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REAL-TIME MULTI- AND HYPER-SPECTRAL IMAGING FOR REMOTE SENSING AND MACHINE VISION: AN OVERVIEW

by
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Summary:
The effectiveness of remote sensing applications including precision agriculture or vision applications such as inspection can be greatly enhanced by combining spectral with the conventional spatial analysis techniques. With spectral data of sufficient resolution it is possible to better distinguish, differentiate, classify, or recognize more subtle features in the imagery and also detect spatially unresolved features. To acquire and properly exploit spectral imagery various new instruments and sensors are needed, and novel image processing algorithms are required. This paper reviews some latest developments in this area of nonliteral image exploitation.

Keywords:
Remote-sensing; machine-vision; real-time; hyperspectral; multispectral; imaging-spectroscopy; precision-agriculture.

1.0 Introduction

Spectral analysis when combined with spatial data adds a significant amount of information that can be used to improve image exploitation and interpretation. The application of imaging spectroscopy has proven very useful for remote sensing as well as manufacturing and laboratory analysis. To combine spectral information with spatial imagery, the sensor or camera has to be able to create images within the user defined narrow spectral bands rather than wide-band imagery that conventional cameras produce. Such hyperspectral sensors, for instance, produce what is commonly referred to as "image cubes" or a stack often containing hundreds of images each in a narrow spectral band. An example of a 32 bands image cube showing several common colored objects is shown in Fig. 1, and several individual images out of the stack in Fig.2. The spectral bands in this cube correspond to the range from 400 to 710 nm in 10 nm increments with about 10 nm bandwidth.

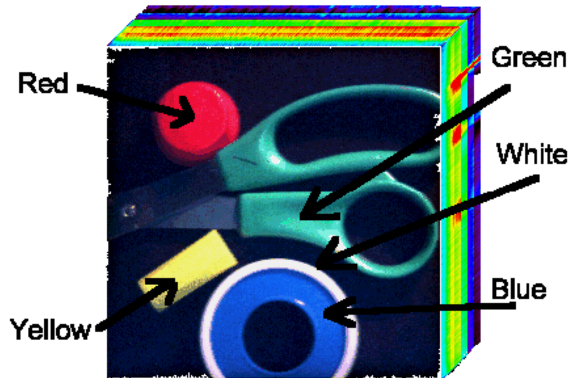


Figure 1. A stack of 32 images of several colored common objects grabbed with OKSI's LCTF camera from 400 to 710 nm.

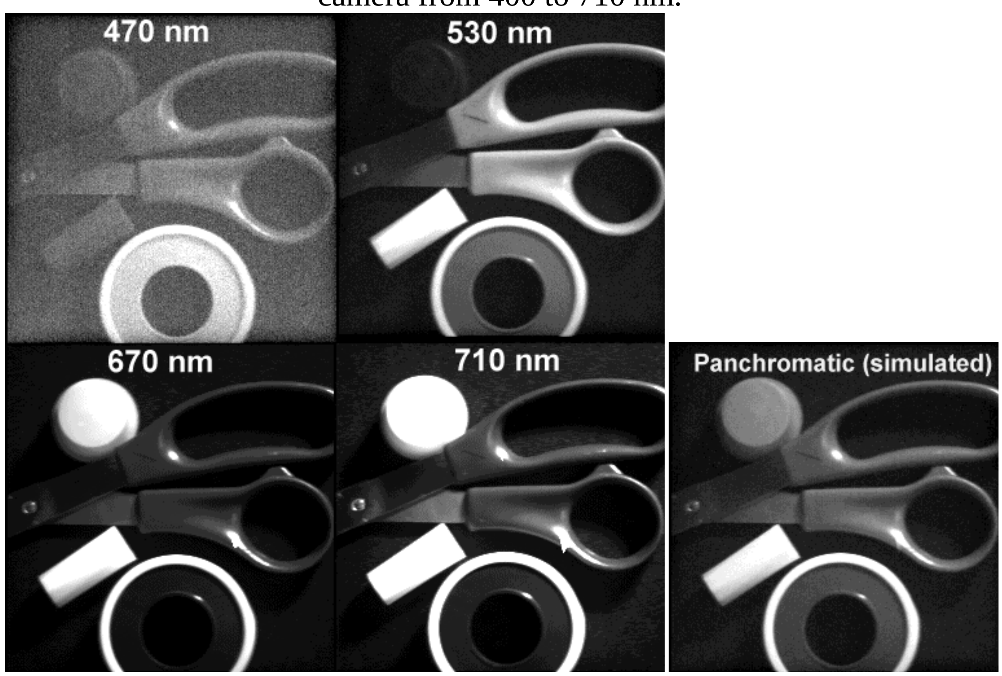


Figure 2: (Left) four bands (blue, green, red and near infrared) out of the image cube in Fig. 1, and (right) the arithmetic mean image of all 32 bands.

