Multislit optimized spectrometer: flight-like environment test results

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ABSTRACT

The NASA ESTO funded Multislit Optimized Spectrometer (MOS) Instrument Incubator Program advances a spatial multiplexing spectrometer for coastal ocean remote sensing from laboratory demonstration to flight-like environment testing. The multiple slit design reduces the required telescope aperture leading to mass and volume reductions over conventional spectrometers when applied to the GEO-CAPE oceans mission. This paper discusses the performance and characterization of the MOS instrument from laboratory and thermal vacuum testing. It also presents the current technology readiness level and possible future applications. Results of an ocean color data product simulation study using flight-like performance data from MOS are also covered. The MOS instrument implementation for GEO-CAPE provides system benefits that may lead to measurable cost savings and reductions in risks while meeting its science objectives.

Keywords: Hyperspectral, multislit, ocean, coastal, geostationary, GEO-CAPE, ocean color, spectrometer

1. INTRODUCTION

Coastal environments are increasingly important to the economy as more people work, play and live near the shore. Existing Earth remote sensing satellite sensors that provide typical ocean measurements from a low earth orbit such as MODIS and VIIRS capture variability from day to day over large areas of the ocean but are not able to resolve diurnal or high spatial resolution features with their once per day revisit time and 0.5-1 km spatial resolution. The National Research Council defined a mission called Geostationary Coastal and Air Pollution Events (GEO-CAPE[1]) to address these measurements needs. Capturing the diurnal, seasonal, and episodic changes in the coastal ocean environment imposes challenging requirements for remote sensing. Reflected sunlight from the ocean is low compared with the reflected light from the atmosphere or land features. It is difficult to achieve signal to noise ratios sufficient to retrieve ocean variables. Primary production for coastal ocean variables is driven by sunlight over the course of the day which requires temporal sampling on scales of a few hours to capture diurnal effects. Finally, full coastal coverage for the continental United States (CONUS) moves the sensor from low earth orbit to geostationary earth orbit (GEO). At the great distance of geostationary orbit, the signal to noise ratio required is very difficult to achieve. The sensor must have sufficient aperture size and stare long enough to build up the signal. Large apertures translate directly into high mass and volume which drives costs up for a geostationary mission. Without a breakthrough technology, a comprehensive remote sensing mission to measure changes in the coastal environment is not likely to move forward with constrained government budgets.

1.1 The multislit solution

To directly address the challenges of remote sensing in the coastal environment from GEO, the Multislit Optimized Spectrometer (MOS) was conceived. The goal of MOS is to provide high SNR and high spatial resolution hourly coverage of the full coast of the CONUS, in a form factor suitable to match hosted payload requirements for a communication satellite at GEO. A 4-slit plate was developed to provide scene multiplexing on a single 2-dimensional focal plane array. Each slit is dispersed into a hyperspectral image on a spatially separate part of the focal plane array which results in the equivalent of 4 independent spectral measurements of different coastal ocean locations at the same time. The concept of operations for coastal measurements from GEO is shown in Figure 1. A scan mirror moves the slit set from west to east collecting spectra continuously until the area between adjacent slits is fully covered (yellow field of regard). The scan then jumps to the red field of regard and executes the same continuous collection scan. The 4-slit case shown above requires ¼ the time to cover the field of regard compared to a single slit spectrometer while achieving the same signal to noise ratio.

