

Field Spectrometry: Techniques and Instrumentation

Field spectrometry is the quantitative measurement of radiance, irradiance, reflectance or transmission in the field. Portable, battery powered spectroradiometers are typically used to make these measurements. In this paper, the discussion will be limited to: 1) visible to near infrared wavelengths, 300 to 2500 nm; 2) examination of geological, man-made, and vegetative materials; and, 3) instrumentation acquiring a continuous spectrum.

There are many reasons why it is desirable to perform spectral measurement in the field, not all related to remote sensing. Field spectra of ground targets that are homogeneous at the scale of the imaging sensor and collected using ambient solar illumination can be used to convert radiance images to reflectance (Conel et al., 1987a and 1987b). Often, field spectra of target materials are collected to allow for more precise image analysis and interpretation (Goetz and Srivastava, 1985). Field spectroscopy is also used as a tool to perform feasibility studies to understand if and how a process or material of interest can be detected using remote sensing. Field spectra of both the material(s) of interest and spectra of other materials present in the environment can be used to address such questions as:

- How much spectral resolution is required for detection?
- What spatial resolution is required for detection?
- What is the best time of year/day for detection?
- What signal-to-noise ratio is required for detection?

Aside from Remote Sensing, field spectrometers are used to make direct material identifications in the field rather than collecting samples for later laboratory analysis. Applications such as aircraft and satellite sensor calibration, development of remote sensing data exploitation methods, remote sensing feasibility studies, and geologic mapping greatly benefit from the use of field spectrometry.

Overview of Considerations in Experimental Design

The first step in the development of a field experiment is the definition of the overall experimental design. Unfortunately, the formulation of an appropriate experimental design is not always obvious. Issues such as the timing of the data collection, spatial scale of the field measurement, target viewing and illumination geometry, and the collection of ancillary data sets must be considered in light of the objectives of the study. It

is the lack of appropriate ancillary data sets that often make previously collected data sets unusable for new applications.

The collection of accurate spectra in the field also requires an awareness of the influences of the various sources of illumination, as well as atmospheric characteristics and winds. Instrument field of view, target viewing and illumination geometry, instrument scanning time, and the spatial and temporal variability of the target characteristics also must be considered. Frequently, the experimental design must be modified to account for the characteristics of the available instrumentation. Instrument characteristics such as signal to noise ratio, radiometric calibration, spectral resolution, spectrum acquisition time and angular field of view all place limitations on the types of spectral measurements that can be made in the field. For example, vegetation canopy spectra collected using a slow scanning instrument will sometimes have small wind-induced absorption features in portions of the spectra when the instrument was viewing more shadow.

Illumination

Two measurements are required in order to determine the reflectance or transmittance of a material: the spectral response of a reference sample and the spectral response of the target material. The reflectance or transmittance spectrum is then computed by dividing the spectral response of the target material by that of a reference sample. Using this method, all parameters that are multiplicative in nature, such as the spectral irradiance of the illumination source and the optical throughput of the field spectrometer, and present in both the spectral response of a reference sample and the target material, are mathematically eliminated.

When determining the reflectance or transmittance of a material in the field, an inherent assumption is the characteristics of the illumination are the same for the reference and target materials.

Variability of the illumination characteristics between the time the reference and target materials are measured will result in errors in the resultant spectra.

Characteristics of Natural Illumination

Spectral measurements are typically made in the field using ambient solar illumination. In the field, the target material is illuminated by three or more sources (see Fig. 1), each with its own spectral characteristics (Curtiss and Ustin, 1988). Unless the target is shadowed, direct solar illumination is the dominant source of illumination. Parameters such as solar elevation angle and atmospheric conditions will affect the overall intensity and spectral characteristics of direct solar illumination. Diffuse skylight illumination can contribute as much as 5-10% of the total illumination

reaching a surface. At shorter wavelengths, diffuse skylight can contribute as much as 20-25% of the total.

