Hyperspectral Imaging for Remote Sensing Applications

Headwall Photonics is a solutions provider that focuses on integrating hyperspectral imaging sensors across a wide range of applications. One of these is remote sensing, which is typically undertaken aboard airborne platforms such as satellites, manned aircraft and UAVs.

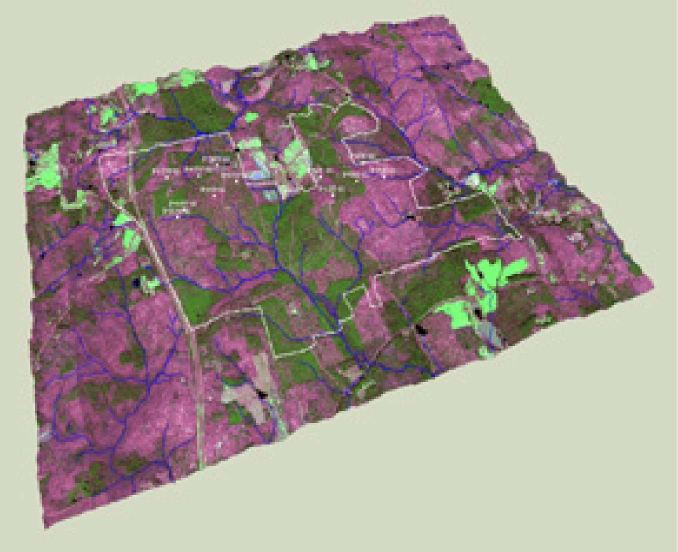
The integration process can be involved, combining high-performance hyperspectral sensors along with application-specific software that allows for meaningful data processing and interpretation. Because remote sensing is as much about software as it is about hardware, this paper discusses the issues and topics meaningful to the user.

As a leader in remote sensing, Headwall welcomes you to learn more about this fascinating topic.

INTRODUCTION

Remote sensing is the science of earth observation and gathering information about our environment and resources from a distance, typically from aircraft or satellites. The 'sensing' capability encompasses a broad range of instruments and technical approaches, with hyperspectral sensing being the most critical and enlightening approach. Collectively, the activities in the field of remote sensing are designed to increase our knowledge of the earth and its various dynamic relationships.

Hyperspectral imaging allows the earth science community to understand issues of environmental monitoring, climate change, earth resource allocation, agriculture yield, disaster monitoring, and other issues that impact the life processes of populations within specific geographies.



This paper primarily focuses on hyperspectral sensors, a reflective sensing technique that uses reflected sunlight to illuminate and measure reflective & absorptive indices to generate spectral signatures (chemical "fingerprints") that are uniquely characteristic of such parameters as plant physiology, crop health, and plant speciation. Hyperspectral sensors are passive by design, measure and record spectral information of the objects within the field of view of the sensor, and thus depend on solar illumination across the field of view.

Remote sensing has been enabled through a large number of satellite (for example, LandSat) and manned airborne platforms that carry a broad range of hyperspectral sensors from the visible/nir-infrared (380-1000nm) through the shortwave (900 – 2500nm) to the long wave spectral regions typically, 8 – 12 microns). Although the topic of remote sensing dates back several decades, the focus here is on emerging techniques that make generating data and providing remote sensing services more effective and efficient.

The emergence and rapid increase in unmanned aerial vehicles (UAVs) as a platform to carry these sensor instruments is resulting in broader deployment around the world. UAVs are far more cost-effective than satellites and even manned aircraft, which thus puts the science of remote sensing into many more hands across the globe. No longer the domain of government entities and large corporations, recent advances in hyperspectral sensor technology and data processing solutions coupled with small, affordable airborne platforms places remote sensing capabilities at a much more local and cost-effective level.

The development of small compact hyperspectral solutions such as Headwall's Nano-Hyperspec® aligned with the burgeoning growth of multi-rotor and fixed wing UAVs has given birth to a new commercial climate of compelling business opportunities and new remote sensing services. Together, these services and opportunities are capable of lifting economies with job growth and a better overall understanding of our environment.

INTRODUCTION TO AIRBORNE HYPERSPECTRAL IMAGING

The analysis of critical spectrum-based signatures is an invaluable tool for the environmental research community. Indices that present themselves specifically in spectral ranges above the visible (400-750nm) are of great interest to the remote sensing community because they can improve our understanding of plant physiology, crop science, geological formations, and the underpinnings of important infrastructure assets such as pipelines, dams and railroad beds.

Spectral imaging instruments fall into several categories, and within those categories different design approaches exist. But the scope of this paper will focus on hyperspectral sensors, which are able to collect literally hundreds of bands of spectral information for every pixel within the field of view. In situations where it is beneficial to collect all the spectral data (comprising many gigabytes of information), hyperspectral sensors compare favorably to their multispectral counterparts that capture only a handful of spectral bands with distinct gaps between them. This can mean the difference between seeing and identifying an invasive disease on a fruit tree and missing it altogether. It can also aid in speciation, since different plant types have their own distinct spectral signature.

To cover a geographical scene with a spectral imaging instrument, motion needs to occur in order to create a slice-by-slice 3D image 'data cube.' Satellites and manned aircraft were obvious choices years ago, but they were costly endeavors. Because the proliferation of small, hand-launched UAS platforms puts the science of airborne remote sensing into the hands of more researchers, understanding the various complexities surrounding integration and deployment is a necessary starting point.

IMAGING SENSOR FUNDAMENTALS

The basic function of a hyperspectral sensor is to capture individual slices of an incoming scene (though a physical slit) and to break each slice into discrete wavelength components onto a focal plane array (FPA). A diffraction grating manages the task of dispersing the image slices into discrete wavelength components. The grating is engineered with a precise groove profile to maintain spatial coherence in one dimension (the length of the image slit, in millimeters) and will cause the spatial information (the width of the slit, in microns) to diffract. This diffraction (dispersion) process allows the spectral content to transverse to known wavelength channels on the sensor.