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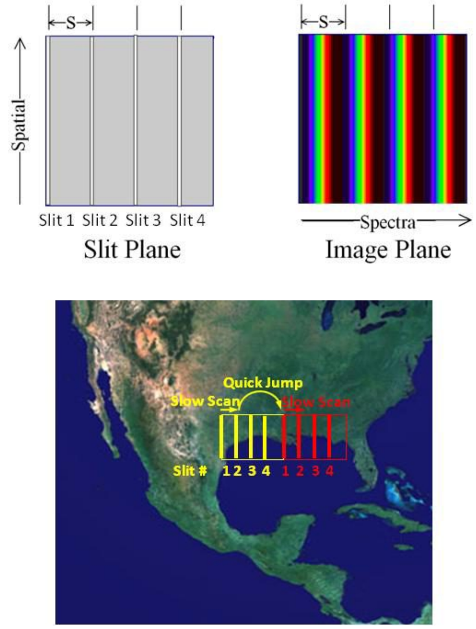


Figure 1. MOS simultaneously images the spectra from multiple slits/ocean regions on a single area focal plane array.

1.2 MOS: A game changer

A conventional instrument designed to meet the GEO-CAPE ocean requirements has an estimated mass of 621 kg (Coastal Ecosystems Dynamics Imager results from an instrument design lab study[2]). In order to determine the benefit in mass and subsequent cost savings of a MOS instrument, a parametric system model was developed to estimate mass variation with the number of slits. The results are shown in Figure 2. It is clear that significant reduction in telescope aperture and mass is gained by increasing from 1 slit to multiple slits. The limited benefit of additional slits beyond 4-5 can be evaluated for a mission specific situation. The ultimate limit to the number of slits is driven by the size of the large focal plane array in the spectral dimension as well as the spectral sampling required. Four slits were selected for the demonstration on the ESTO funded Instrument Incubator Program. The laboratory and subsequent thermal vacuum testing of the instrument was designed to test the multiple slit concept to show capabilities for performing a coastal ocean mission. The ability of each slit to perform ocean color measurements sufficient for valid retrievals is part of the evaluation to follow. Stray light interference and slit to slit crosstalk will be discussed.

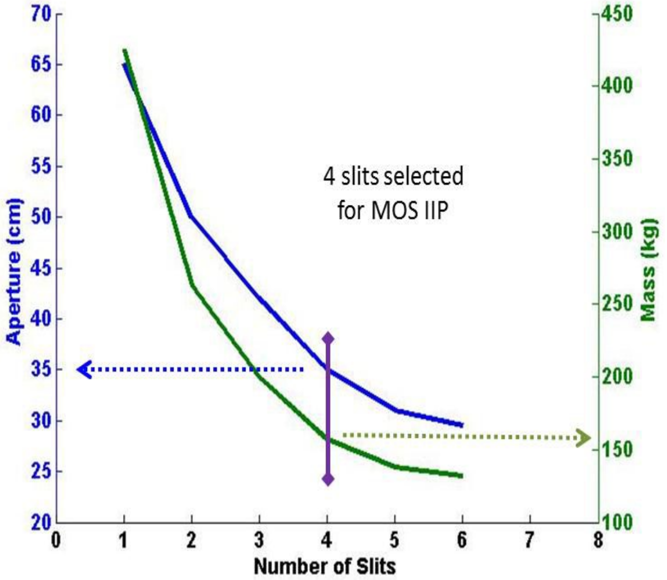


Figure 2: Parametric system model for GEO-CAPE oceans instrument shows significant aperture and mass reduction with a multislit spectrometer

1.3 The MOS instrument

The MOS instrument is a UV-Visible-NIR hyperspectral prism spectrometer based on a novel design form. The mirrors are protected silver coated silicon carbide and the structure is also silicon carbide as shown in Figure 3. The prism is fused silica. The 4-slit plate assembly is made from electroformed nickel. For testing purposes, MOS utilizes a contributed Teledyne Imaging Sensors 2K by 2K HyViSI^{TM} H2RG focal plane array and SIDECAR^{TM} ASIC to provide test images and measurements of opto-mechanical performance.

Figure 3: Two views of the MOS spectrometer show the all silicon carbide structure and mirrors. The focal plane with invar mount is shown in the right image as designed to undergo thermal vacuum testing.

