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Compact visible to extended-SWIR hyperspectral sensor for Unmanned Aircraft Systems (UAS)

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ABSTRACT

A miniaturized, lightweight turn-key hyperspectral sensor package incorporating a single, monolithic spectrograph, telescope and navigation system is being built for airborne applications on small, Unmanned Aircraft Systems (UAS). The sensor is based on Corning's existing MicroHSI 410 Vis/NIR Selectable Hyperspectral Airborne Remote sensing Kit (SHARK) currently used for airborne agricultural monitoring. Under DOE sponsorship, we are extending the approach to cover the full spectral range from 0.4-2.5 microns with a single spectrograph. This will enable rapid aerial surveys of vegetative mass, quality, and carbon sequestration. Other applications include mineralogy, agriculture, and intelligence/surveillance/reconnaissance (ISR).

The sensor features an Offner-type spectrograph machined from a single transmissive block. The monolithic construction provides an unprecedented combination of high performance, low cost and low size, weight, and power. It has an f/1.4 aperture, 5 nm resolution, and measures only 46mm x 60mm x 76mm. The spectrograph block is coupled to a sterling-cooled, back-thinned, HgCdTe FPA covering 0.4-2.5 micron spectral range. The flight package, including spectrograph, camera, telescope, and navigation system weighs less than 2.4kg and can fit on group 1 UASs.

In this paper, we present the design and optical performance of the sensor, and a detailed physical model of detection performance in standard, airborne hyperspectral sensing applications. At 100 Hz data rate, the sensor will achieve shot-noise limited performance with SNR > 250 from 0.4-1.7 microns and SNR>100 between 2-2.3 microns. Operating procedures for airborne monitoring of vegetative properties are also discussed. Initial test flights on a UAS are scheduled for next summer.

Keywords: hyperspectral, Vis/SWIR, extended SWIR, monolithic spectrograph, solid core, unmanned aerial systems, miniature, vegetation monitoring.

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1. INTRODUCTION

Existing visible to extended short wave infrared (VisxSWIR) sensors, such as AVARIS, have demonstrated the utility of airborne hyperspectral sensing in myriad applications, including land-use monitoring, mineralogy, and ISR. High spatial- and spectral-resolution data covering the spectral range of 0.4-2.5 microns allows the identification of materials and vegetative characteristics that are not easily discerned using visible/near infrared (Vis/NIR) hyperspectral sensors. In this work we describe the development of a compact, ready-to-fly hyperspectral sensor for use on small UAVs, with resolution and sensitivity comparable to AVARIS. Smaller, lower-cost VISxSWIR sensors such as this can be deployed for routine and repeated measurements to track time sensitive information and changes over time. The current development is being sponsored by the DOE for monitoring of vegetative state and carbon sequestration at the landscape level, but the sensor can be used for a wide range of applications.

The present effort involves the development of a monolithic VisxSWIR spectrograph, machined from a solid block of CaF_2. This work represents an extension of the existing MicroHSI 410 SHARK (400-1000nm Selectable Hyperspectral Airborne Remote sensing Kit, or simply 410 SHARK, for short) product to 400-2500nm, forming the basis of a new product known as the 425 SHARK. This extended wavelength range capability provides a powerful tool for hyperspectral studies when integrated with a small UAS, as shown in Figure 1. Applications include crop analysis for precision agriculture, which uses HSI sensing to monitor a wide range of variables that affect crops, including moisture content, photosynthetic activity, and weed or pest infestations. With periodic measurements throughout the growing season, farmers can then manage their crops more efficiently and sustainably, improving harvest yields while reducing the negative environmental impact of over-application of chemicals and water. Efficient water usage is becoming extremely important, especially in the drought-ridden areas of California. Additional agricultural applications include crop stress analysis, productivity prediction, and fire hazard alert. This HSI technology also finds application in ISR activities such as IED detection and location, and in geology and mineralogy studies.

Figure 1. Mock-up of 425 SHARK mounted on DJI Matrice-600 hexa-copter.

In demanding applications, miniaturized sensors are required to provide high performance, uncompromised by their small size, weight, and power (SWaP). This performance includes coherent, simultaneous capture of all spectral information corresponding to each spatial pixel, high optical throughput for maximal sensitivity, and low spectral/spatial distortion. Corning has focused its development efforts on all-reflective Offner configuration sensors, resulting in smaller size and lower weight while retaining the low aberration features inherent to the Offner configuration.

Affixed with an entrance slit, an Offner spectrograph captures one spatial line of scene imagery, disperses each pixel of the line into its spectral components in the direction perpendicular to the slit, and focuses the light onto a 2D focal plane array (FPA). To acquire a 2D scene, the line of spectrograph imaging is scanned in a push-broom fashion with synchronous framing of the FPA. This can be achieved with constant forward motion of an aircraft, by mechanical rotation or translation of the sensor, or through the use of a scanning input mirror.

The design and performance of Offner-configuration hyperspectral imaging (HSI) sensors can be further improved by embedding the spectrograph into a solid block of optical material. The high index of the optical block reduces the light ray paths relative to an air- or vacuum-spaced sensor, resulting in a spectrograph that is mechanically, environmentally, and thermally robust, and is auto-aligned, requiring no initial alignment or realignment.

Manufacture of such a monolithic spectrograph requires unique capabilities. The optical surfaces—including the grating—must be cut and polished directly into the monolith, and spatial resolution performance optimization may require that the mirrors and/or grating be configured with non-spherical surfaces. Radiometric optimization may require a grating that is single- or dual-blazed, phase-stepped, or has aberration-correcting periods. High-reflection coatings are applied to the optical surfaces, which are then fully encapsulated for environmental immunity. Other processes coat non-optical surfaces with an absorber to eliminate stray light.

2. SPECTROMETER DESIGN AND PERFORMANCE

2.1 Spectrometer Design

2.1.1 Enabling Technology: Monolithic Offner Spectrograph

Corning developed its patented solid monolithic block Offner spectrometer to enable a compact, high-performance HSI platform. The design has the advantage of significantly lighter weight and smaller size HSI sensors than conventional air-spaced designs. When light travels through a solid block of monolithic material with a higher index of refraction than air, the reflecting angles are smaller for the same numerical aperture (NA). This enables the spectrograph to be significantly more compact, with higher NA, leading to better signal to noise ratio (SNR).

An Offner-based design allows for high image quality and low distortion. Manufacturing the spectrograph from a solid block, allows for tighter tolerances and higher mechanical and thermal stability, and provides lower cost manufacturing.