In an airborne configuration, the sensor 'frame rate' corresponds to the capture of a new 'slice' of the image data cube. The scene in Figure 1 is typical, as it would be represented to the eye (left) and as a grid of CCD pixels (right).

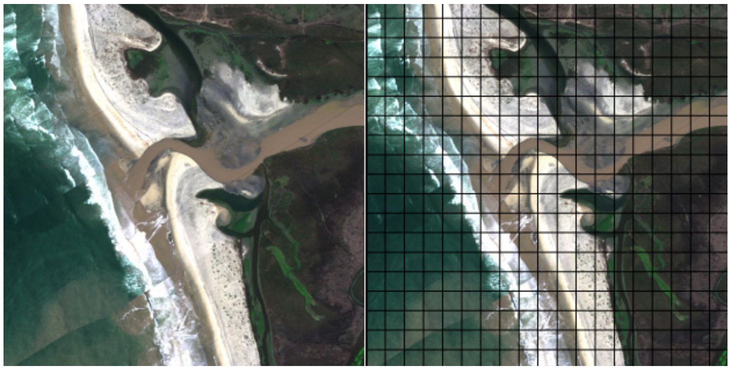


Figure 1: Airborne scene arranged as a grid of CCD pixels

When we view this scene though the slit of the hyperspectral sensor, all we see is the spatial strip that the slit lets through. This would be equivalent to one column of pixels depicted above. You can still see the spatial detail in the image, but only one strip at a time.

As we fly from left to right over the scene, we can take a set of pictures and stitch them together to see the whole scene.

The all-reflective *pushbroom spectral line-scanning technology* used by Headwall captures a spectral line (X spatial and Z spectral) in each frame as shown in Figure 2 below. Sequential frames build up the Y spatial dimension. The pushbroom design is preferred in airborne applications for its ability to provide low distortion for very high spatial and spectral resolution. High throughput means high signal-to-noise and very low stray light. Because it is an all-reflective design, chromatic dispersion issues are eliminated.

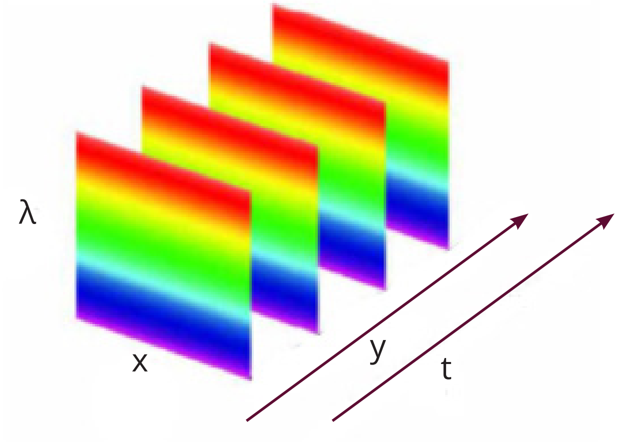


Figure 2: Pushbroom Spectral Line Scanning

In every slit, there are many colors. The hyperspectral system separates the light in each spatial pixel into the different colors in that pixel as shown in Figure 3. Each time the camera takes a picture of the slit, it gets a full frame of spectral data for each pixel. Stacking up each spectral image of the slit as we cross the scene we build up the hyperspectral data cube.

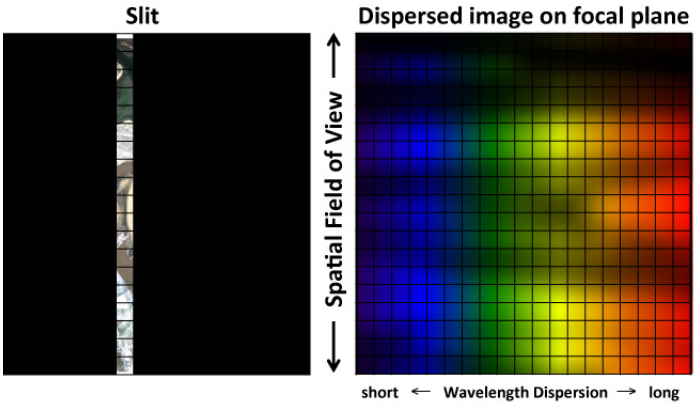


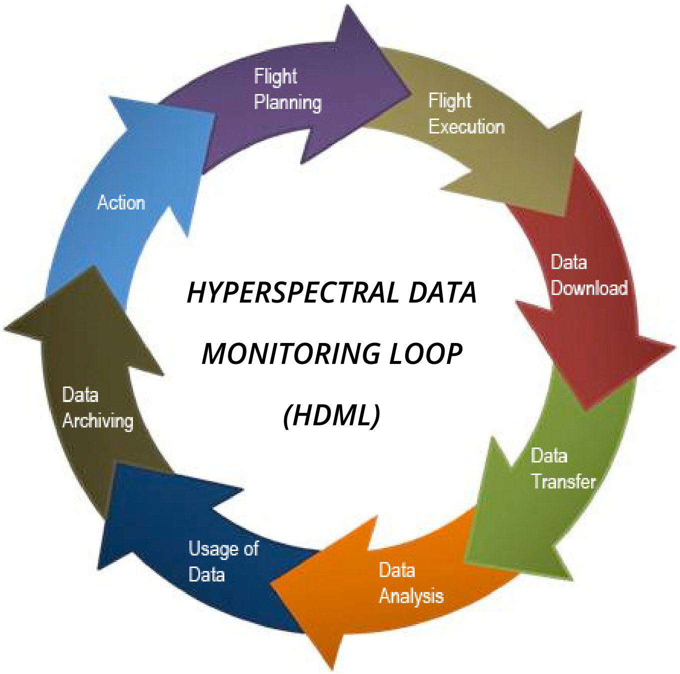
Figure 3: Slit Image and Disbursed

Field-of-View (FOV) is essentially what the sensor can see, and the wider the field of view the more efficient the flight path can be. A given parcel of land can be covered with fewer passes; similarly, more land can be covered per mission. Aberration-corrected diffraction gratings help assure crisp imagery edge-to-edge, meaning more land can be surveyed for a given flight swath which helps optimize limited battery life.