2. AMBIENT TEST RESULTS

2.1 Multislit concept validation

In order to achieve the full benefits of multiple slits acting as independent instruments, it must be shown that the presence of the other slits does not adversely affect the measurements of one. The requirement was set at 1% of the expected ocean signal. Several factors could affect the measurements of a single slit including spectrometer performance and structural and thermal stability. These factors are similar to a conventional spectrometer and will be addressed in the next section. Factors that are specific to a multislit system include in-band and out of band straylight of a single slit as well as out of channel stray light from an alternate slit. Focal plane effects such as blooming can also contribute to cross talk. This study focuses on the opto-mechanical subsystem design and does not include focal plane effects that can be dealt with independent of the multislit concept.

The stressing case for slit to slit crosstalk is found when a relatively dark ocean signal is measured adjacent to a bright cloud signal. Figure 4 shows a cartoon of the scene from the ocean that would produce this stressing case. It is important that the ocean color instrument is able to retrieve the ocean parameters in Slit 2 while it is close to saturation in the 3 other slits. To simulate this condition in the lab, a large integrating sphere was used with a Xenon light source to generate a spectrally broad signal simulating reflected sunlight. Colored filters were used to shape the spectral curve of the incoming light to more closely match the spectral shape from reflected sunlight off the ocean. Due to the differences between reflection of clouds and ocean over the broad range from the UV-NIR, the spectral band of the measurements was broken into 3 measurement regions. For each spectral range, a relative intensity ocean and cloud radiance was calculated. Neutral density filters were used to apply these varying radiance levels to different slits on the focal plane. Figure 5 shows an image of the FPA with ocean signal radiance on the left in slit 2 and the other slits blocked and then with the cloud signal radiance on the right in slits 1, 3, and 4 with slit 2 blocked. The left image captures what the single slit would measure without any other slits in the system. The right image measures the light present in the slit 2 area of the focal plane with that slit blocked directly indicating the stray light contribution. The ratio of crosstalk “noise” from the right image to ocean signal from the left image is the measure of slit to slit crosstalk that is required to be below 1%.

The hyperspectral signal across the focal plane is shown for a source spanning the visible region in Figure 6. Filters were selected to simulate the spectral signature of the ocean over the wavelength range of 450-720 nm. A neutral density (ND) filter with optical density of 1.0 was used to create the expected signal intensity difference between a measured cloud scene and a measured ocean scene. The ND filter was placed in the source path for the ocean measurement and removed for the cloud measurement. Additionally, the ocean scene was blocked during the cloud measurement and the cloud slits were blocked during the ocean measurement. Finally, the 4th slit position was blocked throughout the measurements to provide a background measurement on the detector for each captured image.

For independent measurements from each slit that provide the multiplexing advantage, the crosstalk from slit to slit must be lower than 1% of the in channel signal. Figure 6 shows the crosstalk signal at the ocean slit in red and the ocean signal in blue. The crosstalk is less than 1% as required allowing for an individual measure of ocean color in the stressing scene case.

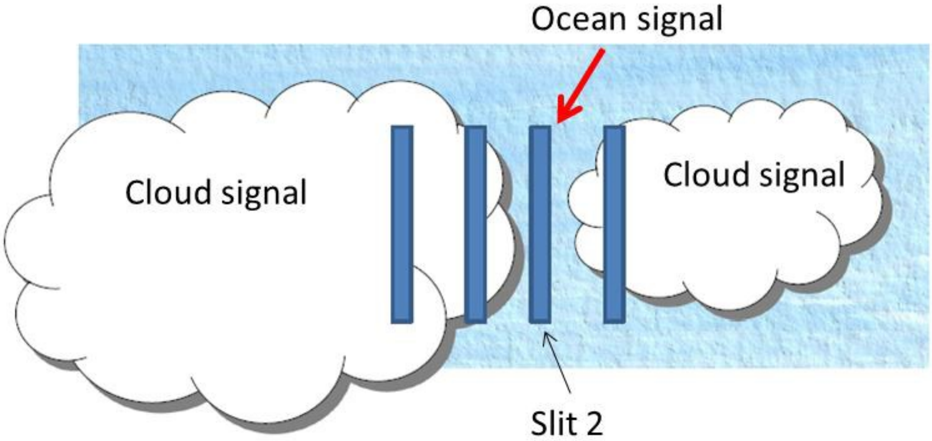


Figure 4: Sketch of stressing slit to slit crosstalk case simulated with lab sources to test concept.

