N. Goldstein, B. Tannian, M. Stark, J. McCann, R. Wiggins, J. Santman, M. Nasca, P. Woodman, M. Saleh and K. Nakanishi, Fabrication and Testing of UAS-Based Visible to Extended-SWIR Hyperspectral Sensor,10th Workshop on Hyperspectral Imaging and Signal Processing: Evolution in Remote Sensing (WHISPERS) (2019).

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FABRICATION AND TESTING OF A UAS-BASED VISIBLE TO EXTENDED-SWIR HYPERSPECTRAL SENSOR

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ABSTRACT

A compact and lightweight visible-to-extended SWIR spectrograph package for class-1 Unmanned Aerial Systems (UAS) is currently in fabrication and will be flight tested in Autumn of 2019. It features a single, monolithic spectrograph, machined from CaF_2, that covers the full spectral range from 0.4-2.45 microns, coupled with an extended-range, HgCdTe camera. The spectrograph comes with a complete flight package including a shutter, navigation system, computer, and on-board processing. In this paper we outline the design, fabrication, and initial flight-testing of the sensor and flight package.

Index Terms—hyperspectral, Vis/SWIR, extended SWIR, monolithic spectrograph, solid core, unmanned aerial systems.

1. INTRODUCTION

UAS-based multispectral and hyperspectral sensors are increasingly being used for mapping applications in agriculture, minerology, and ecosystem research. Low-cost Vis/NIR hyperspectral sensors, such as Corning's MicroHSI 410, provide the capability for routine and repetitive measurements to track-time sensitive information. Many applications, however require operation over the full visible-to-extended short-wave infrared (Vis/SWIR) spectral range of 0.4-2.5 microns.

SSI and Corning are developing such a Vis/SWIR sensor, under The Department of Energy (DOE) sponsorship, for use in vegetative monitoring and ecological research. The performance parameters for the system are summarized in Table 1. The goal is to provide a compact, UAS-based sensor with capabilities similar to that of existing airborne hyperspectral systems such as AVARIS. These include signal-to-noise ratios (SNR) in excess of 200:1, spectral resolution of better than 7 nm, and high spatial resolution. These requirements are met with a single spectrograph machined from CaF_2 that covers the full spectral range. The spectrograph is coupled to an achromatic telescope and an extended-range HgCdTe camera to provide high-resolution hyperspectral imagery. The f/1.5 aperture and efficient optics provide high light-collection (of order 1 million photo-electrons per channel), which leads to shot-noise-limited SNRs of serval hundred to one. The use of common optics for all spectral ranges eliminates the problems associated with merging spectral data from multiple sensors, each with a different spatial footprint on the target.

Table 1. System Performance Parameters

MicroHSI™ 425	Values	UNIT
SWAP		
Mass	2.1	[kg]
Dimensions	12 x 16 x 25	[cm]
Power	35	[watts]
MCT FPA		
Pixel Width (Spatial)	15	[um]
Pixel Width (Spectral)	15	[um]
Spatial Pixels	640	[px]
Spectral Pixels	450	[px]
Maximum Frame Rate	100	[Hz]
Optical		
NA	0.36	[]
f/#	1.5	[]
Focal Length	15.5	[mm]
Aperture	10.5	mm
Spectral		
λ max	2450	[nm]
λ min	385	[nm]
Slit Length	9.6	[mm]
Dispersion	4.6	[nm/px]
Resolution		
Spectral Resolution (FWHM)	1.5	[px]
Spatial Resolution Cross-Slit (FWHM)	1.5	[px]
Spatial Resolution Along Slit (MTF<0.5)	<1	[px]
Distortion		
Smile	<0.25	[px]
Keystone	<0.3	[px]

Figure 1 shows a photo of a flight-weight mockup of the Vis/SWIR sensor flying on a DJI M6000 UAS equipped with a Ronin gimbal. The flight package for the sensor is based on Corning's MicroHSI 410 Vis/NIR Selectable Hyperspectral Airborne Remote-sensing Kit (SHARK). The new Vis/SWIR optical system and SHARK electronics are packaged in a new housing suitable for mounting on a class-1 UAS. In preparation for flight testing, we have been flying both a flight-weight mockup, and the standard Vis/NIR flight package to test compatibility with UAS-base operation. The complete Vis/SWIR package will be test-flown shortly after fabrication is complete. Results may be available in time for the presentation of this paper in September 2019.

