University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Project Definition Document (PDD)

Ho.M.I.E.
(Holographic Microscope Investigating Enceladus)

Approvals

	Name	Affiliation	Approved	Date
Customer	Erik Buehler	ASTROBi		9/13/2022
Course Coordinator	Kathryn Wingate	CU/AES		

1. Project Customer

Name: Erik Buehler
Email: erik@astrobi.space.com

2. Team Members

Name: Brianna Gagliardi **Email:** brga3962@colorado.edu	**Name:** Anna Casillas **Email:** anca3747@colorado.edu
Name: Nicholas Iwanicki **Email:** niiw2361@colorado.edu	**Name:** Eric Dean **Email:** erde3662@colorado.edu
Name: Tess Brodsky **Email:** Tess.Brodsky@colorado.edu	**Name:** Keith Bliss **Email:** Keith.Bliss@colorado.edu
Name: Patricio Ramos **Email:** Patricio.Ramos@colorado.edu	**Name:** Ryan Jones **Email:** ryjo8808@colorado.edu
Name: Alfredo Bautista **Email:** Alfredo.Bautista@colorado.edu	**Name:** Nick Aichholz **Email:** William.Aichholz@colorado.edu
Name: Kellen Martin **Email:** kema0161@colorado.edu	**Advisor:** Dr. Dale Lawrence **Email:** dale.lawrence@colorado.edu

3. Problem/Need

After Cassini's visit to Saturn, Enceladus quickly became a target of the ASTROBi Foundation's interest due to the moon's apparent habitability. In the search for life elsewhere in the universe, ASTROBi has begun researching a low-cost potential mission to Enceladus to investigate potential microbial life. Due to the moon's lessened radiative environment, lower-cost electronics can be used in the detection of prokaryotic life. A spacecraft with a 4U scientific capacity will be sent, with the primary instrument on board being a compact digital holographic microscope, to fly through the geysers on Enceladus and collect samples of the water droplets being emitted from the moon's icy crust. This microscope will be tasked with imaging material from the liquid-vapor plumes and detecting the presence of life. In addition to water, the ice crystals contained salt, silica, methane, complex organics, and nitrogen. Nitrogen is a key element required for life on Earth, and the complex organics detected may have been formed by biological processes. The discovery of life elsewhere in the universe can help us better understand our place in the universe and further educate our investigations of life elsewhere in the universe.

4. Previous Work

There are several examples of life-searching missions, and all of them vary both in approach and success. Mars Rover Missions such as Viking, Opportunity, Curiosity, and Perseverance, were all designed to handle and analyze collected samples from the Martian soil. Additionally, the Dragonfly mission is set to also collect organic samples from Saturn's moon Enceladus. Although there have not been any life-searching missions with a Digital Holographic Microscope (DHM) for sample analysis, there have been several DHM applications in a wide variety of STEM fields, most notably: biomedical engineering. This is due to the non-invasive nature of the microscope and has enabled cell imaging, cell cycle analysis, and particle/bacteria tracking. Holographic microscopes have also proven useful for time-resolved applications, as they can measure instantaneous topography changes, whose only limiting factor is the camera refresh rate. One of the main concerns for microbe detection is that most biological samples are transparent, but thanks to developments in digital holographic microscopy, such as phase contrast microscopy, there is no need for sample alteration to detect biological presence since brightness variations illuminate and show the contrast of phase shifts. Furthermore, DHMs excel at reducing the minimum required sample volume to detect bacteria as they image the whole volume simultaneously. DHMs can continuously track all motile organisms in a sample without missing any potential motion. This greatly increased the probability of detection compared with conventional light microscopes.

5. Specific Objectives

ID	Objective Description	Level 1	Level 2
O1	The microscope shall support the detection and characterization of life in samples of water from Enceladus containing living microorganisms.	The microscope will contain a processing system that will be capable of distinguishing between microorganisms and inorganics in a single image.	The microscope will contain a processing system that will be capable of distinguishing between microorganisms and inorganics in multiple images at the same time.
O2	The microscope shall be flight-like.	The microscope will handle flight vibrational levels and power requirements.	Will achieve Level 1 plus expected flight thermal and acoustic levels.
O3	The microscope implementation shall be a lensless digital inline holographic microscope.	The microscope will use a lens to focus the laser to a point where it will radiate and refract through the sample and then produce an image on a sensor.	The microscope will maximize the amount of useful light and minimize the amount of wasted light through a focusing technique.