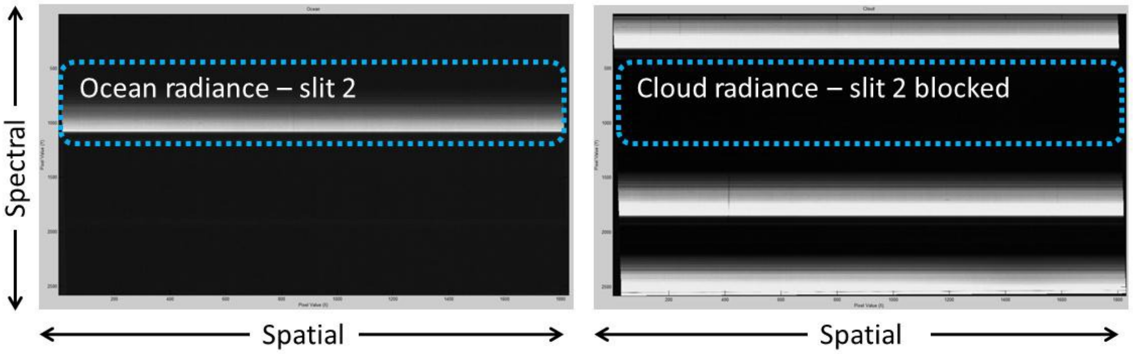


Figure 5: FPA images used for stressing crosstalk analysis. Ocean radiance level in single slit shown on the left and higher cloud radiances on other three slits shown on the right.

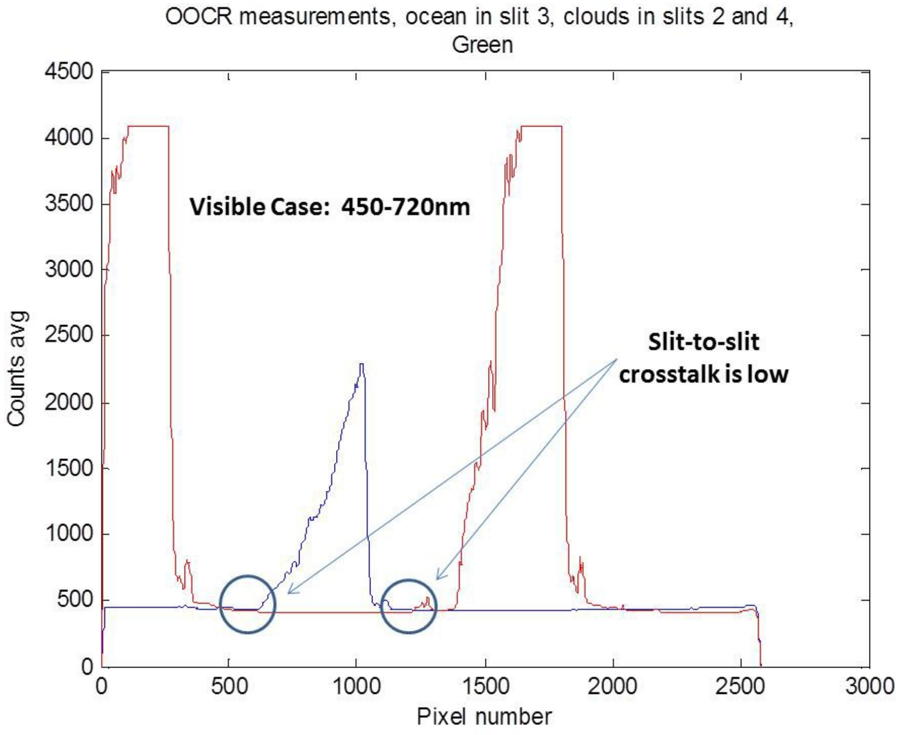


Figure 6: Spectrometer signal measured across the focal plane for a single field point shows very low overlap of slit signals from one to the next.