Instantaneous Field-of-View (IFOV) is the width of a single pixel, and the number of spatial pixels (channels) defines the sensor scan line. The more of these spatial pixels there are, the wider the field of view. The wider the field of view, the more 'efficient' the flight path can be. Several acres of land can be covered with fewer flight lines if the FOV is wide enough.

Spectral resolution of the sensor, measured in nanometers per pixel, is a function of the grating dispersion capabilities, which is why the design and production of the grating is fundamentally important. In grating-based sensors, choose those with master gratings rather than replicates. The result is much better optical efficiency, higher signal-to-noise (SNR), and crisper resolution. Since solar illumination isn't always at its brightest, or directly overhead, SNR is a crucial factor when trying to record image data under these less-than-ideal conditions. The low reflectance of water, for example, will typically call for a sensor having very high SNR characteristics in order to distinguish certain spectral wavelengths. To the extent that a remote sensing application calls for a predominance of over-water flights, this is crucial.

THE AGRICULTURAL WORKFLOW



The Hyperspectral Data Monitoring Loop (HDML) for a typical airborne precision agriculture application comprises eight stages. These activities cover everything from planning and executing the flight all the way to taking action with the collected and analyzed image data. The obvious need for any kind of research endeavor is to determine state changes over time and then develop solutions borne out of the collected data. For agriculture, this means determining the effectiveness of irrigation and fertilizers and spotting telltale signs of diseases early enough to successfully deal with them. The more detailed the image data, the more effective the solutions will be. For example, a hyperspectral sensor can 'see' the spectral signature of an invasive disease that might be present at certain points across a vineyard or citrus grove. Crop scientists thus have the ability to save an entire harvest because hyperspectral image sensors can see a disease condition that might otherwise be invisible. Unseen and thus destructive, agricultural diseases put entire global economies at risk. This is a key reason for the steep, rapid growth of both hyperspectral image sensors and the UAS that carry them. The primary reason to use hyperspectral sensor technology in an airborne configuration is to collect a complete picture of the spectral content of a certain geographical area. This can be a grape vineyard, a citrus grove, a coffee plantation, a rain forest, a geological formation, a petroleum pipeline, a pollution site, or a forest. The opportunities for environmental learning are endless, especially now that UAS craft are smaller, lighter, more affordable, and easier to deploy. Equipped with precision-packed spectral imaging sensors, this new integrated UAS becomes a highly desired tool for researchers around the globe who now are able to distinguish change in certain environmental conditions over time.

The first step in this eight-stage process flow is *flight planning.* With small and light UAS platforms such as the Aibot X6, aerodynamic performance can be impacted by obvious variables such as weather and wind, but also by less obvious ones such as magnetic disturbances. Choosing the correct sensor or suite of sensors is also part of this task. RGB cameras are fine for mapping, surveying, monitoring, inspecting, counting, and volume calculation. Thermal sensors are fine for inspection and monitoring and also plant physiology.

Multispectral and hyperspectral sensors collect data relative to plant analysis, ground analysis, water analysis and management, and overall crop health. There are obviously many more bands of image data with hyperspectral versus multispectral, and the choice often rests with the user and whether they have a good idea of the spectral ranges of interest. If they do, then multispectral sensors might be adequate. But if they don't, hyperspectral sensors collect all the data on a per-pixel basis and can be more useful across a wider range of crop analytics.

Flight planning is made easy thanks to software-driven capabilities from both the UAS side (Aibotix AiProFlight) and the hyperspectral side (Headwall's Hyperspec III and Headwall's Polygon Tool. GPS waypoints are entered into the respective software platforms to tell the UAS where to fly and also when to activate the hyperspectral sensor during flight.

Georeferenced data can be an important requirement, so flight planning also needs to take into consideration the salient differences between real-time kinematic (RTK), GNSS, and GPS and choose the best option. The next step in this process flow is *flight execution.* As mentioned, the respective software platforms help automate everything from the start of the UAS right through operation of the sensors. The AiProFlight software from Aibotix, for example, manages the airborne behavior of the Aibot X6 while Hyperspec III manages the operational aspects of the sensor (the actual data collection). These respective packages are designed to be complementary rather than redundant: AiProFlight does not operate the sensor and Hyperspec III does not operate the X6.

Choosing between manual flight and waypoint flight needs to be done, and users need to prepare themselves for updated flight plans should that be necessary. Obviously, all of this must be done within the guidelines of the regulatory authorities (in the United States, the FAA) and strict adherence to these regulations is absolutely vital.

The third part of the process flow is *data download.* Because gigabytes of image data are being collected by the sensor while aloft, streaming is not yet feasible in most cases. But after the UAS lands, this part of the process involves downloading the data from the sensor or airborne computer onto USB, SD card, or another type of storage. Headwall's Nano-Hyperspec has 480GB of onboard storage, but many other sensors need to be connected to a complementary airborne computer that collects the image data.

It's crucial to check this image data right away, and be prepared for another flight should the quality be less than ideal. Many times a simple calibration on the sensor will remedy the issue, but failing to qualify the data right away means a loss of time and resources.

Analyzing image data allows the crop scientist to get industrial indices such as NDVI (Normalized Difference Vegetation Index), Carbon/Nitrogen (C/N) ratios, Crop-Water Stress Index (CWSI), Leaf Area Index (LAI), and Soil Adjusted Vegetation Index (SAVI). Point clouds can be used for volume calculation while data can be used to count plants.

After analyzing the image data, what next? *Data Usage* involves generating plans for planting, watering, fertilization, and more. The objective is to plan land improvements and management, and change farming practices if necessary. The ability to carry out frequent flights is a byproduct of UAS platforms being small, light and affordable. This in turn allows for strategies to be modified as needed. Using a variety of commercially available applications, it is important to *archive* this data to understand trends over time with respect to vegetation, soil and water among other indices (Figure 4). Because hyperspectral sensors collect all the spectral information for every pixel within the field of view, the ability to process gigabytes of image data is equally important. Most of this work happens during post-processing; that is, after the flight concludes. Airborne platforms (especially a UAS) are at the mercy of aerodynamic variables such as wind and turbulence. Post-processing helps smooth these out, leading to more reliable image data. *Orthorectification* is one vital post-processing task that transforms raw hyperspectral data (from a non-uniform perspective projection) to a uniform orthographic projection, where each adjacent pixel from the sensor indicates a location on the ground that is equidistant to its neighboring pixel. The objective of orthorectification, which Headwall's Hyperspec III software manages, is to remove the distorting effects of tilt and terrain relief.