O4	The microscope's processor shall not impact the microscope's overall thermal performance.	The processor's thermal load shall not impact the microscope's sample specimens.	The processor's thermal load shall not impact the sample or other components.
O5	The microscope payload shall fit within a 1U SWAP allocation.	The microscope shall be 1U in size.	The microscope will be smaller than 1U in size.
O6	The microscope shall survive launch and operational environmental conditions.	The microscope shall be capable of surviving launch from an ABL RS-1 rocket and post-launch maneuvers.	The microscope shall be capable of surviving launch environments exceeding that of the ABL RS-1 rocket as well as surviving environments exceeding those of the planned mission.
O7	The microscope shall have a liquid water interface for receiving and expelling samples under expected operating conditions.	The microscope shall allow for manual loading and unloading of samples.	The microscope shall allow for automatic loading and unloading of samples.
O8	The microscope shall support a 15-year mission life plus 3 years of manufacturing, assembly, testing, and integration.	The microscope and its components will remain functional for the necessary mission duration.	The microscope and its components will remain functional longer than the necessary mission duration.
O9	The microscope's processor and reconstruction algorithm shall be fast enough to keep up with the rate of material collection.	The microscope's processor and reconstruction algorithm will match the rate at which material is collected.	The microscope's processor and reconstruction algorithm will process samples faster than they are collected.
O10	The microscope shall support meeting the mission requirements under a 1 kbps downlink constraint.	The microscope's output data will be compressed to fit a 1kbps downlink.	The microscope's output data will be compressed to fit less than a 1 kbps downlink.
O11	The microscope's behavior shall be controllable via commands from ground control.	The microscope and its subsystems will be capable of being controlled via a ground station.	The microscope will be capable of automatically creating and downlinking detection descriptors for the ground operators.
O12	The microscope shall output its digital data via the orbiter's science data downlink.	The microscope will output data in the specified format.	The microscope will be able to output data in multiple different formats.

6. **High Level Functional Requirements**

ID	Requirement Description	Rationale	Objective(s) Addressed	Validation
FR1	The microscope shall have an x-y resolution < 0.8μm and a z resolution < 2μm.	Z resolution < 2μm is necessary to adequately see bacteria in the sample volume as the average size of a bacteria cell is around 2μm.	O1	Tested with calibration images/items of the desired size.
FR2	The microscope shall have an instantaneous imaging volume > 2 μL.	Guarantees a high data throughput and reduces the amount of computation required.	O1	Validate via analysis with calibrated volumes of water.
FR3	The microscope shall support frame rates from 1 to 100 FPS.	Necessary to accommodate different organism movement speeds and varying sample flow rates.	O1	Tested via the processor with timing.
FR4	The microscope shall support exposure lengths from 0.1ms to 1 second.	The exposure length needs to be short in order to minimize blur as well as minimize noise within the captured image.	O1	Tested via the processor.
FR5	The microscope shall include a processing system for transforming the raw image sensor output into a 3D reconstructed representation.	The purpose of 3D reconstruction is to "see" the whole volume simultaneously, so no material is missed. It also allows tracking of the motion of all motile organisms, simultaneously.	O1, O3, O9	Validated with known objects for comparison.
FR6	The microscope shall include a processing system for identifying and isolating objects of note in sample images.	Due to our limited bandwidth, we cannot send back every image captured. By identifying objects of interest we avoid having to send images that are not of use. Furthermore, by automating the process of image identification we cut down on the time required by researchers to sift through images.	O1, O9, O10, O11	Testing microscope using sterile samples and comparing results with organic samples test.
FR7	The microscope shall include a processing system for sending specific losslessly compressed images back upon request.	Images of interest captured by our microscope orbiting Enceladus must be able to be sent back to Earth to be studied by researchers. Losslessly compressed images will be sent when specific data is requested	O9, O10, O11, O12	Use the 'sent back' images and use algorithms to recover compressed data.
FR8	The microscope shall survive -50°C to 100°C.	The microscope needs to survive launch and operating conditions to achieve desired mission lifespan.	O2, O4, O6, O8	Thermal simulations (virtual or physical) and material specifications.
FR9	The sample volume shall be inserted into the microscope assembly via a manual, human-involved process.	This performance requirement is the bare minimum needed to be able to image a sample in the microscope assembly.	O7	Verify structural rigidity through Solidworks/ Ansys Stress simulations and verify input and output liquid volumes.

FR10	The microscope shall survive the launch vibration conditions of an ABL RS-1 rocket.	The microscope must be able to survive launch on an ABL RS-1 launch vehicle as well as any post-launch maneuvers.	O2, O6, O8	Test with vibration table for specified random vibration frequencies.
FR11	The microscope shall operate from -15°C to 40°C.	The microscope components remain operable within said temperature range to guarantee successful data collection.	O2, O4, O6, and O8	Thermal simulations (virtual or physical) to verify microscope operation in various temperatures.
FR12	The microscope shall consume less than 10W of electrical power while active and less than 0.5W when inactive	Power input beyond this is outside the capabilities of what the satellite can provide for its payload.	O2	Tested using a multimeter during operations and on standby
FR13	The processor shall consume less than 10W of electrical power while active and less than 0.5W when inactive	Power input beyond this is outside the capabilities of what the satellite can provide for its payload.	O2	Tested using a multimeter during operations and on standby
FR14	The microscope assembly shall not exceed 1U in volume.	Required by the customer to minimize costs of the space taken up on the spacecraft.	O2, O5	Measure housing physical dimensions

