INDUSTRIAL TRENDS

Directions in Environmental Spectroscopy

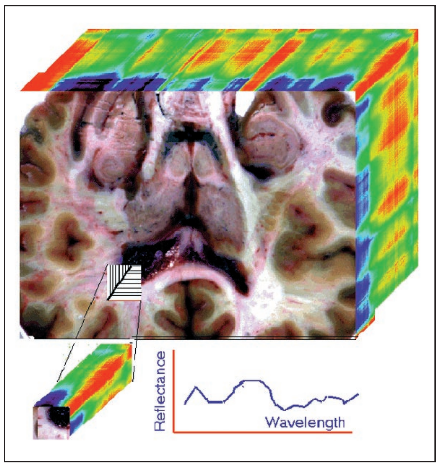
Remote Sensing

Hyperspectral imaging

It is sometimes necessary to analyze and establish the local distribution of properties of interest in a sample that is spatially nonhomogeneous. With conventional spectroscopy one can either tediously scan the entire sample with a focused optical probe or obtain average properties over the entire sample using a single measurement. This is where hyperspectral imaging may prove useful. First, it is helpful to do away with the hype. There is nothing hyper about the technique; *imaging spectroscopy* would do fine as a name. Yet the name is used today to differentiate between various nuances of the technique. A brief historical background will explain.

When in the early 1960s satellites started circling and acquiring photographs of Earth, imaging became a tool for many Earth studies. As in conventional photography, the gray level in a black-and-white image indicates differences in optical properties and thus lends itself for differentiation of materials, etc. Better yet, imaging the Earth through several carefully selected color filters was found to greatly enhance our ability to identify specific crops and study the atmosphere, oceans, the solid earth, the biosphere, and more. This defines the birth of *multispectral* imaging dating back to the early LandSat satellites. Spaceborne sensors such as the Thematic Mapper (LandSat) or the French SPOT satellite produce coregistered images of Earth in several discrete colors, or spectral bands.

Since multispectral imagery in a handful of broad noncontiguous spectral bands facilitated better understanding of our environment, why not extend this concept to a few hundred narrow bands? Thus, spectroscopy for remote sensing, or hyperspectral imaging, was born in the early 1980s with the Airborne Imaging Spectrometer and later on with the Advanced Visible and InfraRed Imaging Spectrometer (AVIRIS), both at NASA/JPL. The jump from multi- to hyperspectral imaging for remote sensing required a different instrument technology. And, although imaging Earth in seven spectrally noncontiguous colors may not be considered spectroscopy, no one can argue with 200+ contiguous bands at approximately 10-nm resolution. But human craving for more never stops. So we are now into *ultraspectral* imaging, with sensors such as JPL's Atmospheric Emission Spectrometer (AES), comprising four separate FT-IR devices with common optics, each with four detectors to spatially resolve the scene. The AES produces thousands of bands at better than 1 cm^{-1} resolution over a broad infrared spectral range. The first spaceborne hyperspectral imager was launched in 1997 on board NASA's Lewis satellite. It contained 384 bands covering the range from 0.4 to 2.5 μm (in what is called VNIR — visible to near-infrared, and SWIR — shortwave IR). Unfortunately, the satellite ran into a control problem, lost power, and fell out of orbit a month later.



Brain activity mapping using hyperspectral imaging. Data courtesy of Drs. G. Bearman of JPL and A. Toga of UCLA.

