential radiation damage, including: TID (300 krad-Si), ELDRS (300 krad-Si), equivalent 1 MeV neutron fluence, SEU/SET LET tolerance and SEB/SEL LET tolerance.

Parts located within the vault whose TID (300 krad-Si) status remains to be dispositioned include the DDC NAND Flash Memory Module (192 Gbit) 69F192G24RPFE, currently rated at 100 krad-Si; it is the only part for which testing is deemed to be required to elevate its TID (300 krad-Si) status to be ready for a Europa lander mission. Other vault parts and a single head part require analysis; these include the Microsemi FPGA RT4G150-CG1657V &/or RT4G150-1CG165 (200 rad-Si rating), the Intersil ISL70061SEH or Intersil ISL70062SEH (100 krad-Si rating), the STMicro Rad-hard 7A point-of-load synchronous step-down regulator RHRPMPOL01 (100 krad-Si rating) and the Microsemi Radiation-Tolerant FPGA RTAX250S (200 krad-Si rating) which is planned for use in the head. All other vault parts not cited specifically here we consider ready to be incorporated within the C-LIFE design with respect to the TID (300 krad-Si) requirement.

For ELDRS (300 krad-Si) testing status, we consider several parts to require testing, all of which are parts located within the head. They are the Intersil Reference 2.5V ISYE-1009EH (50 krad-Si rating), the Intersil 2-terminal Temperature Transducer (AD590) ISYE-1009EH (no rating available) and the TI Dual Wideband, Low Noise, Voltage Feedback Op Amp LMH6628QML (no rating available). Otherwise, several vault and one sensor head part require analysis for ELDRS. In the vault, they are the Cobham LVDS Dual Driver/Receiver T54LVDM055LV (300 krad-Si rating), the Intersil Temperature Transducer ISL71590SEHVF (no rating available), the Intersil ISL70061SEH or Intersil ISL70062SEH (75 krad-Si rating) and the STMicro Rad-hard 7A point-of-load synchronous step-down regulator (100 krad-Si rating). In the head, it is the Intersil QUAD Precision Op Amp ISL70419 (200 krad-Si rating). All other parts we consider tolerant to ELDRS (300 krad-Si).

For the radiation tolerance to equivalent 1 MeV neutron fluence, one head part requires testing: the TI Dual Wideband, Low Noise, Voltage Feedback Op Amp LMH6628QML (no rating available). Otherwise, several vault and head parts have a TBD status, but by analogy to other related parts whose status is more certain, we consider it acceptable for them to be employed in their current configurations. In the vault these include the Cobham LVDS Dual Driver/Receiver UT54LVDM055LV and the Vectron 100 MHz Oscillator 1604F100M0000BF and in the head they include the Vectron 40 MHz Oscillator Single Pair LVDS 1604F040M0000BF and the Vectron 20 MHz Oscillator 1604F20M0000BF. All other parts we consider tolerant to equivalent 1 MeV neutron fluence.

The disposition of many parts—both vault and head—with regard to their tolerance for SEU/SET LET is still not on as definite a footing as is required, but in no case is more testing required, just analysis. In the vault these include: the Cobham LVDS Dual Driver/Receiver UT54LVDM055LV, the DDC NAND Flash Memory Module (192 Gbit) 69F192G24RPFE, the STMicro 3.3 V rad-hard positive fixed voltage regulator RHFL4913S33-03V, the STMicro MICROCIRCUIT,

