Multislit Optimized Spectrometer for Ocean Color Remote Sensing

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ABSTRACT

The National Research Council's recommended NASA Geostationary Coastal and Air Pollution Events (GEO-CAPE) science mission's purpose is to identify "human versus natural sources of aerosols and ozone precursors, track air pollution transport, and study the dynamics of coastal ecosystems, river plumes and tidal fronts." To achieve these goals two imaging spectrometers are planned, one optimized for atmospheric science and the other for ocean science. The NASA Earth Science Technology Office (ESTO) awarded the Multislit Optimized Spectrometer (MOS) Instrument Incubator Program (IIP) to advance a unique dispersive spectrometer concept in support of the GEO-CAPE ocean science mission. MOS is a spatial multiplexing imaging spectrometer that simultaneously generates hyperspectral data cubes from multiple ground locations enabling a smaller sensor with faster revisit times compared to traditional concepts. This paper outlines the science, motivation, requirements, goals, and status of the MOS program.

Keywords: Spectrometer, ocean color spectrometer, imaging spectrometer, GEO-CAPE

1. INTRODUCTION

Coastal zones are wonderfully complex dynamic ecosystems providing critical resources to a continually growing population. The National Research Council identified the "imperative to monitor" the coastal oceans by calling for the Geostationary Coastal and Air Pollution Events (GEO-CAPE) mission[1]. GEO-CAPE's ocean science objectives[1,2] are to

- quantify the response of marine ecosystems to short-term physical events (e.g., storms and tidal mixing),
- assess the importance of high temporal variability in coupled biological-physical coastal-ecosystem models,
- monitor biotic and abiotic material in transient surface features (e.g., river plumes and tidal fronts),
- detect, track and predict the location of sources of hazardous materials (e.g., oil spills, waste disposal and harmful algal blooms), and
- detect floods from various sources, including river overflows.

Meeting these objectives requires high spatial resolution images[2]: <250 m (threshold) or <375 m (baseline). Resolving the dynamics of the short term coastal processes driven by tides, currents, storm surges, and algal blooms requires high temporal sampling[2]: <3 hr (threshold) or <1 hr (baseline). The geostationary vantage point enables the needed temporal and spatial resolutions.

Achieving the hour scale revisit times and high spatial resolution with the requisite signal-to-noise-ratios (SNR)[2] via conventional spectrometer formats leads to large systems with a proportionately large cost for a geostationary launch. To achieve the required performance in a much smaller package Ball Aerospace developed the concept of the Multi-Slit Optimized Spectrometer (MOS). This concept is now being tested and evaluated in a NASA Earth Science Technology Office funded Instrument Incubator Program (MOS-IIP). MOS can accomplish the ocean science mission with a comparatively smaller package while meeting the revisit time, spatial resolution, and high SNR's mandated by the GEO-CAPE Oceans Science Traceability Matrix[2]. This paper outlines the science, motivation, requirements, MOS concept, goals, and status of the MOS program.

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2. MULTISLIT OPTIMIZED SPECTROMETER

2.1 Concept and Benefits

Large area focal plane arrays enable the MOS concept where fore-optics illuminates multiple slits at the entrance to a spectrometer. The spectrometer simultaneously disperses the incident light and images the multiple slits onto the focal plane. From the geostationary orbit appropriate for GEO-CAPE an east-west scan mirror moves the projected slits across the field of regard collecting x-y-λ data cubes for a north-south oriented slit set. Figure 1 illustrates the slit plane, image plane and scanning operations. The time required to collect spectra over an area is reduced by one over the number of slits compared to a single slit spectrometer. MOS performs like multiple imaging spectrometers operating simultaneously.

