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Satellite for Estimating Aquatic Salinity and Temperature (SEASALT) A Payload and Instrumentation Overview

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ABSTRACT

The Satellite for Estimating Aquatic Salinity and Temperature, or SEASALT, is a 6U CubeSat designed to acquire coastal images to measure Sea Surface Temperature (SST) and to develop and utilize an algorithm to estimate Sea Surface Salinity (SSS). SSS can be retrieved in coastal zones by utilizing atmospherically corrected optical images to retrieve remote sensing reflectance (R_{rs}). The R_{rs} and SSS retrieved from that area can then be related through an empirical algorithm accurate for that body of water. Instruments currently used for SSS calculations, such as MODIS and VIIRS, are staged on single satellites that have limited revisit times and low spatial resolutions that make it challenging to implement accurate SSS retrieval algorithms. The Planet constellation imagers have lower revisit times and higher spatial resolution than MODIS and VIIRS, but lack the optical bands to enable retrieval of SSS. SEASALT is designed to address both of these limits. SEASALT utilizes bands centered at 412 nm, 470 nm, 540 nm, and 625 nm in the visible (VIS), and 746 nm, 865 nm in the Near Infra-Red (NIR) to provide accurate atmospheric corrections related to aerosols. It also utilizes a long wave infrared (LWIR) band centered at 12.013 µm for ocean temperature retrieval. A constellation of SEASALT CubeSats would be feasible to launch and operate, allowing for SSS to be retrieved frequently on a global scale.

The SEASALT mission requires a two-year development phase from its current post-instrument PDR state. The SEASALT instrument design has multiple detectors and corresponding optical paths to capture the science bands. The instrument has a large primary catadioptric Ritchey-Chrétien based telescope covering the 412 nm, 746 nm, and 865 nm bands, with the RGB and LWIR cameras each on their own optical paths. The instrument has two custom-designed calibrators; one for the 412, 746, and 865 nm wavelength cameras, which have both a light source and a shutter mechanism, and one for the LWIR camera. Finally, a dual-redundant Raspberry Pi flight computer, based on the MIT DeMi and BeaverCube missions, monitors and controls all payload operations.

In this work, we discuss design trades for payload and instrumentation, covering overall optical design, telescope design, electronic interfaces, and structural design requirements for fitting in a 6U CubeSat and performing its mission. We also present a detailed radiometric performance analysis of the optical path to determine each band's signal-to-noise ratio (SNR) and ensure it will meet mission SSS retrieval requirements.

INTRODUCTION

The Satellite for Estimating Aquatic Salinity and Temperature (SEASALT) is a 6U CubeSat designed to estimate Sea Surface Salinity (SSS) and to retrieve Sea Surface Temperature (SST). Salinity cannot in general be measured directly with optical in-

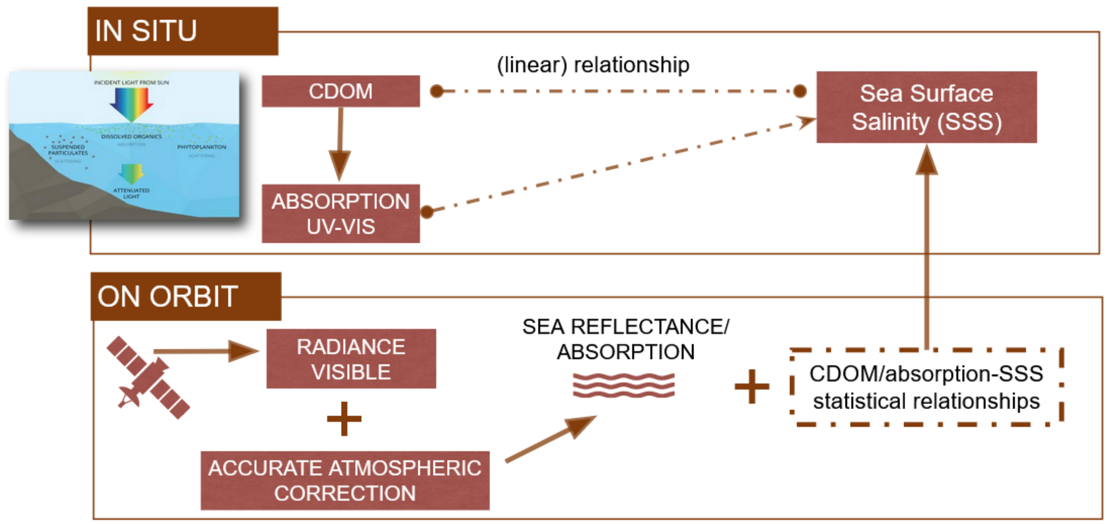

Figure 1: The scientific concept for the SEASALT mission. The measurements taken in situ and on orbit will be combined to form a linear regression algorithm, which will then be used to extrapolate SSS in the area over a larger temporal and spatial area.

