

# Information Across the SPECTRUM

With careful optical design, hyperspectral imaging can expand to commercial applications.

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Advancements in optical sensor technology, coupled with the availability of optics with expanded wavelength ranges, have cleared the way for the commercialization of hyperspectral imaging. Hyperspectral remote sensing provides a non-contact method for acquiring spectral data for each pixel in the visual image of a sample. In its simplest form, a hyperspectral imager involves an objective to gather the image, a dispersive element to split the image into spectral “channels,” and a detector to capture the resultant images.

Early airborne or space-based systems used line-array detectors in a horizontal scan pattern (“whisk-broom” imaging) to image a geographic swath on the ground. More common today are “push-broom” designs, which incorporate stationary area-array detectors. In push-broom designs, the motion of the platform effectively scans the spectrograph slit over the swath to be imaged, reducing instrument complexity and cost by eliminating the need for moving parts (see figure 1). A frame grabber then builds a 2-D (X, Y) visual image at each spectral channel, which proves the third dimension, that of wavelength  $\lambda$ . This process yields a 3-D hyperspectral data cube that can be viewed as an entire image at any wavelength or as a full spectrum of any individual pixel in the image. Such a data cube provides quantifiable, chemical-based spectral information of the target sample.

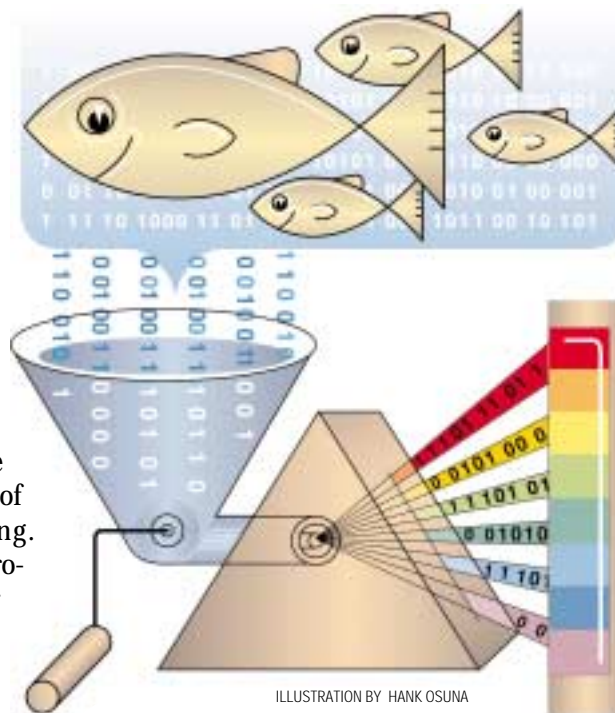


ILLUSTRATION BY HANK OSUNA

Since hyperspectral remote-sensing instruments require expensive launch platforms, early deployments were primarily government-based. Constrained by cost/benefit perceptions and technological limitations, hyperspectral imaging has been slow to take off in the commercial sector. This article addresses the technical aspects of enabling the use of this technology in a greater range of applications.

## Getting Practical

Current data suggests that remote sensing users demand spatial resolutions of better than 1 m; state-of-the-art imagers can achieve resolutions of 300 mm or better. To match this kind of resolution capability with high data throughput, clients are using hyperspectral imagers that can sample from tens to thousands of spectral channels.

Typical parameters for a hyperspectral imager include spectral range, spatial resolution, spectral resolution, and acquisition rate. It is important to note that each channel generates a spatial image that must be evaluated, leading to the creation of extremely large data cubes. Consider industrial process monitoring for a moving-web application (such as textile manufacturing or paper production) that has characteristic spectral features in the visible (400 to 750 nm) and near IR (NIR; 750 to 1700 nm) spectral regions. Assume a moving web of paper or textile approximately 6.6 m wide, moving at

thousands of feet per minute. Traditional approaches, driven primarily by cost considerations, have involved single-point sensors that only measure a small percentage of the web.

