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# Hyperspectral imaging: a useful technology for transportation analysis

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**Abstract.** We address hyperspectral imaging (HSI) technology and its attendant key issue of spectral libraries to enable the exploitation of hyperspectral images for transportation applications. Five key applications are reviewed here: detection/identification of submerged aquatic vegetation in navigable waterways, detection/tracking of oil spills, extracting/assessing road characteristics, mapping impervious surfaces, and the detection/identification of vehicles. Central to all these applications is the need for a comprehensive spectral library in which various reflective spectra are correlated with physical surfaces and environments encountered in transportation. Much of this critical work is being funded by the Department of Transportation through four university consortia, each specializing in one of the key transportation areas of: transportation flows; infrastructure; environmental assessment; and safety, hazards, and disaster assessment for transportation lifelines.  [DOI: 10.1117/1.1497985]

Subject terms: hyperspectral; transportation; remote sensing; imaging; multispectral; spectral signature; spectral libraries.

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## 1 Introduction

Hyperspectral imaging (HSI) produces an image in which each pixel contains response values across many narrow, contiguous bands of the electromagnetic spectrum. This provides a unique spectral signature for every pixel. After specialized image processing involving a spectral library is done, the spectral signature can be used to identify and quantify the target material(s) in each pixel of the image.[1] Considerable work in the area of spectral sensing is being conducted worldwide to identify and collect the specific signatures of materials and to develop the exemplar spectra that carries the essence of the spectral content of the detected material.

## 2 Brief History

The hyperspectral era began with airborne mineral mapping in the late 1970s and early 1980s. The invention of the charge-coupled device in 1969 was a key factor in moving hyperspectral technology forward. In 1989, a major advance occurred with the arrival of the NASA/JPL Airborne Visible/IR Imaging Spectrometer (AVIRIS). The AVIRIS system, a hyperspectral imaging sensor, collects imagery in 220 spectral bands over the spectral range from 400 to 2500 nm. Spurred by this instrument, many other multispectral and hyperspectral instruments were produced. One early airborne entry, deployed in 1986, is the Geophysical and Environmental Research Imaging Spectrometer (GERIS), the first commercial airborne hyperspectral imaging spectrometer. Many ground-based and airborne hyperspectral systems are available today. Only three spaceborne HSI sensors are in orbit today (April 2002): the MightySat II.1 of the Air Force and the hyperspectral sensors, Hyperion and Atmospheric Corrector, both of which are payloads on NASA's Earth Observing-1 (EO-1) Satellite. Hyperspectral sensors scheduled for future satellites include the Coastal Ocean Imaging Spectrometer on the Naval EarthMap Observer (NEMO) satellite and the Australian Resource Information and Environment Satellite (ARIES).

## 3 What is Hyperspectral Imaging?

All objects reflect or emit energy. Receiving this energy for interpretation is called sensing. If instruments located at a considerable distance from the subject being measured do the sensing, it is called ''remote'' sensing. Thus, hyperspectral sensing, as defined here, is the acquisition of information from afar about the chemical composition of an object or its environment based on the energy that is emitted or reflected from the object or its environment.[2] In hyperspectral imaging, the electromagnetic spectrum is partitioned into hundreds of narrow, contiguous spectral bands, sufficient to read the spectral signatures of the materials in the image.[2] Hence, performing hyperspectral imaging of the scene from a space-based, airborne, or ground remote sensor can accomplish identification of objects in the scene. The result is a three-dimensional spatial-spectral data set with two axes of spatial information and one axis of spectral information, termed an image cube as shown in Fig. 1. Typically, the hyperspectral image cube contains millions of picture elements (pixels), providing a rich source of information for identifying and classifying both natural and man-made objects.