One can see that the colored objects have a different appearance in various images. This fundamental feature is the basis for imaging spectroscopy allowing the detection of objects or subtle features in the image, and even the detection of small features that are spatially unresolved. The latter is possible due to the contribution of such minute features to the spectrum of the pixel in which they reside.

The spectra, depicted in Fig. 3, were extracted from individual pixels in the image cube in Fig. 1, at the locations of the various colored objects. It is noted that there are 32 spectral bands corresponding to the number of images in the stack, or image cube. The band numbers on the *x*-axis corresponds to spectral bands starting at 400 nm and increasing in 10 nm increments to 710 nm. These spectra are from the raw image cube uncorrected yet for gain, offset, or integration time. Nevertheless, one can see that the peaks of the spectral signatures of the blue, green and red objects (that are marked up in this black and white rendition of the paper) correspond to the expected location.

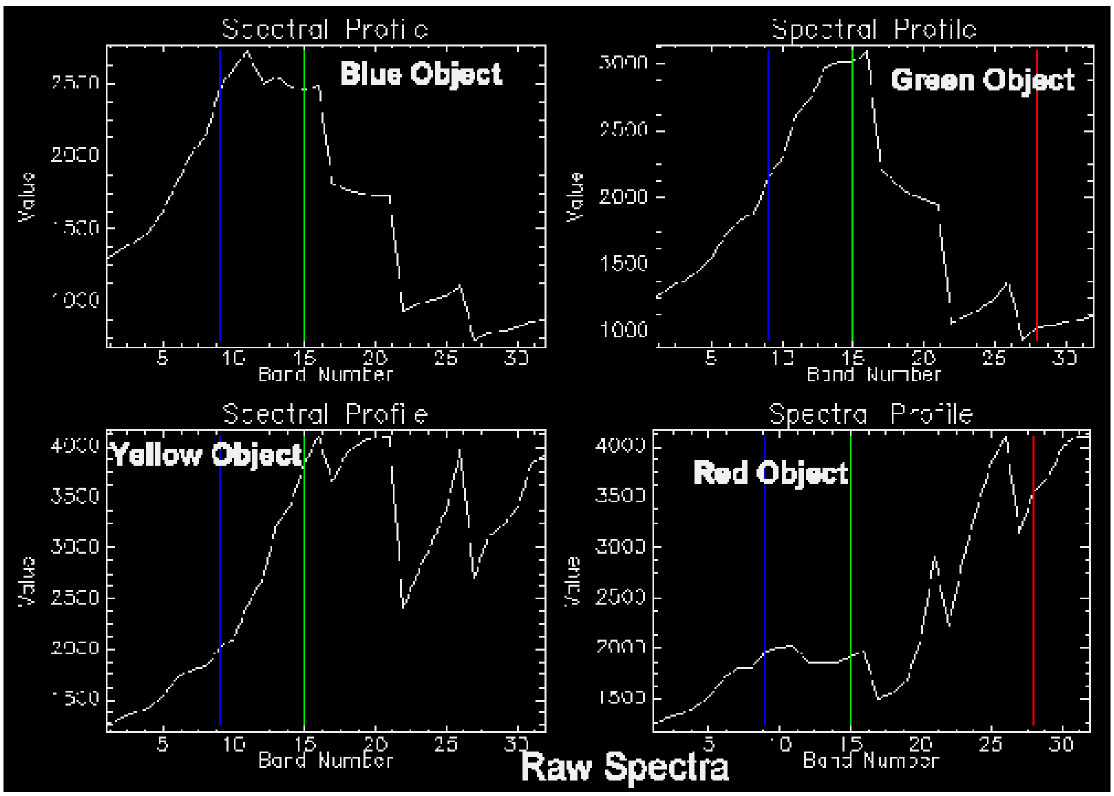


Figure 3. Sample spectra of the objects shown in Fig. 1.

Examples of applications [1] include precision agriculture where remote sensing with hyperspectral imagery can help detect very early on vegetation stress due to pest insects, water depravation, nutrients imbalance, etc. Similarly, such techniques can be used for food, fruits and vegetables inspection.

2.0 Sensors

Imaging spectroscopy data acquisition requires special types of sensors as depicted in Fig. 4. Such sensors capture simultaneously the spatial, radiometric and spectral information contained in the scene.

