

Environmental Application of Hyperspectral Remote Sensing: Managing Liability in an Age of Transparency*

M. E. Evans, L. B. Hall, P. A. Samuels, L. A. Jackson, G. L. Korenaga,
F. E. Hanrahan, D. P. Hagewiesche, M. J. Ainodion, *ChevronTexaco Energy
Research and Technology Company, USA;*
J. M. Ellis, *Ellis GeoSpatial, Inc., USA*

Abstract

Successful and responsible oil and gas exploration in sensitive environments involves monitoring for potential environmental impacts across large geographic areas over the full life cycle of a lease property. Remote sensing, a tool widely used in geologic investigations and the oil and gas industry, can be a valuable new tool for monitoring and tracking environmental change¹. The technology is especially effective for regional, "big picture" environmental management of large leases that may be remote, highly diverse, and difficult to access using conventional environmental sampling techniques. The technology can also aid in prioritizing specific field projects such as locating unrecorded pits. In the current computerized "Age of Transparency" wherein satellite imagery of cities or remote deserts can be downloaded by anyone from the Internet, environmental remote sensing can play an important role in the modern petroleum industry. This paper specifically focuses on hyperspectral sensors and their application to support environmental management in the petroleum industry including vegetation/habitat mapping and oil detection. An example from the ChevronTexaco Overseas Petroleum (CTOP) operated Campo Boscan oil field in Venezuela is presented.

Introduction

The life cycle of an oil field can typically be upwards of 50 years. This period includes the time from initial field surveys through drilling, production, decommissioning, and final property disposition. The environmental management of such large, often ecologically diverse and sensitive environments requires monitoring and data collection techniques that are detailed, reproducible, capable of sampling hectare-sized areas, and reasonably priced. Further, as countries adopt stringent environmental standards, it has become increasingly important to document potential changes in the environment such as might be related to petroleum production or those due to human encroachment and natural change. The ChevronTexaco approach to managing all operations has always been to minimize environmental impact.

Conventional environmental monitoring and sampling typically involves one or more field crews sampling soil, water, and other important media and submitting these samples to laboratories for chemical analyses. Often this requires obtaining access to property not owned or under lease, and does require that the project understand what the background condition is in the surrounding areas. The sampling process is usually iterative requiring multiple phases of field mobilization, analysis and reporting. Field-based surveys are costly, labor intensive, and because the sampling approach is "point-based," the context of the larger ecosystem can be misunderstood.

Remote sensing has been and continues to be a rapidly evolving field. The petroleum and minerals industries have used satellite-based sensors such as Landsat for over 30 years to map geologic structure, detect economic mineral assemblages and assist in the location of potential petroleum reservoirs. The current technology has moved to commercial airborne hyperspectral sensors capable of recording visible and infrared radiation. Mining companies that use the data to better understand their areas of interest currently own some of these sensors. The United States Geological Survey (USGS), other U.S. government agencies including the Environmental Protection Agency (EPA) and many international researchers are using hyperspectral data to

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study the biosphere, from forests to wetlands and coral reefs. As more images are collected and the spectra better understood, the science and supporting computer capabilities will continue to advance.

Chevron, and now ChevronTexaco, began evaluating hyperspectral remote sensing as an environmental monitoring tool in 1998. Hyperspectral sensors are particularly useful for imaging vegetation and for detecting vegetation change or health status. This application has previously been used by the forestry and agricultural industries to monitor pest infestations, water content and vigor following events such as hurricanes. ChevronTexaco has collected and continues to evaluate hyperspectral images obtained in the U.S., Nigeria, Indonesia and Venezuela. Areas of interest include baseline conditions, vegetation health status, success of re-vegetation efforts, free oil on the land surface, and in the Campo Boscan field of Venezuela, mapping and prioritizing former well drilling pits. The case study presented in this paper will discuss an airborne hyperspectral sensor, Compact Airborne Spectrographic Imager (CASI) as used in Venezuela. The imagery is currently being fully evaluated however preliminary results are discussed.

Noted science fiction author, Arthur C. Clarke described an "Age of Transparency" in his novel, "2061: Odyssey Three" wherein technology would allow us to observe each other with equal detail. Landsat 1, the first of 6 so-called multispectral satellite sensors, was launched in 1972, arguably beginning both the modern remote sensing era and the arrival of the age of transparency. Intelligent environmental stewardship will necessitate understanding the appropriate application of remotely sensed imagery to industrial projects worldwide. The data will be increasingly available and important to project managers, government agencies, non-governmental agencies (NGOs) and the general public.

