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Hyperspectral Imaging

For Remote Sensing Application

Manufactured by

Headwall

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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.

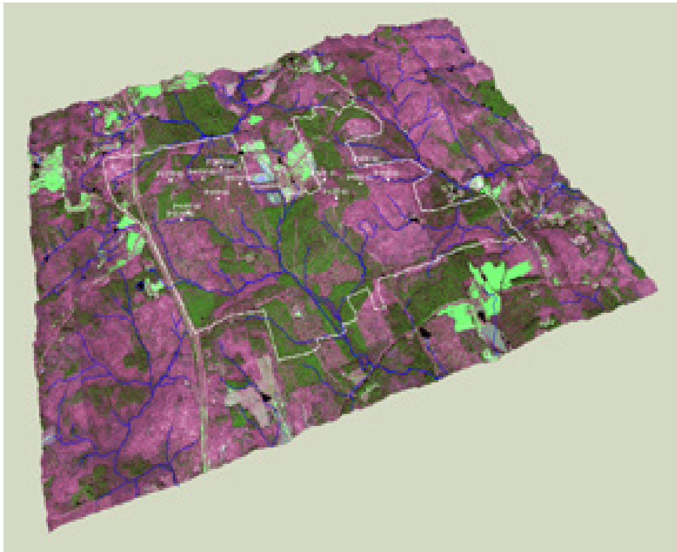
The integration process can be involved, combining high-performance hyperspectral sensors along with application-specific software that allows for meaningful data processing and interpretation. Because remote sensing is as much about software as it is about hardware, this paper discusses the issues and 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 (400-1000nm) through the shortwave infrared (900-2500nm). 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 (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). This provides a full spectrum of data for every pixel in the field of view. 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).

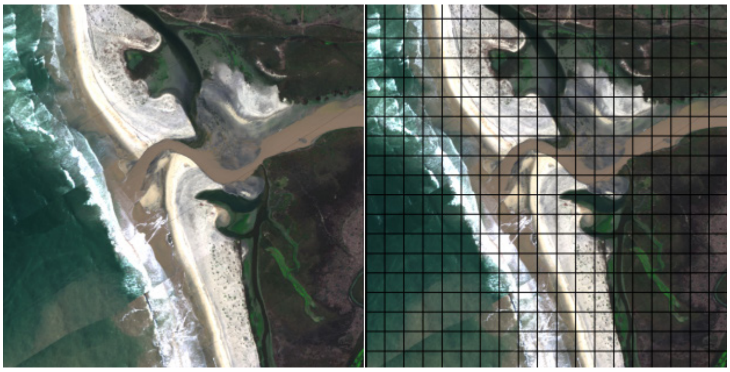


Figure 1: Airborne scene arranged as a grid of CCD pixels

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.

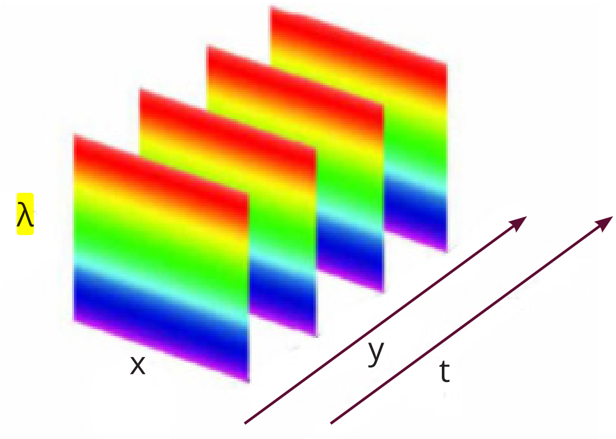


Figure 2: Pushbroom Spectral Line Scanning

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.

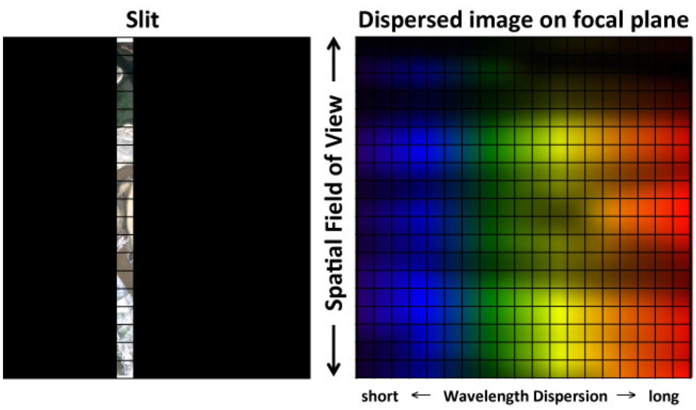
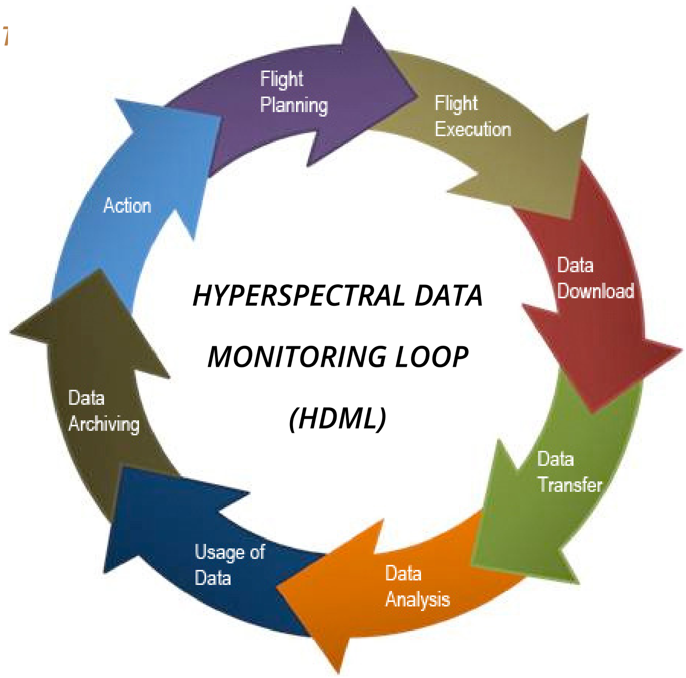