LINEAR, POSITIVE, ADJUSTABLE, LOW DROPOUT, VOLTAGE REGULATOR, MONOLITHIC SILICON RHFL4913A, the Vectron 100 MHz Oscillator 1604F100M0000BF, the IR M3GB2803R305T, the Cobham LVDS Dual Driver/Receiver UT54LVDM055LV, the Cobham LVDS Dual Driver/Receiver UT54LVDM228, the Intersil ISL70061SEH or Intersil ISL70062SEH, the STMicro Rad-hard 7A point-of-load synchronous step-down regulator RHRPMPOL01, the Vorago Microcontroller VA10820 and the STMicro Rad-hard adjustable negative voltage regulator RHFL7913A. In the head they include: the Intersil Reference 2.5V ISYE-1009EH, the Intersil QUAD Precision Op Amp ISL70419, the STMicro 2.5 V rad-hard positive fixed voltage regulator RHFL4913S25-03V, the STMicro 3.3 V rad-hard positive fixed voltage regulator RHFL4913S33-03V, the STMicro Rad-hard 14-bit 20 Mbsps A/D converter RHF 1401, the STMicro 1.5 V rad-hard positive fixed voltage regulator RHFL4913S15-03V, the STMicro Differential Amplifier RHF200, the TI Dual Wideband, Low Noise, Voltage Feedback Op Amp LMH6628QML and the Vectron 40 MHz Oscillator Single Pair LVDS 1604F040M0000BF. The Intersil Temperature Transducer ISL71590SEHVF and the Microsemi FPGA RT4G150-CG1657V &/or RT4G150-1CG165 in the vault, and the Intersil 2-terminal Temperature Transducer (AD590) ISYE-1009EH, the Microsemi Radiation-Tolerant FPGA RTAX250S in the head and the Vectron 20 MHz Oscillator 1604F20M0000BF, can be used as is.

For SEB/SEL LET tolerance, testing is required for a single part, the DDC NAND Flash Memory Module (192 Gbit) 69F192G24RPFE, which is to be used in the vault. For several parts, analysis is required to assess compliance with the requirement. In the vault, the list includes: the STMicro 3.3 V rad-hard positive fixed voltage regulator RHFL4913S33-03V (rating > 68 MeV-cm2/mg) and the STMicro Rad-hard adjustable negative voltage regulator RHFL7913A (rating TBD). In the head, the list includes the STMicro 2.5 V rad-hard positive fixed voltage regulator RHFL4913S25-03V (rating > 68 MeV-cm2/mg) and the STMicro 3.3 V rad-hard positive fixed voltage regulator RHFL4913S33-03V (rating > 68 MeV-cm2/mg).

**Table C.1.** EEE Parts in preliminary C-LIFE electronics design listed alongside manufacturer and location in either Sensor Head or Vault Electronics Controller

| Generic Part Number | Manufacturer | Description | Location |
|---|---|---|---|
| UT54LVDM055LV | Cobham | LVDS Dual Driver/Receiver | CSM/Vault |
| 69F192G24RPFE | DDC | NAND Flash, 192Gbit | CSM/Vault |
| ISL71590SEHVF | Intersil | Temperature Transducer | CSM/Vault |
| RT4G150-CG1657V | Microsemi | FPGA | CSM/Vault |
| RT4G150-1CG1657V | | | |
| RHFL4913S33-03V | STMicro | 3.3 V rad-hard positive fixed voltage regulator | CSM/Vault |
| RHFL4913A | STMicro | Microcircuit, Linear, Positive, Adjustable, Low Dropout, Voltage Regulator, Monolithic Silicon | CSM/Vault |

