Exploring for onshore oil seeps with hyperspectral imaging

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Explorationists evaluating remote terrain can now consider using airborne hyperspectral imaging for detecting onshore oil seeps. Previous to this new technology, the spatial and spectral resolution of sensors was too limited for successful detection of onshore oil seeps.

A cooperative R&D project facilitated by The Geosat Committee Inc. documented the spectral characteristics of seeps and associated oil-impacted soils and constructed a spectral library to enable deployment of the application to other geographical areas. This oil-focused spectral library may have been the first of its kind in the commercial sector and includes signatures with varying amounts of oil, tar, vegetation, soils, and rock.

This library can be used with other handheld, airborne, and satellite hyperspectral sensors to support exploration and environmental applications. The experience gained and this library supports the use of hyperspectral remote sensing for detecting onshore oil seeps and oil-impacted soils globally.

Hyperspectral overview

Airborne hyperspectral imagery is used to map different materials at the surface of the earth based on their spectral characteristics.

Hyperspectral sensors measure the intensity of solar energy reflected from materials over hundreds of wavelengths. They can record visible light (comprised of relatively short wavelengths-blue, green, and red) as well as longer, near-infrared, and short wave-infrared light.

Reflected light is collected into picture elements (pixels) by flying an imaging sensor over terrain. The reflected visible and infrared light is subdivided into 100 to 200, 300+ discrete wavelength bands within each pixel or instantaneous field of view (IFOV). This large number of spectral bands is the basis of the name "hyperspectral," which differs from multispectral sensors that have a handful of spectral bands.[1]

The amount of energy recorded by the hyperspectral sensor within each pixel varies across the wavelength spectrum because different materials on the earth's surface scatter or absorb solar energy to varying amounts based upon the material's physical properties and composition. Hyperspectral sensors are unique in that they have sufficient spectral resolution to identify different surface materials based solely on spectral signatures.

In order to correlate spectral signatures with specific materials, scientists obtain "pure" samples of the material and collect highly accurate, reflected light measurements in the lab or in the field using a portable spectrometer. The measurements allow spectral libraries to be built that contain various hyperspectral signatures that have been positively identified with specific materials at the earth's surface. Spectral libraries have been constructed for numerous minerals, plants, and manmade materials.

Cooperative R&D

A cooperative R&D study was initiated by HJW Geospatial Inc. (HJW) and The Geosat Committee Inc. (Geosat) in early 2000.

This study was designed to measure with ground and airborne hyperspectral technology different materials associated with onshore oil seeps and oil-impacted soils in southern California.[2] The primary objectives of the study were to develop an understanding of the spectral characteristics of oil-impacted soils and seeps[3] and to build a spectral library that would make the detection process more rapid and reliable signatures.

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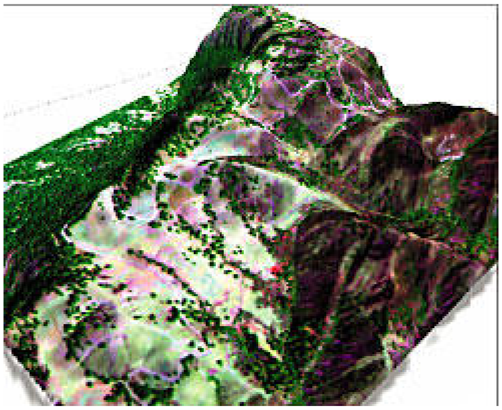
Overview of southern California study area with three field sites used for developing oil seep spectral library. From left, the sites are More Mesa, Sulphur Mountain, and Osborne (Fig. 1).

Chevron, Royal Dutch/Shell, and ExxonMobil sponsored the study and provided key feedback and guidance to the research effort. The airborne hyperspectral imagery was acquired by Earth Search Sciences Inc. (ESSI) during a 1998 group shoot over the Santa Barbara, Calif., area (Fig. 1).

ESSI's Probe-1 airborne hyperspectral sensor used in this study is capable of recording reflected light that spans visible through shortwave-infrared wavelengths into 128 channels or bands (Fig. 2).