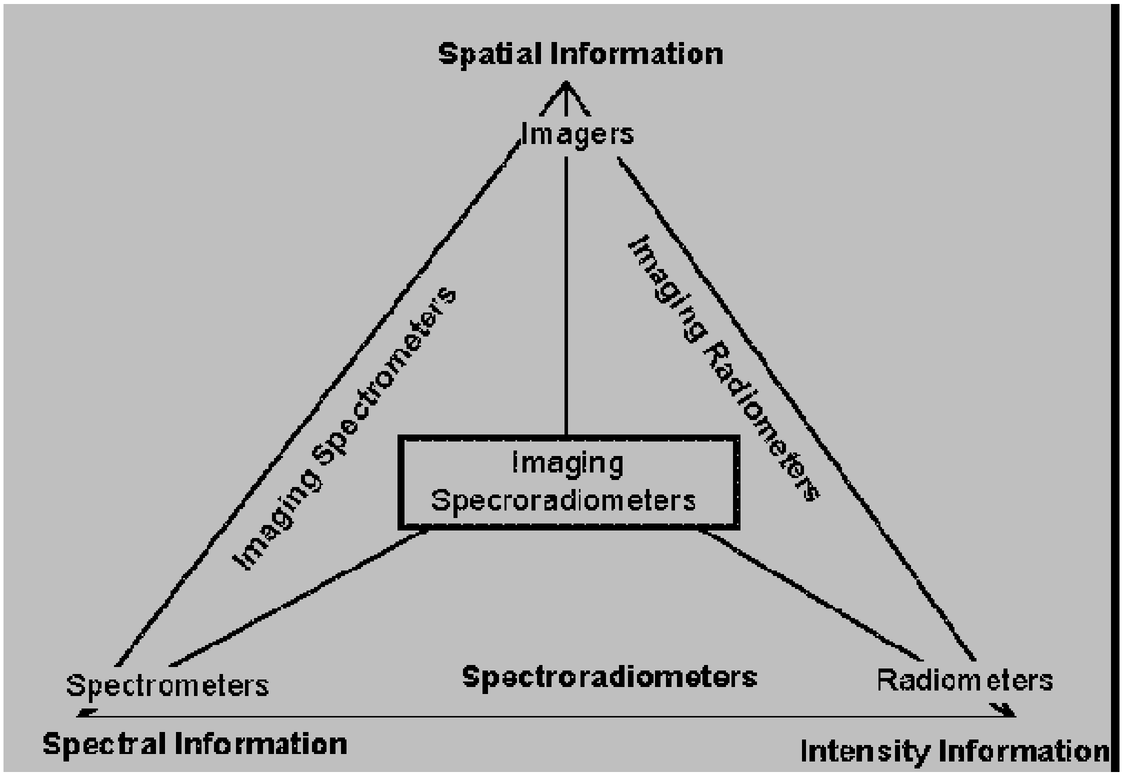


Figure 4. Relationships between various imaging and radiometric measuring systems (adapted from Elachi [2]).

2.1 Air & Space Borne Sensors

There are several operational multi-, hyper-, or ultra-spectral sensors; most are one of a kind and are used for application development [3]. OKSI is developing an airborne system called the Thermal Infrared Imaging Spectrometer (TIRIS) that operates in the long-wave infrared (LWIR), or 7.5 to 14.0 µm spectral range, Fig. 5. This range is appropriate for the detection of various organic compounds in the atmosphere [4] (Fig. 6) and also for thermal and emissivity analysis of the scene. This specific spectral range is one of the so called atmospheric windows in which the atmospheric water vapor and carbon dioxide spectra are relatively inactive. However, because of the variability of the water column in the atmosphere, spectral imagery requires corrections for atmospheric interference, in particular if precision data are required. Further discussion of atmospheric corrections is found in Section 3 on algorithms.

