The Spectral Ocean Color Imager (SPOC) - An Adjustable Multispectral Imager

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ABSTRACT

SPOC (SPectral Ocean Color) is a 3U small satellite mission that will use an adjustable multispectral imager to map sensitive coastal regions and off coast water quality of Georgia and beyond. SPOC is being developed by the University of Georgia's (UGA) Small Satellite Research Laboratory (SSRL) through NASA's Undergraduate Student Instrument Project (USIP). UGA is working with Cloudland Instruments to develop a small scale (<1000 cm^3) multispectral imager, ranging from 400-850nm, for Earth science applications which will fly as part of the NASA CubeSat Launch Initiative.

The project is UGA's first satellite mission and is built by a team of undergraduates from a wide range of backgrounds and supervised by a multidisciplinary team of graduate students and faculty. Development, assembly, testing, and validation of the multispectral imager, as well integrating it into the satellite are all being done in house. At an orbit of 400 km the resulting images will be 90 km x 100 km in size, with a default spatial resolution and spectral resolution of 130 m and 4 nm, respectively.

INTRODUCTION

The SPOC mission will develop and operate a moderate resolution coastal ecosystem and ocean color CubeSat (the first CubeSat dedicated to studying coastal ecosystems of Georgia) and acquire imagery of these ecosystems across a wide range of spectral bands. The SPOC satellite shall capture image data between 400 and 850 nm to monitor: 1) status of coastal ecosystems, especially in the Southeastern United States, 2) estuarine water quality including wetland biophysical characteristics and phytoplankton dynamics, and 3) near-coastal oceanic productivity. SPOC shall use hyperspectral remote sensing techniques to quantify vegetation health, primary productivity, oceanic productivity, suspended sediment, algal activity, and organic matter in selected coastal regions (Figure 1). This mission directly supports NASA's current strategic goals and objectives, including Strategic Goal 2 to *"advance understanding of Earth and develop technologies to improve the quality of life of on our home planet"* and Objective 2.2 to *"advance knowledge of Earth as a system to meet the challenges of environmental change, and to improve life on our planet"* [1]. Data collected by the SPOC mission shall leverage ongoing coastal research efforts within the University of Georgia and shall be shared with relevant actors within coastal communities.

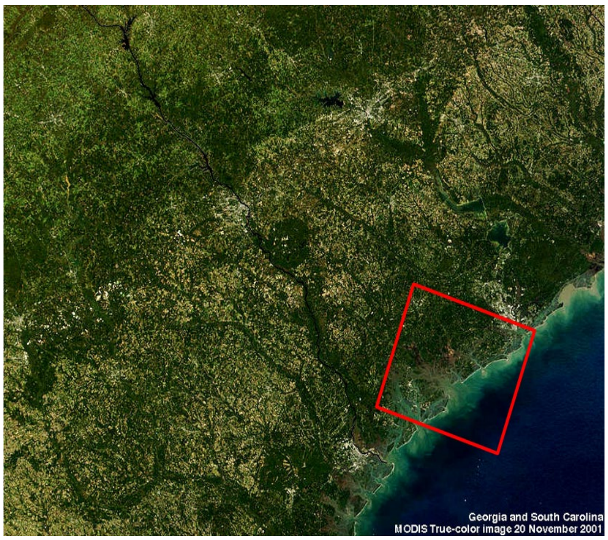

Figure 1: MODIS true color image of Georgia and South Carolina taken on November 20, 2001. The red insert is the estimated size of a SPOCeye image.

BACKGROUND

Coastal ecosystems, which include salt marshes, mangroves, wetlands, estuaries, and bays, are uniquely important to global economic and environmental health—yet are uniquely threatened. The US Environmental Protection Agency estimates that in the eastern United States, coastal wetlands are being lost at twice the rate they are restored [2]. Top threats to coastal environments include development, overexploitation, pollution, eutrophication, altered salinity and sedimentation, and climate change [3]. This is despite the estimated tens of billions of dollars that coastal ecosystems add to the US economy each year, through erosion control, recreation, commercial fishing, and tourism. In addition, wetlands have innumerable benefits for our nation's ecological health, as they provide habitats for thousands of species of birds, fish, and mammals [4]. Monitoring changes in coastal ecosystems can help enable effective responses through conservation, recreation, development, planning, and safety.