ESSI used a very sophisticated airborne sensor built by Integrated Spectronics that records reflected light energy across a span of ~2200 nanometers (nm) from the visible and near-infrared through short wave-infrared wavelengths (VNIR-SWIR, see Fig. 2). The sensor (designated Probe-1 by ESSI) divides the ~2200 nm span into 128 wavelength intervals or bands.

The hyperspectral data, collected by line-scanner technology, were acquired as flight strips with a 5-m ground sampling distance (gsd). The instrument collects data in a cross-track direction by mechanical scanning and an along-track direction by forward motion of the aircraft. Each flight strip covers 2.5 km across and 25 km long. Each flight strip with its 128 bands or layers of data can be considered a hyperspectral "data cube."

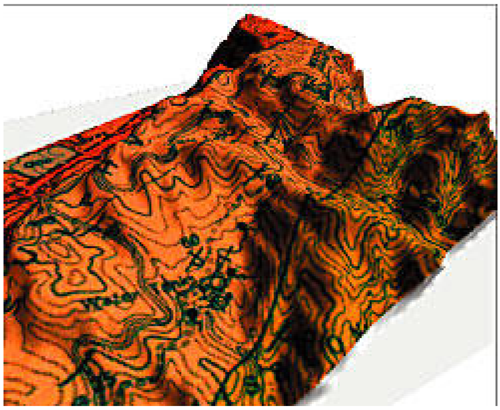


Matching perspective views of hyperspectral imagery and Dibblee Geologic Foundation map showing Dibblee's mapped oil seeps. See tadpole symbols on the map (Fig. 3).

The 1998 group shoot was organized by Geosat and supported by these same sponsors. It was during the 1998 group shoot that HJW discovered evidence that unique hyperspectral signatures could be associated with oil seeps mapped by Thomas Dibblee (Fig. 3). However, there was no field verification of the findings until the 2000 study when HJW sent field crews to the areas of interest with a portable spectrometer, detailed mapping program, and GPS receiver.

Finding an oil seep

The 2000 study focused on portable field spectrometer measurements at three sites: More Mesa, Sulphur Mountain, and Osborne (Fig. 1). In addition, the Probe-1 airborne data cubes were reevaluated using the new field observations and measurements.



The field sites were determined by Pat Caldwell of HJW based on field experience, State of California Mines and Geology publications (especially Hodgson's 1987 contribution), and the Dibblee Geological Foundation (http://dibblee.geol.ucsb .edu/). Dibblee's geologic maps, along with the hyperspectral imagery, were draped over USGS Digital Elevation Models (DEMs) to facilitate the location of "Dibblee oil seeps" on the flight strips (Fig. 3).

HJW sent an experienced crew into the field during August 2000 with the field spectrometer and GPS receiver to confirm that the airborne spectral signatures found during the 1998 study were caused directly by oil seeps and oil-impacted soils (Fig. 4).

Using a portable hyperspectral sensor to collect spectral signatures at Dibblee's oil seep deposit (left) with ground view of same deposit showing partially dying oak tree (right) down- slope (Fig. 4).

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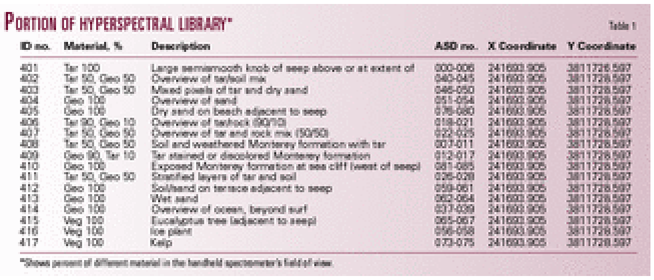
HJW discovered that a very large tar deposit characterized the primary "Dibblee oil seep" at Sulphur Mountain. In addition, there were numerous active oil seeps along the flank of the anticline. There were areas in or near the deposit where vegetation appeared stressed, but there were also areas where vegetation appeared to be vigorous. Botanical observations were collected along with seep samples.

At More Mesa a large oil seep deposit crops out along the ocean beach, while at Osborne numerous seeps and areas of impacted soil were mapped. The same observations and methodology used at Sulphur Mountain were carried out at these two other sites.