struments. Instead, a combination of in situ measurements of colored dissolved organic material (CDOM) and SSS can be related to optical data through a linear regression algorithm to estimate SSS.[1] This relationship, as well as the retrieval method, can be seen in Figure 1. Because the diversity of water types causes different reflectances, developing a global salinity algorithm with this method is not possible. To monitor global salinity and develop individual algorithms for each region of interest, we require a large dataset, temporally and spatially, of matched in situ and remote measurements. Satellites with instruments currently used for taking salinity measurements, such as the MODIS and VIIRS instruments, have low revisit rates, which limits the performance of the derived algorithms. Other satellites with high revisit rates, such as those by Planet, lack a band to monitor CDOM for optimized salinity products, as well as the required NIR bands for atmospheric correction.

These gaps lead to the development of SEASALT. By utilizing a small satellite with a dedicated imaging system, algorithms can be developed for dedicated bodies of water more rapidly and more accurately, extending the area being monitored. Additionally, by utilizing a small satellite platform, it becomes feasible to expand the SEASALT satellite into a constellation, allowing for monitoring of SSS in multiple locations with improved temporal and spatial coverage.

In order to accurately measure SSS and SST, SEASALT images on seven bands, as listed in Table 1. 412 nm is used to measure CDOM, a set of three RGB bands is used for imaging, 746 nm and 865 nm are used to provide top-of-atmosphere (TOA) correction, and wavelengths in the longwave infrared (LWIR) are used to measure surface temperature. Additionally, SEASALT utilizes calibrators for the 412 nm, 746 nm, 865 nm, and 12013 nm bands in order to generate remote surface reflectance (R_{rs}) products that feed into the salinity algorithm. SEASALT will also have a RGB camera on a separate optical path to allow for corroborating images of target sites.

Table 1: Bands used in SEASALT imaging system.[1]

Wavelength [nm]	Regime	Purpose
412	Deep blue	CDOM
470, 540, 625	RGB	Visible RGB
746, 865	NIR	TOA Correction
12013	LWIR	Temperature

Salinity can vary in different water types for various reasons, making it a compelling feature to study. In regions with river discharge, the variance in salinity levels can directly affect the aquatic life in the region. More importantly, salinity can be used to track climate change phenomena. The goal of this work is to advance remote salinity monitoring to track changes in target high-risk locations. The initial SEASALT mission is projected to last for at least six months of operation, with an expected extended life of twelve months. SSS and SST retrieval are its primary mission, and the demonstration of on-orbit optical and thermal calibration sources is secondary.

Science Mission Requirements

To meet the stated scientific mission, SEASALT needs to collect data on four properties: SSS, ocean color (CDOM), SST, and atmospheric data. The summary of these required measurements can be found in Table 2. SSS and SST are both primary goals for the mission. CDOM can be used in developing the salinity algorithm, as it has a inverse linear relationship to SSS.[2] There need to also be specific measurements taken to allow for atmospheric correction of scientific measurements to ensure accurate recovery. A different amount of precision is required to consider the mission a success. In general, the goal is to estimate the success of instruments of VIIRS and MODIS as much as possible. There is a threshold of performance, as well as a goal performance, listed for each requirement.

The precision thresholds listed lead to a requirement for the VIS/NIR radiometric links to close with a signal-to-noise ratio of at least 10 dB.

Concept of Operations

The SEASALT payload consists of both imagers and calibrators. To observe the desired sites, both for coordinated data-taking to develop the algorithm and for collecting observations to monitor SSS, the imagers need to be calibrated approximately once every three days. This number was determined based on the MODIS calibration data collection schedule to measure their sensor degradation.[3] MODIS would calibrate weekly for two years, so, for a projected 12 month mission for SEASALT, it would be performed every three days. This will continue to be evaluated based on the measured sensor degredation.

The full concept of operations for the satellite can be seen in Figure 2. Two types of on orbit calibration are for the LWIR imager and for the NIR/Deep Blue optical path (more detail for the hardware can be found in the Calibrator and Shutter Section). LWIR calibration is performed by closing a shutter with a thermal source, as seen in steps 1 and 2, taking approximately 60 seconds plus the integration time. In order to perform calibration for the NIR/Deep Blue imagers, the satellite must either be in eclipse or a shutter must be used. During the first 6 months of operation, the NIR/Deep Blue calibrations are performed only during eclipse to limit the risk of a failed actuation of the shutter. After this, calibration can be performed at any time. Step 3 of the conops shows the NIR/Deep Blue shutter being actuated closed. The calibration for the NIR/Deep Blue bands is then performed, taking approximately 60 seconds plus integration time. After this, the shutter is lifted, and SEASALT is ready to image. As it approaches the site where the coordinated measurement will be taken, SEASALT will slew to point the camera in the proper location. Images will then be taken on all bands; for a single orbit, each camera shall be used once, resulting in 5 images being taken. Finally, the images will be downlinked, and post-processing will be performed on the images and the calibration data.