A typical hyperspectral sensor might provide 12.9-mm spatial resolution over 512 spectral channels, with a spectral resolution of 1 nm in the visible or NIR range. The number of spatial channels, expressed as an integer, is given by the image field of view divided by instrument spatial resolution. Returning to our example above, in the absence of data compression techniques, such an imager would produce roughly 262,144 data points per frame.

This gives us a simple method for evaluating design trade-offs and the amount of data for analysis. We can express the number of data points per unit area  $N_d$  as

$$N_d = (\Sigma [L_d (\text{max}) - L_d (\text{min})] / R_s) S_c$$

where  $S_c$  is an integer number of spatial channels,  $L_d$  is spectral range in nanometers, and  $R_s$  is spectral resolution in nanometers.

The spectrum for each spatial pixel provides a tool for sample identification through analysis of the spectrum over the wavelength evaluated. One can observe how each spectral plot offers a means to spatially resolve the chemical composition of the sample under test.

### The Offner Spectrograph

Although the above summary describes the design tradeoff for image and data throughput requirements, one area of major concern for instrument integrators is the overall package size of the imaging system. A decade ago, the total amount of imaging data being captured, coupled with the extensive spectral analysis required, presented a challenge for existing computer system resources. Today, imaging systems require innovative designs to improve the total package-size requirements while optimizing spectral resolution and spatial channel count. Such designs are compatible with off-the-shelf computing systems.

We developed a design based on the Offner spectrograph, which provides an effective solution for hyperspectral imagers. The starting point for the design is a pair of concentric spheres, as a result of which the system is free of third-order aberrations. The configuration offers

the advantage of high image quality, low distortion, and low  $f$ -number, making it ideal for spectral imaging. The field of the spectrometer is defined by an entrance slit, the width and height of which match the detector array and pixel size, respectively.

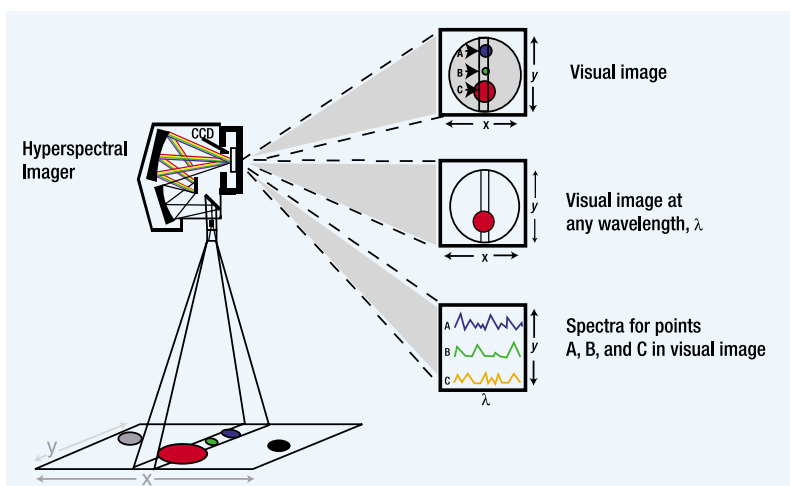
The symmetry of the optical design provides low-distortion, unity magnification, and a relay with the aperture stop on the second surface; the secondary mirror typically incorporates the dispersive grating. To compensate for higher-order astigmatism and the asymmetry introduced by the grating dispersion, designers must optimize the system using the radii, spacings, and tilts as variables.

The off-axis Offner spectrograph design, based on push-broom scanning, reduces aberration to improve the image quality of the system. Typical push-broom systems align with the spatial image of the scene imaged along the columns, while the spectra are dispersed along each row. The central chief rays of each ray bundle are parallel in both the tangential (spatial) and the sagittal (spectral planes), signifying a double-telecentric system with the entrance and exit pupils at infinity. This geometry should be taken into consideration when specifying a lens or telescope to image onto the slit, to prevent vignetting. Although most C-mount and F-mount lenses are non-telecentric, the vignetting is not dramatic except for fast, wide-field lenses or under-filled pupils.