Hyperspectral imagery data represents an effective medium for studying ecological change. Sensors that are hyperspectral in nature will detect, quantify, and record electromagnetic energy for across many narrow spectral bands. Since the bands they detect tend to be much narrower than the bands recorded by multispectral sensors, hyperspectral sensors are said to have higher spectral resolution, which is useful for environmental monitoring and thus the purpose of this mission. Improvements in spectral resolution yield more precise reflectance curves, which can then be measured and compared to study wetland productivity, estuarine water quality, and suspended sediment over time. Examples of hyperspectral sensors that have been used for remote sensing purposes include NASA's AVIRIS and Hyperion. With SPOC's targeted focus on coastal ecosystems, the team shall expand on the work done by previous hyperspectral imaging platforms and use it to better understand the way our coastal ecosystems are changing.

CubeSats, with their low cost and fast development cycles, represent an attractive medium for collecting hyperspectral data on coastal ecosystems. While hyperspectral imaging is possible from a UAV or aircraft platform, CubeSats can be a cheaper alternative when attempting to sample the same large-scale area over a longer period. Data from the SPOC payload will be utilized to further develop Gross Primary Productivity (GPP) and Carbon Sequestration Potential models of salt marshes on the Georgia coast [5]. By combining the payload derived vegetation indices with data from an NSF-funded Georgia Coastal Ecosystems Long Term Research (GCE-LTER) site on Sapelo Island, Georgia, the SPOC team will increase the precision of earlier methods used for GPP estimation, which yielded discrepant results [6,7].

In addition, data obtained through this sensor will be used to map coastal and estuarine water quality using empirical models already developed by the SSRL group [8]. These models will be used to derive the Inherent Optical Properties (IOPs) of several Optically Active Constituents (OACs) including Canopy Chlorophyll-a (chl-a) (proxy for phytoplankton), phycocyanin (PC) (proxy for cyanobacteria), Colored Dissolved Organic Material (CDOM), and Total Suspended Sediment (TSS) [9]. The University of Georgia has an internationally respected team of remote sensing and Earth scientists, coastal ecologists, and modelers in the Center for Geospatial Research (CGR) who address issues of multispectral and hyperspectral airborne and space borne remote sensing of vegetation health, primary productivity, ocean productivity, sediment, and organic matter [9,10]. The development of this payload capability will enhance ongoing NASA, NSF, and National Oceanic and Atmospheric Administration (NOAA) funded research to assess and monitor near-shore water quality and carbon sequestration potential of coastal salt marshes using moderate resolution multi-spectral imagery from Landsat and Moderate Resolution Imaging Spectrometer (MODIS).

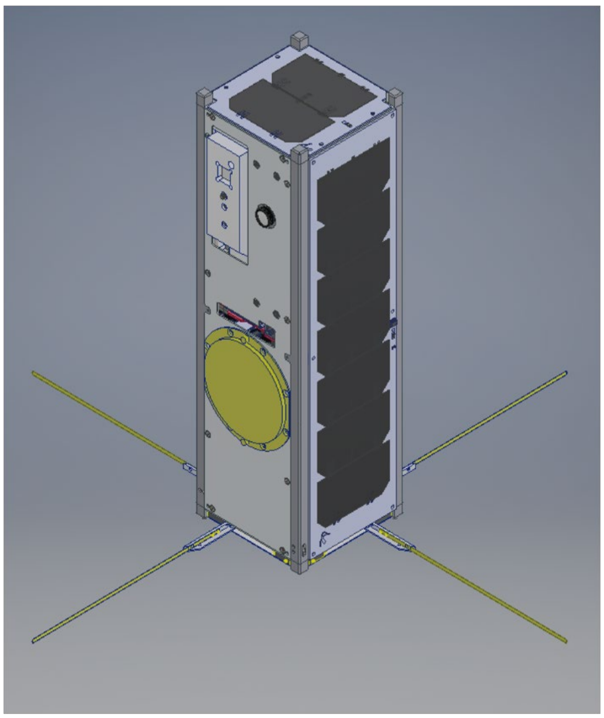

Figure 2: Current SPOC design, a 3U standard CubeSat with deployable antennas.

To meet the research goals laid out in this section a 3U CubeSat with an adjustable multispectral imager is being developed by UGA SSRL, shown in Figure 2. While the mission and payload are aiming to image coastal areas at least once a week with spatial and spectral resolutions of 130m and 4nm respectively, the minimum success criteria for SPOC are:

1) Image one coastal target a month. The images shall have a minimum spatial resolution of 240m;

2) Acquire images between 400 and 850 nm with a spectral resolution of 50nm;

3) Acquire images in the range of 400 to 850 nm bands of Landsat 8 and MODIS bands as well as SeaWIFS bands.