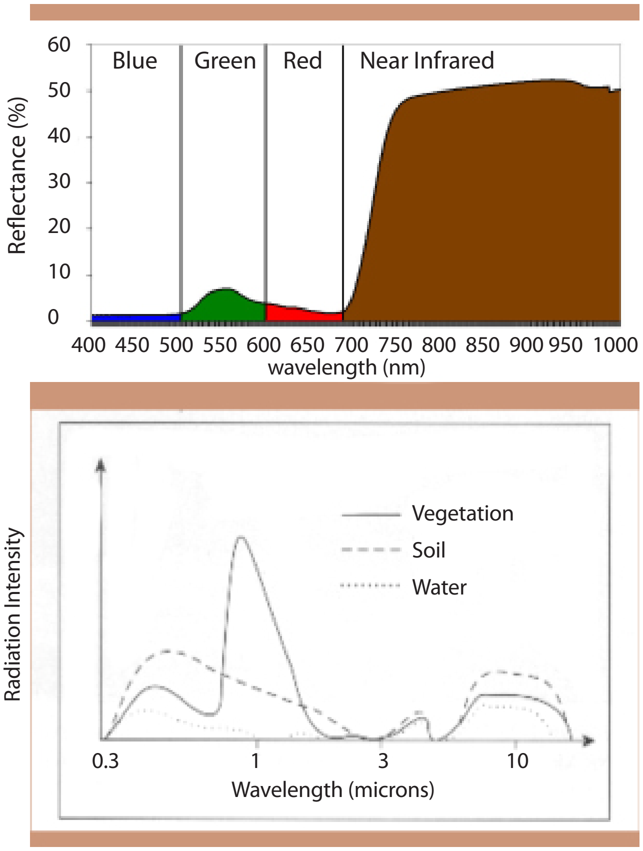


Figure 4: Agricultural trends and indices can be managed through hyperspectral imaging.

Ancillary instrumentation such as LiDAR (a confluence of 'light' and 'radar') and GPS are often joined with hyperspectral sensors as elements of the payload suite to help assure that the collected image data is both complete and precise. Orthorectification is a byproduct of the outputs from all three.

While the eye can only really discern and distinguish between 400nm and 750nm (the 'visible' range), much of what interests the research community falls well above that. The Visible-Near-Infrared (VNIR) range starts at 400nm but extends up to 1000nm. The Extended VNIR range starts at 550nm and goes up to 1700nm, while the Near-Infrared (NIR) range sits between 900nm and 1700nm. Of particular interest to the remote sensing community is the Shortwave-Infrared (SWIR) range of 950nm up to 2500nm. Much of our environmental and agricultural learning occurs in these nether reaches of the electromagnetic spectrum, which is why hyperspectral image sensors are highly desired for remote sensing work. Sensors geared for the Midwave-Infrared (MWIR, 3-5 micron) and Longwave-Infrared (LWIR, 8-12 micron) range are much less common and outside the scope of this paper.

Hyperspectral sensors are typically application-specific instruments defined by spectral range. That is, a Visible-Near Infrared (VNIR) sensor collecting image data from 400-1000nm will not be tuned to 'see' anything in the Shortwave Infrared (SWIR) range (950-2500nm). In many remote-sensing applications (precision agriculture, for example), VNIR sensors will 'see' what scientists want to see. Certain vegetative indices and disease conditions will be 'visible' within this range. But this starts with an underlying assumption that scientists know what they are looking for and where those spectral 'fingerprints' lie. More often, they don't.

In cases where a more complete picture is needed, more specialized instruments are highly desired. The first of these combines both VNIR and SWIR for end-to-end coverage of the spectral range that spans from 400nm to 2500nm. This gives the remote sensing community a single-package sensor that can carry out a wide range of airborne missions. One favored approach is to take a VNIR sensor with a CMOS detector and combine it through co-registered pixels with a SWIR sensor having an MCT detector. The process of 'co-registering' the pixels assures image fidelity across the range, and it also optimizes signal-to-noise performance from one end of the spectrum to the other. Optically, the solution is a high-performing one, and the challenge then becomes one of SWaP (size, weight, power) optimization. While the overall package is presently a bit outside the carrying capacity of today's hand-launched UAS, further footprint and weight reductions will see this solution more mainstream in the near future.

The second sensor package is a high-resolution instrument that keys on the very narrow yet specific spectral range of 755 to 775nm where solar-induced fluorescence occurs. Often measured from satellite-based instruments, an airborne package can help corroborate the data. Environmental research very often involves measuring plant function, vitality, and stress. These indices can be 'measured' by the fluorescence signal emitted by plants during photosynthesis, which occurs roughly between 755nm and 775nm. This 'signal' is highly indicative of plant health and therefore of great interest to researchers. The key is developing a sensor that simultaneous provides high spatial and spectral resolution of 0.1-0.2 nm across the range in a reasonable airborne-friendly footprint that aircraft and some larger UAS can carry. Headwall's high-resolution fluorescence sensor can be tuned to image any 20-30nm-wide pass-band within the interval from 460-800nm without any loss of imaging performance. Since these 'fluorescence signals' can be relatively weak, high signal-to-noise performance is a must. Since the cost to deploy this imaging sensor technology aboard an airborne platform is a fraction of doing so aboard a LEO satellite, more users around the globe can take advantage of its specific capability.