Corning used these principles in the design and manufacturing of the MicroHSI 410, a family of Vis/NIR sensor systems with wavelength range from 0.4-1.0 micron[1,2,3]. Other wavelength ranges in the SWIR were also manufactured and reported in the past[4,5]. The current system is an extension of these previously designed and manufactured sensor systems to a broad wavelength range of 0.4-2.5 microns.

Figure 2 shows a rendering of the VisxSWIR spectrograph design, with ray traces. In contrast to the Vis/NIR design, this design uses IR material (CaF2). As with the Vis/NIR spectrograph, unique manufacturing capabilities are required to fabricate the monolithic design. Corning's experience with diamond turning IR materials enables manufacturing of this spectrograph. All of the optical surfaces, including the grating are fabricated directly into the material. The reflective surfaces are fully encapsulated so that they are highly resistant to corrosion. The resulting spectrograph is mechanically and thermally robust and requires no alignment. Corning's advanced design and manufacturing capabilities have allowed the freedom to optimize aberration correction using non-spherical surfaces for all optical surfaces, including the grating. The grating can be fabricated in single, multiple, or design-specific blaze configurations. These design freedoms are used to produce a spectrograph exhibiting exceptionally low distortion, providing excellent image quality and spectral fidelity.

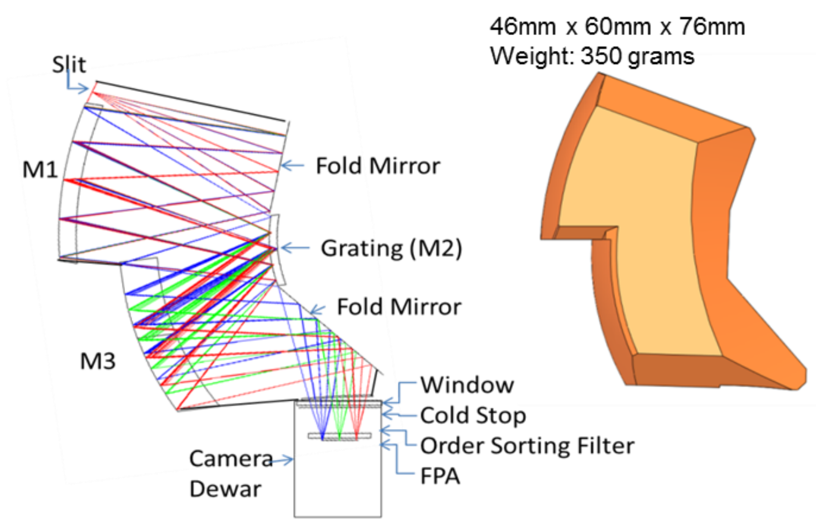

Figure 2. (left) Spectrograph cross-section with ray trace, (right) rendering of the spectrograph solid model

2.1.1.1 Grating

Operation over the extended spectral range of 0.4-2.5 microns requires a complex grating profile. Typically, gratings are blazed at a single angle to maximize transmission over one spectral octave, with diffraction efficiency falling to near zero at wavelengths less than half of the maximum. Corning has the ability to machine gratings with multiple blaze angles and phase shifts, which allows the use of a single grating over a large spectral range[3]. The diffraction efficiency of the grating can also be tailored to match the sensor requirements. For the VisxSWIR spectrograph, the goal is to maximize transmission above 2 microns and near 0.4 microns where the reflected radiance is low. Efficiency in the visible and NIR can be lower, since the radiance is larger. In fact, lower efficiency in the visible and NIR is advantageous, as it helps to provide a more uniform signal across all the bands without saturating the FPA.

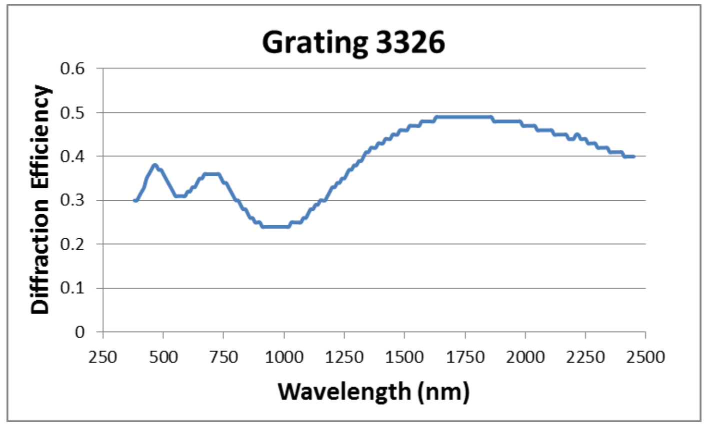

Figure 3. Grating diffraction efficiency for chosen grating

Corning analyzed over 300 grating designs with different blaze angles and phase shift combinations and came up with a design that meets performance goals. This grating profile achieves high diffraction efficiency in both the critical 380-450 nm region and the 2000-2450 nm regions as shown in Figure 3. Corning has cut a test grating, which has shown excellent surface quality as witnessed by the optical profiler image shown in Figure 4.

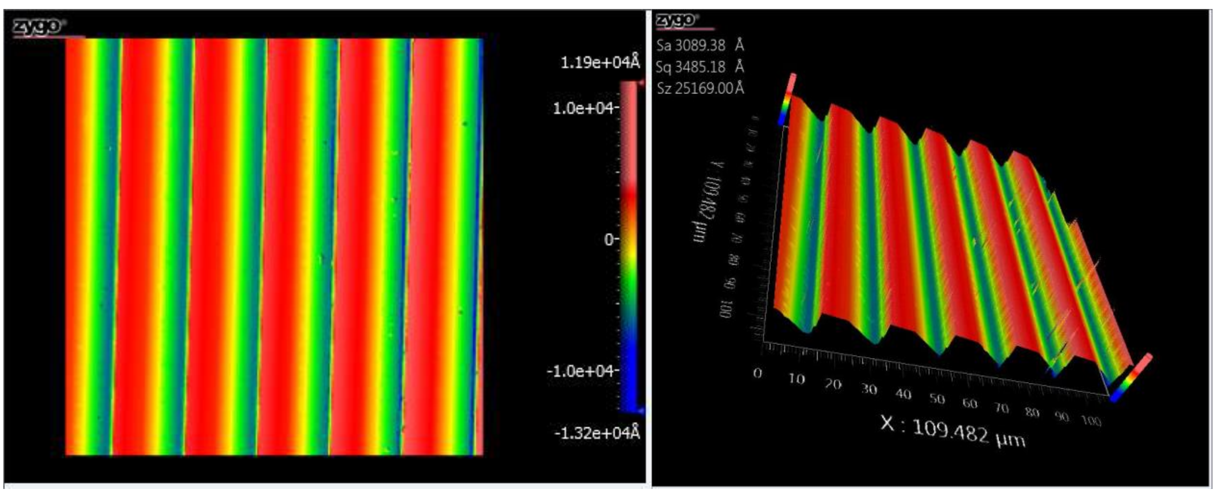

Figure 4. Test grating optical profile.