SPACECRAFT SYSTEMS

The SEASALT payload is designed to be integrated with a commercial bus for a 6U CubeSat. Platforms such as this sometimes provide 4U of payload space in an "L" shaped configuration. To accommodate this, SEASALT utilizes two separate optical paths: one for the NIR/Deep Blue imagers, and one for the LWIR and RGB imagers. We assume the commercial bus shall interact with the SEASALT payload as is shown in Figure 3, providing basic spacecraft functionality, such as receiving and sending data, sending uplinked commands to the payload through a custom payload computer, performing basic pointing, and providing power on three power lines (3.3 V, 5V, and 12V), utilizing current limits and inhibits. It is assumed that the battery will provide 6.8 Ah, and there will be 4 kg of available payload mass.

The payload computer is based on the custom computer utilized on other STAR Lab CubeSat missions, including DeMi[4] and Beavercube.[5] More detail on the construction and operation these computers can be found in the description of those missions, but, in summary, these computers were designed to utilize the Raspberry Pi Computer Module 3 Lite computing platform, providing UART, 3V3, 5V, and USB connections to the payload. To regulate power, a STM32 interface and a USB hub will be utilized. These provide inherent voltage regulation and current limiting, protecting the payload. The flight computer is single-fault tolerant to a CM or voltage regulator failure, and triple-fault tolerant to a flash memory failure.

Table 2: The science traceability matrix for the SEASALT mission. These are the science products that must be measured for the mission success.[1]

Product	Rationale	Measurement	Precision Threshold	Precision Goal
Sea Surface Salinity (SSS)	Key property	VIS/NIR: 390-865 nm LWIR: LWIR: 11.6 µm - 12.5 µm	0.5 PSS	0.2 PSS
Sea Surface Temperature (SST)	Key property	LWIR: 11.6 µm - 12.5 µm	1°C	0.5°C
Ocean Color	CDOM is a proxy for SSS[2]	VIS/NIR: 390-865 nm	30 m GSD	N/A
Atmospheric Corrections	Accurate recovery of sea-related radiance	VIS/NIR: 390-865 nm LWIR: LWIR: 11.6 µm - 12.5 µm	15% error	10% error

Table 3: Band groupings along each optical path, as seen in Figure 4

Optical Path	Bands [nm]
Scientific	412, 746, 865
RGB	470, 540, 625
LWIR	12013

Table 4: Cameras used in SEASALT imaging system.[6,7]

	VIS and NIR Camera	LWIR Camera
Model	Pixelink PL-D797 (Board Level)	FLIR/BOSON 320, 16 Degrees [HFO] 18 MM
Description	Board level camera	Compact LWIR Thermal Camera Core
Quantity	4 each with filters (Table 1)	1 modified with IR Camera Filter defined in Table 1
Dimensions	55 × 38.5 × 30 mm	21 mm × 21 mm × 11 mm
Mass	35.8 g	38 g
Operational Thermal Range	-45° C to 85° C	-40° C to 80° C

MULTIBAND IMAGING SYSTEM

The requirements of the imaging system require simultaneous imaging on seven different bands. Imaging this many bands simultaneously is difficult without moving towards custom-designed push-broom sensors, especially for long-wave infrared bands. For this reason, optical paths are split into separate categories and priorities. Wavelengths of scientific interest (412 nm, 746 nm, and 865 nm) are on a high performance telescope to maximize signal-to-noise ratio (SNR), RGB wavelengths are in a single camera, and LWIR wavelengths are captured by a FLIR Boson 320 camera. The band grouping is shown in Table 3, a visualization of the physical location of the cameras is shown in Figure 4, and a full list of cameras used in the imaging system is listed in Table 4.

Imaging Concepts

In the separated optical paths presented, it is simple to do simultaneous multi-band imaging for the RGB and LWIR optical paths, but the scientific optical path with its telescope requires additional management to be able to image on multiple detectors. Two concepts for multiband imaging are commonly used: chromatic dispersion to separate focal lengths or using a relay group and incorporating beam splitters in the middle to optimize for size, weight, and power (SWaP). These concepts are shown in Figure 5 and Figure 6.