INTEGRATING ABOARD THE UAS

Before the rapid availability and adoption of today's UAS, hyperspectral remote sensing was largely the domain of satellites and manned aircraft. But these platforms can be financially inefficient for the kind of repeatable and continual land surveys needed to spot trends and develop solutions to problems. Hyperspectral sensing instruments are evolving along a parallel track with UAS; both are getting smaller, lighter, and easier to use. Indeed, this confluence of technologies is helping to push our understanding of the climate, agriculture, and geology in fascinating directions.

Aibot X6 with Nano-Hyperspec®

PrecisionHawk®

While the integrated airborne/hyperspectral solution is now much more affordable than ever, it is also more important than ever to be diligent throughout the entire process. Simply acquiring a UAV and bolting a sensor to it is entirely the wrong approach to take, and great care needs to be taken when conceiving the mission.

When selecting UAVs, many choices exist. *Multi-rotor* (Aibot X6, Aibotix GmbH, Germany) and *fixed-wing* (such as the PrecisionHawk) are the two general classifications. Aside from cost implications, the former can take off and land within a very small footprint while the latter needs some sort of runway or launching mechanism. Careful consideration needs to be given to payload size, weight, and power (SWaP). While hyperspectral sensors are getting lighter and more compact, other ancillary instruments such as LiDAR, thermal, and GPS/IMU also take up room and weight. Consequently, selecting a UAS means determining its weight-lifting capabilities with respect to overall flight duration.

Finally, portability is important since these missions are often taking place in remote areas. The more compact the overall package, the simpler it will be to transport and deploy. But the lighter and more easily transported the craft is, the more likely that payload restrictions will exist and flight duration will be curtailed. As noted by the experts at Aibotix, "*Every gram directly influences flight time*."

Some of the key specifications and considerations when planning a UAS for remote sensing activities:

SYSTEM SPECIFICATIONS	CONSIDERATIONS
Unmanned Aerial System (aircraft)	Aircraft size, payload SWaP, flight speed
Hyperspectral sensor	Wavelength operational region (VNIR, NIR, or SWIR), Spatial & Spectral resolution, Frame Rate, Quantum Efficiency, Signal-to-Noise ratio, SWaP
Data Processing Unit	Data Storage write-time performance, SWaP
GPS/IMU	High v. Low Resolution Geo-Orientation accuracy, sampling rate
LiDAR	Flight height, weight, accuracy

To reinforce the need for precise and careful integration, Aibotix notes that small UAVs are susceptible to winds. In other words, their wind tolerance threshold is lower than on a larger UAV. And because the hyperspectral sensor is a line scanner, it needs to be aligned to the ground for good results. Wind is the enemy of that effort, which means that a stable gimbal is required. Here, Aibotix recommends two-axis stabilization (roll and pitch) using a brushless gimbal with excellent damping capabilities.

TYPICAL FLIGHT PARAMETERS	MINIMUM	TYPICAL	MAXIMUM
Altitude (m)	50	100	200
Flight Duration (m)	10	20	60
Flight Speed (m/s)	2	8	12
Land Coverage (Hectares/minute)	0.4	1	4
Spatial Resolution (cm)	5	7.5	10

For a frame of reference to the reader, the Aibot X6 fully instrumented weighs 5.5 kg (12.1 lb.) and can capture 5 hectares (ha) in 10 minutes of continued flight time at a speed of 4 meters per second and an altitude of 100m (328 feet). A hectare is roughly equivalent to 2.47 acres. Battery changeover takes seconds, and the altitude envelope ranges from 20 to 200m. These are typical altitudes and speeds for the Headwall Nano-Hyperspec® VNIR that exhibits a maximum frame rate of 300Hz. The number of spectral bands collected is 270; the number of spatial bands is 640. Dispersion per pixel (nm/pixel) is 2.2, and the unit draws 13 watts maximum. On-board storage of 480GB is equivalent to about 130 minutes at 100 frames per second.

TYPICAL SPECTROMETER PARAMETERS	VNIR (400-1000nm)	NIR (900-1700nm)	SWIR (900-2500nm)
Pixel Size (microns)	7	20	30
Spectral Resolution (Bands)	800	333	250
Spatial Resolution	1600	640	320
Frame Rate (fps)	100	100	100
Data Rate (MB / second)	256	42.6	8

In small UAV situations, power draw for the sensor and other instruments has to be carefully managed with respect to what is needed to fly the craft itself. So quite literally the integration process involves calculating geographical coverage area, time aloft, weight, altitude, and other variables. The draw needed by the sensor payload can be mitigated somewhat by automatic triggering that uses GPS waypoints (essentially a polygon) to determine exactly where the scanning operation will occur. The Aibotix AiProFlight works together with Headwall's Hyperspec® III software for both sensor operation and waypoint management to deliver completely autonomous operation. The practical result is that the craft flies exactly where intended while the sensor collects data exactly where it needs to.

As governmental agencies (the FAA in the United States, for example) sharpen their focus on safety, these autonomous operational characteristics are most welcome. In addition, higher levels of automation through intuitive and interactive software platforms means that missions can be planned and executed very rapidly. Since remote sensing often involves numerous flights over different or similar terrain, software can actually become the key differentiator not only while airborne but also during post-flight data download and analysis. Missions thus become more predictive, more valuable, and more time-efficient.

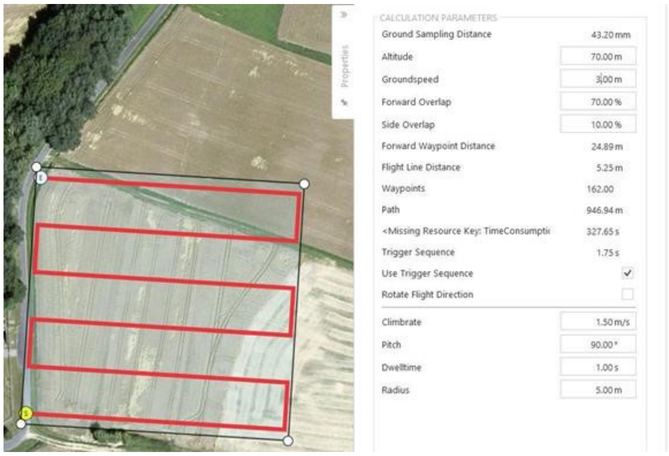
SOFTWARE APPLICATION

To illustrate the benefit of mission efficiency derived from application software, we'll discuss both the Aibotix AiProFlight® and Headwall's Hyperspec® III. As briefly noted earlier, the former is focused on maneuvering the Aibot X6; the latter is managing sensor operation while aloft. Hyperspec III also handles the key post-collection tasks that help turn the image data into useful information.