Since the unit is constructed entirely from reflective optics, it can accommodate any wavelength band from the UV to the long-wave IR spectral regions without suffering the Fresnel losses associated with broadband coatings on conventional lenses. Reflective optics also suffer from less scatter, which allows the instrument to detect weak signals in an environment with higher background noise. The convex diffraction grating can also be tuned during manufacturing to

provide the necessary chromatic dispersion and peak efficiency to match most camera formats currently available. Unlike filter or scanning Fourier-transform IR spectrometers, a grating spectrometer obtains the spectra of each point in a line simultaneously, thus avoiding the mixing of spectral signatures in temporally changing scenes.

To obtain the maximum amount of sample information from the light available, optical system integrators for hyperspectral imagers must focus on



**Figure 1** A hyperspectral imager uses a dispersive element to image a scene (top) over discrete spectral channels (middle) to produce spectra for each pixel (bottom).

ATTRIBUTE	FUNCTION	ADVANTAGE
Aberration-corrected gratings in Offner configuration	Wavelength discrimination	High-resolution imaging
	Near diffraction-limited imaging	Improved optical precision
	Wide spectral range	Multi-application design
Holographic gratings	High signal-to-noise ration	application-specific performance
"Tight" optical system design	low field distortion	Large field of view
f/2 aperture	high system throughput	Faster image acquisition times Higher sensitivity for low-light applications
Long aperture slit	Push-broom technique High channel count	Larger area for sampling Enhanced sensor field of view
Large back focal length	Open architecture	Design options for camera flexibility

application-specific requirements. Original equipment manufacturers in spectrometer design have validated the various tools and expertise in wavelength management through use of differing technologies. The wavelength-management technology used in the Offner configuration takes advantage of the dispersion created by the grating equation,  $d(\sin \alpha - \sin \beta) = m\lambda$ , where  $d$  is the groove spacing,  $\alpha$  is the angle of incidence,  $\beta$  is the diffraction angle,  $m$  is an integer, and  $\lambda$  is the wavelength. The dispersive implementation by use of grating technology allows the optical sensor designers to demultiplex discrete wavelengths from a common input source. This allows the use of a variety of off-the-shelf components, which reduces project risk and time to market.

Design tradeoffs for hyperspectral solutions should include consideration of a number of application-specific optical design features (see table). Through modeling techniques, optical designers can optimize component parameters to create systems that achieve the total optical sensor capabilities required to sense the spectral ranges with appropriate resolution to identify "finger-printed" compound signatures (see table).

Remote-sensing pioneer Alex Goetz, co-founder of Analytical Spectral Devices (Boulder, CO), sees significant benefits for process manufacturing companies. "With the development of this technology, including high-speed signal processing, there now exists a great opportunity to utilize hyperspectral sensing up close in a variety of industrial applications including process control."

Commercial applications for hyperspectral imaging include industrial processing, environmental management, and biomedicine. Jack Buckley of the Massachusetts Division of Fisheries and Wildlife sees hyperspectral imaging as an important technology for the investigation of environmental change on plant and animal species. "Remote sensing and

hyperspectral imaging allow for advanced capabilities for the visualization and optical characterization of biological systems," he says.

The medical and life science industry is already reaping the benefits of hyperspectral imaging. Richard Gomez, director of the hyperspectral imaging center at George Mason University (Fairfax, VA), notes the effectiveness of hyperspectral microarray scanners for dealing with slide fluorescence from impurities, improving stray light rejection. The technology has clinical potential as well, including cancer diagnostics and retinal imaging to detect diseases such as age-related macular degeneration, diabetic retinopathy, and glaucoma. "Data obtained from high-resolution spectral imaging provides new information to diagnose, classify, and treat these retinal disorders," Gomez says. "The potential applications of hyperspectral imaging to medical imaging and the life sciences are enormous. I foresee the number of applications in these areas clearly outnumbering the applications involving the remote sensing of the earth." oe

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#### Further Reading

1. *Headwall Photonics U.S. Patent 6,266,140.*
2. *The 10-Year Remote Sensing Industry Analysis, Jim Plasker, ASPRS (2002).*
3. *Hyperspectral Imagery Market Forecast, 2000–2005, Aerospace Report No. TOR-2001(8511)-1.*