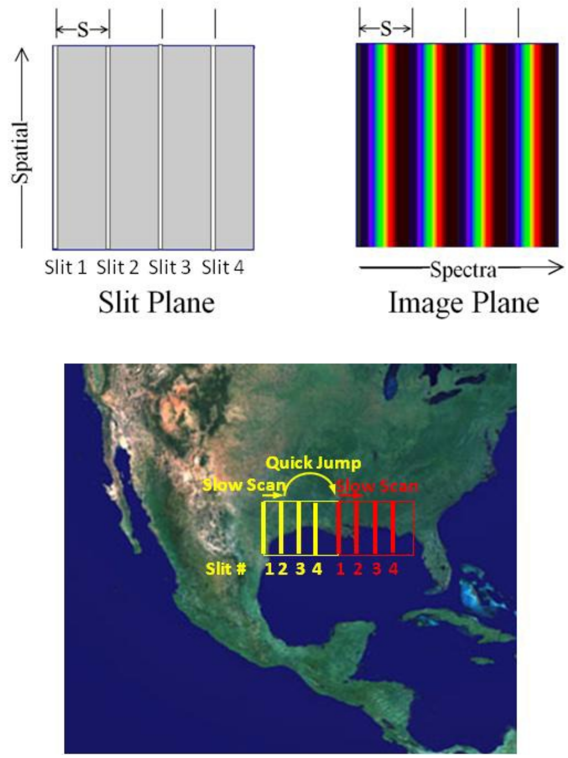

Figure 1. MOS simultaneously images the spectra from multiple slits on an area focal plane array. From a geostationary orbit a scan mirror moves the slit set from west to east collecting spectra continuously until the area between adjacent slits is fully covered (yellow field of regard). The scan then 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.

From a systems engineering perspective the time saved in covering the field of regard can be reallocated. The f/# of the optical system can be slowed by decreasing the telescope aperture. As enabled by the geostationary orbit the integration time at each east-west spatial location can be increased to achieve the necessary SNR. The reduction in the telescope aperture immediately results in a smaller payload with less mass. Figure 2 shows the aperture and system mass reduction as a function of the number of slits. We have developed a parametric model that shows a strawman 1-slit system weighing 425 kg whereas an equally performing 4-slit MOS weighs just over 150 kg—a mass savings of 275 kg.

The secondary benefits of the aperture reduction are a smaller scan mirror and eased opto-mechanical tolerances. The strawman system slows from f/3 to f/7.5. The diffraction limited depth of focus for example increases by over a factor of 6 meaning easier alignment and larger on-orbit despace allocations. MOS's benefits cascade into lower level requirements resulting in a significantly lower risk, more robust optical system.

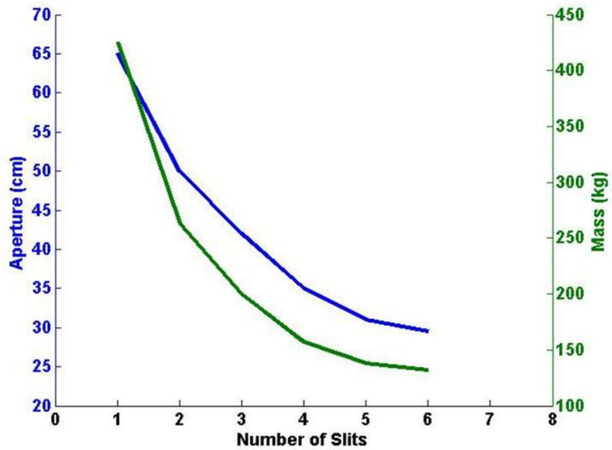

Figure 2. A parametric system model predicts the reduction in the aperture size and consequent system mass reduction as a function of the number slits.

2.2 GEO-CAPE Requirements

The GEO-CAPE Ocean Science Traceability Matrix (STM)[2] provides the instrument requirements flowdown from the science objectives. Table 1 lists the driving requirements for the oceans sensor that impact the MOS concept. The spatial and spectral resolutions directly limit the number of received photons while the temporal resolution over the field of regard restricts the dwell time at one east-west location. The solar zenith angle and solar radiance determine the scene radiance. Since the effective focal length and detector pixel size are used to achieve the spatial resolution, the entrance aperture is the final instrument parameter that can be adjusted to meet the signal to noise requirements.

Table 1. Excerpt from Version 4.1 of the GEO-CAPE Oceans Science Traceability Matrix: Instrument Requirements most relevant to MOS concept demonstration.