Hyperspectral data missions are typically (but not always) flown linearly as depicted on the mission-plan graphic shown in Figure 5. The wider the field of view, the wider these flight lines can be. In other words, a sensor with crisp (aberration-corrected) imaging performance at the edges can cover more ground and collect more data per flight segment.

A 'map view' within both Aibotix AiProFlight® and Hyperspec® III defines the parameters of flight and sensor operation. Ordinarily, the sensor will be 'triggered' to collect data sets within a geographical polygon of specified GPS waypoints that represent a portion of the flight plan. Parameters such as flight altitude and sensor focal length (a function of the lens attached to the sensor) will influence the ground resolution and thus the captured area on the ground. The software monitors these parameters and gives continual feedback to the operator in order to maintain mission parameters.

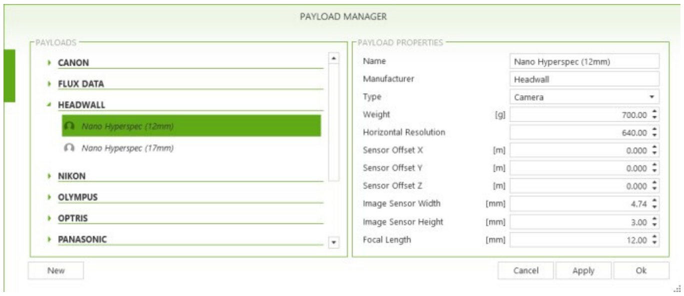
In autonomous flight mode, the Aibot X6 can fly along waypoints automatically. The route is set with the Aibotix AiProFlight flight-planning software and transmitted wirelessly to the Aibot X6.



CALCULATION PARAMETERS

Ground Sampling Distance	43.20 mm
Altitude	70.00 m
Groundspeed	3.00 m
Forward Overlap	70.00 %
Side Overlap	10.00 %
Forward Waypoint Distance	24.89 m
Flight Line Distance	5.25 m
Waypoints	162.00
Path	946.94 m
<Missing Resource Key: TimeConsumptic	327.65 s
Trigger Sequence	1.75 s
Use Trigger Sequence	☑
Rotate Flight Direction	☐
Climbrate	1.50 m/s
Pitch	90.00 °
Dwelltime	1.00 s
Radius	5.00 m

Figure 5: Typical mission plan for hyperspectral imaging (courtesy Aibotix)



PAYLOADS

- CANON
- FLUX DATA
- HEADWALL
  - Nano Hyperspec (12mm)
  - Nano Hyperspec (17mm)
- NIKON
- OLYMPUS
- OPTRIS
- PANASONIC

PAYLOAD PROPERTIES

Name		Nano Hyperspec (12mm)
Manufacturer		Headwall
Type		Camera
Weight	[g]	700.00
Horizontal Resolution		640.00
Sensor Offset X	[m]	0.000
Sensor Offset Y	[m]	0.000
Sensor Offset Z	[m]	0.000
Image Sensor Width	[mm]	4.74
Image Sensor Height	[mm]	3.00
Focal Length	[mm]	12.00

Sensor database with integrated Headwall Nano Hyperspec® sensor and different focal lengths (courtesy Aibotix)

With the help of pre-planned routes, the Aibot X6 can perform inspection and mapping flights of any pattern without manual piloting.

Since hyperspectral data is measured in gigabytes rather than megabytes, 'streaming' isn't practical or feasible at present. But thanks to tremendous cost reductions in flash memory, Nano-Hyperspec has taken the data-storage function from an external drive onto an internal 480GB solid-state drive (SSD). This eliminates the weight and complexity of a separate computer and its ancillary cabling while significantly improving data-transfer speed. 480GB is more than enough for any reasonable mission, and data is transferred rapidly via Ethernet so another flight can commence soon after.

There are several deployment scenarios for hyperspectral imaging across remote sensing, from satellites and manned aircraft to hand-launched UAS platforms. Even stationary pan-and-tilt or point-and-stare configurations are used in the field of remote sensing, either on the ground or atop masts. Remote sensing isn't exclusively the province of airborne applications. Similarly, there can be situations where multiple sensors need to be controlled and coordinated in order to cover the VNIR (400-1000nm) and SWIR (900-2500nm) ranges concurrently.

This wide variety of use cases suggests that one software platform with functionality modules enabled or disabled is a preferred approach. This strengthens familiarity with the software over time by users, who will appreciate the common GUI even though their mode of use might have changed. Application software also needs to be intuitive and easy to use, which is sometimes an afterthought. But since hyperspectral imaging is reaching a broader audience outside the scientific optical imaging domain, simplicity is key. To the user, hyperspectral imaging is a means to an end and a new tool for them to use. The software therefore needs to take into consideration answers the tool can provide, and focus on presenting this information in a meaningful yet flexible way.

For remote sensing, application software is a key factor in selecting a hyperspectral sensor. Generally, the software is tasked with two functions. The first is automatically controlling the sensor while aloft. This includes using polygon functionality to trigger sensor operation based on specific GPS-defined waypoints. Since image cubes usually comprise gigabytes of data, it is important that collection occurs only within a user-defined geographic perimeter. In addition, applications that comprise more than one sensor (a VNIR combined with a SWIR, for example) need a software package that can independently control the operation of each.

The second function of the application software suite involves the important post-processing tasks that allow the user to analyze and manage the data after the craft has landed. Many thousands of dollars can be spent on ENVI®, which is a very capable suite of post-processing functions offered by Exelis for geospatial analysis and spectral image processing. But the hyperspectral sensor manufacturers themselves offer capable software packages as an affordable add-on. Headwall's Hyperspec III software is one such example.