| | | | |
|---|---|---|---|
| RHFAD128 | STMicro | 8 CH, 50ksps- 1Msps, 12 bit A/D Converter | CSM/Vault |
| 1604F100M0000BF (TBR) | Vectron | 100 MHz oscillator | CSM/Vault |
| UT01VS33L | Cobham | Voltage Supervisor | DRM/Head |
| ISYE-1009EH | Intersil | Reference 2.5V | DRM/Head |
| ISL71590SEH | Intersil | 2-terminal Temperature Transducer (AD590) | DRM/Head |
| ISL70419 | Intersil | IC, QUAD Precision Op Amp | DRM/Head |
| RTAX250S | Microsemi | Radiation-Tolerant FPGA | DRM/Head |
| 2N5794UC | Semicoa | Dual Matched NPN switching transistor | DRM/Head |
| RHFL4913S25-03V | STMicro | 2.5 V rad-hard positive fixed voltage regulator | DRM/Head |
| RHFL4913S33-03V | STMicro | 3.3 V rad-hard positive fixed voltage regulator | DRM/Head |
| RHF1401 | STMicro | Rad-hard 14-bit 20 Msps A/D converter | DRM/Head |
| RHFL4913S15-03V | STMicro | 1.5 V rad-hard positive fixed voltage regulator | DRM/Head |
| RHF200 | STMicro | Diff Amp | DRM/Head |
| LMH6628QML | TI | Dual Wideband, Low Noise, Voltage Feedback Op Amp | DRM/Head |
| 1604F040M0000BF | Vectron | Oscillator 40MHz Single Pair LVDS | DRM/Head |
| M3GB2803R305T | IR | | PWR/Vault |
| UT54LVDM055LV | Cobham | LVDS Dual Driver/Receiver | CSM/Vault |
| ISL70061SEH or | Intersil | | CSM/Vault |
| ISL70062SEH 10A | | | |
| RHRPMPOL01 | STMicro | Rad-hard 7 A point-of-load synchronous step-down regulator | CSM/Vault |
| 1604F20M0000BF (TBR) | Vectron | 20 MHz oscillator | DRM/Head |
| RHFL7913A | STMicro | Rad-hard adjustable negative voltage regulator | CSM/Vault |

**Table C.2.** Parts Radiation Status

| Generic Part Number | TID | ELDRS | Equivalent 1 MeV Neutron Fluence | SEU/SET | SEB/SEL |
|---|---|---|---|---|---|
| UT54LVDM055LV | 300 | 300 | TBD | TBD | >100 |
| 69F192G24RPFE | 100 | N/A | 1.00E+14 | TBD | TBD |
| ISL71590SEHVF | 300 | 50 | 2.00E+12 | TBD | >86.4 |
| RT4G150-CG1657V<br>RT4G150-1CG1657V | 200 | N/A | 1.00E+14 | Resource Dependent | >103 |
| RHFL4913S33-03V | 300 | 300 | 1.00E+14 | TBD | >68 |
| RHFL4913A | 300 | 300 | 2.00E+12 | TBD | >68 |
| RHFAD128 | 300 | N/A | 1.00E+14 | TBD | >125 |
| 1604F100M0000BF (TBR) | 300 | 50 | TBD | TBD | >120 |
| UT01VS33L | 300 | N/A | 1.00E+14 | >80 | >110 |
| ISYE-1009EH | 300 | 50 | 3.00E+13 | TBD | Immune |
| ISL71590SEH | 300 | 50 | 2.00E+12 | TBD | >86.4 |
| ISL70419 | 300 | 100 | 3.00E+13 | TBD | Immune |
| RTAX250S | 200 | N/A | 1.00E+14 | Resource Dependent | >117 |
| 2N5794UC | 300 |  |  | N/A | N/A |
| RHFL4913S25-03V | 300 | 300 | 1.00E+14 | TBD | >68 |
| RHFL4913S33-03V | 300 | 300 | 1.00E+14 | TBD | >68 |
| RHF1401 | 300 | N/A | 1.00E+14 | TBD | >116 |
| RHFL4913S15-03V | 300 | 300 | 1.00E+14 | TBD | >120 |
| RHF200 | 300 | 100 | 2.00E+12 | TBD | >120 |
| LMH6628QML | 300 | TBD | TBD | TBD | >80 |
| 1604F040M0000BF | 300 | 50 | TBD | TBD | >120 |
| M3GB2803R305T | 300 | 300 | 1.00E+14 | TBD | >100 |
| UT54LVDM055LV | 300 | 300 | TBD | TBD | >100 |
| UT54LVDM228 | 300 | N/A | 1.00E+14 | TBD | >100 |
| ISL70061SEH or ISL70062SEH 10A | 100 | 75 | 2.00E+12 | TBD | >86 |
| RHRPMPOL01 | 100 | 100 | 2.00E+12 | TBD | >70 |
| 1604F20M0000BF (TBR) | 300 | 50 | TBD | TBD | >120 |
| VA10820 | 300 | N/A | 1.00E+14 | Resource Dependent | >110 |
| RHFL7913A | 300 | 300 | 1.00E+14 | TBD | >68 |

### Applicable Documents

The documents in Table C.3 are available upon request.