PAYLOAD

The optical layout for the payload SPOCeye (Figure 3) was designed by Cloudland Instruments with SSRL building and testing the optical structure and housing. The design of the payload is laid out with incoming radiation entering the optical structure through a long pass filter, thus eliminating most wavelengths below 420nm. Next a telescope style lens system will focus the light onto a linear slit before it interacts with the grating spectrometer. After passing through the linear the slit, the light is collimated by a collimating achromatic lens, to ensure all the light interacting with the spectral grating is parallel. The spectral grating consists of a 150 line per mm grating blazed for 500 nm. The final lens, the camera lens, re-images the spectrally dispersed image of the entrance slit onto the CMOS array. Overall, the spectrometer breaks down into two sections, the fore-optics, which focuses the light onto a slit, and the spectrometer, which uses the light that passes through the slit and disperses it across the 752x480 pixel CMOS array.

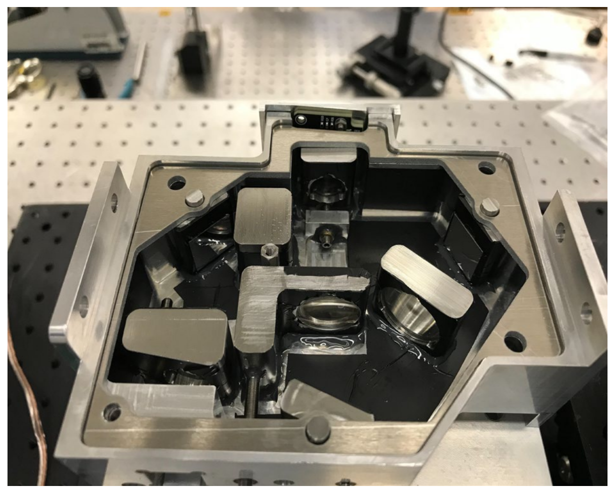

Figure 3: SPOCeye optical layout and housing showing the 11 optical elements of the system. The entrance pupil is located at the bottom of the image.

The 752-pixel wide slice is moved across the scene in a “push broom” scanner manner, with the image being built up slice by slice. The wavelengths for the slice are dispersed across the height of the array, 480 pixels, with a resolution of about 1.042 nm per row. For each slice the entire array must be read out creating a 750x480 pixel image for each corresponding ground-based slice.

This CMOS array is designed for low cost video applications and runs at a maximum speed of 55.55 frames a second. The longest exposure that can be supported at this readout rate is about 17.5 milliseconds. From a CubeSat orbit of 450 km or below, with a ground velocity of 7500 meters per second, this is about 131 meters of motion during a 17.5 ms exposure. Optics blur and the motion blur could result in a star-like white spot on the ground and end up being around 2.4 pixels in size on the array (Full Width Half Maximum, or FWHM), an issue that will be further addressed during testing and characterization of the optical payload.

The raw hyperspectral data generates up to 3000 frames of 10-bit data, for a total data volume of 1.35 gigabytes per scene. This is far too large of a dataset to be returned to earth over a CubeSat (S-band) downlink in one pass. Within the payload system, the data is currently set to be aggregated before being stored on the onboard processor by summing 4 rows together to produce 4.16 nm wide spectral data. SPOCeye is connected to a PicoZED board which controls the CMOS sensor; and is where initial binning will occur. This initial binning significantly reduces file sizes needed for data downlink while still preserving the hyperspectral properties of the dataset.

To address our main science questions while working within the limits of the CubeSat platform, i.e. data downlink limitations, the spectral data will be binned even further to 16 user defined bands. Different binning schemes will be utilized for each band to optimize signal-to-noise ratio (SNR) and to generate bands of various bandwidths and band centers within the original 400 – 850nm range. These bands will be defined by ground-based commands uploaded by the user during the scheduling of data acquisition passes. The adjustable nature of the data collected by SPOC provides numerous advantages.

1) Binned datasets result in a higher SNR and thus provides more useful data;

2) Since the mission is limited by S-Band downlink capabilities storing less data results in more locations that can be imaged;

3) The 16 user defined bands allow for more opportunities for cross calibration with existing legacy sensors;

4) The freedom to choose bands within the sensor range creates the possibility of observing phenomenon outside the scope of the original mission.

Verification and Testing

Guiding the mechanical design of the payload were several numerical simulations to gauge performance of the spacecraft. These simulations include structural eigenfrequency analysis, shock and random vibration, as well as dynamic thermal analyses [11, 12]. Due to the geometric sensitivity of the optics, thermal strain analyses were of interest to determine displacement of optical element due to temperature changes, figure 4. These models provided insights for design and are verified by unit testing as will be described momentarily.