2.1.1.2 Order Sorting Filter

The spectrograph also requires an order sorting filter to reject higher diffraction orders. The order sorting filter is placed within the camera Dewar, directly above the focal plane. Because of the extremely large spectral range of 0.4-2.5 microns, many different wavelengths can fall on the same pixel, each with a different diffraction order. For example, the pixel corresponding to 2.4 micron light in first order, is also illuminated by 1.2, 0.8, 0.6, and 0.4 micron light in 2^{nd} through 6^{th} order respectively. An order sorting filter is used to block all wavelengths below 1.3 microns or so. Shorter wavelength pixels require different spectral filters with lower wavelengths spectral cutoffs. Corning has designed a compound order sorting filter with four different band-pass filters which can be mounted above the focal plane to provide complete high-order rejection for all of the pixels. The camera maker will align this to the focal plane according to a mutually agreed upon ICD. The order sorting filter provides in excess of three orders of magnitude of blocking for all out of band wavelengths, and an average in-band transmission of 90%.

2.1.2 Camera

The spectrograph block is coupled to a sterling-cooled, back-thinned, HgCdTe FPA covering 0.4-2.5 micron spectral range. The camera has 640X512 pixels, with pixel size of 15 µm. The camera's maximum frame rate is 120 Hz. The order sorting filter (OSF) is integrated in close proximity to the FPA, to maintain high performance throughout the wide wavelength range. The sensor has quantum efficiency greater than .85 throughout the spectral range, a large well depth of >1 Me-, and low read noise, leading to high SNR as shown below.

2.1.3 Sensor Performance

The sensor is comprised of the spectrograph described in Section 2.1.1 with the camera described in Section 2.1.2, and a 15mm focal length fore-optic lens. The sensor performance parameters are shown in Table 1.

Table 1. Sensor performance parameters

MicroHSI™ 425	Values	UNIT
MCT FPA		
pixel width (spatial)	15	[um]
pixel width (spectral)	15	[um]
Spatial pixels	640	[px]
Spectral pixels	446	[px]
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]
Δλ	2065	[nm]
Slit length	9.6	[mm]
dispersion	4.6	[nm/px]
dispersion	300	[nm/mm]
spectrum width	6.8	[mm]
Distortion		
Smile	<0.2	[px]
Keystone	<0.2	[px]

The spectrograph's design shows that the MTF is over 0.5 for all wavelengths and field positions. Point spread function at several field positions and wavelengths are shown in Figure 5. The square box represents a 15 micron pixel. The RMS spot size for all fields and wavelengths is under 12 µm.

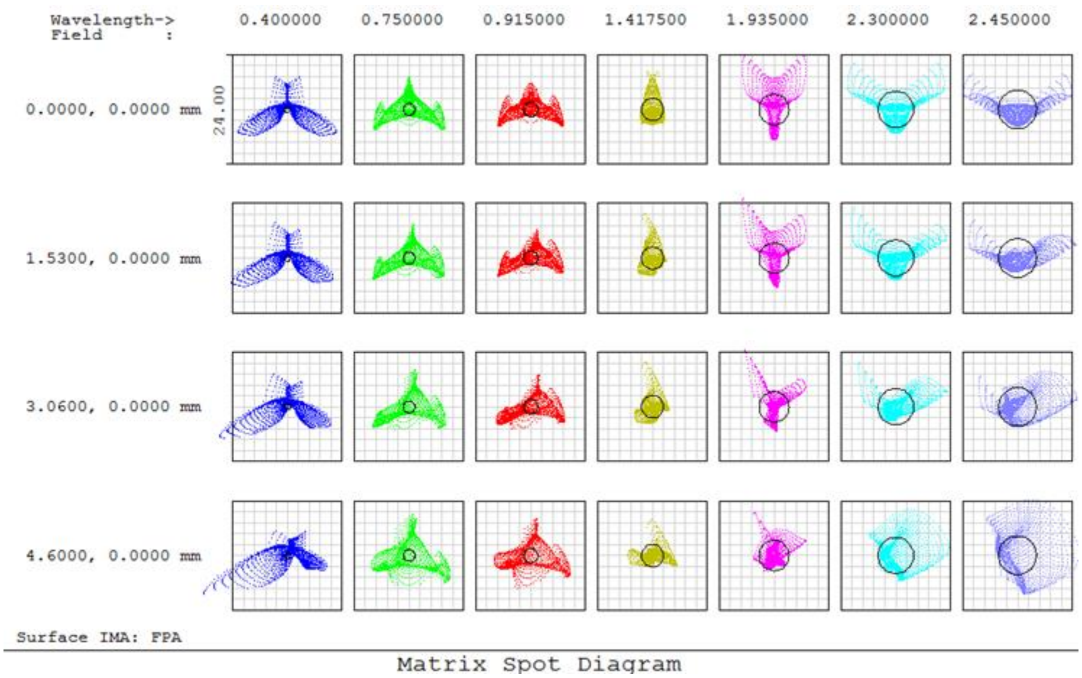

Figure 5. Spot size diagrams for seven wavelengths and four field positions.

The spectrograph's predicted throughput is shown in Figure 6. This includes the solid block material transmission, grating efficiency, and all the reflective surfaces, including the foreoptics.