While using chromatic dispersion for multiband imaging can utilize fewer optical elements, it can require longer optical trains compared to relay systems. Additionally, making optical trains smaller in chromatic dispersion based multiband imaging systems requires higher Abbe number glass lenses, which at a certain point due to finite filter bandwidth can cause image smearing on the detectors. For this reason, we chose to use a relay-based design for multiband imaging.

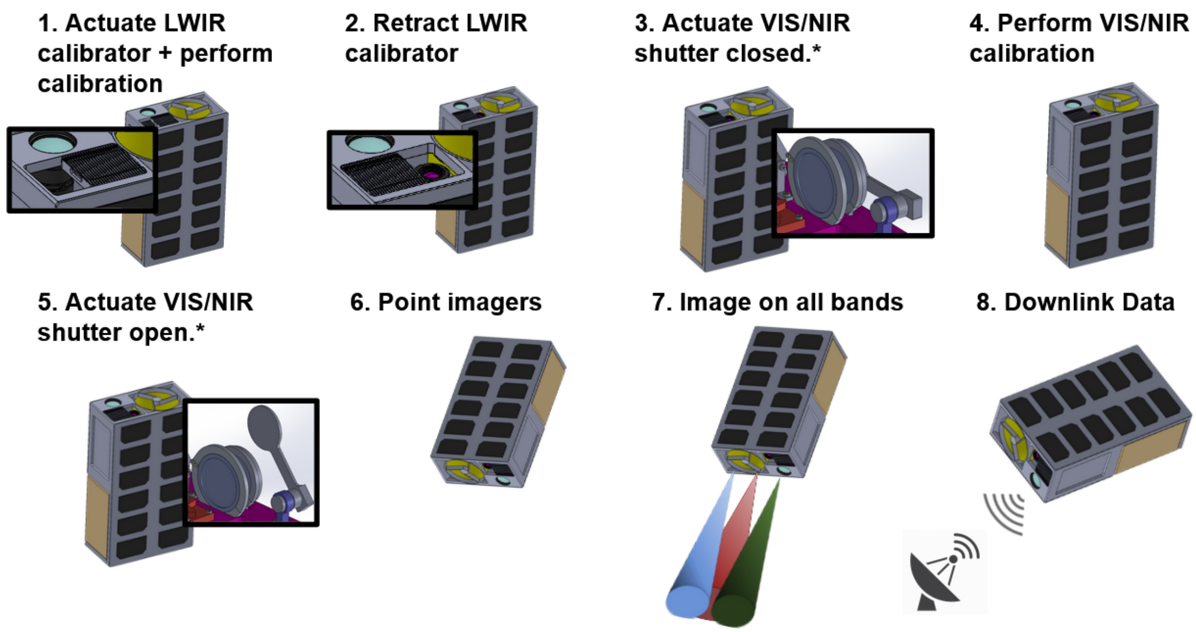

Figure 2: Concept of operations for SEASALT satellite. Steps 3 and 5 are only performed after the first 6 months of operation; otherwise, the NIR/Deep Blue calibration is only performed during eclipse.

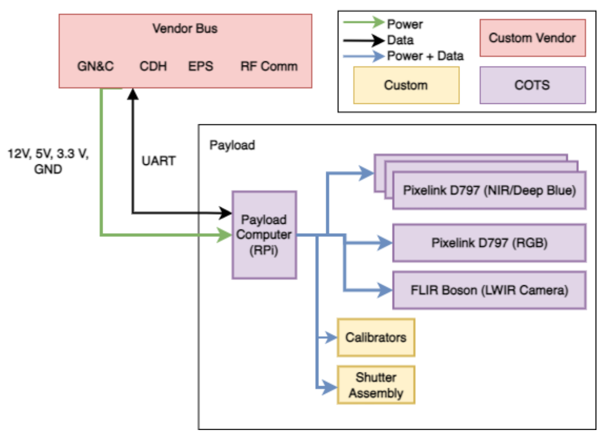

Figure 3: The bus payload interface for SEASALT, showcasing both the data and the power paths. We assume that a commercial bus provides the non-payload operations for the satellite.

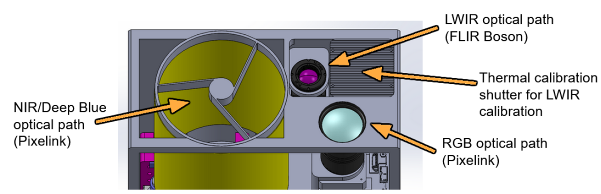

Figure 4: Imaging paths on nadir-pointing face of the satellite.

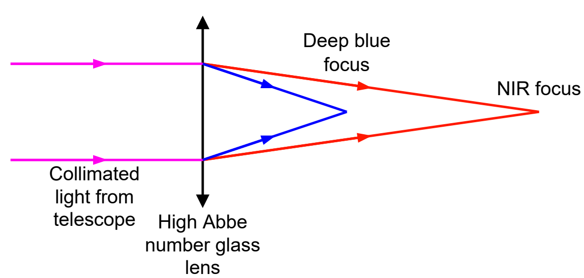

Figure 5: Chromatic dispersion multiband imaging concept.