Figure 1. Flight-weight model on a UAS

2. FLIGHT PACKAGE

Figure 2 shows two cross sectional views of the flight package and identifies key components. The optical system consists of a telescope (fore-optic), the solid-block spectrograph, and camera. The fore-optic is bolted to the exterior of the package and has a down-looking field of view. A shutter is used to collect dark frames for background subtraction. Internal electronics include an Inertial Navigation System (INS), computer, frame grabber, and camera electronics. The package has external connections for power, (12V battery), ethernet (for setup), USB, and a GPS antenna which is mounted on the top of the UAS. Camera data and 6-Degrees-of-freedom position data is collected, time stamped, and stored by the onboard computer. On board processing includes the computation of an Image Referencing Metadata (IGM) file containing the location of the ground-sampled footprint for each pixel, and level-1, radiometrically-calibrated hyperspectral imagery after dark subtraction and non-uniformity correction. Data is stored in ENVI format and can be post-processed after flight using standard processing tools.

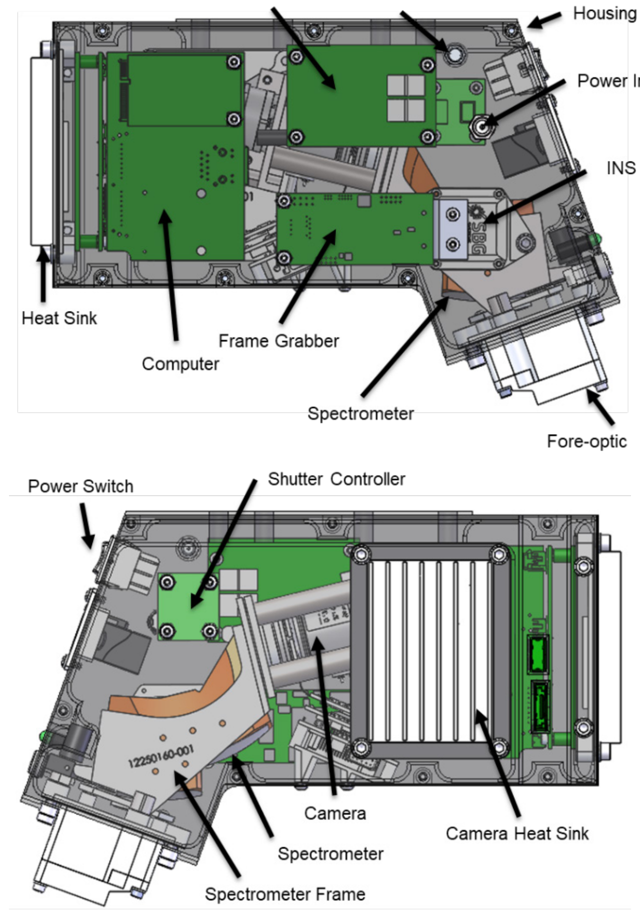

Figure 2. Cross sections of sensor flight package.

3. OPTICAL SYSTEM

The spectrometer core is based on Corning's patented, monolithic, Offner spectrometer design used in the MicroHSI410 Vis/NIR sensor. In this new design, shown in Figure 3, the spectrograph is machined out of a solid block of CaF_2. Figure 4 shows a partially machined spectrograph mounted in its machining fixture. The spectrograph is an Offner-type design with 3 nearly concentric curved surfaces, (M1, M2, and M3) and two folding mirrors. M2 is a concave diffraction grating machined with single-point diamond tooling.

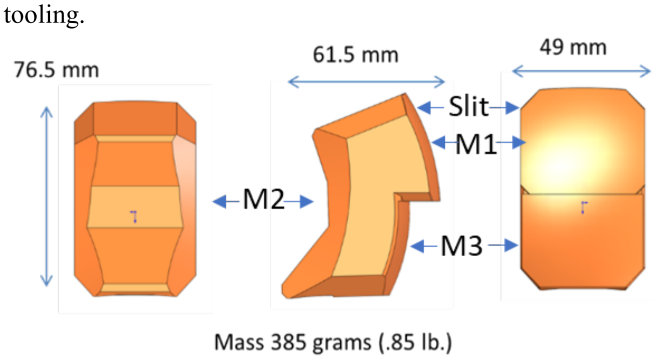

Figure 3. Solid-core Offner Spectrograph.