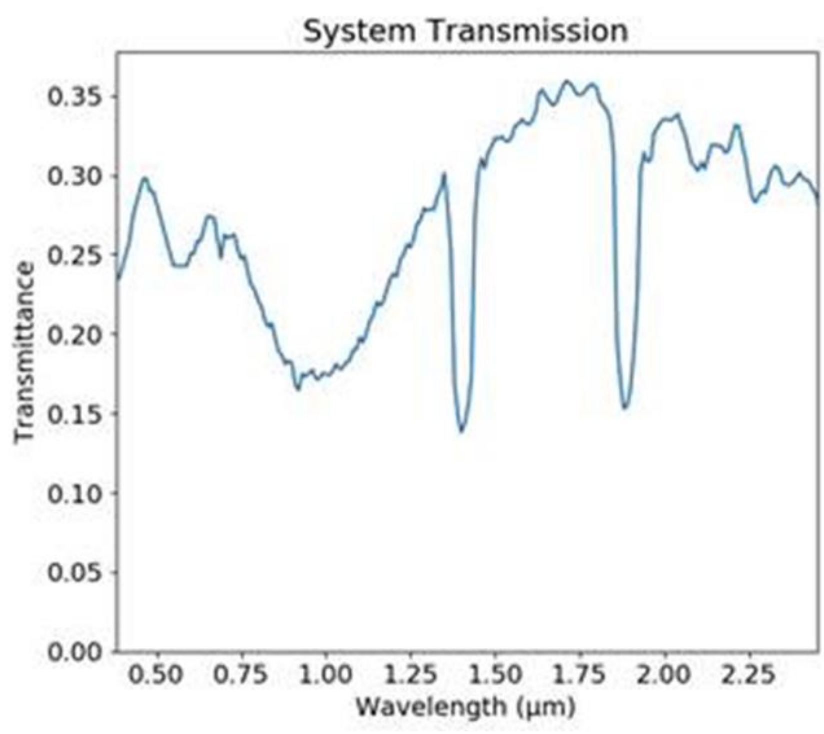

Figure 6. System transmission.

The distortion is under 3 micron in all cases, significantly below 20 percent of a pixel.

2.2 Fore-Optics

2.2.1 Fore-Optics Design

The flight system is intended to be mounted on small, low flying UAS's. For this application, a compact, reflective telescope with focal length of 15mm and f/1.4 (matched to the spectrograph) was designed. This translates to a field of view (FOV) of 100m at an altitude of 150m, or a half angle of 18.4 degrees, and an instantaneous field of view (iFOV) of 15cm. The telescope is compact (60x60x37 mm) and lightweight.

Figure 7 shows the layout of the fore optics, and the fore optics including its housing. The fore optics is comprised of two non-spherical reflective surfaces, taking advantage of Corning manufacturing capabilities to machine precise surfaces, including free-forms.

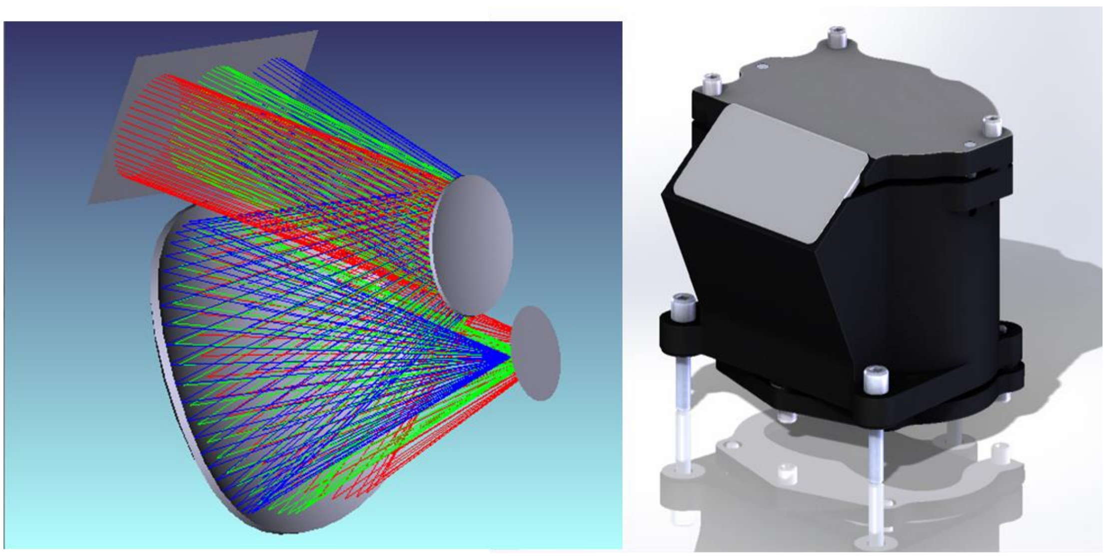

Figure 7. (Left) Fore-optics layout. (Right) Fore-optics in the housing.

2.2.2 Fore-Optics Performance

The fore optics maximum spot size of 2.75 microns and low distortion does not degrade the performance of the spectrograph. The modulation transfer function is shown in Figure 8.

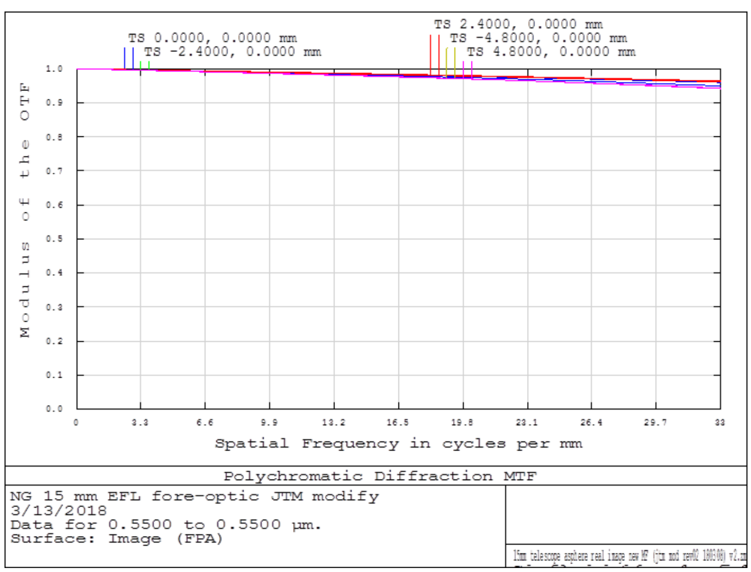

Figure 8. Modulation Transfer Function for the Foreoptics.

2.3 Flight Package (SHARK)

The 425 SHARK's flight package is based on the Vis/NIR 410 SHARK production unit[6]. It is designed to be a complete turnkey system mounted on small, low flying UAS's and will utilize proven components and software from the 410 SHARK. Common parts include the high efficiency microprocessor control and data acquisition subsystem, solid state disk (SSD) storage, a precision MEMS-based closely coupled INS (Inertial Navigation Subsystem), and GPS antenna. Besides the new Vis-Extended SWIR camera and cooler, other additions to the electronics package consist of a Camera Link interface, and shutter. Expected power usage during data collection is estimated to be ~25 W. The SSD is sized to store multiple 45-minute missions without requiring valuable field time to off-load data from the system. External interfaces are a gigabit Ethernet port for command, control, and data transfer, a USB 3.0 port for data transfer, and two status LED's.