Telescope

The telescope is a Ritchey–Chrétien design with two hyperbolic mirrors for best off-axis imaging performance. Recent advances in mirror design and manufacture have allowed for relatively larger primary mirrors in small satellites,[8] motivating our choice to go for a similarly large aperture for a CubeSat with

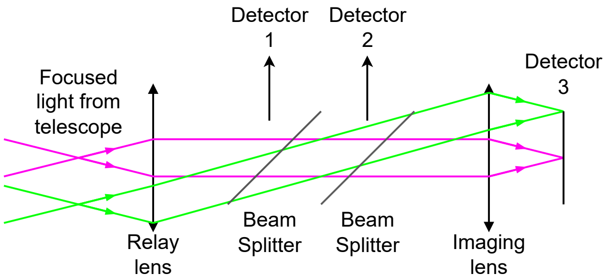

Figure 6: Relay lens multiband imaging concept.

Table 5: Imaging performance summary for scientific optical path.

Property	Value
Imaging Rate	One image per orbit of target location with each of 5 detectors
Resolution	3208 × 2200 pixels
GSD	30 m
SNR	10 dB for salinity retrieval cameras
FFOV	2.2 deg

a 90 mm primary mirror. The telescope is designed for minimum length as it is preferable to maximize the space behind it for the relay group. However, shortening the telescope's length increases the obscuration factor which lowers SNR. Hence, a 20% obscuration factor is chosen. Additional corrective optics in the telescope are used to improve off-axis imaging performance.

Current Design

The current design of the multiband imaging system is shown in Figure 7. Light exiting the telescope produces a single image which then gets sent to the relay group. The relay group collimates the light again, and a 99/1 beam splitter allows for the use of the calibrator in this optical setup without losing excessive amounts of power. A long pass dichroic splitter efficiently separates wavelengths below 420 nm, through which a 412 nm detector with a 10 nm filter can then image the deep blue band. The remaining two bands are slightly too close together to be able to use a dichroic splitter, and so a 50/50 splitter is used to split the remaining signal into the 746 and 865 nm detectors, each with their own narrowband filter. A summary of imaging performance for this system is shown in Table 5.

Radiometric Analysis

A radiometric analysis based on using atmospheric luminance[9] is conducted to understand signal-to-noise ratio (SNR), which can then be benchmarked against contemporary salinity retrieval instruments. Additionally, SNRs below the mission requirement of 10 dB can have an effect on the salinity retrieval.[1]

Table 6: Signal-to-noise ratio received on every imaging band.

Wavelength [nm]	SNR [dB]
412	14.42
470	20.08
540	19.65
625	18.26
746	20.33
865	20.05
12013	9.21

The complete list of signal-to-noise ratios is given in Table 6. The most limiting case is the 412 nm band, since it has a very limited bandwidth of 20 nm which supports the best science data but is detrimental to the signal to noise ratio in the band. For this same band, VIIRS has a 25.5 dB signal to noise ratio at a revisit time of approximately 14 days.[10]

CALIBRATOR AND SHUTTER

As part of a technology demonstration, integrated, optical and thermal calibrators are being developed for on-orbit use as part of the SEASALT payload. The cameras used in SEASALT are CMOS, which means they can have pixel nonlinearities[11] and degredation due to radiation.[12] The use of an on-orbit optical calibrator can help monitor these throughout the mission. This calibration is not required to meet the needs of the SEASALT mission, and thus it has been defensively designed to not interfere with the functionality of the cameras.

The optical calibrator, as seen in Figure 8, covers the VIS and NIR bands. It is incorporated in the optical bench and inserted into the optical path via a 1% transmittance beam splitter. This can be seen in Figure 13. During the primary mission, calibrations can only be performed during eclipse. After, a shutter, also seen in Figure 13, is utilized to extend calibration to be performed at any time during the orbital cycle. To further insure against a failed shutter mechanism, an incorporated one-time fusible