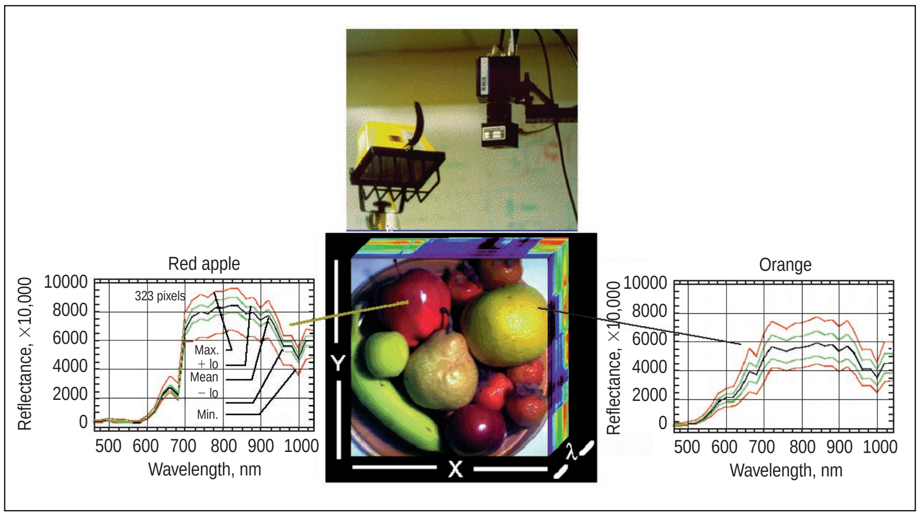
PHOTODISC, INC.

Several experimental airborne hyperspectral imagers (HSI) are operated by Department of Defense (DOD) agencies, including the HYDICE (also VNIR/SWIR) and SEBASS (MWIR — midwave IR, roughly 3 to 5 μm, and LWIR — long-wave IR, sometimes called thermal IR because the Planck radiation emitted by objects at ambient temperature of 300 K peaks in the range, roughly 8 to 12 μm). The spectral ranges used by these airborne sensors correspond to the atmospheric windows where atmospheric gases, mainly H_2O and CO_2 exhibit weak spectral features. Even in these windows the atmospheric scattering, absorption, and emission introduce considerable artifacts for which the imagery must be corrected. Two new DOD spaceborne HSI are scheduled for launch around 2000, the Coastal Ocean Imaging Spectrometer (COIS, VNIR/SWIR), and Warfighter (VNIR/SWIR, plus a multispectral MWIR). A comprehensive list and links to instrument-related web sites can be accessed from reference 1.

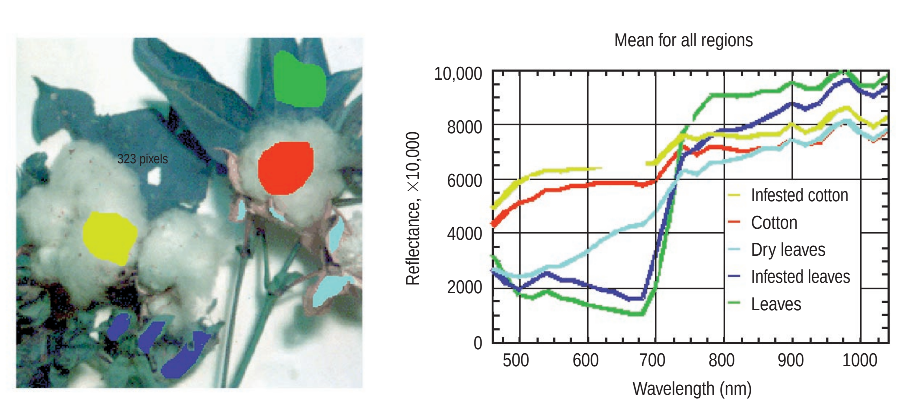
If readers think that this all starts and ends with space and remote sensing, they should withhold judgment. The technology is literally coming down to Earth — and to their own labs, for that matter. In addition, combining spatial with spectral analyses may have some interesting advantages.

TECHNICAL BACKGROUND

The data product or output of a hyperspectral sensor is a stack of images of a scene, or a sample, acquired in contiguous bands over a spectral range and is often referred to as the *image cube*. This cube has two spatial dimensions, and the third dimension is wavelength; radiant intensity is recorded at each point in the cube. There are several methods for acquiring hyperspectral images.



An image cube contains radiant intensity at each x-y-λ location. A liquid crystal tunable filter is used in conjunction with a CCD camera for this lab work.