Hyperspectral sensing allows the analyst to perform reflectance or fluorescence spectroscopy on each spatial picture element (pixel) of the image scene. Spectral resolution is a measure of the narrowest spectral feature that can be resolved by a spectrometer. One of the more common ways to characterize spectral resolution is to determine the full width at half maximum (FWHM) of an instrument's response to a monochromatic signal. Spectral sampling interval is the interval, in wavelength units, between data points in the measured spectrum. Generally, the spectral sampling interval is smaller than the instrument's spectral resolution. For HSI applications, a spectral resolution of about 10 nm and a spectral sampling interval of about 2 to 3 nm are required. The signal to noise ratio (SNR) of spectrometers can range from 10:1 to 1000:1. If the SNR is inadequate, increasing the spatial or spectral resolution will not increase the information quality of the HSI image. Many of the spectral bands are correlated, and the information content does not always exceed the information from multispectral imagery, which uses fewer, broader, spectral imaging bands. Spectral band selection and SNR performance of HSI imaging sensors are ongoing design issues, driven by the spectral resolution required to correlate physical materials with their spectral signatures in ever-growing spectral libraries.

## 4 Atmospheric Effects

The effect of the atmosphere on electromagnetic (EM) radiation complicates the use of HSI sensors.[3] Molecular absorption, molecular scattering (Rayleigh), aerosol absorption, aerosol scattering (Mie), optical turbulence, reflection, refraction, and atomic processes all affect EM propagation through the atmosphere. There are certain spectral regions, referred to as "atmospheric windows," where gaseous absorption is at a minimum. Most HSI sensors operate primarily in these window regions.

Understanding atmospheric effects and correcting HSI imagery data to remove their impact remains an important element in utilizing HSI sensors. The reliable correlation of specific physical characteristics to spectral signatures received from target objects depends on understanding the phenomenology of transmission, absorption, reflectance, or emittance of electromagnetic radiation between target and sensor as a function of wavelength. The amount of radiation reflected from a surface depends on the wavelength band under consideration, its angle of incidence with the surface, the orientation of the sensor in relation to the surface and the illuminant, the material's molecular composition, and the surface structure. There are materials that absorb photons of one frequency and emit photons of a lower frequency, without any significant increase in temperature. These are luminescent materials. Luminescence can be one of two kinds, fluorescence and phosphorescence, depending by how long the light lasts after turning off the excitation energy. This is called the decay time. In fluorescence, the decay time is very short (less than 0.003 s). In phosphorescence, the decay time is much longer.

## 5 Spectral Signature Libraries

A good understanding of background and object spectral signatures and their dynamic behavior in realistic environments is essential to the exploitation of hyperspectral imagery for operational applications. To achieve this level of understanding, the HSI analyst has to address atmospheric effects, autonomous intelligent processing, spectral signature database usage, subpixel mixing retrieval techniques, scene generation models, and other spectral techniques. The most vital component in all of this is a good spectral signature library.[4,5] Spectral libraries need to be populated with spectral signatures of target surfaces measured in the laboratory, field, and from the collected sensor image itself. The spectral signature within a pixel of the hyperspectral image consists of an average of the reflectance of all materials seen by that pixel. For example, for a spatial resolution of 10 m, the spectral response for a truck rest stop will consist of a combination of the spectra of all man-made object types (asphalt concrete, etc.) and the soil, grass, etc., within the 10-m picture element (pixel). Field data collections to populate the spectral library consist of obtaining spectrometer readings (or object samples) for as many of the categories/classes of man-made and natural material types as possible. Reflectance readings obtained in the field should be representative of those obtained by airborne or satellite remote HSI sensors. For instance, these truck rest stop categories could include grassy fields, parking lots, vehicles, trees, and buildings. Sample each category from various angles and heights. It is also valuable to collect actual material samples for laboratory analysis of reflectance to provide end-points in the analysis. The leaf, soil, and litter measurements are done in a laboratory and involves the use of a power-stabilized known light source and calibration standard. The spectral signatures collected should be used to develop exemplar spectra, which capture the spectral content of the materials.

A further consideration is that of sample stratification, i.e., whether to collect many readings in a single location or to collect few samples at many locations, depending on project goals or site conditions. Interpretation of hyperspectral remote sensing data to determine standard man-made and natural material types (asphalt, vegetation, aluminum, water, soil, and rock type) can be accomplished without much ground-truth or validation data. However, ground-truth data should still be collected, if possible, to determine specific conditions about material types such as vegetative stress, age of the asphalt, or specific water quality criteria. In general, the following collections of types of ground-truth or validation data are recommended: atmospheric conditions, dark and light calibration targets, surface water, ground characteristics (soil, rock, and vegetation), and man-made objects.