Background

The human eye can detect the portion of the electromagnetic spectrum referred to as visible light. The colors of blue, green orange and red correspond to the spectral wavelengths of approximately 0.4 to 0.7 micrometers (μm). The primary source of spectral energy on earth is the sun, which emits a spectrum whose main wavelength interval is from 0.2 to 3.4 μm (ultraviolet (UV), visible, and infrared (IR) radiation). Portions of the incident solar radiation are reflected by the upper atmosphere, or absorbed by the atmospheric components of carbon dioxide (CO_2) and water vapor. The remaining unfiltered spectral energy is absorbed or reflected by objects on the earth's surface in a manner that conveys specific information about the object. The spectral signature is unique to the object or an object class and is based on the target's surface structure and molecular composition and on the incident radiation. Our eyes see this as color, size, shape, texture, etc. Modern remote sensing takes advantage of digital spectral imaging techniques to record reflectance information not visible to the human eye.

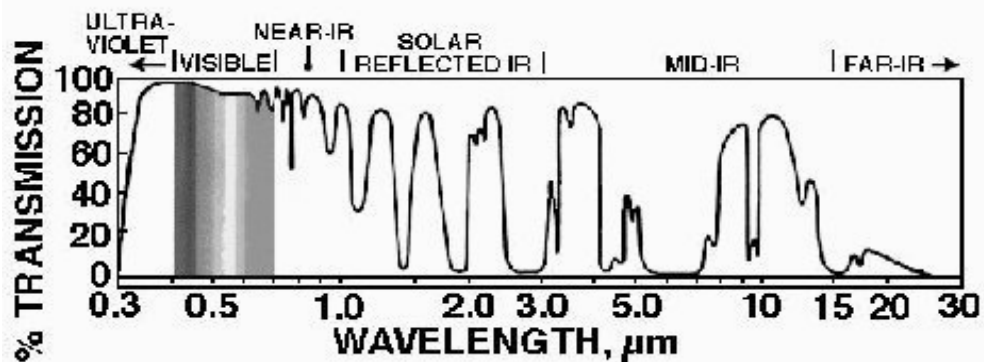


Figure 1: The electromagnetic spectrum²

About 100 years ago, remote sensing involved simple black and white photography obtained from hot-air balloons. As cameras and aircraft evolved, remote sensing moved to color photographic systems aboard airplanes and currently includes optical imaging sensors aboard satellites. One of the first such satellites, Landsat 1, was capable of recording 4 bands of spectral data on about an 80 m square picture element (pixel). There have been 6 Landsat satellites, the latest, Landsat 7, in 1999 (Landsat 6 did not make orbit), has 6 bands of spectral data with 30 m resolution (3 visible bands (0.45 - 0.7 μ m) and 2 near-to-reflective infrared bands (0.7 - 1.2 μ m)), 1 thermal band with 60 m resolution (10 to 12 μ m) and 1 black and white band with 15 m resolution. Since the first Landsat was launched, there have been a host of other so-called multispectral satellite sensors launched from other countries. Most of these satellite systems have been commercialized so that it is now possible to obtain a remotely sensed image of the entire earth's surface, or that of just a portion corresponding to a specific area of interest.

Landsat imagery has been used by the geological sciences for almost 30 years to successfully locate and develop important mineral resources, including oil. Multispectral data does not however, contain sufficient spectral detail to accurately identify specific mineral or vegetation types. Further, satellite imagery is often limited in its ability to spatially resolve objects on the earth's surface. Beginning in 1982 and continuing to the present, hyperspectral sensors mounted in survey aircraft have been providing the spectral detail necessary to observe the specific wavelength features that can accurately be called a spectral signature. Hyperspectral sensors are the most advanced optical remote sensing systems, with some capable of detecting and recording up to 228 spectral bands across the visible and medium wavelength IR portions of the spectrum (typically 0.4 to about 2.5 μ m). Pixel sizes are on the order of 3 to 5 m. The technology has been used worldwide to detect surface-water pollution discharges, map sensitive vegetation distribution, monitor agricultural plant communities, detect vegetation health adjacent to volcanic vents, and map the disturbance of natural drainage adjacent to canals near oil wells.

Space-based remote sensing also continues to evolve. Several high spatial resolution (1m or less) black and white sensors are currently in orbit. Only one true hyperspectral imager, Hyperion, is currently in orbit, however, several were lost during launch in the last few years. It is anticipated that additional sensors will be deployed in the next 5 to 10 years.