Analysis of infested and healthy cotton plants reveals significant spectral differences, thus allowing automated inspection.

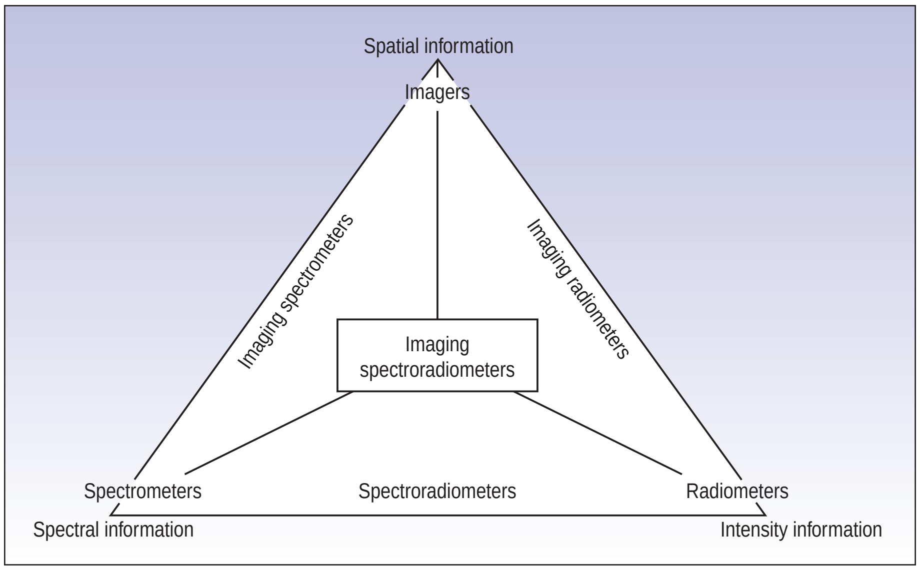
In a laboratory or other stationary applications, a science-grade digital camera, combined with an electronically tunable filter (ETF), act as a slitless spectrometer. ETFs transmit radiation in a narrow spectral range that can be selected electronically and tuned in milliseconds. Commercial ETFs are made of liquid crystal or acousto-optical materials and they operate over the VNIR to MWIR range. An image is acquired, and the filter is tuned to the next band to acquire the next image, building up the image cube one band at the time (i.e., complete x-y at one λ). Because the transmittance of the filter strongly depends on the wavelength, the exposure time of the camera has to be controlled to maximize the dynamic range of the system in each band. The images are then corrected for the variabilities in exposure time, spectral characteristics of the filter, sensor quantum efficiency, optical system, and illumination conditions.

In remote sensing applications, the fore-optics image a narrow strip of the scene in the cross-track y direction onto an entrance slit. A dispersive element (grating or prism) produces the spectra of all points at the slit. The focal plane contains a two dimensional detector array that records the multiple images of the entrance slit that are projected at contiguous bands. One frame corresponds to a slice of the image cube in the y-λ direction. To minimize image distortions, the spectrometer must be free of astigmatism and coma; torroidal gratings are typically required. The motion of the airplane or satellite is used to cover the spatial data in the along-track x direction for imaging the next strip of the scene. This approach is called pushbroom. In a whiskbroom system, only a linear detector array is required. A scanner is used to project an image of the strip of scene in the cross-track y direction, one pixel at a time. A spectrometer disperses the incoming radiation, forming multiple images of the pixel, at all wavelengths, on the linear array. Again, the forward motion is used for the along-track imaging. Other techniques are also possible (more details are found on-line in the *Hyperspectrum Newsletter* also accessed from reference 1).

DATA EXPLOITATION

Typical objectives of exploitation techniques are to

- classify and segment the image into areas exhibiting similar spectral properties
- search for areas that exhibit a particular spectral signature of interest



Hyperspectral imaging systems capture spectral, spatial, and radiometric information (2).

- determine the composition of a mixture of material within a spatial resolution (an image pixel)
- locate signatures of unresolved objects (those that are spatially smaller than a single pixel).