Knowledge of atmospheric conditions of temperature, wind direction, wind speed, incident solar radiation, humidity, haze, or aerosols are used to correct the hyperspectral image for conditions in the atmosphere that interact with both the incoming solar illumination of the ground target and the reflected EM energy collected by the HSI imaging sensor. To minimize shadows, hyperspectral images are usually collected at or near solar noon, with the window being from about 2 h prior to 2 h after noon, ideally in clear weather. However, with newer 16-bit data quantization sensors, some information can be obtained under overcast conditions. The biggest factor affecting reflectance into the HSI sensor is the sun angle. It will have a large impact on the overall albedo (brightness) of the spectra and will dominate the "minor" types of spectral changes that are being measured. Depending on latitude of the study site, collection of hyperspectral images early in the spring and late in the summer can become infeasible due to low sun angles. Sun angle varies with the time of day and day of year. The

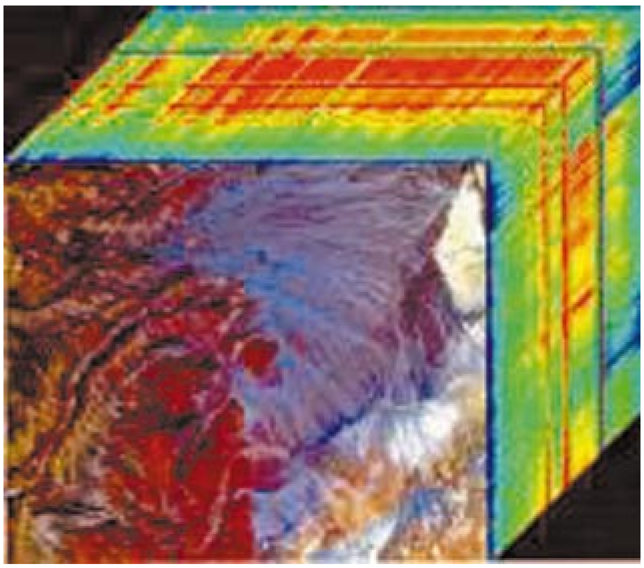

**Fig. 1** Hyperspectral image cube.

**Fig. 2** True color image of truck rest stop.

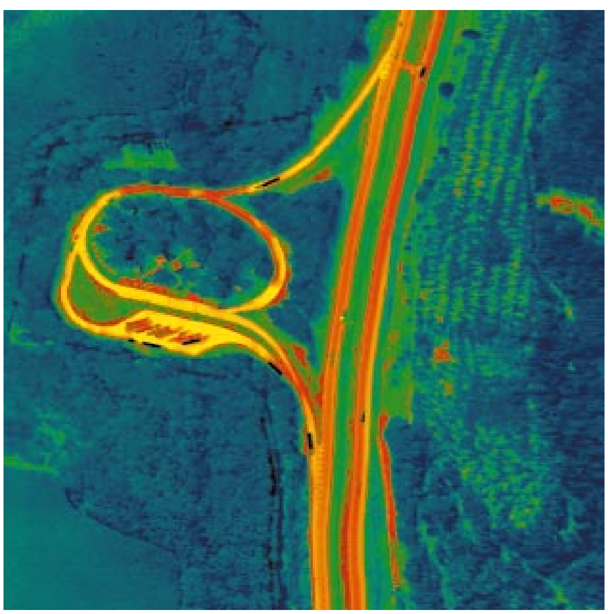

**Fig. 3** Thermal image of truck rest stop.

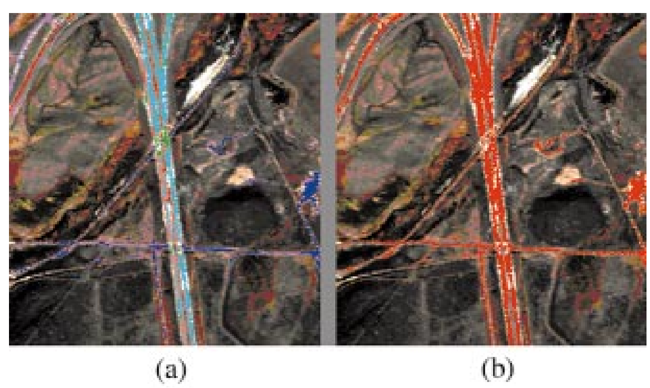


**Fig. 4** (a) Road composition and condition derived from AVIRIS data, and (b) generic ''road'' overlay.

optimal time for acquiring field spectra (and HSI image data) is within $+/-2$ h of solar noon, when the sun angle changes most slowly with time.

The reflectance measurements from dark and light targets with known spectral response serve to calibrate the hyperspectral imagery and to correct for atmospheric influences. Dark or new asphalt makes a good dark calibration target and cement pads or a large roof make a good light calibration target. Field crews need to dress in low reflective clothing in darker colors. Reflection from field equipment needs to be mitigated, so that bright white vehicles need to be parked at a distance or covered with dark cloth. The goal of fieldwork is to identify sufficient information on the ground that will support the image interpretations, not to duplicate them.

## 6 Hyperspectral Remote Sensing in Transportation Applications

Have you ever wondered how raptors, like the Eurasian Kestrels, can pick fields with high densities of prey while flying at high altitudes? They can do this because they can see the ultraviolet (UV) light reflected from the urine trails of voles, and know to stop there and feed. That means when they soar overhead, they scan fields and meadows for that unique spectral signature of the meadow vole urine—with nature's own HSI sensor and a spectral library containing (among others) the spectral signature of meadow vole urine.