Scattered Light

The spectral characteristics of the illumination scattered off surrounding objects are determined by their reflectance characteristics. In the case of a forest clearing, as much as 20% of the illumination in the 750 - 1200 nm wavelength range can be attributed to sunlight scattered off the surrounding forest canopy (Curtiss and Ustin, 1988). The person and the instrument making the measurement are an important source of surroundings scattered light. Objects in the surroundings also effect the overall illumination of the target surface by obscuring a portion of the diffuse skylight and shading the target from direct solar illumination. The magnitude of both the diffuse skylight and light scattered from surrounding illumination components is determined by the solid angle subtended by these sources when viewed from the reference frame of the target surface.

The surface texture of the material being measured also effect the relative proportion of the various sources of illumination. When compared to a smooth surface, a surface with a rough texture will tend to have a higher proportion of illumination from the diffuse and scattered sources relative to direct solar illumination (Curtiss and Ustin, 1988).

Characteristics of Artificial Illumination

The use of artificial illumination allows:

- More control over illumination and viewing geometry
- Increased control over sample geometry
- Operation during non-optimal conditions (e.g. cloud cover or at night)
- Measurement of reflectance and transmittance in the deep atmospheric absorption bands.

Several problems with using artificial illumination include: 1) difficulty in maintaining a constant distance between the sample or reference and the light source when measuring samples with irregular geometry; and 2) lights can 'cook' vegetation samples (water loss, chlorophyll degradation).

A typical lamp configuration for indoor use is shown in Figure 2. The light source can be either incorporated into the field spectrometer (often precluding the use of solar illumination) or can be provided in the form of an optional accessory that mounts to the light collecting optics of the instrument.

Atmospheric Characteristics

Atmospheric Transmission

Absorbing molecules in the atmosphere strongly modify the incoming solar irradiance (Goetz, 1992). All of absorption features described in this section will increase in intensity as the atmospheric path length of the incoming solar radiation increases (e.g. with changing solar elevation angle). By far, water vapor is the strongest modifier of the incoming solar spectrum (Gao and Goetz, 1990). Water vapor has absorption features spanning the solar reflected region of the spectrum (see Fig. 3), and varies both spatially and temporally.

Carbon dioxide has strong features in the 2000-2200 nm range (see Fig. 4), a region of major interest for the identification of layered silicate minerals (Goetz, 1992). Carbon dioxide is a well mixed gas, thus the intensity of the absorption features associated with carbon dioxide are not as variable as those of water vapor, but the intensity does decrease with increasing altitude. Other major atmospheric components that influence the atmospheric transmission spectrum are shown in Figure 5.

Clouds

The presence of partial cloud cover is indicative of highly spatially and temporally variable atmospheric water vapor (Gao and Goetz, 1992). Because of the large influence of water vapor on the atmospheric transmission (see Fig. 3), variability of atmospheric water vapor between the time when the reference and target measurements are made will result in errors in the resultant spectrum. Minimizing the length of time between the measurement of the reference sample and the target can reduce the error due to atmospheric water vapor variability.

While they are difficult to see and often appear inconsequential, the presence of cirrus clouds tends to produce significant variability in atmospheric water vapor (Gao and Goetz, 1992) that can be measured by the field spectrometer. Simply standardize the instrument on the reference panel, and then continue to view the reference panel with the instrument. If the atmospheric conditions are stable, the computed reflectance of the panel will be a flat spectrum with near 100% reflectance. If atmospheric conditions are unstable, the computed reflectance of the panel will vary over time and will show absorption minima or maxima (depending on whether atmospheric water vapor is increasing or decreasing) at the wavelengths corresponding to the water vapor absorption features. In this way, it can be determined whether spectral data with sufficient accuracy can be acquired.

In addition to the errors produced by time varying

atmospheric water vapor, partial cloud cover also greatly increases the intensity of diffuse skylight illumination (Curtiss and Ustin, 1988). This tends to “fill in” shadows and reduce the contrast between surfaces with dissimilar surface textures. If the goal is to collect field spectra for image calibration or interpretation, spectra should be collected under illumination conditions similar to those at the time the image was collected.