The cost to obtain remotely sensed data is also declining as the technology advances. Basic satellite imagery can be obtained for several thousands of US dollars (USD), with more advanced imagery or imagery mixtures costing tens to hundreds of thousands USD. Airborne imagery for a specified contract scene presently costs from several hundred thousand to near 2 million USD, depending on the size of the area under investigation and the sensor chosen. An option for lowering survey costs is to collect multiple contract scenes as the sensor flies across the country. This is referred to as a "group shoot." For the near future, it can be expected that the higher spectral and spatial resolution images will primarily be obtained through contract airborne surveys.

Environmental Remote Sensing

Environmental field surveys can be costly in remote areas, where the operations cover large tracts (e.g. pipelines), include water bodies or dense vegetation. Hyperspectral imagery has significant potential to aid environmental monitoring and detection efforts by providing spatially comprehensive data that can stand alone or complement existing, conventional environmental data products. Beginning in 1998, Chevron and now ChevronTexaco, began evaluating this technology to support a number of key environmental management decision making opportunities on and around existing operations including:

- Establishing environmental baselines
- Identifying plant species, distribution and health status
- Characterizing soil properties including oil staining
- Mapping ecological units and habitat distribution
- Surface-water quality monitoring

Environmental Baselineing

Environmental baselineing is the collection of data from a variety of media in an area of interest in order to document the pre-development conditions or to establish a current condition against which to compare future observations. Hyperspectral remote sensing is a useful new tool for the petroleum industry where detailed regional data is needed for site and lease management². The technology allows ecosystem scale information to be collected in areas with little or no ground access, although the interpretation is enhanced by some amount of ground-truthing obtainable even by helicopter. With a minimal amount of initial interpretation to understand existing conditions, the data can be stored and used as an asset that increases in value with time (“data in the bank”), or to solve specific project problems.

Vegetation Mapping

The general shape of reflectance curves for green vegetation is similar for all species and is distinct among all common, naturally occurring materials². Green plants exhibit a sharp intensity change over a short spectral distance that is formed by strong chlorophyll energy absorption near the red wavelength (0.6 μm) and high reflectivity at the near-IR wavelength (0.76 μm). As shown in figure 2, this curve shape is referred to as the red-edge. Note also in figure 2 the differences in spectral curves for vegetation, soil and water. Changes in the health status of plants are often expressed as a shift of this red-edge toward longer or shorter wavelengths. Although not detectable by the human eye, this spectral change can be indicative of senescence, water deprivation or toxic materials. Other spectral changes in vegetation detectable by hyperspectral techniques occur at wavelengths corresponding to water absorption (0.94 μm) or the actual total chlorophyll absorption depth at 0.6 μm . The image analyst will work collaboratively with ecologists and plant physiologists to create detailed maps of vegetation distribution and vigor. With the appropriate ground-truth data to identify actual plant stress causes, these maps can help environmental managers detect and prioritize potential impacts. Although vegetation spectra vary over the life cycle of the plant, spectral libraries are being compiled based on the efforts of many researchers. Some of these libraries are currently available on the Internet.

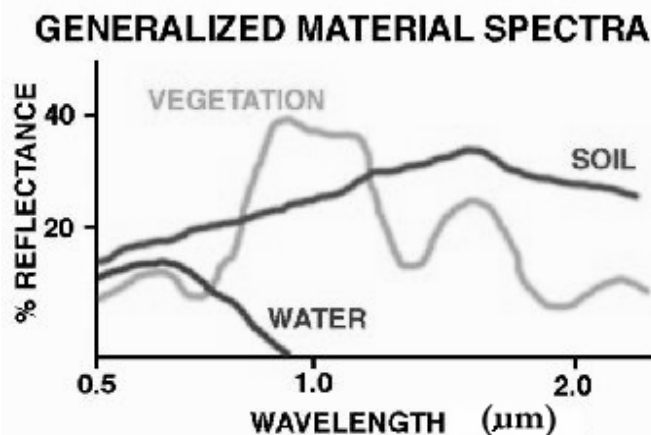


Figure 2: Generalized spectral signatures of soil, vegetation and water ²

Soil Properties and Oil Detection

Soil reflectance depends mostly on the surface moisture, organic content and mineral concentrations of the soil being imaged. Significant salinization, such as salt crust, evaporitic pans and highly alkaline surface soils are detectable using hyperspectral imaging².

An area of current research with respect to hyperspectral spectrometry is the identification and mapping of oil and oil stained soils. Starting as early as 1982, remote sensing scientists have been evaluating the detectability of land surface effects due to petroleum at depth. The Patrick Draw oil field in Wyoming is one area extensively studied throughout the 1980s using Landsat imagery^{3 4}. These studies focused on observed sagebrush color-tonal anomalies as recorded in satellite imagery. More recent investigations have focused on using a NASA sponsored imager, Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), to detect mineralogical affects due to ancient oil seepage⁵ or the direct spectral signature of oil⁶. A newer, 128-channel airborne sensor, commercially deployed as HyMap and Probe-1, is being evaluated for it's ability to directly detect oil^{7 8} due to specific spectral absorption features, especially in the shortwave-infrared wavelengths.