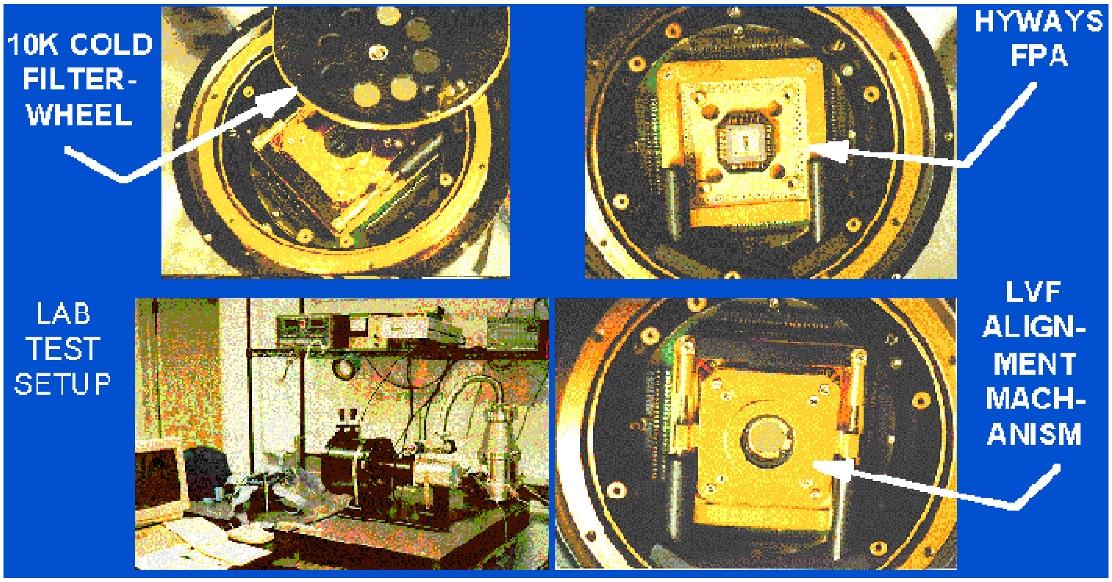


Figure 5. The TIRIS Sensor details.

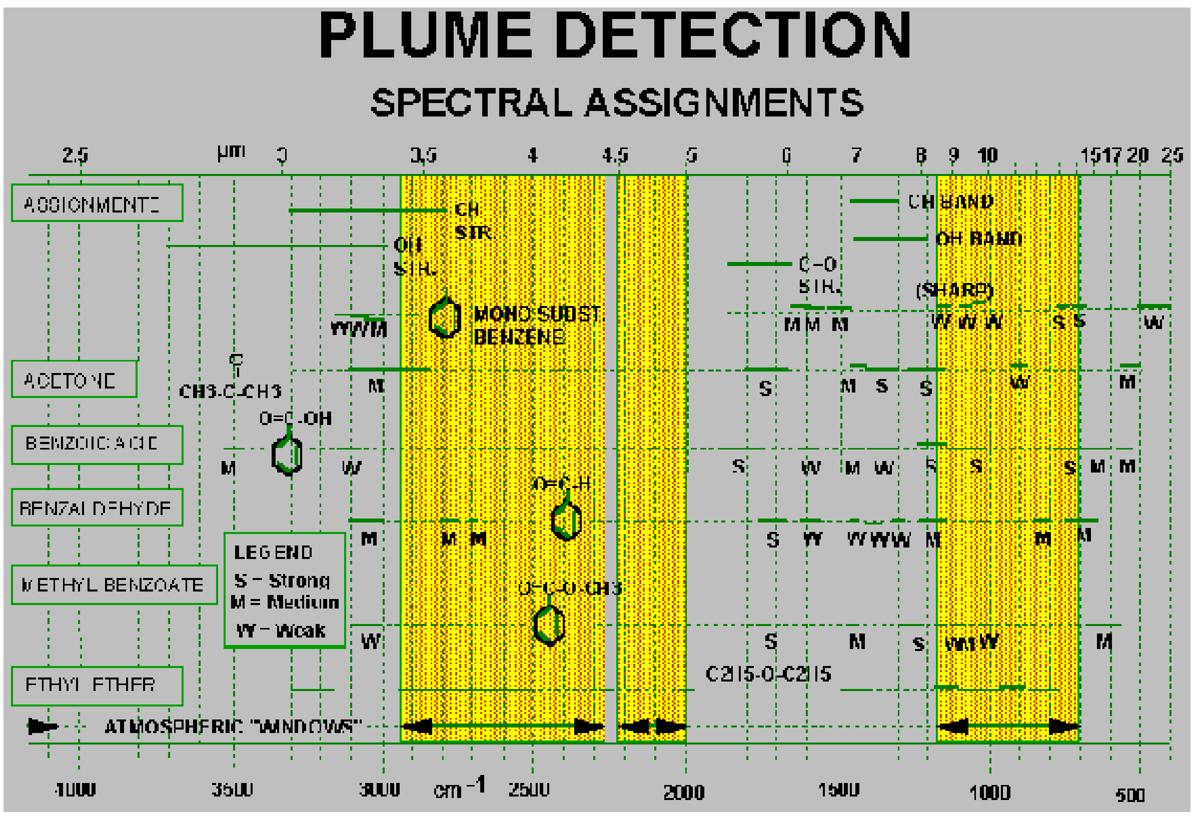


Figure 6. The atmospheric windows and spectral assignments of some organic functional groups.