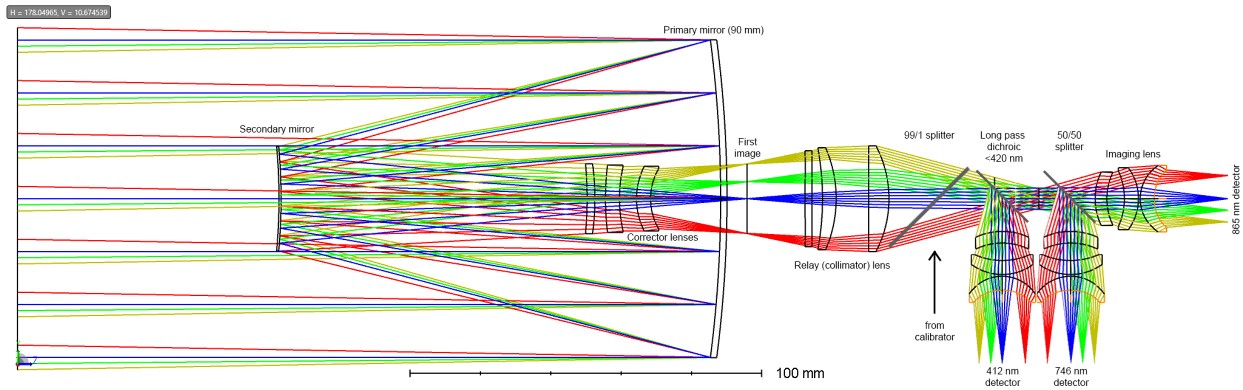

Figure 7: Scientific imaging system with annotated optical paths.

spring loaded link will swing the shutter out of the primary optical path.

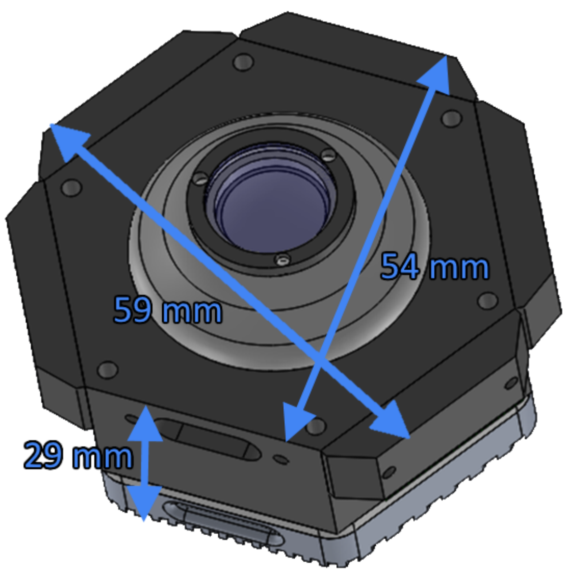

Figure 8: SEASALT Optical Calibrator showing the optical port, LED sources around the perimeter, power/data port, and the thermal stage heatsink.

The discrete light sources are provided using well characterized precision current controlled LEDs that are projected through a band narrowing filter. The diffuser is a based on a dual integrating sphere geometry, where the small LED specific sphere performs a first diffusion which, in turn, illuminates the primary sphere, Initial tests, shown in Figure 9, using a 4 cm diameter sphere with a 2 cm exit port have demonstrated better than 2% linearity throughout the entire frame.

The LEDs are thermally controlled using a Peltier driven stage to hold temperature at a known value.

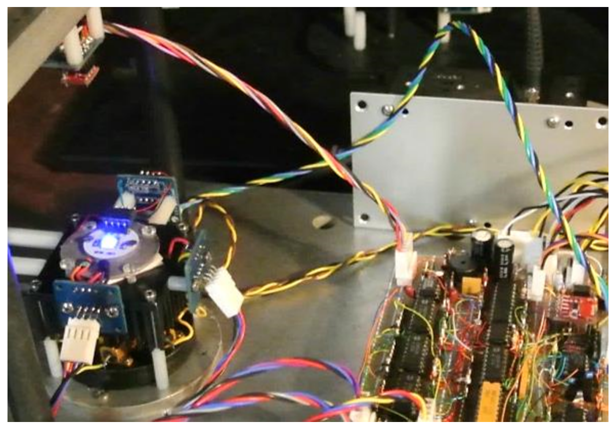

Figure 9: Full fidelity optical system showing thermal stage, LED under test, reference radiometer, and control circuitry.

The estimate for a calibration sweep for all three optical channels is less than 10 seconds including commanding the calibrator and acquiring the image. The data will then be processed to reduce file size as an offset map. Any gross outlying pixels will be flagged.

The calibrator employs an internal multiband radiometer which in turn can be vicariously cross calibrated while on orbit as it views the same scene as the cameras and provides a bulk value for comparison. A simple 4 wire serial and power interface accepts commands from the flight computer and in turn responds with a fixed length data field that includes light values, source temperature, and other diagnostics.

The LWIR calibrator, shown in its final design in Figure 10 and in its prototype form in Figure 11, provides a uniform Peltier driven reference that is capable of operating over a wide range of temperatures. Mounted within the spacecraft structure, this shutter remains retracted during normal operations and slides over the LWIR during calibration. Similar to the optical calibrator shutter, a one-time release mechanism is incorporated in the event of an actuator error.