Characterizing an oil seep

An Analytical Spectral Devices (ASD) spectrometer capable of measuring VNIR-SWIR spectral response was used to spectrally characterize the oil seeps.



PORTION OF HYPERSPECTRAL LIBRARY*

Table 1

ID no.	Material, %	Description	ASD no.	X Coordinate	Y Coordinate
401	Tar 100	Large semismooth knob of seep above or at extent of	000-006	241693.905	3811726.597
402	Tar 50, Geo 50	Overview of tar/soil mix	040-045	241693.905	3811726.597
403	Tar 50, Geo 50	Mixed pixels of tar and dry sand	046-050	241693.905	3811728.597
404	Geo 100	Overview of sand	051-054	241693.905	3811728.597
405	Geo 100	Dry sand on beach adjacent to seep	076-080	241693.905	3811728.597
406	Tar 90, Geo 10	Overview of tar/rock (90/10)	018-021	241693.905	3811728.597
407	Tar 50, Geo 50	Overview of tar and rock mix (50/50)	022-025	241693.905	3811728.597
408	Tar 50, Geo 50	Soil and weathered Monterey formation with tar	007-011	241693.905	3811728.597
409	Geo 90, Tar 10	Tar stained or discolored Monterey formation	012-017	241693.905	3811728.597
410	Geo 100	Exposed Monterey formation at sea cliff (west of seep)	081-085	241693.905	3811728.597
411	Tar 50, Geo 50	Stratified layers of tar and soil	026-028	241693.905	3811728.597
412	Geo 100	Soil/sand on terrace adjacent to seep	059-061	241693.905	3811728.597
413	Geo 100	Wet sand	062-064	241693.905	3811728.597
414	Geo 100	Overview of ocean, beyond surf	037-039	241693.905	3811728.597
415	Veg 100	Eucalyptus tree (adjacent to seep)	065-067	241693.905	3811728.597
416	Veg 100	Ice plant	056-058	241693.905	3811728.597
417	Veg 100	Kelp	073-075	241693.905	3811728.597

*Shows percent of different material in the handheld spectrometer's field of view.

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A systematic measurement program was designed for the handheld spectrometer to determine the effect that different mixtures had on hyperspectral. The field crew was able to carefully measure ground surfaces that were composed of a single material or some mixture of materials using the handheld device. In particular, discrete areas were measured that had liquid oil or tar associated with different amounts of vegetation or soil (Table 1).

These data were processed to determine the spectral characteristics of different mixtures and also the difference between impacted and nonimpacted sites.

These ground measurements were used to better understand the spectral signatures being recorded within airborne pixels that cover 25 sq m. Developing an understanding of the effect of mixtures on spectral signatures is essential for properly interpreting the airborne pixels as they are very rarely composed of one material. In addition, these controlled ground measurements were used to build the spectral library so essential for deploying airborne and satellite technology with confidence elsewhere.

The field spectra collected with the ASD, GPS readings, field descriptions, and samples were then compiled and evaluated. The spectral signatures of both the ground and airborne data for similar materials were consistent. The sensor successfully detected the signal from surfaces impacted by oil.

HJW's research indicates that the full spectrum from visible through short wave-infrared light (VNIR-SWIR) needs to be carefully analyzed to differentiate oil-impacted pixels from those that are not impacted. New work processes were developed by HJW analysts with ENVI image processing software to successfully extract this subtle signal from the data cube.

To better understand sites, they "unmixed" the signatures of materials occurring within a pixel, allowing the identification of individual materials as well as providing information on their relative abundance.

The physical properties and composition of soils that were impacted with oil compared with soils that were not impacted were sufficiently different to allow differentiation of these areas by this sophisticated airborne sensor. The sensor's narrow bands and high signal-to-noise characteristics enable this differentiation. However, the sensor can only detect these differences if the hydrocarbon-based material is not excessively masked or too subtle.