ChevronTexaco is currently evaluating the HyMap sensor's ability to detect oil at the land surface at sites in the US and Nigeria. A sensor known as Compact Airborne Spectrographic Imager (CASI) was used to image the Campo Boscan field and preliminary results will be discussed.

Ecological Units and Habitats

Vegetation and soil mapping using hyperspectral remote sensing can allow biologists, ecologists and other environmental risk assessors to determine habitat distribution and identify potential impacts to higher faunal species. Point source water discharges that impact stream species or shoreline habitats can be identified and addressed. Sensitive habitats can be identified in order to manage emergency response. Further, invasive, nuisance vegetation species that crowd out high-value native habitat can be identified for potential environmental benefits trading.

Water-Quality Monitoring

In surface water, algae, suspended solids, temperature, salinity, etc., can have distinct spectral characteristics detectable using hyperspectral imagery. Shallow biological communities such as coral reefs are currently being studied in several locations around the world⁹. Due to the unique spectral absorption characteristics of water, hyperspectral imaging has limited capability in mapping seafloor or lake-bottom conditions. Significant ground-truth data is required to make water-quality monitoring a viable remote sensing alternative, making this a less applicable technique in areas with limited access.

Oil Industry Applications

Either alone or in combination, the previous environmental remote sensing techniques have a range of possible applications for the petroleum industry including:

- Evaluating large tracts of land for environmental status prior to purchase, or for understanding liability when a lease is terminated or turned over to new operators
- Locating pipeline or other chemical leakage
- Tracking environmental change for community outreach and government reports
- Developing environmental sensitivity indices
- Monitoring restoration or remediation efforts
- Determining vegetative density and species type most appropriate for drilling/exploration sites

Campo Boscan Case Study

Background

The Campo Boscan Field is located approximately 40 kilometers (km) southwest of the city of Maracaibo, Venezuela on ranchland in the state of Zulia (figure 3). The field was discovered in 1946 by Chevron Overseas Petroleum Company (COPI) and is currently operated by ChevronTexaco under a 20 year Operating Service Agreement signed with Petroleos de Venezuela (PdSVA) in 1996. Current production capacity for the field is in excess of 115,000 barrels of oil per day (BOPD). Due to the weight of this crude and the reservoir depth, some of the largest pumping units in the world are employed. The primary product from this crude oil is

asphalt, which is manufactured in such places as the ChevronTexaco refineries in Perth Amboy, New Jersey and Pascagoula, Mississippi.



Figure 3: Location of Campo Boscan field within Venezuela

Encompassing an area of approximately 900 km², the field sits in a region referred to as the Maracaibo Depression. Predominantly flat-lying (slopes on the order of 2 % or less), the field is crossed by the 160 km long Palmar River that forms the predominant hydrologic influence in the area. The Palmar River basin includes approximately 2195 km² and drains into Lake Maracaibo after flowing for 30km across the Campo Boscan Field.

Native vegetation within the producing field has been largely substituted by pasture for cattle grazing. In fact, most of the producing wells sit within privately owned ranches. About 15% of the total field area is native riparian forest, located primarily along the Palmar River and its tributary banks. Cattle ranching and oil production have co-existed in this region for at least the last 50 years.

The Campo Boscan Development Project was proposed in 1996 and included expansion of the Zulia 9 processing station, the installation of new producing and injection wells, and the construction of new gathering and flow lines. One of the key components of this planned expansion was the pinpoint location and remediation of unlined, open oil/water pits. The Project's Restoration and Revegetation Plan would improve the local ecology by returning pit areas to a vegetated state, primarily grazing pasture in the ranching areas.

In 1996, Campo Boscan obtained orthorectified, digital color aerial photographs and satellite imagery from the sensor known as SPOT (**S**ysteme **P**robatoire d' **O**bservation de la **T**erre). These were used to construct an extremely accurate digital basemap for the program's Geographic Information System (GIS). CASI imagery was obtained simultaneously with additional aerial photography during December 2000.