2.2 Spectrometer performance

In addition to verifying multi-slit performance, it is important to demonstrate that each slit performs as required to meet the requirements for ocean color retrievals. Figure 7 shows spectrally resolved multi-line laser measurements in each slit as dispersed across the focal plane. Each slit acts independently to resolve the spectral lines.

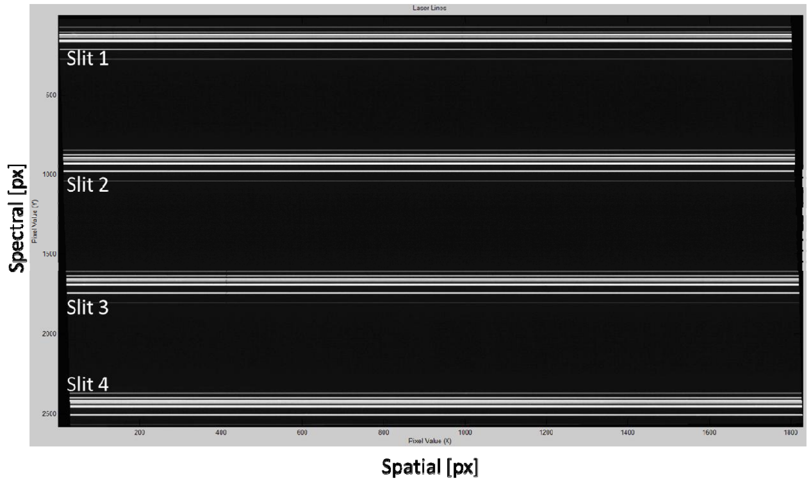


Figure 7: Spectrally resolved laser lines individually sampled by each slit on the focal plane

The measured standard spectrometer performance parameters along with the GEO-CAPE requirement are shown in Table 1. In some cases the GEO-CAPE requirements have been derived from a higher level requirement of the Science Traceability Matrix[3]. Variation from slit to slit can be calibrated from laboratory measurements and removed from the Level 1B data products to reduce variability of the retrievals. Thermal vacuum performance parameters show that these values do not change significantly over the expected temperature range on orbit.

Table 1: Spectrometer performance meets mission requirements for each slit

Parameter	Geo-CAPE requirement	Ambient performance	TVAC performance
Smile (μm)	≤ 27	3	6
Keystone (μm)	≤ 8	7	8
MTF	≥ 0.5	0.5	0.5
Spectral resolution (nm)	≤ 5	≤ 5	≤ 5
Polarization	≤ 1%	Not tested	1% (w/o telescope)

3. THERMAL VACUUM TEST RESULTS

The next step in proving the capabilities of the MOS spectrometer for the GEO-CAPE mission is to show that performance requirements can be met in vacuum over the range of on-orbit temperatures for a geostationary orbit. The MOS sensor was installed in a thermal vacuum chamber with a window to transmit sources with variable spectra and radiance. Operational and survival temperatures and vacuum conditions were defined following the NASA Goddard General Environmental Verification Specification (GEVS) requirements. The plot of temperature excursions during testing is shown in Figure 8. The performance results are included in Table 1 as compared to the ambient testing and GEO-CAPE requirements.