Parameter	Threshold	Baseline
Spectral Range	345-1050 nm	340-1100 nm
Spectral Sampling (FWHM)	2 nm	0.25 0.40 nm
Spatial Resolution (nadir)	375 x 375 m^2	250 x 250 m^2
Temporal Resolution: Routine Coastal U.S.	$\leq$ 3 hrs	$\leq$ 1hr
SNR for 10 nm FWHM over 350-800 nm range	$\geq$1000	$\geq$1500

2.3 Point Design for GEO-CAPE Payload and MOS-IIP Test Elements

Figure 3 shows the block diagram for a GEO-CAPE Oceans payload. Light from the scene enters the optical system through a recloseable door then reflects from a 2-axis scan mirror. A three mirror telescope directs the light to a dichoric beam splitter; one arm feeds a SWIR camera while the other the spectrometer. The spectrometer disperses and images the light onto a large area focal plane array. Our point optical design based on this block diagram meets the GEO-CAPE Oceans requirements.

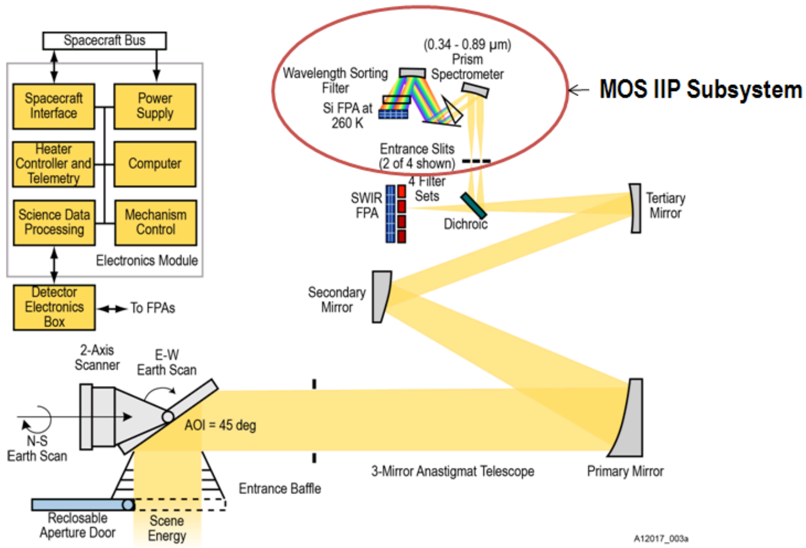

Figure 3. GEO-CAPE Oceans payload concept based on a Multi-Slit Optimized Spectrometer. The payload concept design shows the spectrometer at the heart of a scanning payload. Light enters the instrument, reflects off of a scan mirror and is focused with a three-mirror telescope onto the entrance slits of the spectrometer.

The MOS-IIP will design, build, and test the spectrometer subassembly derived from this point design. Figure 4 shows the test elements of the MOS program. Central to the program is the test of the spectrometer through thermal vacuum testing and launch level vibrational testing with the goal of achieving a Technology Readiness Level (TRL) of 6 for the spectrometer opto-mechanical subassembly. Selected targets will be imaged into a thermal vacuum chamber onto the spectrometer entrance slits. A Teledyne HyViSI™ H2RG collects the imaged spectra and test electronics relay the images to a PC for analysis. The opto-mechanical subassembly will be tested to validate the MOS concept against the GEO-CAPE requirements.