The mechanical design of the complete, assembled system is shown in Figure 9 and contains the spectrometer, camera, cooler, fore optics, and data acquisition electronics. Estimated weight is less than 2.4 kg and the dimensions are 9.4" x 4.9" x 4.7".

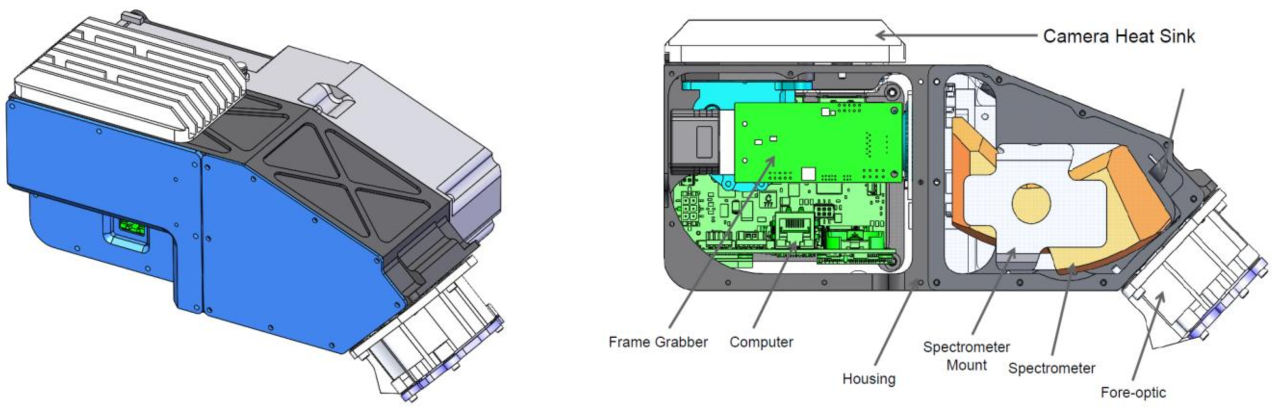

Figure 9. The SHARK complete turn-key system.

We will mount the Shark425 in a DJI Matrice-600 hexa-coptor equipped with a three-axis gimbal.

2.4 Signal and Noise Projected System Performance

The overall system level signal and noise performance can be projected based on the known sensor and camera performance characteristics. We show here the results of simulations for the spectrograph, sensor, and camera design described above. The simulations start with a detailed calculation of the radiance at the sensor for a particular scene and viewing situation. SSI's MODTRAN atmospheric propagation code is used to calculate the scene radiance, which is then propagated through the sensor optics and converted into a photoelectron signal at the FPA. Dark current and sensor noise are calculated based on the camera characteristics and the thermal radiation from the scene and optics. The sensor response function is based on the detailed spectral response of the detector and the system transmission, as shown above. Each simulation shows results for two different frame rates; the maximum frame rate of 100 Hz, which is used for rapid data collection, and a rate of 25 Hz, which uses the full dynamic range of the FPA. The later can be used for increased SNR at slower scan rates

Figure 10 shows the signal and noise for a scene of constant reflectance used as a performance benchmark; a nadir-viewing sensor at 100 m is focused on a 25% reflective Lambertian surface with a 45-degree solar zenith angle and mid-latitude summer atmosphere. Figure 11 presents similar curves for a typical coniferous forest, with wavelength-dependent reflectance.

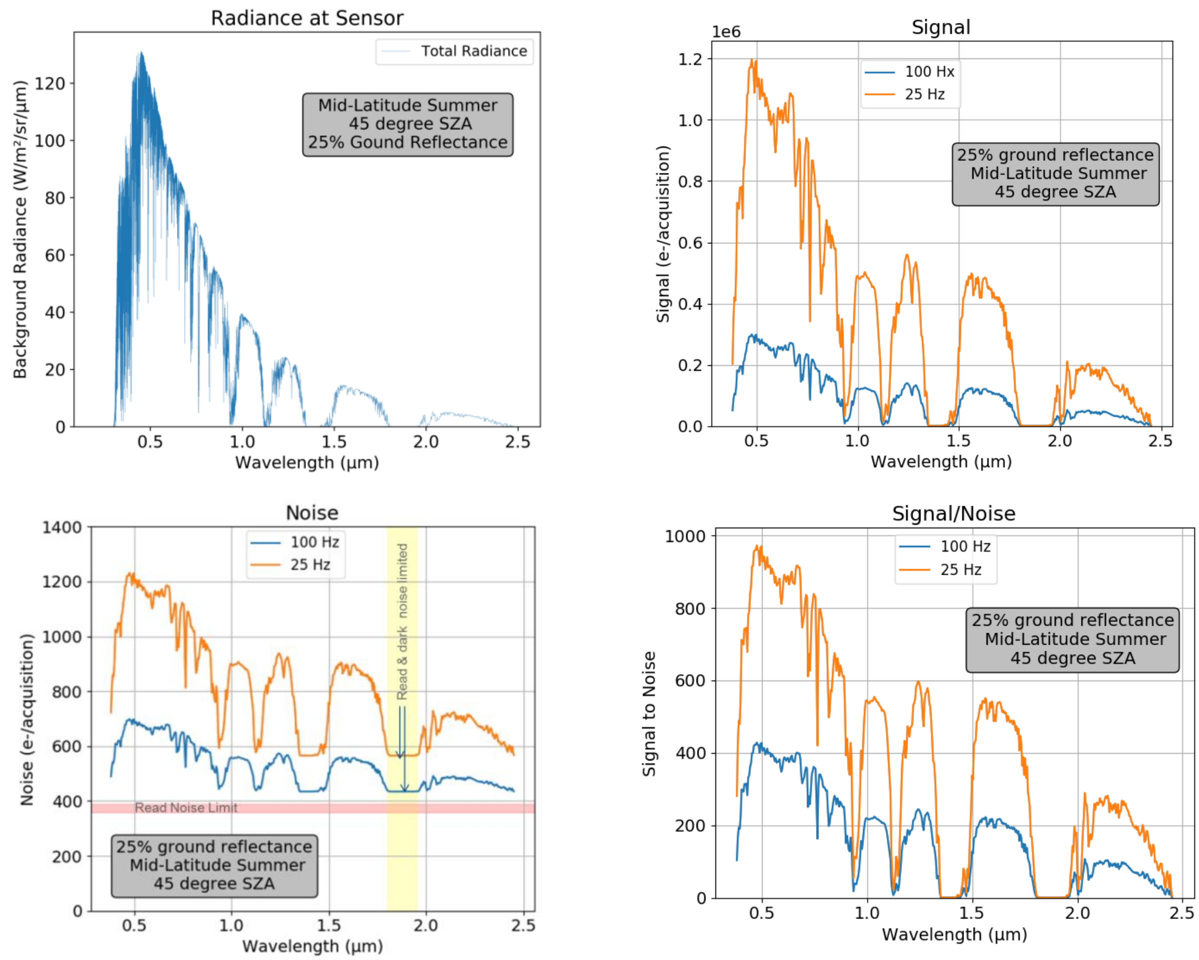

Figure 10. Simulation results for 25% ground reflectance.