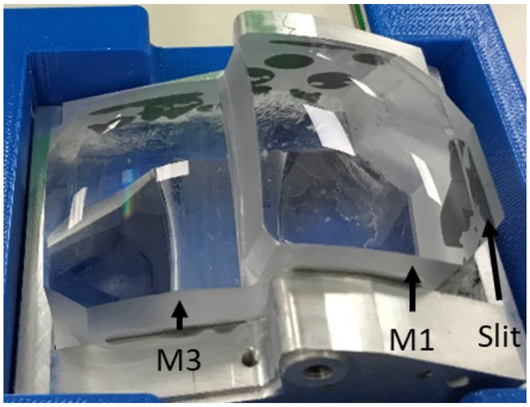

Figure 4. Partially completed spectrograph block. The top surface shows M3, M1, and the slit plane (left to right).

Figure 5 shows the folded optical path of the spectrograph. Light enters through a machined slit, is collected by M1, diffracted by the grating on M2, and refocused by M3 to form a dispersed image of the slit on the camera focal plane (FPA). A multi-zone order-sorting filter near the focal plane blocks all higher-order diffracted light.

The monolithic design offers a number of advantages over conventional air-spaced spectrographs:

1. The higher index of refraction of the solid block allows for smaller size, and higher throughput compared to conventional air-spaced designs, as the numerical aperture inside the solid material is less than that in air. This enables f/1.5 light collection
2. Machining the spectrograph from a solid block allows for tighter tolerances and higher mechanical and thermal stability.
3. The machining operations give the optical designer free rein to use non-spherical optics. This Vis/SWIR design takes advantage of aspheric and toroidal surfaces to produce higher resolution in a smaller package.
4. The machining process automates manufacturing and eliminates most alignment steps, resulting in lower production costs.

The net result is a small compact, lightweight, and inherently stable spectrograph.

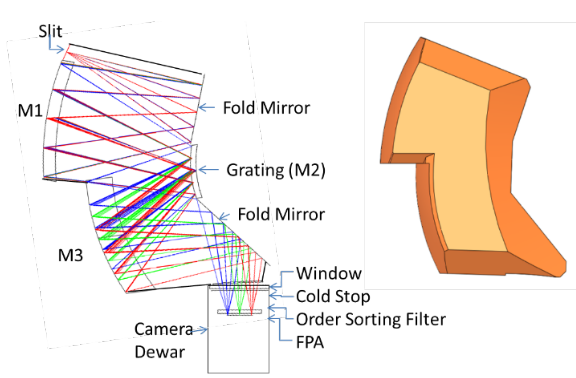

Figure 5. Ray Trace of spectrograph, Camera, and OSF.

The spectrograph is coupled to a sterling-cooled, back-thinned HgCdTe camera with a 640x480 pixels on a 15-micron pitch. This provides 640 spatial channels along the slit dimension and 450 spectral channels.

The fore-optic is a two-mirror, reflective telescope with a wide field of view and high throughput. Figure 6 shows a cross section view of the telescope along the cross-slit axis. The entrance window, primary and secondary telescope mirrors, and focal plane (slit plane) are shown. The telescope bolts onto the spectrometer frame and is aligned with precision pins. The f=15.5 mm focal length provides wide angular coverage of +/-18º, enabling low-altitude data collection with a UAS. Alternative designs use a longer-focal length telescopes for operation at high altitudes. The use of a telescope rather than a lens system eliminates chromatic aberrations, which would otherwise limit the spatial resolution in SWIR optical systems. The telescope also offers better monochromatic resolution, with a modulation transfer function better than 90% (at the pixel frequency) throughout the field of view. This ensures that the telescope does not limit the spatial resolution of the sensor, as is the case for almost all sensors that use refractive optics.

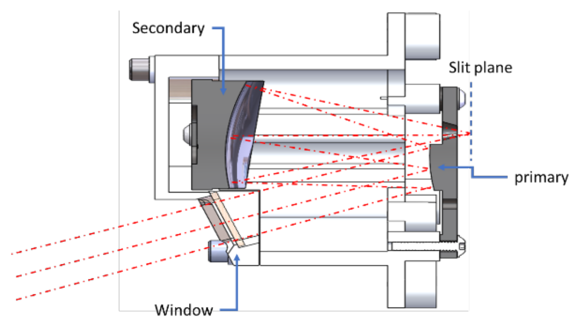

Figure 6. Cross section of fore-Optic telescope.