The power, data interface, and data format structure are identical to the optical calibrator. Due to the low heatsink mass and lack of convective transfer, the duration of thermal steps is limited. A typical calibration routine will bring the black body radiator (BBR) into the camera FOV after an imaging sequence has occurred. The thermal stage will then slew the BBR to a temperature 15 deg C below the initial condition and step up in 5 or 10 deg steps at uniform intervals to a maximum of 35 deg.

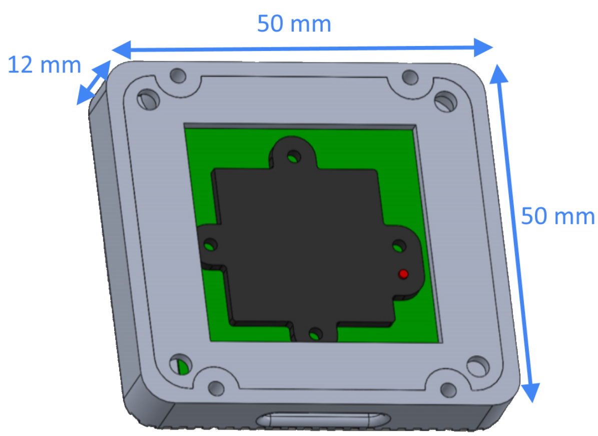

Figure 10: Detail rendering of the LWIR thermal calibrator. Shown are the black body radiator, temperature sensing thermistor, printed circuit board, power/data port, and the integrated shutter housing heatsink

SEASALT PAYLOAD

The full interior of the CubeSat can be seen in Figure 12, with detail on the main optical path in Figure 13 and on the secondary optical path in Figure 14.

The main optical path applies the design as shown in 7, featuring the detectors, splitters, and lenses. The path has been placed on a raised stand to center the optics with the telescope, to allow space for the calibration light source, and to allow space for the wiring of the hardware (not shown). The shutter assembly similarly is centered on the main optical path for calibration. The secondary optical path contains the LWIR camera and its calibrator, the RGB camera

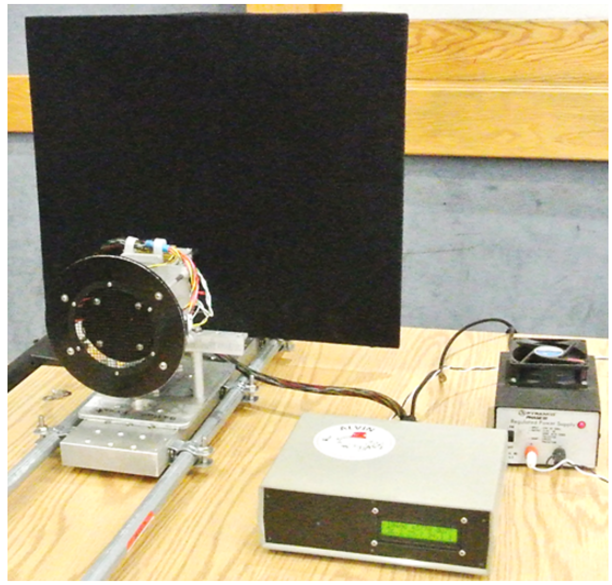

Figure 11: Laboratory 3 zone version of the thermal calibrator showing the control electronics and power supply.

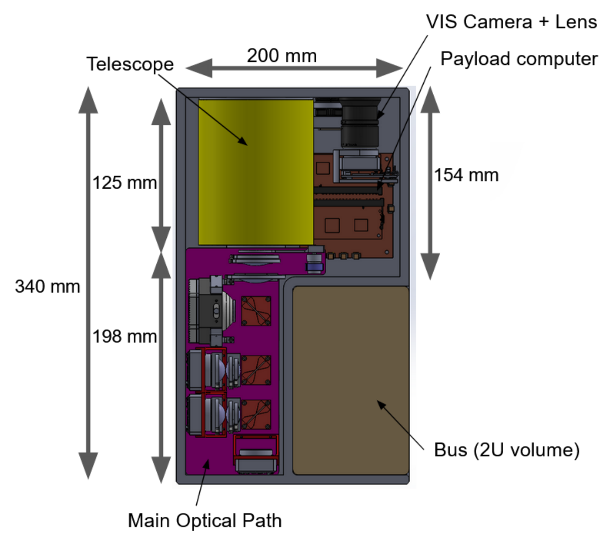

Figure 12: The interior of the CubeSat, showing both optical paths, including the telescope, and the commercial bus.

and its lens, and the payload computer. All of the internal of the CubeSat is designed with margin to allow for multiple configurations of internal wiring, depending on the commercial bus chosen.