The upper left-hand side of Figure 10 shows the radiance incident on the sensor. The upper right shows the photoelectron signal at the sensor. The lower left shows the sensor noise and lower right shows the signal to noise ratio (SNR). The noise floor of the sensor at is about 400-600 e- depending on exposure time. It arises from a combination of read noise and optical thermal emission from the thermal background, with the latter being dominant at lower frame rates. This noise floor can be observed in the water bands (e.g. 1.8 µm), where there is effectively no signal. The noise in the brighter bands is dominated by the shot-noise on the signal. The SNR below 1.8 microns is determined solely by the shot noise and is, in general, greater than 200:1 for scenes of moderate reflectance. At longer wavelengths, there is less incident radiation, and the SNR is generally of order 100:1 and varies linearly with signal intensity.

The actual SNR for a given scene depends strongly on the scene reflectance. Figure 11 shows the signal and SNR for a typical vegetative scene, in this case a conifer forest based on a standard reflectance profile in the MODTRAN code. Note the characteristically lower signal levels in the visible, below the Chlorophyll red edge near 0.7 microns where vegetation is highly absorptive, the higher signal levels throughout much of the NIR where vegetation is highly reflective, and the lower signal levels in the extended SWIR above 2.0 microns, where there are significant absorptions form a variety of vegetative chromophores.

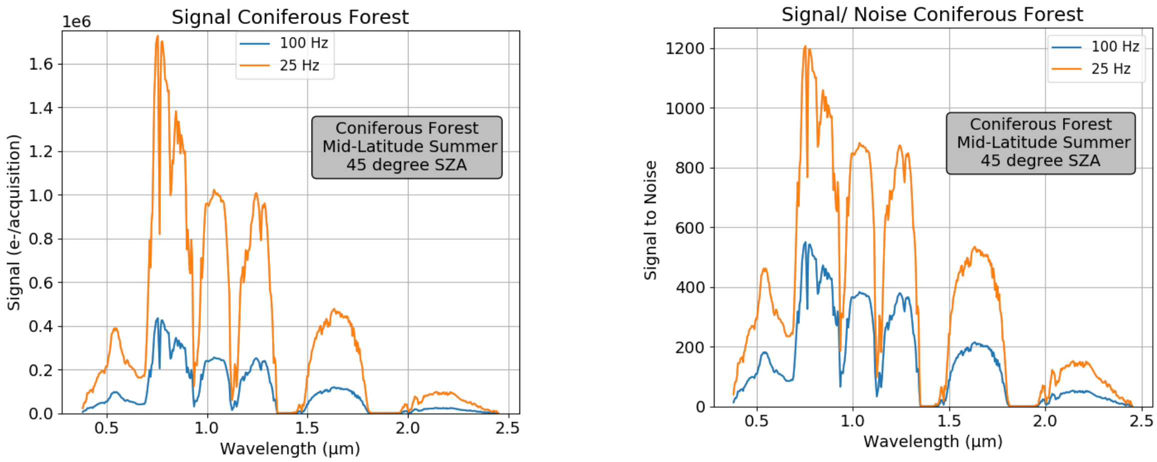

Figure 11. Simulation results for coniferous forest.

2.5 Software

Command and control of the 425 SHARK is very similar to the 410 SHARK's web based GUI, requiring no other applications to be installed on the user's computer except for a compatible browser. Any browser that supports Java such as Internet Explorer® or Firefox® can be used. Alternatively, the SHARK can be controlled by another device, through the Ethernet socket interface, sending commands detailed in the application programming interface (API). The SHARK's web pages are shown below.

The user loads the desired profile and integration time using the "System Control" page. The "Status" page is displayed once the system is loaded, see Figure 12. The "Sensor Control" page allows the user to stop and start the recording of data, and the "Waterfall" window is a real-time display of the unregistered image data (Figure 13).

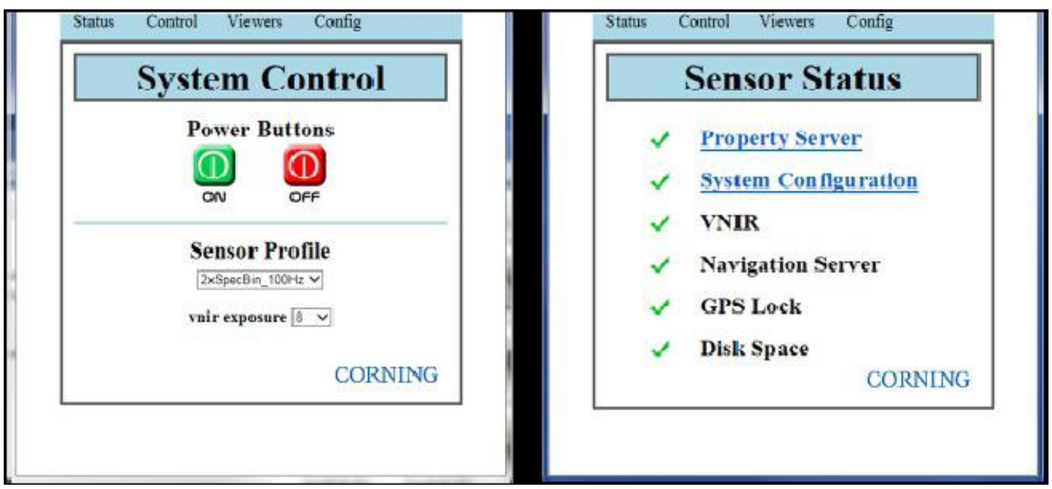

Figure 12. (Left) System Control web page. (Right) Sensor status web page.