**Table C.3.** Applicable Documents

| Document Number | Document Title | Revision (if applicable) |
|---|---|---|
| MIL-STD-883-1, Method 1019.9 | "Ionizing Radiation (Total Dose) Test Procedure" | L |
| MIL-STD-883-1, Method 1017.3 | "Neutron Irradiation" | L |
| ESCC Basic Spec 25100 | Single Effects Test Method and Guidelines: ESCC Basic Specification No. 25100 | |
| 5962-07227 | SMD for ADC128S102<br>"Microcircuit, Digital-Linear, CMOS, 8 Channel, 50 kSPS TO 1 MSPS, 12 BIT Analog to Digital Converter, Monolithic Silicon" | C |
| 5962-03220 | SMD for M3G2805R2S<br>"Microcircuit, Hybrid, Linear, 5.2 Volt, DC/DC Converter" | C |

**Test Procedures**

All TID and ELDRS testing shall be performed in accordance with MIL-STD-883 Method 1019.9; all neutron fluence testing shall be performed in accordance with MIL-STD-883 Method 1017.3 and all SEE testing shall be performed in accordance with ESCC 25100, unless otherwise specified within this document. Table C.4 summarizes the test conditions for the components that will require additional TID or ELDRS testing.

**Table C.4.** Test conditions for the components that will require additional TID testing

| | |
|---|---|
| Number of Test Samples | 5 Test samples + 1 non-irradiated control (from same wafer lot) |
| Bias Conditions | Unbiased during irradiations[1] |
| Dose Rate | 50 ≤ Rate ≤ 300 Rad(Si)/sec (Condition A) |
| Desired Dose Level | 300 kRad(Si) |
| Exposure Temperature | Room Temperature (24°C ± 6°C) |
| Electrical Parameters to be Measured | All the electrical parameters outlined in the associated vendor's datasheet or the associated SMD document shall be measured during testing.[2] |
| Test Flow | 1. Perform a test readiness review on the irradiation test chamber to verify that the uniformity of the irradiation field across the test samples shall be ≤ 10%.<br>2. Perform a test readiness review on the electrical bench-top setup to verify that the setup has adequate repeatability and adequate measurement resolution to take the desired electrical measurements during testing.<br>3. Perform the pre-exposure electrical parameter measurements on the test samples and the control. |

| | |
|---|---|
| | 4. Irradiate the test samples to the desired dose level at the desired exposure temperature.<br>5. Perform the post-exposure electrical parameter measurements on the test samples and the control.<br>6. Write a test report in accordance with Section 4.0 of this document. |
| Test Facility | Primary: Cobham’s Test Facility in Colorado Springs, CO<br>Backup: Honeywell’s Test Facility in Clearwater, FL |
| Period of Performance | Test development and testing shall take no more than 60 days from start to finish.<br>Test Reports shall be generated and submitted 30 days from the completion of testing. |

*Notes:*

*[1] Since the components are unpowered for the majority (>99%) of the mission, the test samples shall be unbiased during the TID irradiation(s) to better simulate the actual radiation conditions that the components will undergo during the mission.*

*[2] If the list of critical electrical parameters is known prior to testing, that list maybe substituted in place of the datasheet/SMD electrical parameter list.*

## Test Reporting

The test results shall be summarized in a test report that also includes details on the following:

1. The number of test devices irradiated.
2. An exposure log for all the test devices.
    a. Include the start and stop times for each irradiation.
    b. Include the dose rate or the dose accumulated for each irradiation.
    c. Include the temperature of the irradiation chamber for each irradiation.
3. The bias conditions of the test devices during irradiation(s).
4. A list of the electrical parameters that were characterized pre and post irradiations.
5. A list of the test equipment that was utilized for the electrical parameter measurements.
6. A description of the dosimetry system utilized during the irradiation(s).
7. List any deviations from the test procedures outlined in this document that occurred during the irradiation(s) and/or during the electrical parameter characterization.
8. List any abnormalities observed during irradiation and/or during the electrical parameter characterization.