Another multispectral airborne system that OKSI built recently for the USDA is shown in Fig. 7. This four 1024×1024 12-bits CCD digital cameras system operates over the visible to near infrared (VNIR) portion of the spectrum. The system flies at about 5,000 feet altitude and the cameras are pointed to produce overlapping images. Each camera is equipped with a bandpass filter that simulates one of the LandSat's TM bands. Special device drivers were developed to assure that all cameras capture images in a complete synchronization.   The USDA is currently testing this system for airborne scouting of cotton fields.

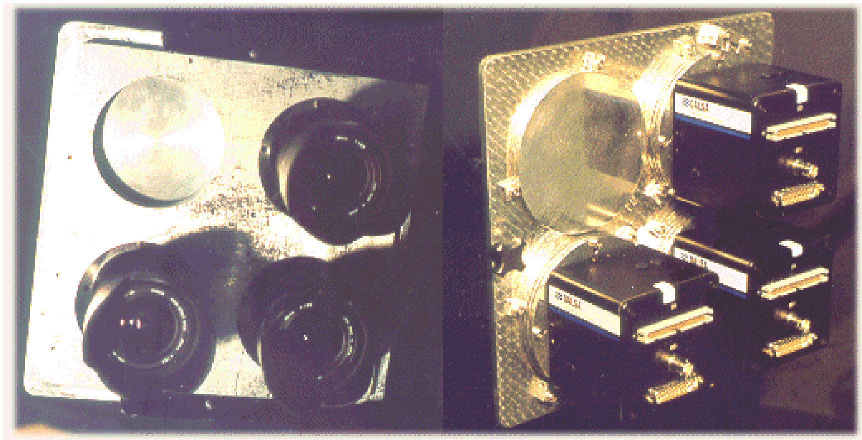


Figure 7.   A front and back views of the mounting and camera alignment rig of the four (3 shown) camera multispectral airborne system built by OKSI for the USDA.

2.2   Sensors for Ground Truth and Spectral Vision

While air and space borne sensors such as TIRIS and others use the pushbroom or whiskbroom approach to capture spectral imagery, ground based sensors operate more conveniently in a framing mode.   OKSI's liquid crystal tunable filter, LCTF, based spectral camera, Fig. 8, is one such device, that was used to capture the data in Figs 1 through 3.   The LCTF is an electronically tunable filter, that can be tuned to any desired wavelength by a computer command.   LCTFs are available in various configurations operating over the spectral range from 400 nm to 1,700 nm (VNIR to short-wave infrared, SWIR), with various bandwidths.   The system comprises a digital video camera, the LCTF, an apochromatic lens that is corrected over the spectral range of operations, a frame grabber board in a data acquisition PC.   In addition, special software has been developed to synchronize between the frame grabber board, the LCTF and the digital camera. The images are saved in a flat file format and can be viewed and analyzed by the proper software and algorithmic techniques as depicted in Fig.1.

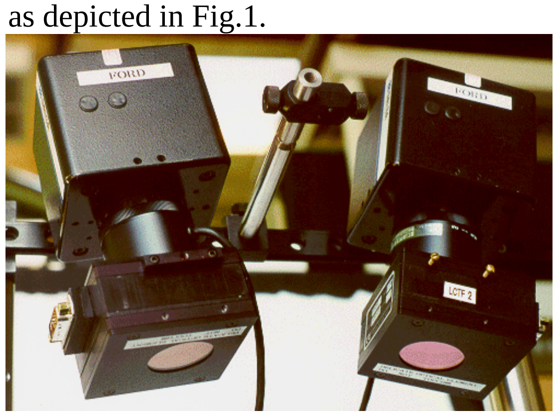


Figure 8.   A stereo imaging spectrometer system.

Because the LCTF's transmission is a strong function of the wavelength, the exposure time at each wavelength has to be properly adjusted.   To this end the software interface shown in Fig.9 is designed to allow the user to select and create a sequence of bands for the image cube of interest, and assign an exposure time to each band. A preview feature allows the user to verify that the exposure is appropriate for the amount of lighting at the given spectral range. During image preprocessing, the entire image cube data are compensated for the variable integration time, and also pixel by pixel corrected for gain and dark current offset. Once corrected, analysis of the spectral imagery can be used for automated classification and identification of the objects or portions of the scene.