In man-made systems, we combine the hyperspectral sensor with a global positioning system (GPS) and inertial measurement unit (IMU) to collect images with spectral data in each pixel, plus geospatial knowledge of the observed target area. An application to transportation example utilizes hyperspectral sensors in the UV (ultraviolet) and IR (infrared) wavelengths to locate and track oil spills in oceans or transportation waterways. With knowledge of slick locations and movement, decision makers can more effectively plan countermeasures to lessen the pollution impact. Remote sensing systems operating in the visible region of the spectrum are not effective because oil shows no spectral characteristics in the visible region, which can be used to discriminate oil against a water background. A number of UV/IR airborne remote sensing systems have been assembled and are in operation around the world as reported by Fingas, Brown, and Mullin.[6] In the U.S. and Canada, the U.S. Coast Guard, Canadian Coast Guard, and Environment Canada operate airborne oil spill remote sensing systems. These kinds of systems are the most common form of oil spill tracking. HSI remote sensing for oil spills by satellite may provide the capability to monitor oil on the open ocean around the clock. There are no comparable industry-owned systems currently available. A weakness with current capabilities is the inability to discriminate oil against backgrounds of beaches, weeds, or debris. Additional spectral library data are needed. Several general reviews of oil spill remote sensing are available.[7]

For transportation trafficability mapping, it is essential to identify soil composition. According to Kruse, Boardman, and Lefkoff of Analytical Imaging and Geophysics, the strong points of using hyperspectral data for trafficability mapping are detection, identification, and mapping of surface composition.[8] One of their conclusions is that data fusion is required to enhance the information extracted from hyperspectral data to achieve desired "classical" trafficability products. These findings among others suggest that no one sensor can provide the depth of information for all applications. It is always wise to develop remote sensing program strategies that take advantage of the multitude of sensors that are available, such as imaging radar and Lidar, to produce specific application products. One such data fusion approach is the Texaco Energy and Environmental Multispectral Imaging Spectrometer (TEEMS).[9] A breakthrough optical imaging spectrometer, TEEMS is mounted aboard an aircraft and is integrated with synthetic aperture radar (SAR) imagery to permit data collection during night or day and through dense cloud and forest cover. The system can assess water quality and identify the area's soils and minerals as well as its organic compounds. The TEEMS imaging spectrometer system has a state-of-the-art optical scanner and multiple spectrometers to cover the UV, visual (VIS), near infrared (NIR), short wave infrared (SWIR), and thermal infrared (TIR) spectral ranges. Data acquisition with georeferencing and coregistering of UV, VIS, NIR, SWIR, TIR, and SAR channels can be achieved in one flight path. The optical system measures more than 200 selected wavelengths of reflected and emitted radiance across these wavelength bands. HSI plays a significant part in such a sensor suite because of its unique ability to identify and quantify the composition of the material in the scene, if contained in a spectral library. TEEMS comes with real-time recording capability and the ability to process several hundred square miles of geological and environmental data per day.

