Multi-Slit Optimized Spectrometer: An Innovative Design for Geostationary Hyperspectral Imaging

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Abstract: Multi-Slit Optimized Spectrometer is a spatial multiplexing hyperspectral imager designed to reduce mission cost and risk for hyperspectral sensing from geostationary orbit. The multi-slit prism design resulting in 50% telescope aperture reduction will be presented.

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1. Introduction

The National Research Council's recommended NASA Geostationary Coastal and Air Pollution Events (GEO-CAPE) science mission 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" [1]. 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 Multi-Slit Optimized Spectrometer (MOS) Instrument Incubator Program (IIP) to advance an innovative dispersive spectrometer concept in support of the GEO-CAPE ocean science mission.

One objective of the GEO-CAPE mission, an Earth Science Decadal Survey [1] Tier II mission focuses on the dynamics of coastal ecosystems, river plumes, and tidal fronts. The event imager sensor will collect hyperspectral data on the science of short-term processes, land-ocean exchange, impacts of climate change and human activity, and episodic events and hazards. The GEO-CAPE website [2] expands on these ocean science objectives.

Moderate spatial resolution imagery, 250 to 375 meters meets these objectives adequately resolving tidal fronts, river plumes and phytoplankton patches in the coastal ocean [3, 4]. Temporal resolution of 1 to 3 hours resolves the dynamics of coastal processes (e.g., tides, wind-driven currents, storm surges, and algal blooms); for hemispherical coverage this is optimally achieved from a geostationary orbit. Achieving the required short revisit times, spatial, and spectral resolutions at high signal-to-noise-ratios (SNR) using a conventional spectrometer leads to a complex, large, and heavy sensor resulting in high risk/cost when deployed to geostationary orbit. This paper outlines the instrument concept for a NASA IIP investigation of a Multi-Slit Optimized Spectrometer that by virtue of spatial multiplexing, the simultaneous hyperspectral imaging of multiple locations offers significant reductions in system complexity and mass. The multiplex scaling is proportional to the number of slits projected from geostationary orbit onto the Earth. The realized temporal efficiency can be reallocated to a reduced aperture decreasing the overall sensor complexity, envelope, mass and subsequent mission risk.

The MOS IIP, started in May 2011, has designed and will build and characterize a prototype multi-slit spectrometer satisfying a relevant subset of the requirements for the GEO-CAPE Event Imager mission. In collaboration with Oregon State University, three defined studies will validate MOS's ability to generate data products required for GEO-CAPE Ocean science. Specifically, we will investigate the impact on coastal water (CW) products by spectral sampling, out-of-band response, and signal to noise ratio. MOS characterization data, Hyperspectral Imager for Coastal Ocean (HICO) data sets, and the studies will inform the validation of the multi-slit spectrometer concept for the GEO-CAPE Event Imager mission. This combined effort will parameterize the CW product's uncertainty arising from the spectrometer performance traceable to the slit number selection, the multiplex scaling. The spectrometer will be vibration tested to launch levels and the performance characterized in a relevant operational thermal vacuum environment. The planned activities will raise the hardware's Technology Readiness Level to 6.

2. GEO-CAPE Mission Driving Requirements

The GEO-CAPE Ocean Science Traceability Matrix (STM) [5] provides the instrument requirements flowdown from the science objectives. Table I lists the driving requirements for the UV-visible ocean sensor that the MOS concept impacts.

TABLE I. GEO-CAPE Oceans Instrument Driving Requirements

Parameter	Requirement
Spectral Range	340 – 890 nm
Spectral Resolution (FWHM)	5 nm
Spatial Resolution (nadir)	375 x 375 m^2
Field of Regard	± 9° E/W
Temporal Revisit: Target Events	1 hour
Temporal Revisit: Routine Coastal US	3 hours
Solar Zenith Angle	± 70°
SNR for 10 nm FWHM over 380 – 800 nm range	1000

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 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 requirement.

3. The MOS Spatial Multiplexing Concept

The Multi-Slit Optimized Spectrometer extends the conventional single slit prism spectrometer design by having multiple entrance slits displaced in their width direction. Each slit produces a full spectrum on the focal plane but originates from displaced ground samples. A large area focal plane array collects the hyperspectral imagery from multiple ground pixels simultaneously amounting to spatial multiplexing as suggested in Fig. 1.