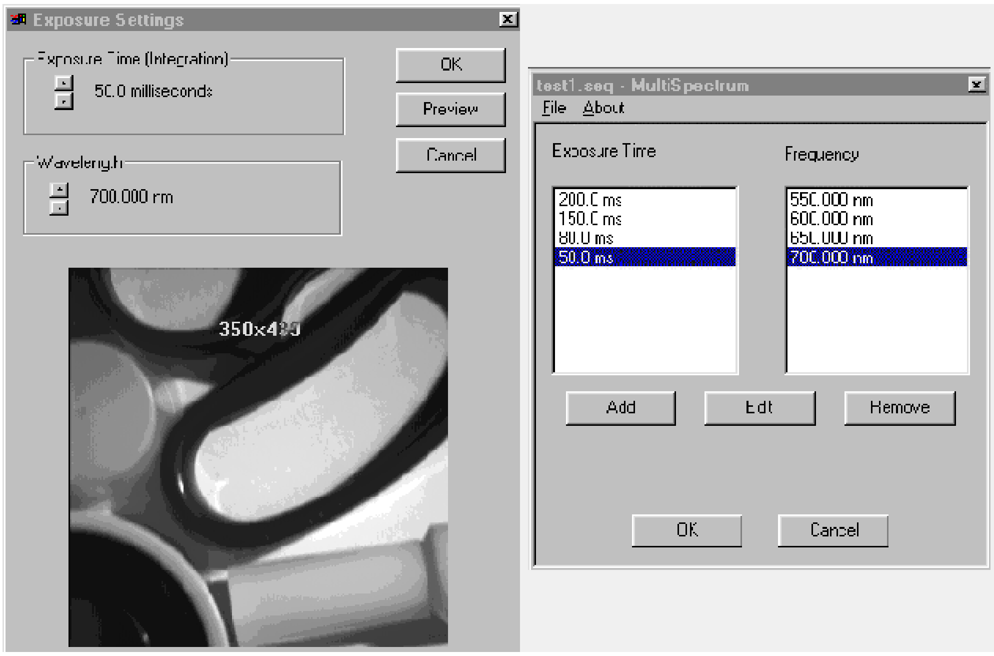


Figure 9. User interface for selecting bands for the image cube.

2.3 Other sensors

A new OKSI designed short-wave infrared (SWIR) low noise, 16-bits, 256×256 pixels HgCdTe camera operating from 1 to 2.5 μm is shown in Fig. 10. The focal plane array (FPA) is cooled to LN_2 temperature to keep the dark current and detector noise to a minimum. This camera will also be eventually incorporated into an imaging spectrometer.

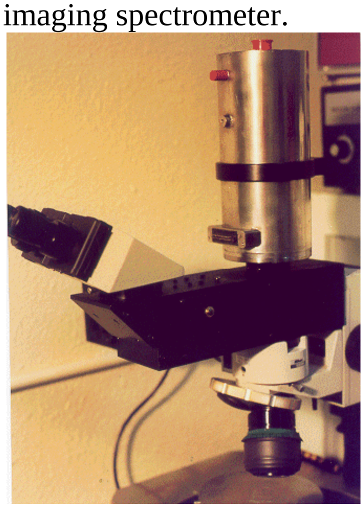


Figure 10. Microscope mounted low noise SWIR camera.

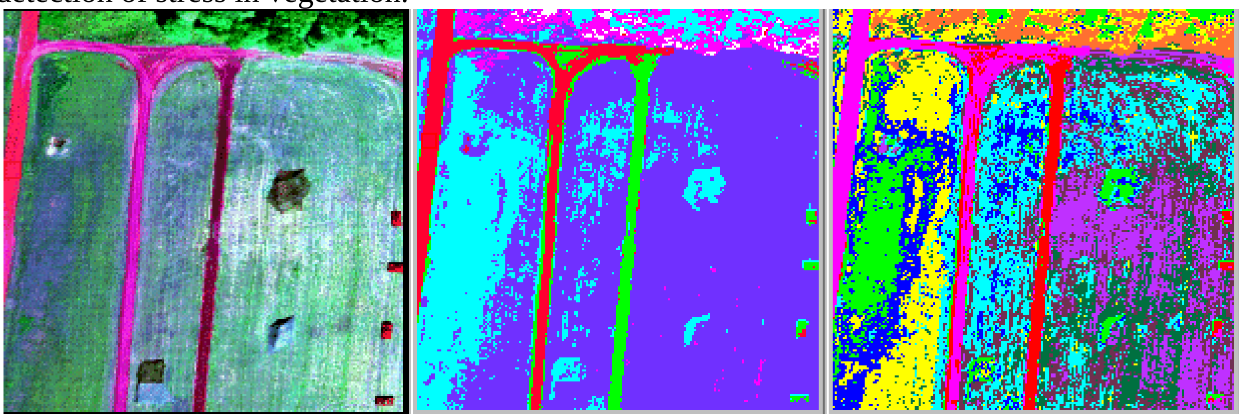
3.0 Algorithms

In general, analysis techniques are based on (i) spectral libraries of known materials where the goal is to match the scene spectra with a known library signature, or (ii) scene classification based on imagery data with no use of libraries. Several commercial software programs are available for handling and analyzing multi- and hyperspectral imagery, and OKSI is using ENVI (distributed by RSI or Boulder CO). The purpose of all these algorithms is to help the image analyst detect and locate objects or regions of interest, and sometimes, to replace the analyst and automatically process the image. Over the years OKSI has also developed a supplemental suite of algorithms for hyperspectral analysis that have been implemented in as an add-on package [5] to ENVI. These include:

- Image Preprocessing tools [6], primarily for image enhancement:
  - ✓ Supervised principal components analysis (PCA)
  - ✓ Supervised generalize eigenvalue transformation (GET)
- Supervised classification using Neural networks:
  - ✓ Radial bases function (RBF) network
  - ✓ A very fast training paradigm for a feed forward network using alternating directions singular value decomposition (AD-SVD)
- Unsupervised classification:
  - ✓ An optimized clustering algorithm
  - ✓ A Kohonen Self Organizing Map (SOM) neural network
- Subpixel object detection algorithm based on fast anomaly detection
- Synthetic hyperspectral cube generator for benchmarking performance of algorithms: this tool uses spectral libraries to generate image cubes for:
  - ✓ Classification tests
  - ✓ Anomaly detection tests
  - ✓ Subpixel unmixing algorithms
- "Realistic color" RGB representation of image cubes (for VNIR sensors) based on the CIE tristimulus functions
- Camera interface for using OKSI's LCTF based camera for ground truth acquisition
- Gain, offset and radiometric calibration tools for data cubes (specifically for use with the previous item).
- Additional tools under development:
  - ✓ Physics based atmospheric corrections (this approach solves the "inverse problem" of atmospheric retrieval based on models such as Modtran [7], via fast global optimization)
  - ✓ Realtime lossless compression for hyperspectral sensors data.
  - ✓ Sensor / Detection Algorithm performance validation model.

Sample applications of algorithmic analyses of various hyperspectral images are depicted below. Fig. 11 was acquired by HYDICE, a DoD operated VNIR-SWIR sensor with 210 spectral bands. The image shows various objects of interest, and the results of algorithmic operations that can autonomously detect such objects. In practice, when conducting remote sensing analysis of large areas, manual analysis is tedious and unreliable. Such algorithms that can independently detect regions of interest and cue the analyst can be of significant help.

Another example of anomaly detection algorithm is depicted in Fig. 12. In this case another HYDICE image (left image) has been used to select a spatial subset for analysis (center image). The objects of interest in this image range in size from several pixels down to less than a single pixel. The image on the right depicts the results of the anomaly detection analysis, detecting all the objects down to the smallest one being about 1/10 of a pixel size. This kind of subpixel analysis [8] can not be performed with panchromatic imagery nor with conventional color video. Such automated capabilities of the system to detect areas that are somewhat different from their neighborhood can greatly aid the analyst in identifying defects in food products, or for early detection of stress in vegetation.



(a) (b) (c)

Figure 11. Example of clustering operations on HYDICE sensor imagery: (a) image, (b) OKSI's clustering, (c) supervised classification operation.