Building a spectral library

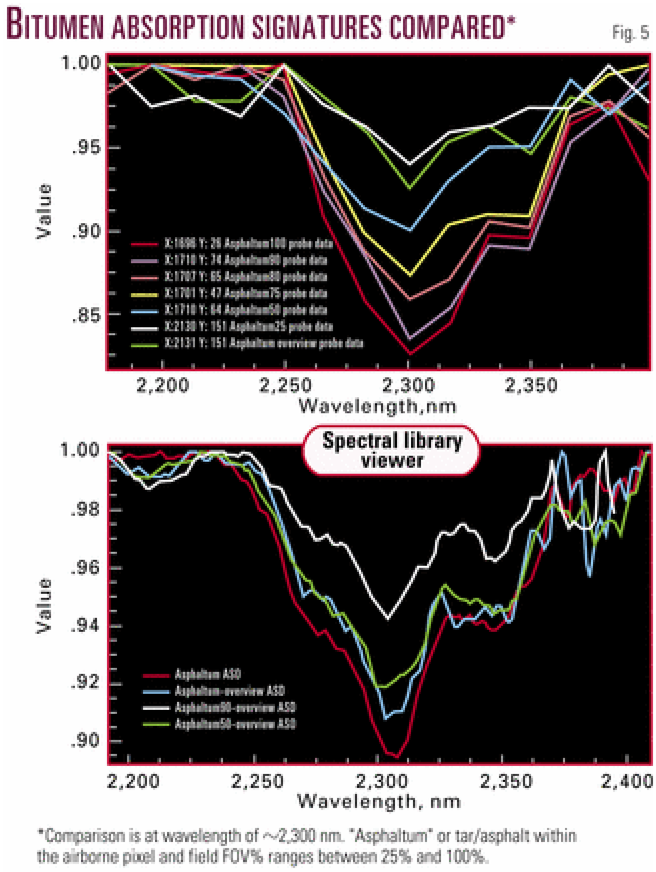
Hyperspectral sensors are unique in that they have enough spectral resolution to identify individual surface materials based solely on spectral signatures.

At each of the field sites in this study numerous spectra were collected of different materials (Table 1). These individual spectral signatures were archived in ENVI and ASCII format and integrated into a geographical information system (GIS) with global positioning system (GPS) coordinates, ground photographs, field observations, and ancillary data.

To build a robust library, a cost-effective, GPS technology that would ensure 1 to 5-m accuracy for the field sites was needed. Such a level of accuracy would enable other researchers to revisit the oil seep, outcrop, or impacted soil area in the future. It would also provide a consistent level of location accuracy for spectra, samples, and ground photographs in our GIS.

In addition, these ground control points could be used to improve the georectification of the hyperspectral imagery. To achieve the 1 to 5-m accuracy, we used a high-end, handheld GPS receiver, a moderately priced GPS receiver, and post-processed code-phased GPS data. Trimble's on-line mission planning program, SatView, was used to determine satellite availability and expected signal strength for the days the crew was in the field.

While we successfully used the portable spectrometer in our field program to acquire spectral signatures of surfaces covered 100% with oil and tar, we were unable to find pure pixels in the airborne imagery of these field sites.



BITUMEN ABSORPTION SIGNATURES COMPARED* Fig. 5

*Comparison is at wavelength of ~2,300 nm. "Asphaltum" or tar/asphalt within the airborne pixel and field FOV% ranges between 25% and 100%.

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Given the importance of understanding how the airborne sensor records varying amounts of tar, we systematically analyzed an airport runway that had undergone recent repaving with fresh tar-asphalt. We chose pixels within this runway that were visually composed of varying amounts of tar (from 25% to 100%) and compared this gradation to the ASD field data (Fig. 5).

For purposes of this article we focus only on the documented "bitumen" absorption feature that occurs ~2300 nm. The depth of this absorption feature correlates very well to the amount of bitumen (or tar and asphalt) in the field IFOV and airborne pixel (Fig. 5). The similarity between the coarser airborne spectra and the field data is striking and further substantiates using sophisticated VNIR-SWIR sensors for airborne mapping of oil-impacted surfaces.