Fig. 1 shows the instantaneous projection of three slits onto the scene and the dispersed spectrum from each slit imaged onto the focal plane. To generate the hyperspectral image cube over the field of regard from geostationary orbit, a scan mirror moves from west to east covering the gap between the instantaneous slit images. This generates an “image block”. Two “image blocks” are shown in Fig. 1, one yellow and one red. After generating the first “image block” (yellow) the scan mirror jumps to the start of the next “image block” (red). The scan repeats for the next “image block” (red). For a geostationary payload with an agile scan mirror, image blocks could be anywhere in the hemisphere making the instrument capable of both routine coastal coverage and high revisit monitoring of coastal events. A Multi-Slit Optimized Spectrometer based instrument accommodates the GEO-CAPE Event Imager temporal resolution, field of regard, and event monitoring requirements. For a fixed signal to noise ratio, spatial multiplexing enables MOS to cover the field of regard faster than a single slit spectrometer with the same basic parameters. As an example, a five slit MOS covers the same area five times faster than its single slit counterpart when all else is equal. Alternatively, for fixed coverage time, a five-slit MOS requires an optical aperture roughly half that of a conventional system with the accompanying mass and volume reductions. Strawman designs suggest the conventional spectrometer requires a payload of the scale 550 kg while the MOS version is roughly 165 kg. Consequently, for the same mission, a MOS is smaller and lighter compared to a single slit design.

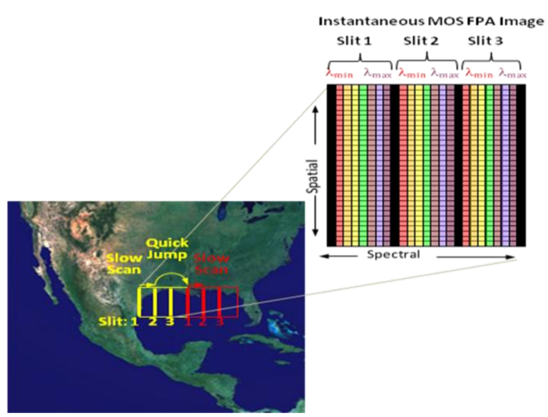

Fig. 1. Three slit MOS operating from geostationary orbit

For each image snapshot, the spectrometer yields the spectrum along the three separated N-S lines. For applications where the number of spectral channels is less than the number of spatial channels, the mission benefits from using a Multi-Slit Optimized Spectrometer where the payload aperture, mass and volume are reduced. With a single telescope, a single spectrometer, and a single focal plane, MOS performs like multiple single slit spectrometers.

4. Design Decisions and Steps Forward

The MOS concept, spectra of multiple ground samples falling on the focal plane at the same time, requires out of band rejection, i.e. mitigating the impact of light from adjacent slits contaminating its neighbors. For determination of coastal ocean data products, a derived requirement of less than 1% out of channel signal is part of the MOS design. To meet this out of channel requirement and the mission driving requirements, a prism spectrometer design form was selected that uses mainly slit displacement to manage the overlap of spectra from adjacent slits.

In this first year of the IIP project, parametric trades were performed to determine the optimal number of slits. A study of the signal to noise ratio at the required sampling frequency for the mission of less than 1 hour for the full coastal US led to a scaling of instrument telescope aperture with the number of slits in the spectrometer. It is clear from Fig. 2 that the greatest decrease in telescope aperture and hence overall instrument mass occurs for the change from 1 to 4 slits. Further increase to the number of slits slowly continues to bring down the mass, but not nearly as dramatically as from 1 to 4. For this reason, the number of slits selected to demonstrate the concept on the MOS IIP is 4. The prism design is optimized to fit 4 slit images on the focal plane with proper spacing to avoid overlap.

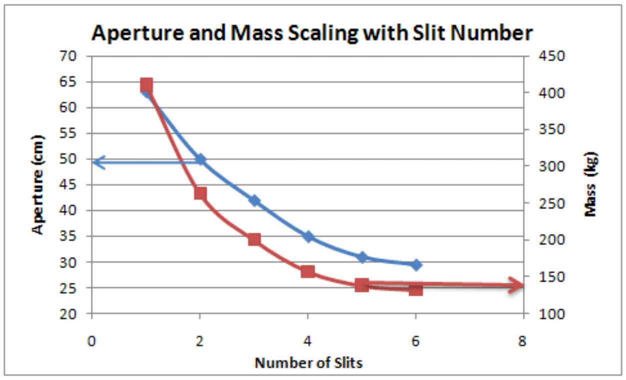

Fig. 2. Instrument telescope aperture (left axis – blue curve) and total instrument mass (right – red curve) variation with number of slits

Currently, the MOS design is nearly complete and the procurement and build phase will begin soon. Test development is also underway as the goal is to raise the Technology Readiness Level to 6 with vibration and thermal vacuum testing. The as-built instrument will demonstrate the MOS concept and prove key performance parameters that will reduce risk and reduce cost for the upcoming GEO-CAPE mission as well as future hyperspectral imagers at GEO.

5. References

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