5. SENSOR PERFORMANCE

Detailed testing of the spectral and spatial resolution of the sensor will begin shortly after fabrication, and results may be available by the time of the presentation in September of 2019. Testing procedures are outlined in the companion paper [Stark, 2019]. These will include edge measurements to test the limiting resolution in both the cross-slit and along-slit directions, spectral characterization using atomic emission lines, and keystone and smile measurements. Table 1 summarizes some of the projected performance parameters based on analysis of the optical design. We anticipate that both the spectral and spatial resolution will be limited primarily by the size of the pixel and slit, both of which are 15 microns wide.

We can project the signal level and for any given scenario based on a complete system level model that takes into account the angular acceptance of the optics, the diffraction efficiency of the gratings, the transmission of the optics, and the predicted radiance for the scene. Figure 7 shows projected performance for a standard scene with 25% reflectance mid-latitude summer atmospheric composition, a

45-degree Solar Zenith Angle (SZA), no clouds, and 18 km visibility. The top figure shows a MODTRAN calculation of reflected radiance at the sensor. The middle figure shows the collected photoelectron signal, which is calculated based on the input radiance and the optical system characteristics. Results are shown for the maximum frame rate of 100 Hz and a slower frame rate of 25 Hz that provides the maximum SNR by nearly filling the pixel well, which has a full-well capacity of 1.4 electrons/pixel/frame. The bottom curve shows the SNR calculated based on the camera read noise and shot noise. The system is shot-noise limited at all wavelengths below 1.8 microns (except for the centers of the water absorption bands). The sensor is primarily read-noise limited at wavelengths above 2 microns. The projected SNR is in the hundreds for almost all bands of interest.