The objective of this device is to successfully image, detect and potentially characterize any microbial life that may be present in the samples collected from the liquid geysers on Enceladus. The overarching goal of ASTROBi is to find a cost-optimized solution to producing a digital holographic microscope imaging the plume material. The scope of this project will focus on the development of a flight-like digital holographic microscope capable of imaging microorganisms and micro-scale featureless cells. This device must operate safely within its environment to not harm individual samples and must be capable of operating in a microgravity environment. This device must ultimately be able to capture a raw “hologram” image of a sample from a sensor output, dispose of said sample, reconstruct the hologram into a complete 3D representation of the contents of the sample volume, detect the presence of life-like motion within the hologram, and transmit the necessary information to a ground station with the minimum number of bits.

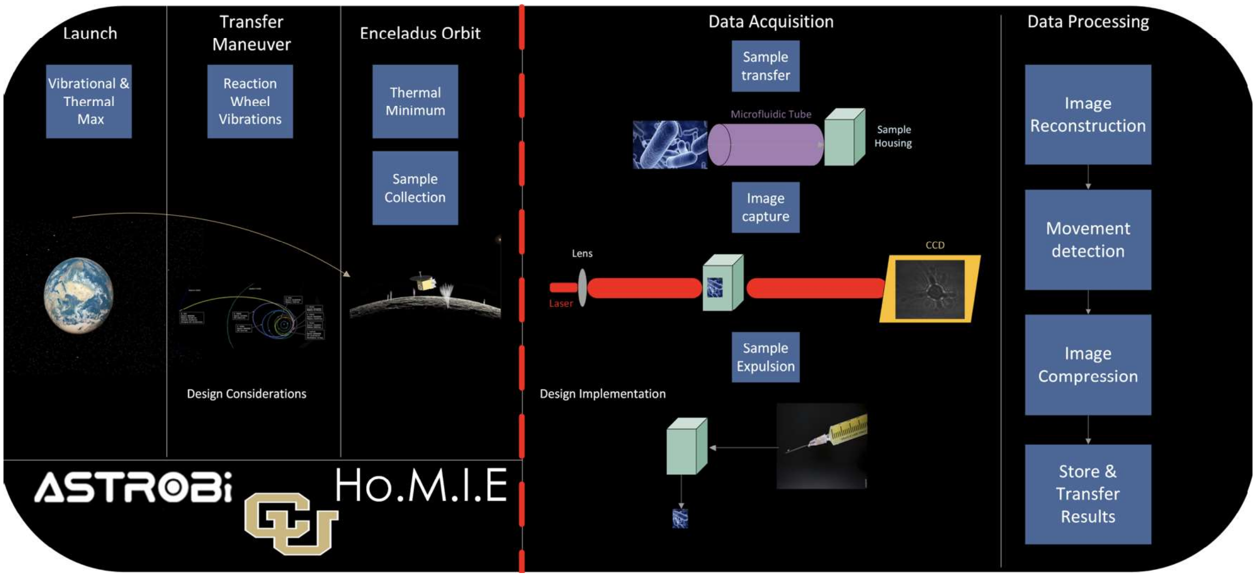

Figure 1: Con-Ops Diagram

7. **Critical Project Elements**
    a. Microscope Core Interfaces
        i. Microscope Core Interfaces will be responsible for supplying power, thermal, data, and sample transfer capabilities to the core aspects of the microscope. Without any one of these transfer capabilities, the microscope core will not be able to operate and achieve the mission goals.
    b. Spacecraft Interfaces
        i. Spacecraft Interfaces will be responsible for supplying power, thermal, data, and sample transfer capabilities to the entirety of the microscope module. Without any one of these transfer capabilities, the microscope module will not be able to operate and achieve the mission goals.
    c. Microscope Functionality
        i. Microscope functionality is key to achieving the desired performance requirements, such as resolution, FPS, and exposure length.
    d. Reconstruction Algorithm
        i. Reconstruction of images would be impossible without an algorithm to do so. This algorithm will render the microscope functional and will allow for the detection algorithm to process the created images
    e. Detection Algorithm
        i. The functionality of the detection algorithm will be responsible for the identification and isolation of objects of interest in sample images.
8. **Sub-System Breakdown and Interdependencies**
    a. Power
        i. The power source comes from the satellite's main power supply, an RTG
        ii. Supplies power to the processor, image sensor, and laser
    b. Data Handling

i. Image and hologram data must be transferred from the onboard processor(s) to a designated bulk storage device, where they will be stored and available to be sent upon request from a ground station.
ii. The data handling will be reliant on the image reconstruction, detection, and compression processes to supply the data.