Perhaps the most valued post-processing task that Hyperspec III provides for the remote sensing community is orthorectification. This is the process of removing the effects of image perspective (tilt) and relief (terrain) for the purpose of creating a planimetrically correct image. The resulting orthorectified image has a constant scale wherein features are represented in their 'true' positions. This is a crucial function because aerodynamic effects on a UAV can lead to images that are 'less true' than desired. While a stabilized gimbal is a given for these instruments, the addition of orthorectification adds a greater measure of data accuracy. Headwall's Hyperspec III software has the ability of 'overlaying' data onto Google maps to verify location accuracy.

Another post-processing task useful to the remote sensing community is radiance conversion using radiometric calibration. Radiometry is the science that allows users to answer the question, "how much light is there?" Radiometric calibration is the process by which we can get a true measure of how much light is in the scene. This 'radiance' value is converted into more meaningful reflectance values useful for analysis.

The sheer volume of image data collected during remote sensing missions suggests that 'point analysis' is a valuable function of any hyperspectral image software. For example, an overflight of an entire orchard or vineyard will point to certain areas (or 'points') that require more specific analysis. A single tree canopy, for example. The ability to export spectral data from selected points within the scene into Excel allows for quicker analysis and action. Similarly, 'batch-processing' of image data is a useful function within Hyperspec III that improves mission efficiency.

Other software functions that the remote sensing user will find useful include user-selectable wavelength bands and NDVI modules. The Normalized Difference Vegetation Index (NDVI) is a numerical indicator that uses the visible and near-infrared bands of the electromagnetic spectrum to analyze remote sensing measurements and assess whether the target being observed contains live green vegetation or not. Since vegetation (or lack of) can be an indicator of vitality or stress, a means by which this can be accurately measured is a highly desired function.

COMBINING INSTRUMENTS

Remote sensing missions often need to combine a variety of data-collecting instruments, all interconnected and optimized for size, weight, and power (SWaP).

The simplistic view of bolting a hyperspectral sensor to an affordable UAV misses the obvious: other instruments are needed to carry out the mission. These include a Global Navigation Satellite System (GNSS), a high-class Internal Measuring Unit (IMU), and a Light-Detection and Ranging (LiDAR) unit.

The reality is that while not all these elements are needed for every given mission, the accuracy of the collected hyperspectral image data depends on them communicating seamlessly. Every manufacturer within the remote-sensing ecosystem understands that the UAS platform is the 'go-to' technology for the work that scientists wish to do. So while the airframes themselves are getting more affordable and lighter, so too are the payloads. Headwall's Nano-Hyperspec® is less than half the weight of the sensor it replaces while integrating previously external functionality within the box. LiDAR is a perfect complement to hyperspectral sensing because it reduces uncertainty in predictive ecosystem modeling by adding useful terrain and elevation data. Velodyne's LiDAR has migrated from a large cylindrical unit to one approaching the size and weight of a hockey puck (the VLP-16). Similar trends with GNSS and IMU units are progressing rapidly with their respective manufacturers.

One of the realities of airborne remote sensing with respect to hyperspectral data collection is variability in solar illumination. A companion instrument called a Fiber-Optic Downwelling Irradiance Sensor (FODIS) can be mounted to the upper side of a UAV to bring solar light via fiber-optic cable into the sensor. The instrument comprises a small spectrometer, a cosine diffuser, and a fiber optic cable that connects to the entrance slit of the hyperspectral sensor. FODIS continually measures the spectrum and magnitude of surrounding solar illumination, which will necessarily change with respect to flightpath or cloud cover. With captured irradiance, the accuracy of spectral reflectance on targets (the ocean, for example) is assured. The raw data is converted to irradiance, which is then combined frame-by-frame with the image data to yield a calibrated, normalized data cube.

While the instruments themselves are carefully chosen, so too are the cables that connect them. They need to exhibit fast data-transfer rates while being light and rugged. Since every gram matters, it's clear that cabling between the instruments and power supply needs to be addressed with respect to weight and placement.

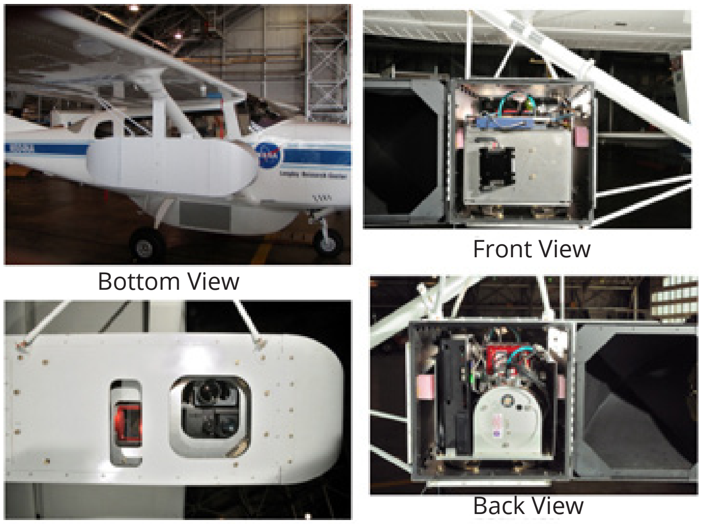
One excellent example of a multi-sensor deployment is the G-LiHT application at NASA Goddard (Greenbelt, Maryland USA). The term denotes the combination of LiDAR, Headwall's hyperspectral, and thermal to study the composition, structure, and function of terrestrial surfaces.

Hyperspectral collects narrow-band image data in the VNIR range of 400-1000nm while the thermal sensor is more broadband. As noted previously, LiDAR gives terrain detail. Collectively, these three instruments (plus a FODIS radiometer) are bringing NASA's understanding of environmental conditions to an entirely new level.

NASA outfitted its Cessna 206 with this instrument suite, using a wing-mounted pod with cutouts on the bottom as shown in Figure 6. The key initial task was to determine whether data collected from this aircraft-mounted setup would validate data collected by Earth Observing Satellites (EOS) such as Landsat 7 & 8, World View, and Earth Observer 1. Indeed, the correlation was found to be exceptionally precise, which means that NASA has a more cost-effective and flexible solution for environmental data collection than simply relying on satellite overflights.