As indicated earlier, ChevronTexaco has been evaluating hyperspectral technology from various sensors, since 1998. The Campo Boscan imagery was collected with several initial desired

outcomes: create an environmental baseline, help locate oil/water pits over the entire lease area and improve the existing vegetation/land use maps. The CASI sensor chosen for the Campo Boscan survey is a 48-channel, airborne hyperspectral instrument with a spectral range from 0.4-1.0 μm . This spectral range is referred to as the visual/near infrared or VNIR. The instrument's spatial resolution is 4m and the width of a surveyed flight line is 2.5 km. The entire Campo Boscan survey included 23 flight lines, although initial interpretation has been on portions of only 2 of these flight lines (figure 4). The availability of the orthorectified digital imagery in the GIS allowed a very high level of spatial accuracy to be obtained in the hyperspectral analysis.

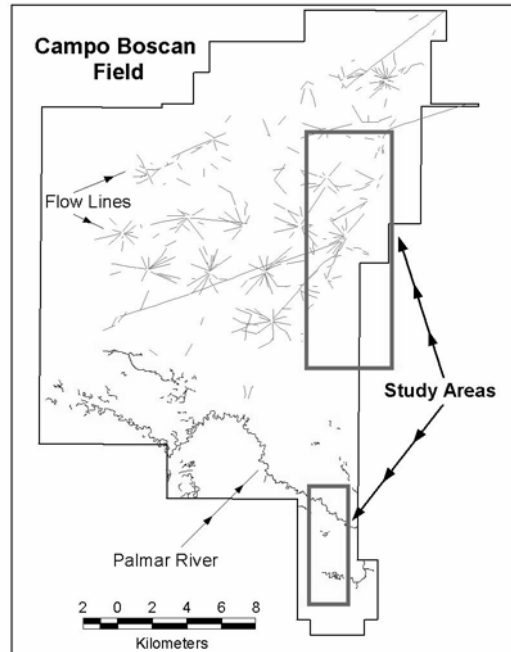


Figure 4: Location of CASI imagery analyzed in this study

Image Interpretation

One of the primary products of environmental hyperspectral data analysis is a vegetation map showing classes of vegetation such as trees, shrubs and grasses. Depending on the detail of the ground-truth data available, specific spectral signatures can be extrapolated across an entire scene allowing species types to be mapped. The Campo Boscan imagery has been preliminarily classified with 3 general vegetation types, pasture, shrub and forest, with sub-classes including over-grazed pasture, renewed pasture, canopy forest, and palm trees. Comparison of the analyzed image with a 1996 vegetation and land use map shows detail in the hyperspectral image that the previous mapping effort was unable to document. Along the Palmar river (figure 4, lower study area), classification of the CASI imagery enabled mapping the extent of forest and different vegetation types. In addition, the analysis also indicated that the forest cover along the Palmar river is spectrally different from the forest adjacent to the southern tributary as shown in figure 4. The distribution of vegetation in the south is also clearly different from that in the north, as is the presence of more bare soil. Field verification of the analysis would be necessary to understand the source of the spectral differences between the north and south parts of the flight line. It is clear however that the CASI sensor was very successful for vegetation distribution mapping.

Previous research has indicated the importance of measuring spectral response in wavelengths beyond what the CASI sensor is capable of measuring^{7 8}. In particular, a so-called bitumen absorption feature at 2.3 μm has been identified as a feature in pixels impacted with oil. The CASI imagery was noted to exhibit a consistent and unique spectral signature between 0.4 and 0.9 μm at limited pixels within the flight strips analyzed. The spectral signature of these pixels

displayed consistently decreasing values of reflectance across the visible light spectrum. The reflectance values of these pixels are also low in the near-infrared spectrum as compared to the surrounding pixels that contain either vegetation or bare soil. The GIS imagery suggests that at least some of these pixels could be related to pits that contained oil at the time of the survey. Field verification will be required to determine the cause of the spectral response and whether the CASI data will be applicable for mapping oil/water pits across the entire lease.

Conclusion

The petroleum industry has successfully used remote sensing to support exploration for over 30 years. New hyperspectral technology is currently being used by ChevronTexaco at sites around the world to support its ongoing commitment to environmental stewardship. Data collected from the Campo Boscan oil field suggest that the CASI sensor has excellent application for vegetation mapping, especially when linked to high spatial accuracy orthophotographs. The applicability of the sensor in oil detection studies may be highly dependent on local conditions that enable a subtle but unique visible-near infrared spectral signature to be observed. Opportunities for the petroleum industry include reduced costs, more detailed and exact environmental data, potential defensive applications and as a complement to conventional environmental monitoring. Development of the sensing technology will likely continue to advance, with more accurate and detailed satellite sensors launched in the years to come. As these satellites continuously circle the earth and collect environmental data, this publicly available information will contain details about petroleum operations worldwide.

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