c. Thermal
   i. Heat transfer will be controlled by the payload baseplate which is kept between -20C to 40C
   ii. During operation system temperature shall be kept between -5C to 5C
   iii. The thermal subsystem will draw heat from components such as the laser, image sensor, and onboard processor, and transfer it to the spacecraft baseplate which will act as a heat sink.
   iv. The thermal subsystem will provide heat to components that need it, such as the sample distribution system, by drawing heat from the spacecraft baseplate which will act as a heat source
d. Optics
   i. The optics system will take the laser and focus it on the sample and sensors. The optics subsystem will provide the base of the image reconstruction system.
   ii. The image sensor will be dependent on the power and thermal system to remain within its operational limits.
   iii. Images captured by the optical sensor are sent to the front end software of the processor where it is reconstructed and sent to the back end for imaging output.
e. Image reconstruction
   i. The holographic image produced by the optics will be processed by a reconstruction algorithm to obtain cross-sectional images throughout the test section
   ii. The Image Reconstruction subsystem will rely on the onboard processor, and in turn, the power subsystem, to produce the holographic image
f. Image Detection & Compression
   i. Processed images will be searched for movement or objects of interest. The information pertaining to these findings will be compressed and prepared to transmit
   ii. The Image Detection & Compression subsystem will rely on the onboard processor, and in turn, the power subsystem, to be able to analyze and compress any images of note

To facilitate effective planning and building it is essential to break down the project into individual subsystems. These subsystems perform separate tasks and interlink with other subsystems in order to accomplish the high-level tasks expected of this microscope.

9. Team Skills and Interests

Team member	Skills/Interests	Critical Project Elements
Brodsky, Tess	MATLAB, Python, Git, RF, PCB Design, Computer Vision, STK	Systems Integration
Gagliardi, Bre	Project Management, Communications, MATLAB, C/C++ NPSS	Project Management
Dean, Eric	MATLAB,C/C++,Python,Solidworks	Reconstruction & Detection Algorithms, Compression

Bautista, Alfredo	MATLAB, C/C++, Solidworks	Microscope Core Interfaces
Casillas, Anna	MATLAB, C/C++, Python, Optics	Mechanical Microscope & Core Interface
Ramos, Patricio	Solidworks Modeling/Simulation, git	Spacecraft Thermal & Electrical Interface
Bliss, Keith	Mechanical Fabrication/CAD, Electronics/PCB Design, C/C++	Microscope Core Interfaces & Spacecraft Interfaces
Martin, Kellen	MATLAB, Python, C/C++, git	Reconstruction & Detection Algorithms
Aichholz, Nick	MATLAB, C++, Electronics, SolidWorks (CSWA)	Chief Financial Officer, Reconstruction Algorithm
Jones, Ryan	SolidWorks, Algorithm design/optimization, MATLAB , C/C++	Image Reconstruction & Detection Algorithm Image Compression
Iwanicki, Nick	Matlab, C/C++, Data Handling, PCB Design/Fabrication	Spacecraft Electrical Interface, Spacecraft Data Interface, Power Supply and Management

10. Resources

Critical Project Elements	Resource/Source
Spacecraft Electrical Interface	Bob Marshall / Scott Palo (CU Boulder ASEN)
Spacecraft Thermal Interface	Xinlin Li (LASP)
Data Transmission	Bob Marshall / Scott Palo (CU Boulder ASEN)

11. References

1. Buehler, E., "Holographic Microscope Resources," *Google Docs* Available: https://docs.google.com/document/d/126EsHAgEEi7H3ZuZ0Xzs7Wnltxe2_osxLGaiIe-T8HQ/edit?usp=sharing.
2. ASTROBi Foundation. 2022. *ASTROBi Foundation Missions - ASTROBi Foundation*. [online] Available at: <https://astrobi.space/missions/>
3. Bedrossian Manuel, Lindensmith Chris, and Nadeau Jay L.. Astrobiology. September 2017, 17(9): 913-925. https://doi.org/10.1089/ast.2016.1616
4. McCartney, M. R., and Smith, D. J., "Electron Holography: Phase imaging with nanometer resolution," *Annual Reviews* Available: https://www.annualreviews.org/doi/10.1146/annurev.matsci.37.052506.084219.
5. Sandia National Laboratories "Digital holography reconstruction algorithms to estimate the morphology and depth of non-spherical, absorbing particles"
6. M. Kanka, R. Riesenberg, H. J. Kreuzer "Reconstruction of high-resolution holographic microscopic images"
7. James L. Flewellen "Digital Holographic Microscopy for Three-Dimensional Studies of Bacteria"