Wind

Wind can be a source of error if the material being measured moves during the time the spectrum is acquired. If a spectrum is slowly scanned, changes in the amount of shadow in the instrument field-of-view will result in erroneous “features” in the spectrum. Vegetation canopies are especially susceptible to wind induced errors, due to their large proportion of shadow. Instruments using an array detector, or those that scan the spectrum rapidly, are not significantly affected by wind.

Vegetation

The absorption features seen in vegetation spectra are all related to organic compounds common to the majority of plant species (Peterson et al., 1988; Gao and Goetz, 1992). The information about a plant canopy is contained in the relative intensity of the various absorption features rather than in the presence or absence of a specific absorption feature. The major spectral absorption features can be attributed to plant pigments (chlorophylls, xanthophyll, and carotenoids) and water. Other, minor, absorption features are attributable to other chemical components; these include cellulose, lignin, proteins, starches, and sugars. Non-photosynthetic components of the canopy have spectra dominated by absorption features attributed to lignin and cellulose.

Because of the complex three-dimensional geometry of a plant canopy, light returned from the canopy is a composite mixture of multiply reflected and/or transmitted components (Curtiss, 1990; Curtiss and Maecher, 1991; Curtiss and Ustin, 1989). The canopy level optical signal is dependent upon illumination and viewing geometry, canopy structure, leaf optical properties, and the optical properties of other vegetative and non-vegetative components in and below the canopy. The strong dependence on illumination and viewing geometry can be seen in Figure 6. Both the overall brightness of the canopy and the shape of the spectral signature (e.g. the red to infrared ratio for the canopies in Figure 6) are reliant on the illumination and viewing geometry. It is only by controlling the viewing and illumination geometry that changes in canopy reflectance attributable to the canopy itself can be detected.

True differences in reflectance between several canopies may be due to either a difference in the canopy structure or in leaf/needle optical properties (Curtiss and Maecher, 1991). Using the data presented in Figure 6 as an example, for almost all viewing geometries, a conifer canopy will appear darker in the infrared than the broadleaf canopy, even though the reflectance of the individual needles and leaves may be almost identical.

Observed differences in canopy level reflectance may be attributable to differences in leaf level optical properties or other large-scale structural properties of the canopy. Important structural properties include

- leaf/needle size
- leaf/needle density at the branch level
- number of years of needles retained (conifers)
- branching angles

When differences are observed between canopies of the same species, it is almost always due to differences in canopy or branch level structure.

Rocks, Soils and Man-Made Materials

Unlike vegetation, the shape of the spectral signature of rocks and soil tend to be invariant with varying viewing geometry. Due to changes in the amount of shadow in the field-of-view of the spectrometer, the overall brightness of the observed spectrum does change with illumination and viewing geometry. Absorption features in the spectra of rocks and minerals (see Figure 7) are due to the presence of specific molecular groups and are often diagnostic of the minerals present in the sample (Abrams et al., 1877; Hunt, 1980).

The dependence of the optical properties of man-made objects on the viewing and illumination geometry fall somewhere between that for vegetation and for rocks and soils, depending on the amount of light transmission through elements of the target and on the surface texture of the object. The reflectance spectra of objects with translucent elements and highly textured surfaces have an angular dependence more like vegetation, while those with opaque elements have an angular dependence more like spectra of rocks and soils.

Instrumentation

Spectral Resolution vs. Sampling Interval

While the terms “spectral resolution” and “spectral sampling interval” are often used interchangeably, they refer to very different characteristics of a spectrometer. Spectral resolution is a measure of the narrowest spectral feature that can be resolved by a spectrometer. It is also defined as the full width at half maximum

(FWHM) response to a spectral line source. The spectral sampling interval of a spectrometer is the interval, in wavelength units, between data points in the measured spectrum.

For hyperspectral Remote Sensing, a spectral resolution of about 10 nm and a spectral sampling interval of about 2 to 3 nm is required (Goetz and Calvin, 1987, Goetz, 1992b). The requirement for 10 nm spectral resolution is driven by the spectral resolution of the hyperspectral sensor (about 10 nm). A spectral sampling interval of about 2 to 3 nm provides 3-4 data points in the field spectral data. This ÓoversamplingÓ of the spectrum results in less degradation of spectral resolution when resampling the field spectral data to match the wavelengths of the hyperspectral sensor channels. Analysis methods utilizing derivative spectra greatly benefit from oversampling the spectrum.