Some of the more interesting data sets collected by G-LiHT include vegetation surface models and indices, forest canopy metrics, digital terrain models (DTM), NDVI, photochemistry analysis, pigment indexes, and much more. Within the fields of forestry, precision agriculture, geology, and environmental monitoring, this collection of data is incredibly useful in not only providing a snapshot in time but also in evaluating trends.

Since an aircraft such as a Cessna is a readily deployed and relatively economical asset, G-LiHT proves that multiple and frequent flights over a geographical area can enable trend analysis. Is there an invasive species that is encroaching or receding? Is there a disease condition that is growing or shrinking? Are irrigation and pesticide treatments helping or hurting?

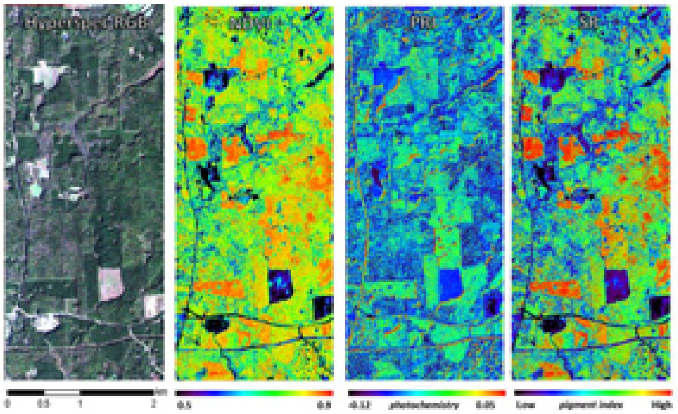


Front View

Bottom View

Back View

Figure 6: Deployment aboard Cessna 206 (courtesy NASA)



Imaging spectroscopy at 2m spatial resolution (courtesy NASA)

Indeed, the key benefit in remote sensing activity is that missions be economically feasible and frequent. If data from a low-flying Cessna validates results from LEO satellites, then it suggests that this sort of data-collection precision will eventually find its way aboard small and affordable UAS platforms as well. Clearly, the trends of instrument miniaturization and precision are leading researchers in that direction. The more affordable a completely integrated UAS gets, the more remote sensing activity can take place.

These small and efficient flying packages become more available to universities and small research laboratories, to vineyard and citrus operations, to coffee plantations, and crop scientists in economically impoverished areas. Our collective learning about the environment increases rapidly and significantly thanks to the ability of remote sensing to reach more users around the globe.

CONCLUSION

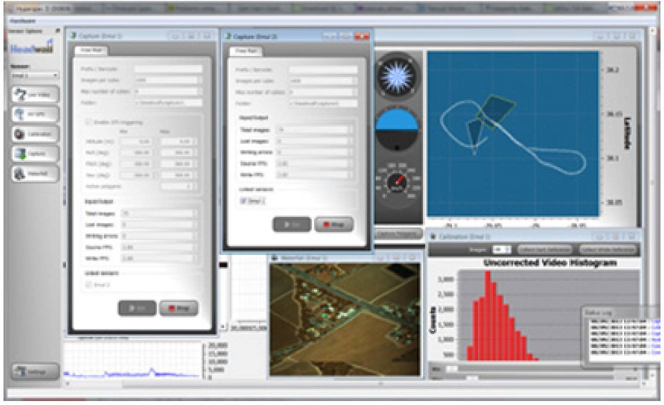
Historically, remote sensing has encompassed a wide variety of environmental learning pursuits using satellites and aircraft. These can be costly endeavors, and certainly high cost becomes an impediment to wide scale adoption. But as instruments get smaller, more affordable, and more intuitive, the ability to mount them aboard drones (UAVs) means that more users around the globe can contribute to our collective environmental learning through their own remote sensing missions.

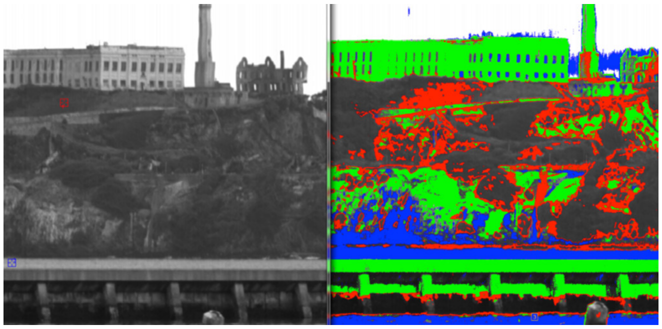
The UAS (unmanned airborne system) is common description for a UAV outfitted with remote sensing instruments, which can comprise hyperspectral, LiDAR, thermal, or any combination thereof. Since these instruments are each measuring different but complementary things, software is key to making sure the collected data from each device is normalized and corrected so that the overall picture is accurate and free of artifacts and distortion. The software can actually be more of a differentiator than the hardware, since valuable mission-critical tasks are largely software-driven.

Integrating hyperspectral with airborne platforms is a challenge that Headwall can help manage, which reduces time-to-flight and overall cost while making sure the entire flight package is optimized for the mission. Since there are many choices for UAVs and payloads, understanding the variables and tradeoffs is something Headwall excels at.

Overall, the marriage between small, affordable UAS platforms and hyperspectral imaging sensors from Headwall is a perfect one. More missions can be undertaken since these airborne '*systems*' are more affordable and portable than ever. Trend analysis is more thorough and actions are more precise, whether for crop science or agricultural speciation.

Hyperspec® III *software for airborne applications*





Hyperspectral image taken of Alcatraz in San Francisco using Headwall's Hyperspec® VNIR (400-1000nm) sensor

CONTACT INFORMATION

Headwall Photonics, Inc.
601 River Street, Fitchburg, MA 01420
+978- 353 - 4100
www.headwallphotonics.com
e-mail: information@headwallphotonics.com