The Department of Transportation (DOT), in response to the Transportation Equity Act for the 21st century, has implemented a research program for remote sensing in transportation in partnership with leading academic institutions, service providers, and industry. The program seeks innovative applications of commercial remote sensing and geospatial information technologies to solve priority transportation requirements. One definite innovative application of remote sensing and geospatial information technologies is the use of hyperspectral imaging to meet priority transportation requirements. The utility of nonliteral hyperspectral sensing becomes evident where literal conventional imaging fails. Conventional remote sensors, for example, cannot see the subtle differences in material composition that allow the aging process of asphalt or the deterioration of pavement to be examined. Hyperspectral sensors can detect these changes in material composition. Under this program, the DOT created the National Consortia on Remote Sensing in Transportation (NCRST) (see *http://www.ncrst.org*), which is composed of four university consortia that are addressing the key transportation issues: infrastructure, environmental assessment, traffic flows, and disaster assessment, safety and hazards. They have all taken the initiative to include hyperspectral sensing as part of their remote sensing programs. The consortium led by Mississippi State University is focusing on environmental assessment, and the consortium led by the University of New Mexico is looking into transportation issues of safety, hazards, and disaster assessment. The University of California, Santa Barbara, which leads the group studying infrastructure, is developing accurate road extraction and road quality assessment techniques using high spatial resolution imagery and hyperspectral imagery.[10] Their initial focus has been on the use of AVIRIS to perform road feature extraction. They have developed a regionally specific urban material spectral library. The library was developed by taking measurements in the field, using an analytical spectral device (ASD) spectrometer trained on materials at a relatively short distance, e.g., 1 to 2 m. Signatures are clustered to detect similarities and dissimilarities between materials. However, they have had limited success in achieving accurate road centerline mapping using AVIRIS hyperspectral data. Asphalt road surfaces can be confused with composite roof shingles. Processing filters are being investigated to distinguish between these two materials. Once the road extraction technique is developed, they plan to utilize the spectral library to map road quality using HSI imagery.

The University of Arizona (UA), part of the traffic flows group led by Ohio State University, has built a spectral library of vehicle paint and pavement signatures to recognize cars from hyperspectral satellite imagery.[11] By comparing the image spectral measurements to the library, vehicles may be recognized and classified. UA performed spectral measurements of vehicle paint and pavement signatures using a spectroradiometer, and used these data to obtain graphs showing the characteristics of different paint colors and pavement types in different weather conditions, such as cloudy and clear skies.

The George Mason University, another member of the traffic flows group, is applying hyperspectral sensing technology to truck rest area monitoring[12] and traffic flow management, and is developing a web-based spectral library for spectral information relevant to transportation flow applications.[4] In Fig. 2 the true color image of the truck stop shows the trucks that are parked on the rest stop and those that are entering and leaving the rest stop. Figure 3 is a thermal image of the same scene shown in the other figure clearly showing trucks with refrigerants as black in color. Although these images were taken with a multispectral scanner, what this illustrates is the need to fully exploit the whole electromagnetic spectrum and not just the visible and near IR. The Geophysical and Environmental Research Corporation (GER) that took the images with their multispectral airborne imaging spectrometer system (GER EPS 31T) provided these truck rest stop images. This instrument has 31 spectral bands, 28 in the visible and near infrared (VIS/NIR: 400 nm to 1050 nm), 2 in the short wave infrared (SWIR: 1800 nm and 2200 nm), and 1 in the thermal infrared (TIR: 8.0 $\mu$m to 12.5 $\mu$m). Some hyperspectral systems like the Spatially Enhanced Broadband Array Spectrograph System (SEBASS), with its 3.0 to 13.6 $\mu$m spectral coverage, can cover the long wave infrared part of the spectrum.