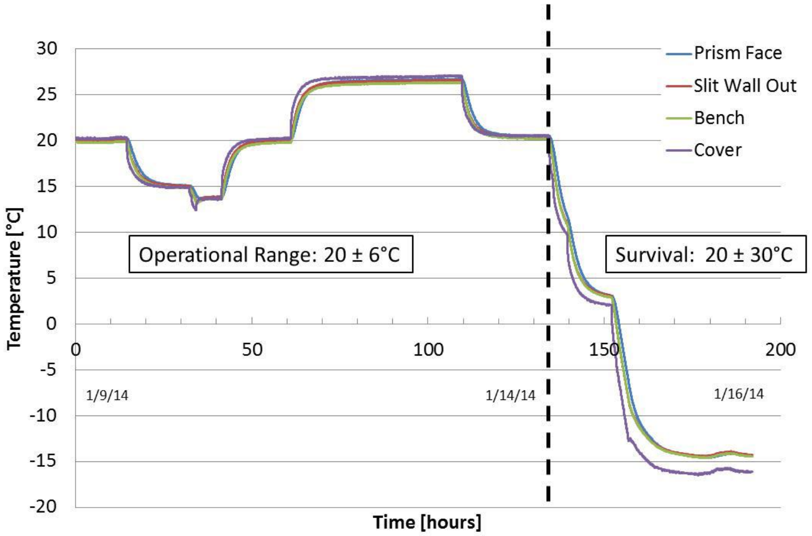


Figure 8. Vacuum thermal cycles reached operational performance and survival goals for the geostationary flight like environment.

Extensive structural, thermal, and optical performance (STOP) analyses were performed on the MOS opto-mechanical assembly to show the ability to survive launch and on-orbit conditions. The thermal vacuum testing was designed to validate this analysis. Vibration testing to launch loads has not been completed to this point but upon completion will move the spectrometer subassembly to Technology Readiness Level of 6.

4. CONCEPT VALIDATION: MOS SIM RESULTS AND AIRBORNE TESTING

In order to demonstrate the MOS spectrometer capabilities to perform the GEO-CAPE coastal ocean mission, the measured instrument parameters were incorporated into a simulation tool to show the data product retrieval expected. The simulation tool reads in a scene from the Hyperspectral Imager for the Coastal Ocean (HICO), applies a matrix of manipulations to simulate the parameters of the instrument that are matched to MOS laboratory test data, and ultimately provides a retrieval of ocean properties as shown in Figure 9. An example of the ocean color product and expected