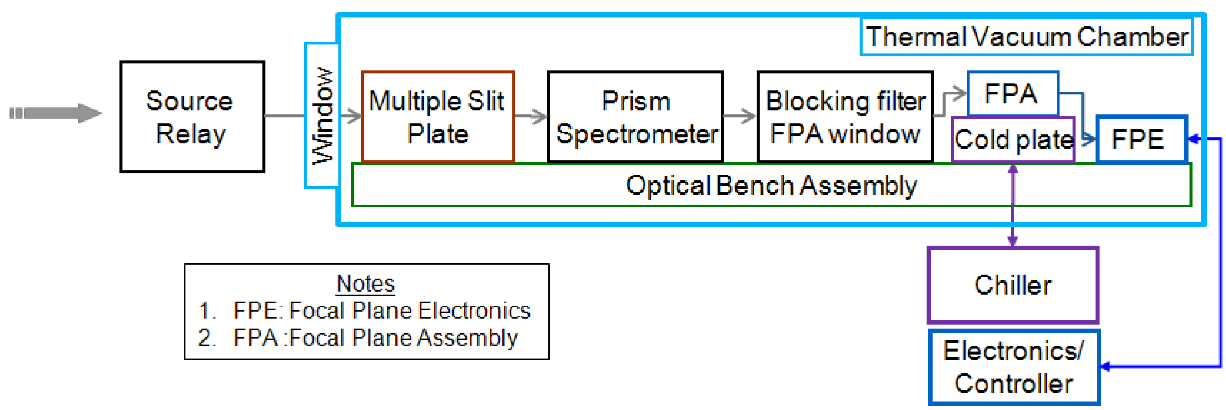

Figure 4. MOS IIP test block diagram showing the subset of the point design that will be designed, built and tested.

In collaboration with Oregon State University, three defined studies will validate MOS's ability to generate data products required for GEO-CAPE Ocean science. Data collected from the MOS testing will be used to investigate the impact on coastal water (CW) products by spectral sampling, out-of-band response, and signal to noise ratio. MOS characterization data and Hyperspectral Imager for Coastal Ocean (HICO)[3,4] data sets will inform the validation of the multi-slit spectrometer concept for the GEO-CAPE Oceans mission. This combined effort will parameterize the CW product's uncertainty arising from the spectrometer performance traceable to the selection of the number of slits, the multiplex scaling.

2.4 Program Status and Schedule

The opto-mechanical design is complete. Figure 5 shows the prism spectrometer design that enables MOS. A complete Structural-Thermal-Optical-Performance model has identified two configurations that perform under in the predicted geostationary thermal environment: carbon composite structure with Zerodur optics and a SiC structure with SiC optics. Optics and structure will be ordered the summer of 2012. System testing will be complete in the third quarter of 2013 with the mission suitability study complete in April of 2014.

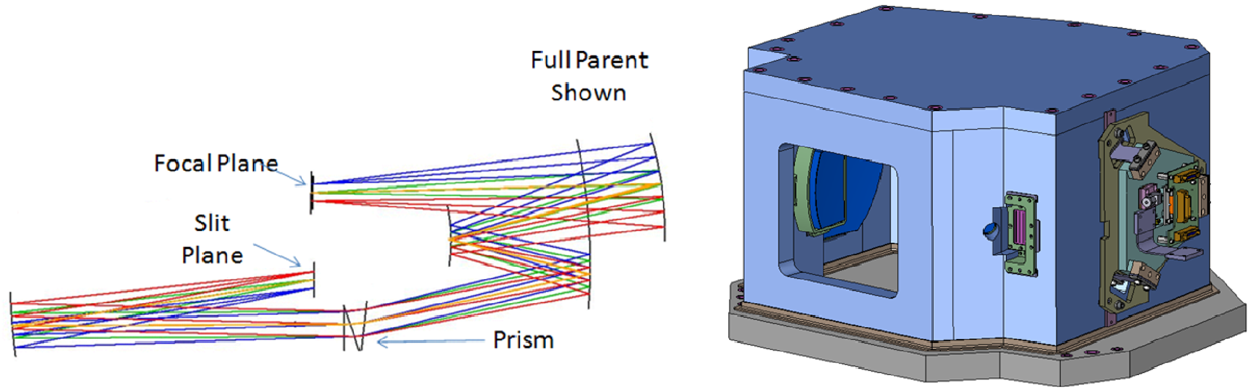

Figure 5. MOS uses a prism spectrometer design that achieves a wide field of view, good imaging performance, and low smile and keystone. Folding of the optical design (left) compactly packages into the CAD model (right).

3. SUMMARY

We have outlined the Multi-Slit Optimized Spectrometer concept and its benefits, a comparatively smaller payload with lower risk and mission cost for the GEO-CAPE Oceans mission. The goals, major tasks and studies planned for the IIP were described. These activities drive to the common outcome of validating the suitability of the MOS for the GEO-CAPE coastal ecosystems mission. The spectrometer subsystem will be qualified to launch vibrations and be tested in a relevant space environment. Upon completion of the IIP the spectrometer subsystem will be at TRL 6.

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