Submerged aquatic vegetation (SAV) can be a hazard to navigation in various inland and coastal waterways. Traditional aerial camera surveys cannot differentiate epiphytic algae on submersed vascular plants or differentiate many benthic marine algae species, including many macrophytes, which can cooccur in the same SAV beds. EPA, USGS, and GMU recently demonstrated the use of airborne hyperspectral remote sensing imagery to map submersed aquatic vegetation in the tidal Potomac River for near to real-time resource assessment and monitoring applications.[13] Field surveys for pilot sites determined SAV presence, species, and distribution. Airborne (HyMap) hyperspectral imagery and in-situ spectral reflectance measurements using a field spectrometer were obtained for the pilot sites in spring and early fall of 2000. GMU participated in the development of a spectral library database containing selected ground-based and airborne sensor spectra for use in image processing. The goal of the spectral database research is to automate the image processing of hyperspectral imagery for potential real-time material identification and mapping.

Once the diagnostic spectral signatures are extracted from hyperspectral data, actual identification of the material reflecting these spectral signatures is still one of the most difficult challenges to the full exploitation of hyperspectral technology. It is clear that a first step to making transportation applications more effective is that information techniques must be used to manage and process the voluminous amounts of data involved in developing these important spectral libraries. Areas as large as 100 $km^2$ can be mapped from an airborne hyperspectral sensor in a day with 1-$m^2$ spatial resolution. If the data quantization is 10 bits and the sensor has 220 spectral bands, one day's work can produce 220 Gbits of information. For a spaceborne hyperspectral system like the Hyperion, which takes only 24 s to collect a hyperspectral image cube from a ground area of 180 km long by 7.5 km wide and a pixel size of $30\times30$ m (each pixel containing 220 spectral bands with 12-bit quantization), the amount of data will be much larger.

Impervious surfaces consisting mainly of constructed surfaces such as rooftops, driveways, sidewalks, roads, and parking lots, which are covered by impenetrable materials such as cement, asphalt, concrete, brick, stone, and compacted soil, are good indicators of urbanization. It is interesting to note that the majority of these surfaces are also associated with transportation. Hyperspectral imaging can be very effective in monitoring the extent of urbanization. All we need are the spectral signatures of these materials, and whole areas can be mapped in one day with an airborne HSI system.

The ability to perform automated pattern recognition and information extraction from hyperspectral data, and the distribution of the results to the users in a timely manner is crucial for commercial operations. Time is money. For example, the hyperspectral image in Fig. 4(a), demonstrates the ability to quickly classify roads. The various colors in the hyperspectral image show different paving materials and surface conditions that affect road safety. That kind of information is not available from the image shown in Fig.


**Fig. 5** AISA hyperspectral system.

4(b). The University of New Mexico consortium provided these images.

## 7 Hyperspectral Systems

### 7.1 *Ground-Based Systems*

Ground-based hyperspectral systems are essential to gather laboratory and field spectral signatures of the targeted materials that are under study or relevant to the application in mind. For transportation applications, the spectral signatures of man-made materials such as asphalt, concrete, petroleum products, metals, and spectral signatures of natural materials, such as water, soils, and various vegetation specimens are needed. These spectral signatures are utilized to populate a spectral library to use in spectral signature matching algorithms for HSI image analysis. Various commercial companies like Analytical Spectral Devices, Incorporated (www.asdi.com) offer these portable and hand-held systems for sale.