Figure 3: Slit Image and Disbursed

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 Hyperspectral Data Monitoring Loop (HDML) for a

DIFFRACTION GRATINGS

-- https://www.shimadzu.com/opt/guide/diffraction/02.html

Diffraction gratings are optical components critical for a wide variety of applications including spectrometers, other analytical instruments, telecommunications, and laser systems. Gratings contain a microscopic and periodic groove structure - which splits incident light into multiple beam paths through diffraction, causing light of different wavelengths to propagate in different directions. This makes the function of diffraction gratings similar to that of dispersion prisms, although the prism separates wavelengths through wavelength-dependent refraction instead of diffraction

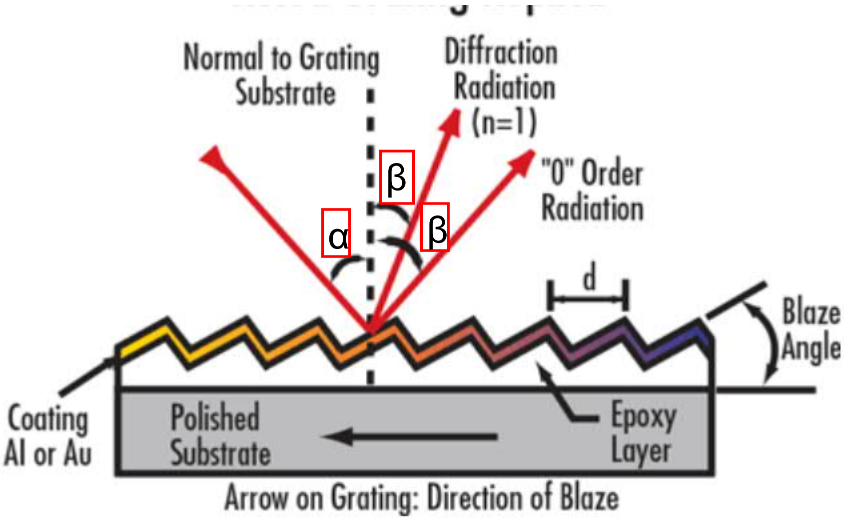


Figure 3: *Ruled diffraction gratings typically feature triangular grooves.*

Light incident on a grating is diffracted following the grating equation:

$$n\lambda=d(\sin\alpha+\sin\beta)$$

n is an integer value describing the diffraction (or spectral) order,
λ is the light's wavelength,
d is the spacing between grooves on the grating,
α is the incident angle of light, and
β is the diffracted angle of light leaving the grating.
Constructive interference of different diffractive wavefronts occurs at integer multiples of the wavelength, which is why "n" appears in Equation 1.
m defines the diffraction orders, where diffracted angles n = 1 are considered to be "1st order" diffraction, angles where n = 2 are considered to be "2nd order" diffraction, and so on. If n=0, light is either directly reflected off the grating or transmitted through it, depending on if it is a reflection or transmission grating, and this light is considered the "0 order" diffraction.