Image cubes are very large files; a 256 × 256 pixel scene, at 64 bands produces 4.2 Mpixels. When digitized to 10 or 12 bits, the file size is 8.4 Mbytes. Airborne image cubes are often more than 200 Mbytes in size. Handling, displaying, visualizing, and processing such files requires efficient programming tools.

The algorithms used for analysis are variations on the common chemometric tools used in conventional spectroscopy. When combined with spatial image processing techniques, one can obtain a powerful tool for complete sample analysis. Many general-purpose analytical techniques are statistical in nature and use principal component analysis, parametric analysis, library match, etc. More complex techniques use phenomenology models and optimization techniques to minimize a mismatch function between model predictions and sensor data.

APPLICATIONS

Earth remote sensing using the AVIRIS was already mentioned, with geology (e.g., mineral identification) and forestry (e.g., stress detection) among the prominent usages. The U.S. Geological Survey has had great success in using the technology and validating the results with ground-truth measurements. The military hopes to use hyperspectral systems for applications ranging from terrain classification to detection of camouflaged targets.

During the Cold War the U.S. government was able to predict crop yields in the Soviet Union and Eastern Bloc using multispectral imaging (yet it sometimes failed in predicting yields in the United States, resulting in sales commitments that created shortages at home). Today's goals include hot areas such as precision farming with the objective of early detection of localized problems in crops that can be corrected by local treatment. Examples include irrigation- or fertilization-related stress or pest management. Early remote detection can lead to eradication of pests or disease by local application of remedies before an entire field is damaged, necessitating aerial spraying of costly and environmentally unsafe insecticide. The major hindrance to commercialization is the cost of data products and the lack of capability for fast distribution of specific data products to millions of growers.

Environmental monitoring is another hot topic. The Thermal InfraRed Imaging Spectrometer is a unique prototype of an airborne passive sensor designed to detect hazardous organic compounds in the atmosphere. It will monitor the upwelling radiation from the background terrain and then, using an inverse problem formulation (with atmospheric propagation computer models such as Modtran), it will retrieve the composition of the atmosphere, including any pollutant plumes. Applications here include tracking hazardous spills during derailment, detecting plant fires, stack remote monitoring, and detecting chemical warfare compounds, illicit drugs manufacturing facilities, etc.

The application of the technology to online inspection is also straightforward. For example, imaging spectroscopy can readily help detect bruises during fruit packing; inspect tomatoes, rice grains, seeds, or meats; or determine whether food products are sufficiently cooked.

Spectroradiometrically accurate color measurements and color uniformity determination is another important area. Image cubes of a sample can accurately be converted to the CIE color space, pixel by pixel, for quality inspection in manufacturing and color matching of parts.

In medical applications, combined with active laser excitation, it is possible to map fluorescence of biological tissue. The fact that malignant and benign cells exhibit different autofluorescent signatures (or fluorescence due to differential retention of dyes) can be used in cancer detection. Moreover, as the biochemistry of cells changes because of changed activity level, their spectral signatures also change, allowing the imaging and creation of activity maps.

SUMMARY

Hyperspectral imaging has passed the point of scientific curiosity and is now under active evaluation by researchers in dozens of fields.

REFERENCES

(1) *http://www.techexpo.com/opto-knowledge.*
(2) Charles Elachi, *Introduction to the Physics and Techniques of Remote Sensing* (Wiley Interscience, New York, 1987).

FURTHER READING

• *Remote Sensing of Environment. Vol. 24, No. 1. Special Issue on Imaging Spectroscopy* (Elsevier, Amsterdam, 1988).
• More than a dozen volumes of proceedings of the International Society for Optical Engineering (SPIE, Bellingham, WA) since 1981, on the topics of imaging spectrometry, imaging spectroscopy, and algorithms for multispectral and hyperspectral imaging.

Nahum Gat
Opto-Knowledge Systems, Inc.
4030 Spencer Street, Suite 108
Torrance, CA 90503◆