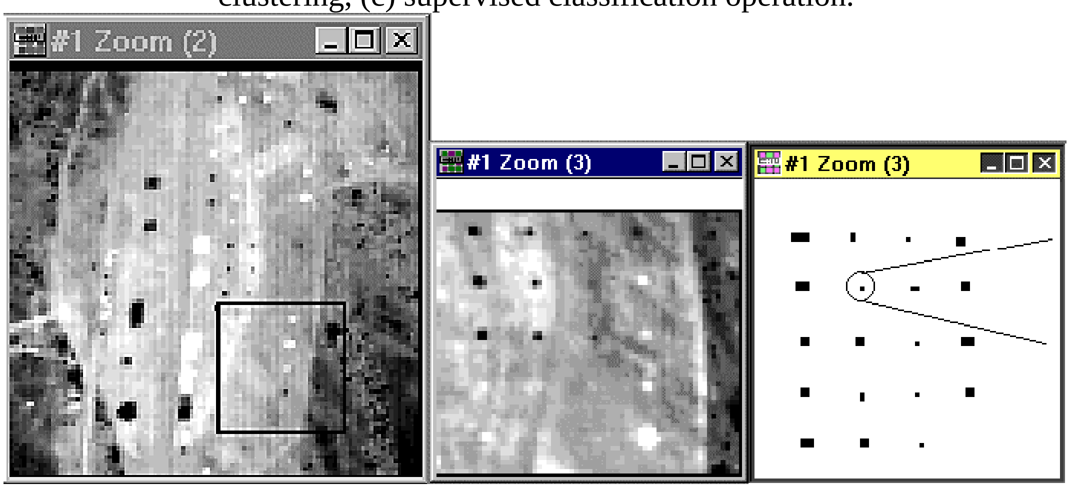
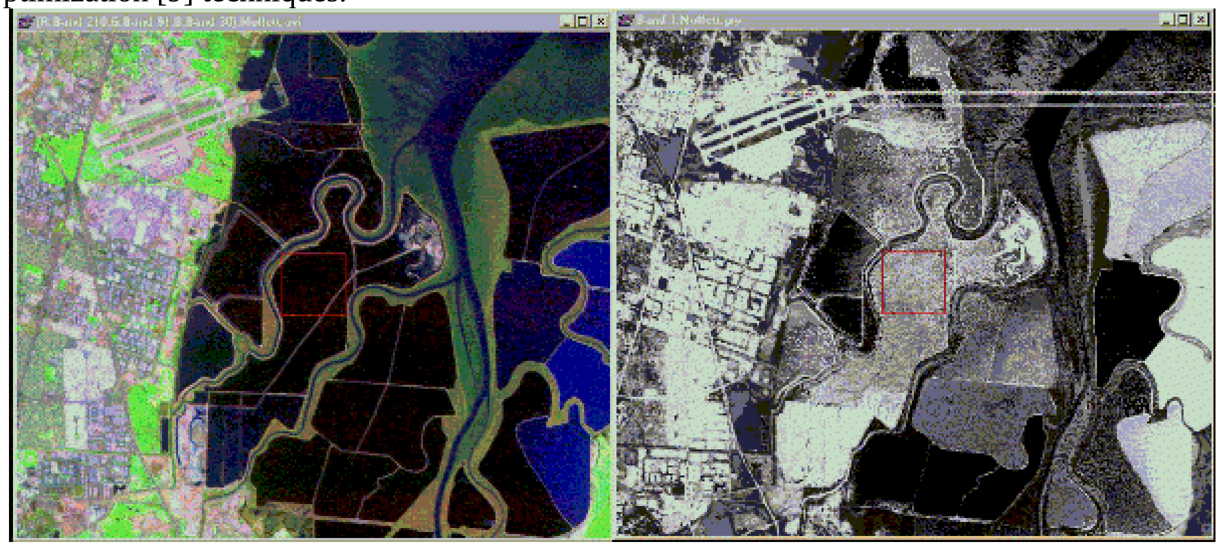


Figure 12. Anomaly detection algorithm applied to HYDICE imagery pick specific points that are different from their surroundings.

Finally, neural networks (NN) can also be used for image exploitation and may even provide some advantage over linear techniques. The difficulty with NN is often associated with a long training time. Once trained, however, image analysis is fairly rapid. NN also have the potential of developing general purpose analysis tools that can be used repeatedly with many images taken at various times and different locations. To this end, however, there is a need to incorporate preprocessing steps based on the phenomenology to remove artifacts due to atmospheric interference and the temporal and seasonal variability related to the solar illumination (these would not be of any concern in a vision/inspection system). The removal of such effects is still a very difficult process, based on detailed scientific analysis — and therefore is not yet ready for wide commercial use. Nevertheless, the application of an unsupervised NN classification to an AVIRIS imagery is depicted in Fig. 13. AVIRIS is a whiskbroom VNIR-SWIR sensor operated by NASA that produces 224 spectral images. This figure demonstrates the ability to recognize and classify different zones (water ponds) that are very similar in their physical appearance.

OKSI is exploring a new technique that addresses the atmospheric corrections problem, using a procedure that can be implemented in a commercial product for use by non-experts. This technique uses the imagery combined with a full physic based model of the atmospheric propagation, in order to retrieve the atmospheric parameters. The retrieval process is known as a solution to the inverse problem, that OKSI is attempting to solve using advanced global optimization [9] techniques.



(a) (b)

Figure 13. (a) AVIRIS image of the Bay Area and Moffett Field, (b) NN classified image output.

4.0 Summary

Multi- and hyper-spectral imaging techniques can greatly enhance the image exploitation, improve inspection, analysis, and detection capabilities in remote sensing and vision applications. New types of sensors are available to acquire the imagery. New software tools based on sophisticated algorithmic paradigms are also available. This technology that is not much more than ten years old is undergoing very fast development. The technology is being tested and applied to new fields, and the impediments to wide spread use often are the fact that end-users are unaware of the potential enhancement that can be achieved. In the long run, the technology could bring about major cost savings in applications such as remote sensing for precision agriculture and for inspection. Turnkey systems that includes an LCTF based camera and image exploitation tools are available. Such systems can be custom configured, including camera and LCTF features, to the specific end user needs. Similarly, custom airborne sensor systems are available, or remote sensing acquisitions services can provide the necessary data for end users' application.

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