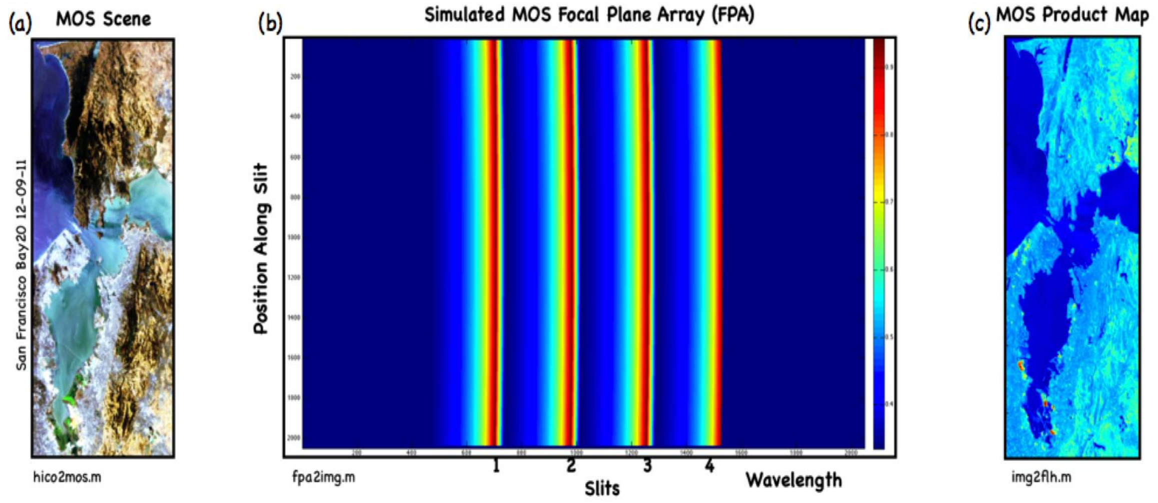
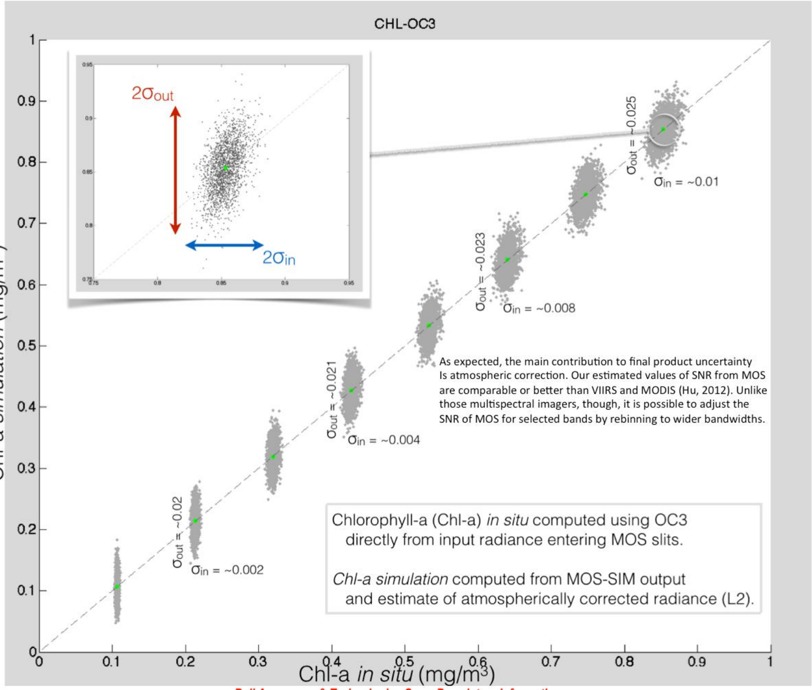


Figure 9. Steps of the MOS simulator include an input coastal ocean scene from HICO, a simulated detector image, and the output ocean data product.

retrieval based on MOS performance parameters and mission concept of operations is Chlorophyll a as shown in Figure 10. The retrieval is limited by atmospheric signal as is the case for current on-orbit sensors such as MODIS and VIIRS. The SNR of a point model design for a MOS coastal instrument is comparable to those multi-band sensors, but the additional adjacent channels from the MOS hyperspectral sensor provide increased SNR in particular spectral bands due to binning.

The next step to validate the MOS concept is to use the sensor for coastal ocean remote sensing from an airborne platform. In the fall of 2014, the MOS instrument will be installed on an airplane and flown over the coast of California along with in-situ validation sensors in the water. The four slits will be aligned perpendicular to the direction of travel of the plane. Each slit will map out the same region in the water separated in time by only a few seconds dependent on aircraft altitude and speed. The validation that each slit provides an independent hyperspectral measurement of ocean properties paves the way for the implementation as a GEO satellite sensor with the reduced mass and risk of the multi-slit design.



As expected, the main contribution to final product uncertainty Is atmospheric correction. Our estimated values of SNR from MOS are comparable or better than VIIRS and MODIS (Hu, 2012). Unlike those multispectral imagers, though, it is possible to adjust the SNR of MOS for selected bands by rebinning to wider bandwidths.

Chlorophyll-a (Chl-a) *in situ* computed using OC3 directly from input radiance entering MOS slits.

Chl-a simulation computed from MOS-SIM output and estimate of atmospherically corrected radiance (L2).

Figure 10: Simulated retrieval of Chorophyll a with the MOS sensor shows comparable retrievals to current LEO sensors[4]

5. ACKNOWLEDGEMENTS

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