### 7.2 *Airborne Systems*

Airborne hyperspectral sensors are available in a variety of sizes and prices. For example, Specim offers the Airborne Imaging Spectrometer for Applications (AISA), in Fig. 5, which is inexpensive, compact, and has a very versatile graphical user interface that is easy to use with several efficient operating modes and features that may be changed during flight within seconds. The Flight Landata, Incorporated's Computerized Component Variable Interference Filter Imaging Spectrometer (C2VIFIS) system is a miniaturized direct-sensor-to-computer HSI system. It can capture 96 spectral bands of pushbroom hyperspectral images in an automatic operation mode and can fit on a small unmanned air vehicle. ITRES Research Limited offers the Compact Airborne Spectrographic Imager 2 (CASI-2), which is a pushbroom imaging spectrograph that is intended for the acquisition of visible and near-infrared hyperspectral imagery. Temporary installation of the CASI-2 system in a light aircraft can typically be accomplished in several hours. The Galileo Group's hyperspectral sensor is a new generation, state-of-the-art digital imaging sensor for acquiring hyperspectral imagery with high spatial and spectral resolutions. Integrated Spectronics manufactures the hyperspectral scanner, HyMap, which is a ''plug and play'' scanner that operates in light aircraft with a standard camera port. The Earth Search Probe-1 and Advanced Power Technologies, Incorporated's Aurora airborne hyperspectral systems can deliver authoritative spectral information to the end user in many industries. There are many more commercial airborne hyperspectral systems available. The bottom line is that the commercial world is ready to provide the airborne hyperspectral sensors!

### 7.3 *Spaceborne Systems*

The Air Force Research Laboratory (AFRL) MightySat II.1 (Sindri) Fourier Transform Hyperspectral Imager (FTHSI) was launched on 19 July 2000. FTHSI contains 256 spectral bands, covers a spectral region between 470 to 1050 nm, a swath length of 20 km, and a swath width of 13 km. Because FTHSI uses a Fourier system, it can record the full spectra without any time delay and can decouple the spatial and spectral signatures. The TRW Hyperion and the Atmospheric Corrector hyperspectral instruments, both part of the Earth Observing-1 satellite, were placed in orbit on 21 November 2000 as part of NASA's New Millennium Program. The Atmospheric Corrector is a moderate spatial resolution (250 m) imaging spectrometer, with spectral coverage of 0.85 to 1.5 um, a spectral resolution of 2 to 6 nm, and 256 spectral bands, with a 185-km (115 mile) swath, the same as Landsat 7's ETM+. The Hyperion hyperspectral sensor, which follows Landsat 7 as part of a satellite constellation, is an advanced high spatial resolution (30-m) instrument capable of resolving 220 spectral bands at wavelengths from 0.4 to 2.5 $\mu$m with a 10-nm spectral resolution. The S/N is 100:1 in the VNIR and 50:1 in the SWIR. Hyperion data is providing more detail of the Earth's surface than is currently available from multispectral instruments, such as the ETM+ instrument on Landsat 7.

## 8 Conclusions

In summary, the spectral signature libraries of materials important to transportation are expanding and getting better. Remote sensing applications of hyperspectral imaging to transportation will surely increase because transportation is a very fertile area for remote sensing from the ground, air, and space. This powerful HSI technology[14–18] has proven that it can cover large areas in reasonable times for the detection and identification of materials in a targeted scene. It can provide timely, accurate information on submerged aquatic vegetation (SAV) distribution and density to control SAV negative effects on the commercial and recreational traffic through navigable waterways. This technology can also be used to see and detect petroleum products and other hazardous materials on the ground from an aircraft and/or spacecraft.[5] The effects of increasing urbanization can be measured by detecting and mapping impervious surfaces. Rest stop facilities can be better managed and better planned by examining the deterioration of pavements from aircraft. Being able to detect vehicles and traffic obstacles through their spectral signatures might allow the application of subpixel analysis to traffic flow using spacecraft HSI systems. Sensing the materials involved and the surrounding environment for possible problems can help the maintenance of transportation infrastructure. Extracting road features and road quality information from HSI data is possible. Potential problems with leakage in the truck's containers and or problems in the ground foundation can be helped by this technology that can see what the eye cannot. Successful applications of HSI in transportation will facilitate the construction of better transportation facilities, lead to better transportation policies, and help the development of better ways of responding to natural and accidental disasters affecting transportation.

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