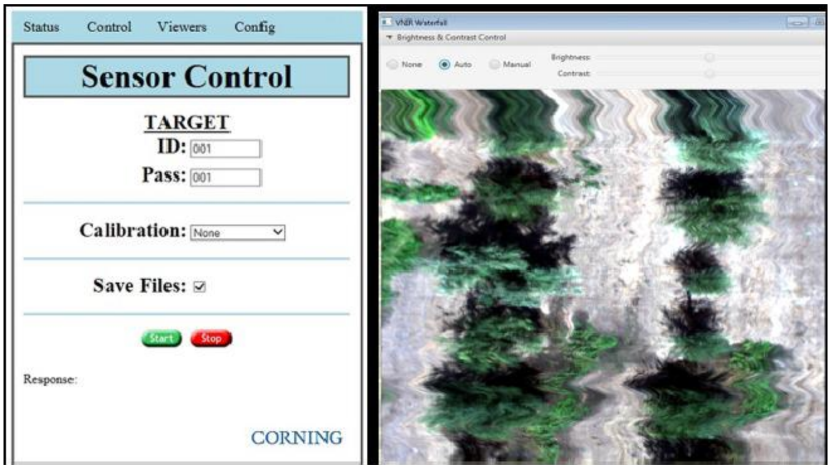

Figure 13. (Left) Sensor Control web page. (Right) Real-time waterfall display.

The "Navigation" page displays the INS data stream and is updated at 1 Hz. It includes UTC time, aircraft heading, aircraft ground speed, aircraft position, and aircraft attitude. The "Histogram" page maps the raw Digital Number (DN) to the number of sample elements that report that DN. By monitoring the histogram and comparing it with the scene, the user can monitor the exposure to determine if the imagery is being underexposed or overexposed (Figure 14).

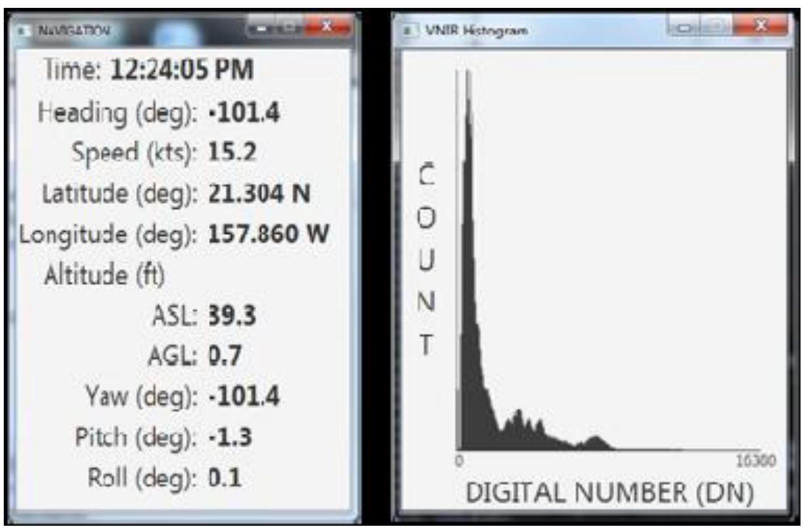

Figure 14. (Left) Navigation web page. (Right) Histogram web page.

2.5.1 Processing

The 425 SHARK stores data in formats compatible with Harris Geospatial's ENVI image processing tool. Two files are created for each raw hyperspectral image and written to the SSD; one is a flat file containing the image data in short integers and the second file is an ASCII header file with fields describing the layout of the data such as number of pixels, bands, and lines, data type, interleave type, etc. of the image file. The maximum size of the image files is configurable by the user.

For each HSI frame or line, the navigation data is retrieved from the INS and combined with data from a DEM (Digital Elevation Model). This data is used compute the latitude and longitude for each spatial pixel in the image. This coordinate information is stored as an ENVI IGM (Input Geometry) file allowing easy geo-referencing of the HSI image data with ENVI's built-in "Georeference from IGM" function. Figure 15 illustrates the geo-referencing process.

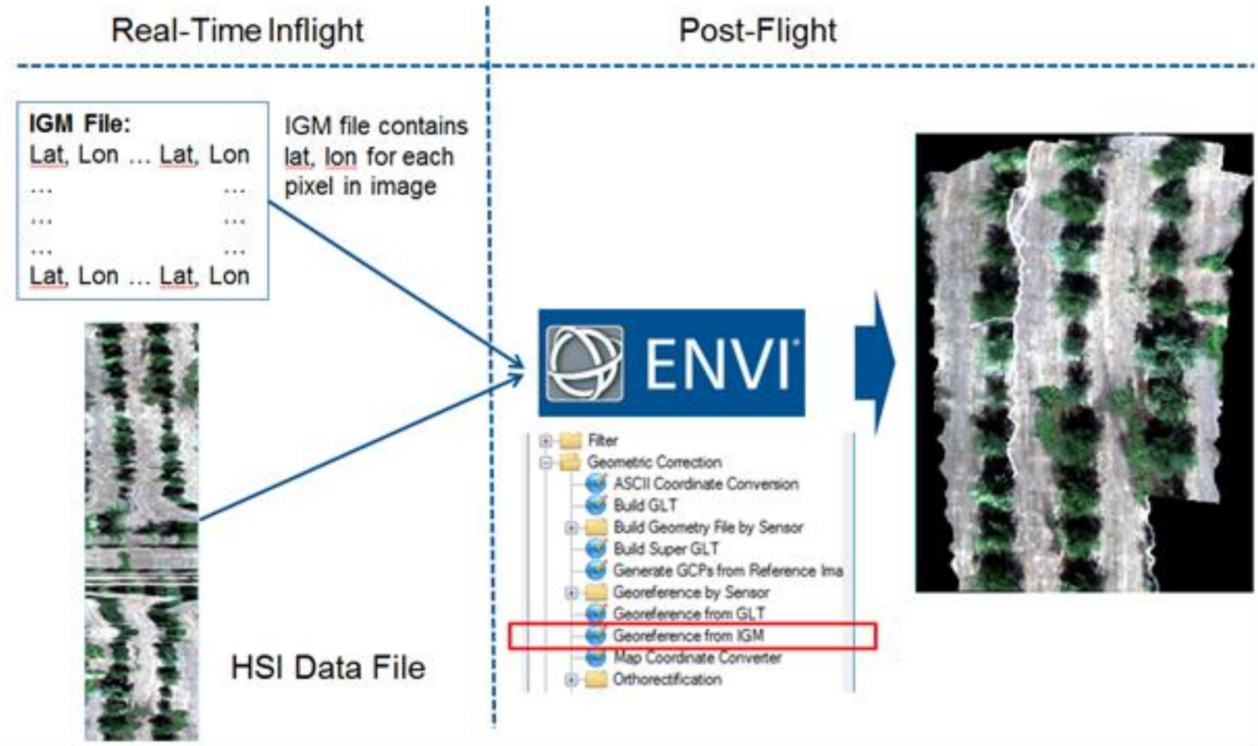

Figure 15. The geo-referencing process.