Spectrometer Design

Spectrometers used in currently available field spectrometers are either based upon a fixed grating and an array detector or a single element detector and a scanning grating. One of the drawbacks of an array-based spectrometer is that the signal-to-noise ratio (SNR) is tied to the sampling interval as well as the spectral resolution (Smith, 1992). In a scanning spectrometer, the SNR is independent of spectral sampling interval. Array detectors in the 350 -1000 nm region of the spectrum (VNIR) have sufficient sensitivity to allow spectra to be collected with spectral resolutions well above the 10 nm resolution required for hyperspectral remote sensing studies. Typical VNIR spectrometer designs provide 3 to 5 nm spectral resolution with a spectral sampling interval of better than 2 nm.

In the VNIR, fixed grating array detector-based spectrometers provide the best performance for most Remote Sensing.

Due to the rapid fall-off in energy of the solar spectrum in the 1000 to 2500 nm region of the spectrum (SWIR), spectrometer design is strongly driven by the need to maintain an acceptable SNR. In general, a loss of SNR is not acceptable in exchange for decreased spectral sampling interval, thus the use of an array detector in the SWIR spectral region generally precludes spectrum oversampling. While scanning spectrometers do not have this limitation, they have the drawback of not being able to measure all wavelengths simultaneously. This can result in errors due to changes in the target during the measurement of the spectrum; however, this limitation is overcome by rapidly scanning the spectrum.

Traditionally, scanning SWIR spectrometers have used lead sulfide (PbS) detectors. Due to the lack of sufficient frequency response, the use of PbS detectors precludes rapid scanning. Indium gallium arsenide (InGaAs) detectors have the high frequency response required for rapid scanning (less than 100 milliseconds to scan from 1000 to 2500 nm). InGaAs detectors have the added advantage of having a higher sensitivity than PbS and do not require an optical chopper, as does PbS. These increases in performance over PbS allow the design of a rapid scanning spectrometer with equivalent or better SNR performance than a PbS array detector based spectrometer. A scanning design has the added advantage of having a spectral sampling interval that is less than one fifth the spectral resolution, without a reduction in SNR.

Additional Illumination

While it is possible to include the illumination source within the spectrometer, this limits the applications that can be addressed and the types of targets that can be measured. Because of the need to hold illumination and viewing geometry constant between the field and image spectral data, field spectra collected for either hyperspectral sensor calibration or for direct comparison with hyperspectral image data are best collected using ambient solar illumination. The use of a built-in light source precludes the measurement of radiance or irradiance or targets such as vegetation, with a complex three-dimensional structure, that can only be measured in the field using solar illumination.

Spectrometer Field of View

Existing field spectrometers use one of two basic approaches to collect light energy and deliver it to the spectrometer. In some spectrometer designs, foreoptics are used to form an image of the target on the entrance slit of the spectrometer. This approach results in a ground field of view (GFOV) that has the same shape as the spectrometer entrance slit (often a rectangle with a height to width ratio of more than 10:1). If more than one spectrometer is used in an instrument (e.g. a VNIR and SWIR spectrometer), it is often difficult to ensure both spectrometers are viewing the same GFOV. The use of optical fibers to deliver the light to the spectrometer results in a circular GFOV.

Splitting the optical fiber bundle within the instrument to deliver light to the various spectrometers accommodates the use of more than one spectrometer. The size of the GFOV is determined by the angular field of view of the instrument and the distance to the target. While optics can be added to modify the angular field of view of a field instrument, this is often practical only for those instruments utilizing optical fibers for light collection.

Experimental Design

Time of Day / Year

The timing of collecting the field data is important if field spectra are to be used to calibrate or interpret a hyperspectral image. Reflectance spectra used to interpret a hyperspectral image should be collected under illumination conditions similar to those when the image was acquired.