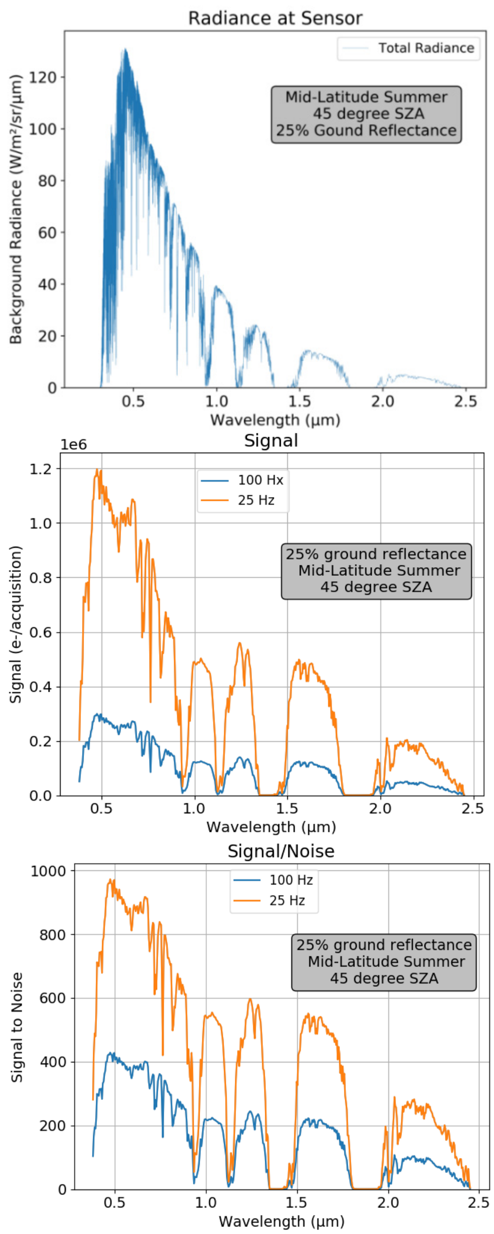

Figure 7. Predicted signal and SNR for a standard scene

5. FLIGHT DATA AND POST PROCCESING

Initial flight testing of the UAS and flight package has been performed, using the MicroHSI410Vis/NIR sensor as a surrogate for the Vis/SWIR sensor and 1.2 kg of ballast to replicate the mass of the Vis/SWIR sensor. This allows us to test the flight package electronics, gimbal stability, and flight characteristics of the fully loaded system. Figure 8 shows typical georeferenced imagery and Normalized Difference Vegetation Index (NVDI) data products. Hyperspectral imagery data and IGM files were downloaded from the SHARK flight package and processed in the ENVI environment. The geo-rectified data shows clean edges with minimal distortion, suggesting that the combination of the UAS, gimbal, and on-board INS was sufficient for georectification. Spectral calibration panels (right-hand-side of image) were used to verify sensor radiometric performance. Full spectral, Vis/SWIR data will be collected in Fall 2019, upon completion of the Vis/SWIR sensor.

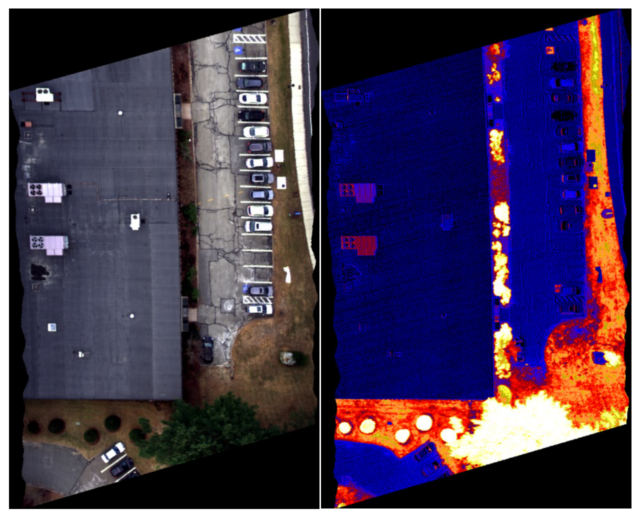

Figure 8. Geo-rectified RGB imagery and NDI maps.

6. PLANNED TEST CAMPAIGNS

We are scheduled to participate in a series of test campaigns in cooperation with our DOE sponsors and partners throughout the 2019 and 2020 growing seasons. This involves a series of test flights over well-instrumented research plots in order to develop and test metrics for vegetative health, vegetative mass, plant phenotyping, and to correlate these metrics with ground measurements of biological samples. The overall goal is to develop methods for large scale mapping of biological traits over large areas.

The ready-to-fly Vis/SWIR sensor package is particularly useful for ecology, climate, and agronomy researchers for several reasons. It offers on-demand imaging from leaf- to canopy-scale using a commercially available UAS. The sensor requires only one camera to measure the full spectral range, reducing the size, weight, and power requirements while eliminating errors in co-alignment of products combining two systems. Further, the single-block optical path spectrometer minimizes the system size over traditional open-air path optics. All data is collected by a single data acquisition system and immediately stored for processing.

7. SUMARY

We are currently fabricating a compact, ready-to-fly Vis/SWIR hyperspectral package based on a monolithic Offner spectrograph machined from solid CaF_2. The sensor is a product extension of Corning's existing Shark 410 sensor that covers the Vis/NIR spectral range. The new sensor, dubbed the 425 SHARK covers the full spectral range of 0.4-2.5 microns with a single spectrograph and a single HgCdTe FPA. It includes an f=15 mm telescope and all necessary electronics in a package weighing less than 2.2 kg that can be flown on a variety of class-1 UASs. The sensor has 680 spatial channels with sub-pixel spatial resolution, and 450 spectral channels with 4.7 nm spacing. Typical operation is as a push-broom HSI sensor operating at a 100 Hz frame rate. Signal-to-noise performance is projected to be greater than 250:1 from 0.4-1.8 microns, and greater than 100:1 from 2-2.4 microns. Initial test flights with a surrogate sensor and a dummy payload has proven the capability to fly on a UAS and collect properly geo-rectified hyperspectral data cubes. The full Vis/SWIR sensor is scheduled for flight testing in Autumn 2019, and will be applied in DOE sponsored research tests scheduled for the 2019 and 20020 growing seasons

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support from DOE under SBIR Contact No. DE-SC0015126, Daniel Stover Program Manager, and the advice and collaboration of Sean Serbin of DOE Brookhaven National Laboratories in defining future measurement campaigns.

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