3. APPLICATIONS

3.1 Shark Applications

Corning's 410 SHARK sensor is the more compact, visible to NIR (400 nm – 1000 nm) model of the SHARK sensor family. Like the 425 SHARK, it is a fully self-contained system including hyperspectral sensor, inertial navigation system, on-board computer and storage. It's diminutive size and weight enables deployment on the smaller, quad-copter class of UAV's such as the Draganflyer® Commander and DJI™ Matrice 100.

Precision farming is an upcoming and growing market for hyperspectral sensing, with the potential to enable farmers to manage their crops more efficiently and sustainably. Farmers can monitor a wide range of variables that affect their crops using HSI data products. These include moisture content, photosynthetic activity (senescence), vegetation stress, and weed or pest infestations. The goal is to improve harvest yields while reducing the cost and environmental impact of over-fertilizing or excessing use of chemicals and water.

Vegetation indices provide field metrics and are combinations of surface reflectance at two or more wavelengths designed to highlight a particular property of vegetation. They are derived using the reflectance properties of vegetation. More than 150 vegetation indices have been published, with each index designed to accentuate a particular property. Indices such as ReNDVI (Red-edge Normalized Difference Vegetation Index), measuring greenness, are designed specifically for hyperspectral sensors with high spectral resolution and narrow bandwidths.

3.2 Expansion of 410 SHARK Applications to 425 SHARK

The Shark425 will be a slightly larger version of the 410 SHARK that can be applied in agricultural, mineralogy and ISR applications that require the full visible to extended SWIR spectral range. It can be mounted in a variety of mid-sized multi-copters or fixed wing UAS.

3.2.1 Monitoring of Vegetative Properties

The combination of wide wavelength range (visible through extended SWIR) and the ability to deploy the sensor on low-flying UAVs as well as larger aircraft will provide new capabilities for a variety of remote measurement applications, including ecological studies, agriculture, and mineral exploration.

Ecological studies sponsored by the DOE seek to measure carbon mass, leaf water, and other indicators of plant and ecological health. Combining measurements from different heights will provide the ability to scale data measured at the leaf level to the landscape level for wide-area surveys. The extended wavelength range of the sensor provides a wealth of spectral measurements that can be correlated with plant properties, including those desired for precision agriculture. Much of this information requires both hyperspectral resolution and SWIR coverage[7,9,11]. The SWIR regions of 1150–1260 nm and 1520–1540 nm have been shown to be optimal for leaf liquid water retrieval[9]; the 2000-2200 nm region is useful for thin canopies. Other wavelengths in the SWIR and extended SWIR are useful for estimation of cellulose, nitrogen, soil organic matter, lignin, and carbohydrates[7], and for assessment of photosynthetic capacity[8].

3.2.2 Other Applications

Hyperspectral coverage of visible through extended SWIR wavelengths provides access to a wealth of spectral features associated with minerals. Hyperspectral remote sensing has become an established technique for broad-area mineral exploration; a number of studies are described in a recent review[10]. However, there are very few systems that, like the 425 Shark, that cover the full required spectral range in a single sensor, and that will be competitive with our projected system price.

3.6 Planned Testing

The initial application of the Shark 425 will be for DOE-sponsored vegetation research, aimed at monitoring plant health and carbon sequestration at the landscape scale. The goal of the initial test is to document how vegetative-state indicators vary from the leaf scale to the landscape scale, and to conduct periodic surveys of a well-instrumented research plots at a variety of measurement heights. Measurements taken at standoff distances of 10m will yield 1cm resolution at the ground, while survey measurements at a height of 150 m will provide a native resolution of 15 cm, which can be further degraded to simulate landscape-scale measurements. Survey measurements will be taken several times during the growing season, and will be supported by ground truth measurements, including collection of plant specimens for wet-chemistry analysis of carbon content and other metrics of interest.

For large area surveys, the sensor would be flown in pushbroom mode, to generate 100m wide hyperspectral image swaths. In a typical survey, the UAS would be flown at a velocity of 5m/s and data would be recorded at 100 Hz, to provide a 680x1000x 400 hypercube, every 10 seconds. When flown in a regular lawnmower pattern, with 2x oversampling, a 1 km square area can be recorded during a single 30-minute flight (Figure 16).

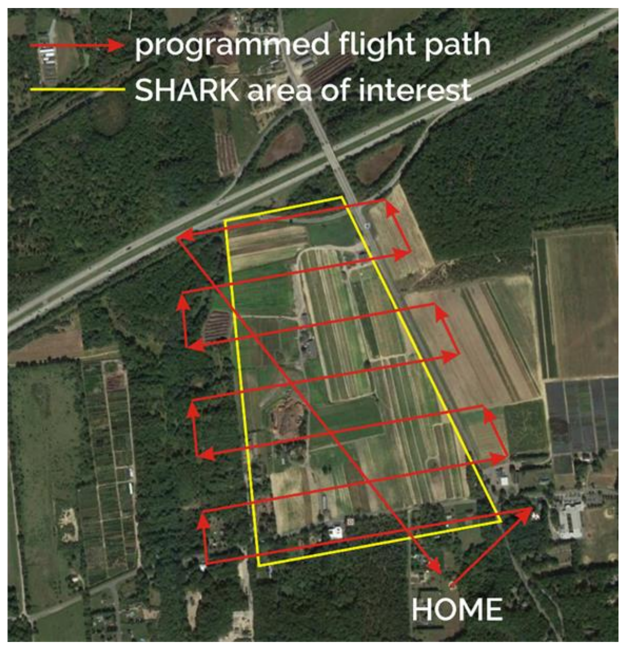

Figure 16. Example flight path over an area of interest.

4. CONCLUSIONS

We present a design for a compact, ready-to-fly VisxSWIR 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 2.4kg that can be flown on a variety of class 1 UAVs. The sensor has 680 spatial channels with sub-pixel spatial resolution, and 460 spectral channels with 4.7 nm spacing. Typical operation is as a pushbroom 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 form 2-2.4 microns.

The full sensor package will be available for test flights in early 2019. Initial applications will be in vegetative status monitoring in support of DOE ecology research. Other applications include agriculture, mineralogy, and ISR.

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