CONCLUSIONS & FUTURE WORK

In conclusion, we present the full payload design for an instrument that can be used to accurately

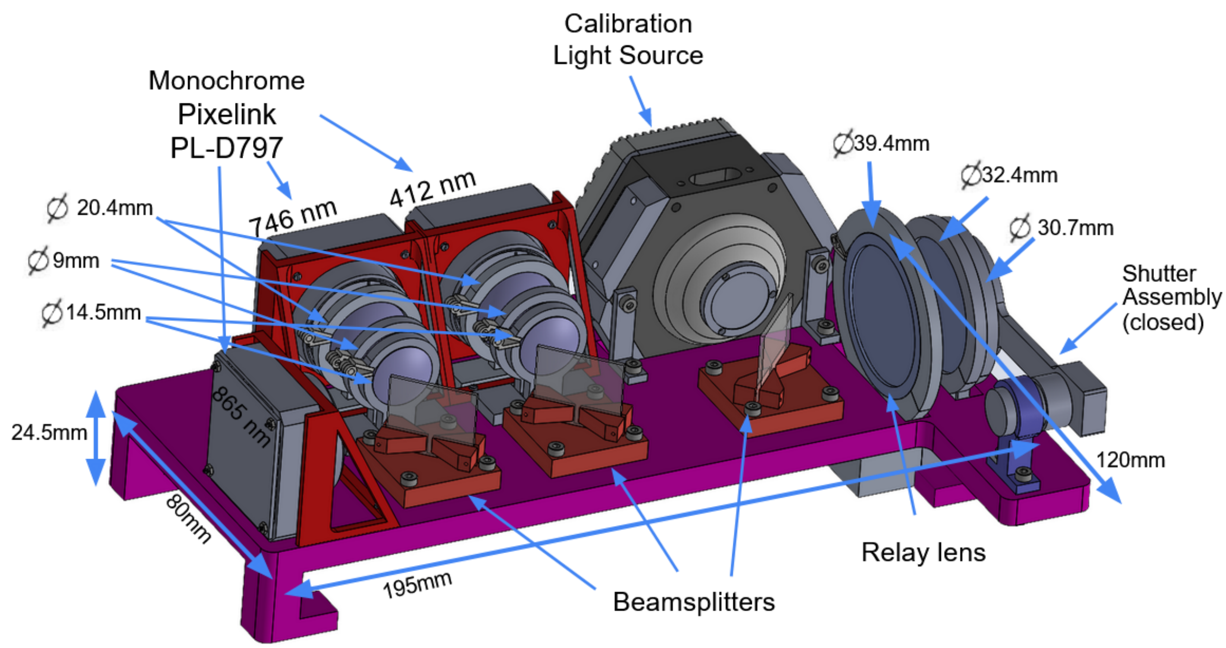

Figure 13: The main optical bench. This design utilizes three Pixelink cameras, each with their own lenses to match the desired bandwidths, the calibrator, beamsplitters, and the shutter assembly (shown closed).

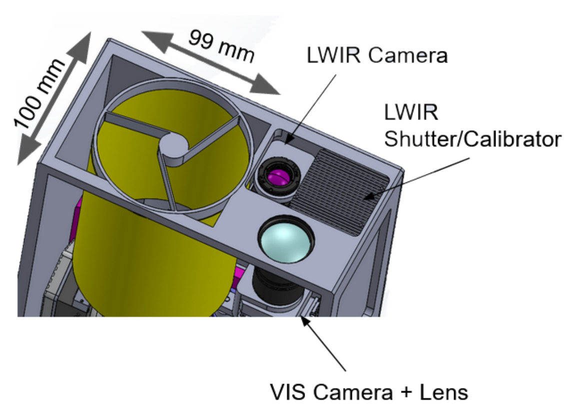

Figure 14: The top of the satellite, showing both the telescope and the secondary optical path. The secondary path contains the LWIR camera, its shutter, and the RGB camera.

retrieve salinity from CDOM concentration using additional bands in the NIR for atmospheric correction. The mission and future constellation can be dedicated to imaging bodies of water, something that is not currently supported by many multiband satellite imaging systems that primarily focus on land. The full payload fits in approximately a 4U volume leaving an additional 2U for bus subsystems. Payload design is validated within the sizing constraints, and a radiometric analysis derives the signal-to-noise ratio of the onboard imaging systems. The SNRs are slightly lower than contemporary instruments used for salinity retrieval, but the mission has a much more frequent revisit time compared to instruments such as the Visible Infrared Imaging Radiometer Suite (VIIRS) on NOAA's Suomi satellite and the Operational Land Imager (OLI) on Landsat 8/9.

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