TRANSMISSIVE GRATING

https://www.imt.kit.edu/hyper-spectral-imaging.php

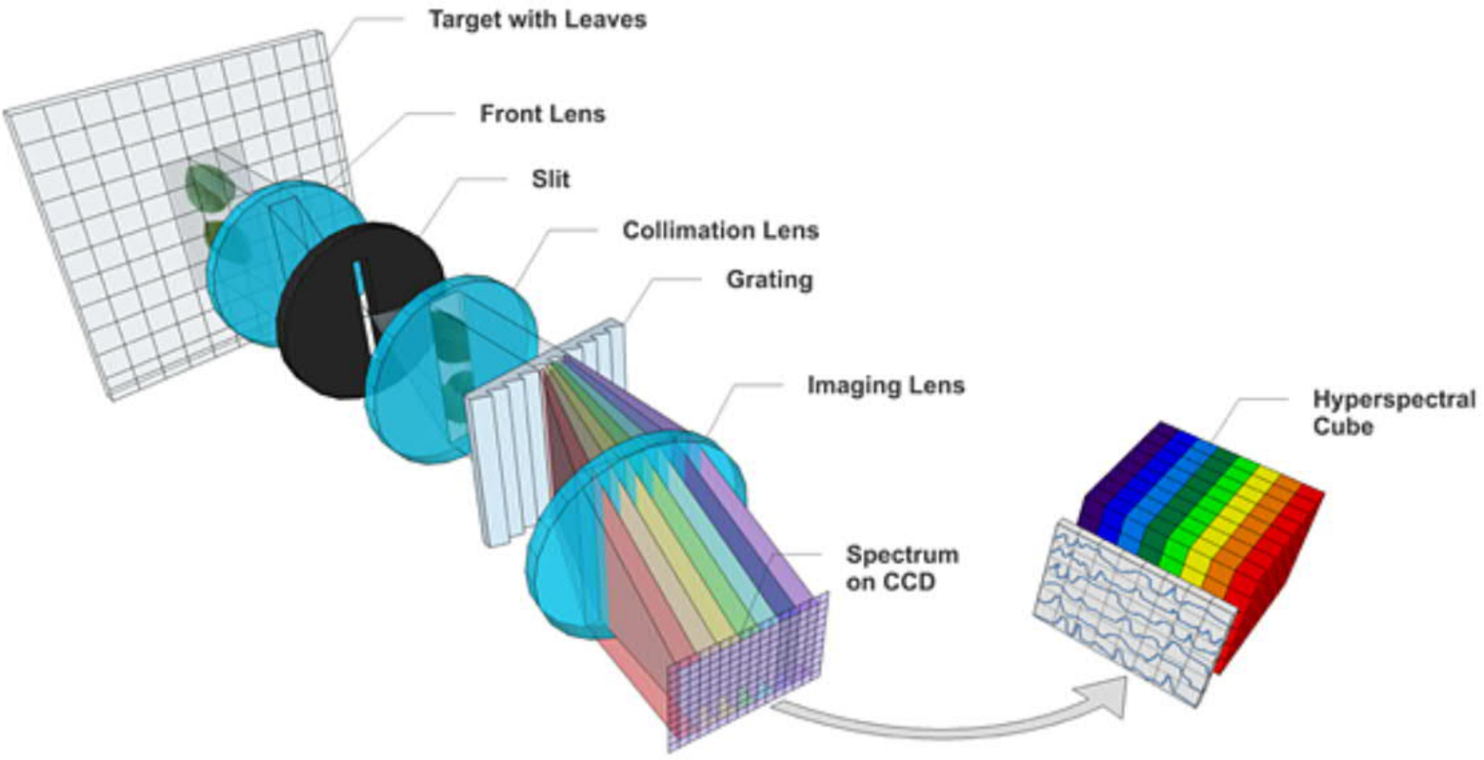


Figure 1: Schematic representation of the pushbroom hyperspectral imaging technique.

REFLECTIVE GRATINGS

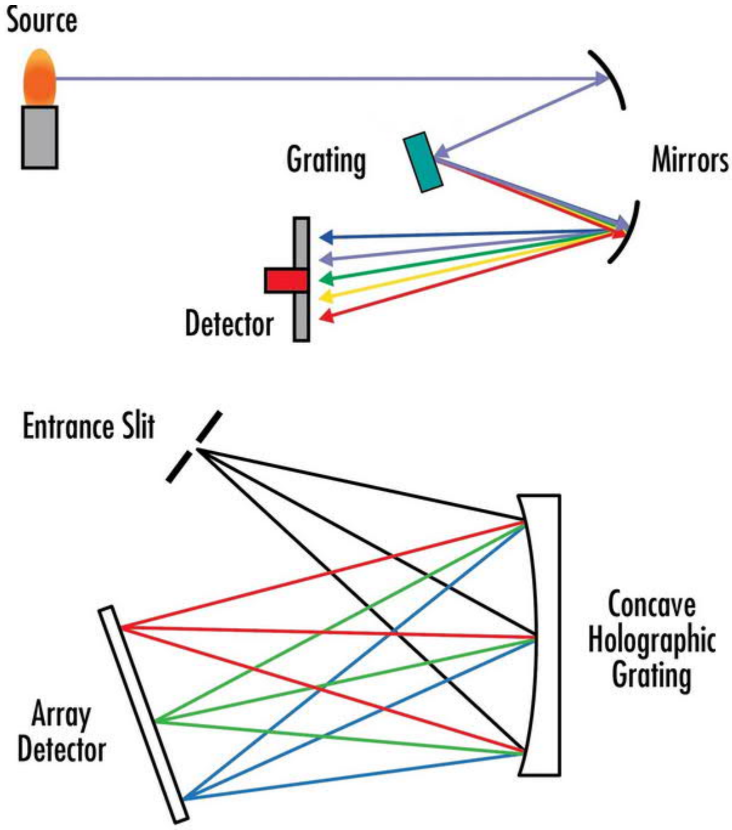


Figure 6: *Both plane grating spectrographs (top) and concave grating spectrographs (bottom) use stationary gratings to separate incident wavelengths into different pixels on a detector array.*