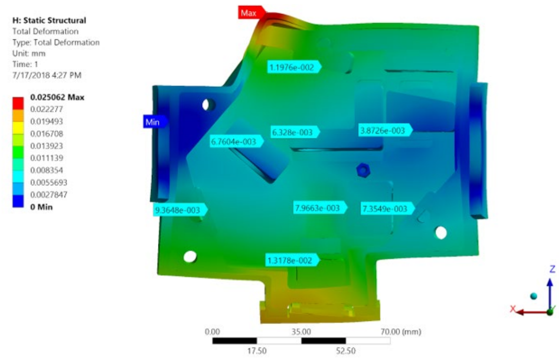

Figure 4: Modeled deformation due to thermal strain from -10 to 30 C temperature change

Initial SNR tests on the sensor were provided by Cloudland Instruments in Table 1. The table shows the 20 nm bandwidth pixels and their associated SNR. These tests are currently being validated and verified.

Table 1: Simulated Signal to Noise for a select band.

Wavelength	Band Center	FWHM	SNR
443	453	20	181
490	500	20	185
510	520	20	171
555	565	20	157
670	680	20	139
750	760	20	83
865	875	20	63

Calibration and characterization testing were just completed at NASA Goddard, including final alignment before gluing the lens mounts into place. Other testing included stray light, spot sizes, polarization sensitivity, variation of radiometric response with temperature, and exposure time nonlinearity. Current ongoing tests include radiometric calibration and spectral calibration, see figure 5. Once processed the results from these tests will allow for accurate cross calibration with existing sensors and therefore more scientifically robust measurements [13].

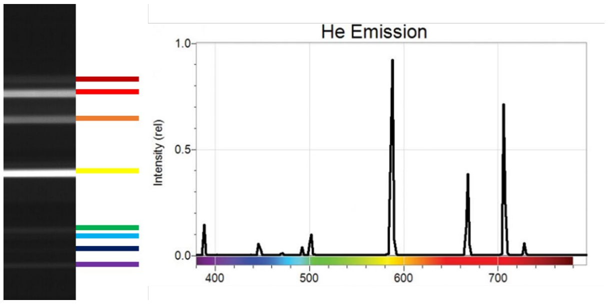

Figure 5: Left, spectral alignment testing using a Helium source. Right, reference image from Vernier.

SUBSYSTEMS

The SPOCeye payload is supported by various systems including a finder scope, 4D Systems uCam-III. The finder scope will produce and RGB image with 515 m resolution and will be used to help with image geolocation of the main payload. Other systems within SPOC include:

- Clyde Space 3U Frame
- Clyde Space attitude determination and control system (ADCS):
    - ADCS Motherboard
    - 3-Axis Reaction Wheels
    - Fine Sun Sensor (x2)
    - Z-Axis Magnetorquer
    - Taoglas GPS Antenna
- Clyde Space Electrical Power System (EPS):
    - 40 WHr Battery
    - 3UA EPS
    - 3U Solar Panel (x3)
- Clyde Space on board computer (OBC) w/ GPS
- Communication:
    - F'Sati UTRX Rx/Tx
    - F'Sati STX-B Tx
    - ISIS Turnstile Antennas
    - F'Sati SANT Patch Antenna

These systems are supported by a custom-built core avionics interface board.

TIMELINE

The Spectral Ocean Color mission was funded as part of the NASA Undergraduate Student Instrument Program in 2016. In 2018 it was selected for launch through NASA's CubeSat Launch Initiative. SPOC is currently slated for launch in Q4, 2019 on a crew resupply mission to the International Space Station where it will be deployed using a NanoRacks Deployer.

In late spring of 2019, the payload underwent testing and validation at NASA Goddard. The fully integrated SPOC stack is set for full system testing at NASA Ames in late summer 2019.

GROUND SYSTEM

The University of Georgia Small Satellite Research Laboratory has a ground support system located on campus. The ground station is a trackable system that is integrated with Ball Aerospace COSMO mission command and control software. The station has a dual software defined/hardware defined radio system capable of utilizing frequencies between 10 Hz and 6 GHz. The station was designed to communicate with VHF/UHF/S-Bands designated for amateur satellite communication, figure 6.

Figure 6: UGA SSRL ground support equipment

CONCLUSION

There are still some milestones that need to be met to ensure the SPOC mission is successful. Regarding the payload, calibration data need to be further processed to ensure the system is fully characterized before launch. The fully integrated satellite still needs to undergo full environmental testing, including vibrational, before it can be handed off to NanoRacks.

Overall, this mission is providing UGA with its own space-based data sets and allowing students at UGA to be involved at every step of the data process. The science data will be used by UGA scientists to monitor vegetation health, water quality, and wetland status off the coast of Georgia, specifically focusing on the Sapelo Island National Estuarine Research Reserve. Additionally, with its tunable bands, the sensor could be used across the state and across the globe to monitor agriculture, algal blooms, drought conditions, etc.

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