The spectral library has to be used appropriately for reliable detection of oil-impacted surfaces. In addition, analysts need to understand the environmental conditions into which the library is being applied. Some issues that should be considered include:

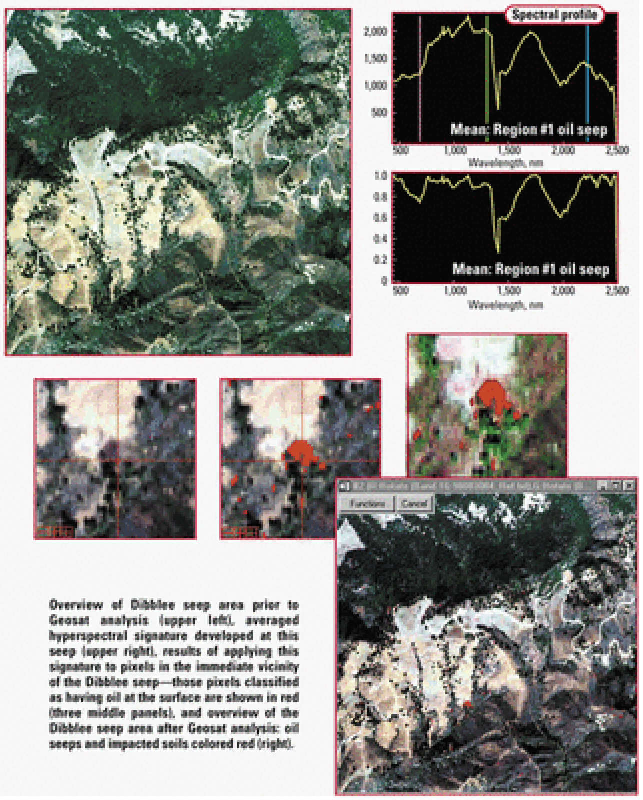
- Using only the bitumen absorption feature (Fig. 5) as the sole basis for detection is unreliable. Several zones along the VNIR-SWIR wavelength range need to be evaluated when determining the probability that a pixel has been impacted by oil.
- Using local training sites with known materials at the surface significantly improves the confidence level for detecting oil-impacted surfaces.
- Other researchers have noted a diagnostic feature occurs at 1703 nm. However, this is very close to a major water absorption feature that attenuates much of the signal.
- Calcite and dolomite have a pronounced absorption feature in the same wavelength range as bitumen. However, the shapes of the features are different and need to be differentiated.
- Sensors display some calibration differences when compared with each other. Fig. 5 displays the slight offset between the bitumen absorption feature recorded by the ASD handheld spectrometer and the Probe-1 airborne sensor. This difference has to be understood and integrated into the analysis.
- Many materials in our society can be hydrocarbon-based, including roads, parking lots, and roofs. Plastics and oil stains on surfaces can cause confusion. Depending on the objectives of the study, these materials need to be identified and eliminated from the interpretation.
- Onshore oil-impacted sites are rarely apparent in the various color combinations of original or spectrally compressed bands.
- Pixels with oil-impacted surfaces are usually mixed with other materials and have a weak signal. They rarely show as purer "endmember" pixels, minimizing the value and reliability of some of the more automated processing algorithms.

- The more experience the analysts have processing for the subtle hydrocarbon-based signal, the more reliable the interpretation.

Exploring for other oil seeps

ANALYSIS OF DIBBLEE SEEP AREA, CALIFORNIA

Fig 6



Overview of Dibblee seep area prior to Geosat analysis (upper left), averaged hyperspectral signature developed at this seep (upper right), results of applying this signature to pixels in the immediate vicinity of the Dibblee seep—those pixels classified as having oil at the surface are shown in red (three middle panels), and overview of the Dibblee seep area after Geosat analysis: oil seeps and impacted soils colored red (right).

Click here to enlarge image

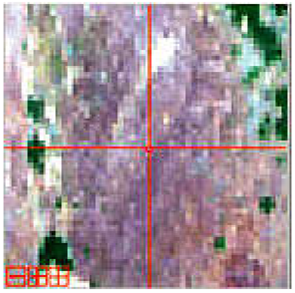
The spectral signature obtained at the primary Dibblee seep (Fig. 4) was extrapolated across the surrounding terrain (see Fig. 6) to determine if other seeps seen in the field could be detected. This conservative extrapolation successfully detected numerous small oil seeps/oil-impacted soils away from the main seep.

An area about 20 km east of the primary Dibblee seep was also analyzed (Fig. 7). This extrapolation clearly shows the technique maps significant oil seep-oil staining in several areas. Field verification of the interpretation is recommended with the results being used to improve the processing for generation of a more reliable map. The location of these impacted sites should be integrated with surface and subsurface structure and stratigraphy, historic and current oil field maps, and topography to better understand the exploration significance of these oil seeps/oil-impacted soils.

Integrating patterns of oil seeps and impacted soils derived from the hyperspectral imagery with

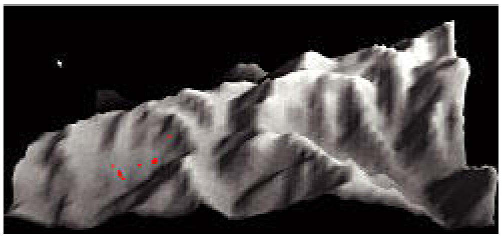
Extrapolation of technique beyond Dibblee seep area. Upper left shows unprocessed area, upper right shows processed scene with pixels classified as having oil seeps and impacted soils in red. Lower left and right are close-ups (Fig. 7).

digital elevation models (DEMs) can improve understanding the spatial relationship between oil-impacted surfaces and topography (see Fig. 8). Draping structural and stratigraphic maps over the same DEM (see Fig. 3) enables correlation of surface oil seepage with geology.



The exploration area of interest should be analyzed using a natural color rendering of hyperspectral imagery or some other imagery to eliminate manmade features with hydrocarbon-based material at the surface (asphalt-covered roads or plastics). Some linear features classified as oil-impacted surfaces can be seen along the plunging nose and flank of the anticline shown in Fig. 8B. These features may be sections of road composed of manmade asphalt or partially covered by oil associated with storm runoff.

Multiple applications

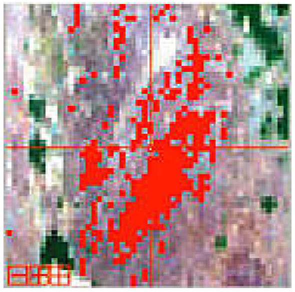


Integrating classified oil seeps and impacted soils (red patterns) with digital elevation models enables 3D correlation with geology. View looking north (Fig. 8a) where red patterns reveal distribution of oil seeps mapped by Thomas Dibblee (see Fig. 3).

This cooperative R&D effort provides fundamental support for deploying hyperspectral imaging to detect onshore oil seeps.

View looking southwest (Fig. 8b in the photo at right) at plunging anticline 20 km southeast of the Dibblee seeps shows several areas of oil-impacted soils and surfaces.

The oil-focused spectral library, combined with appropriate work processes, skill, and experience, will enable earth scientists to begin considering VNIR-SWIR imaging as another tool for improving onshore exploration. This study demonstrates that hyperspectral technology would be an effective tool to better understand the probability of oil seeps across remote geologic structures.[5]



Detecting oil seeps is a very important but relatively narrow application for hyperspectral imagery. These images are a very rich data set that can be used for many applications that support the exploration effort, including significantly improving surface geologic maps of stratigraphy, lithology, and structure. Indirect indicators of hydrocarbon seepage, such as altered soils (iron oxides, clay, calcite, etc., changes) and stressed vegetation can also be effectively interpreted from hyperspectral imagery.

In addition, while providing primary information to explorationists, hyperspectral data cubes can simultaneously be exploited for fundamental environmental information. This environmental information can include baselines, change detection, and the status of plant communities, vegetation vigor, infrastructure (wells, pipelines, tanks, etc.), water (holding ponds, dredged channels, etc.), local population, and impacted sites.[4]

Extracting this unique knowledge about the environment from the data cubes significantly reduces the risks associated with acquiring hyperspectral imagery exclusively for exploration as it enables managers to better understand and manage the asset during all stages of development.

Acknowledgments

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