Time of day and date are the major controlling factors of direct illumination geometry, while atmospheric conditions relating to scattering and clouds are the major factors controlling the geometry and relative intensity of indirect illumination (Curtiss and Ustin, 1988).

If field spectra are to be used to convert a hyperspectral sensor image to a reflectance spectrum, spectra should be acquired simultaneously with image acquisition. If this is not possible, a water vapor correction should be made to the image prior to its conversion to reflectance (Gao and Goetz, 1990) data.

Sampling Strategy

The selection of a particular sampling strategy should be based upon the objectives of the study. If the objective is to determine the detectability of a target material or of a process affecting the spectral signature of a target material, the sampling strategy must encompass examples of the target material under all expected conditions as well as all other background materials. Consideration must be given to all the processes modifying target and background spectral signatures; these include illumination, slope and aspect, and target surface architecture.

Adequate collection of vegetation is even more problematic due to the wide range of processes that affect the spectral signature. These include soil chemical properties, soil reflectance, water availability, time of day, time of year, cloud cover, temperature, and relative humidity.

If the purpose of a study is to understand how a process affects the spectral signature of a target, without consideration of how background materials and other sources of variability effect the spectral signature, variance from sources other than the one of interest should be minimized in the selected targets. This is achieved by carefully controlling viewing and illumination geometry, often in a laboratory. This type of study is often performed as a feasibility study prior to a full study evolving collection of spectra of background material.

Viewing Geometry

The selection of an appropriate viewing geometry depends upon whether the spectra are used for image

analysis or for a feasibility study. For image analysis, a viewing geometry similar to the airborne sensor is required. For a feasibility study, it is possible to eliminate much of the variance present in an image data set by fixing the viewing and illumination geometry. For vegetation, spectra can be acquired at the spatial scale of the leaf/needle, branch, or canopy. Canopy level spectra are most suitable for image analysis and interpretation. Rarely can leaf/needle or branch level spectra be used directly to interpret an image. Leaf/needle and branch level spectra are useful to understand how the canopy level spectra are influenced by changes in leaf/needle and branch spectral changes, as opposed to changes in the canopy structure.

Ancillary Data Sets

Collection of appropriate ancillary data sets is as important as the collection of field spectra. The measurement of processes and material properties directly influencing, or correlated with, the collected spectra are essential to the understanding of the variance observed in a hyperspectral image data set. It is often necessary to collect a set of spectra with ancillary data in order to validate predictions made using the main field spectra plus an image data set.

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Figure captions:

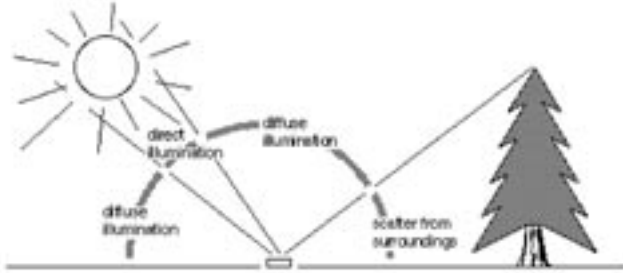


Figure 1. The primary sources of illumination. Note that it is possible to have several sources of light scattered off of surrounding objects, each with its own unique spectral distribution.

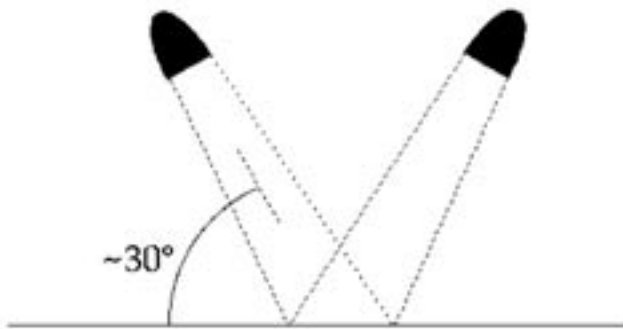


Figure 2. A typical lamp configuration for artificial illumination; the sample is viewed with the collecting optics of the spectrometer nadir to the sample. To use this setup, place one or two 200 to 500 Watt quartz-halogen cycle tungsten filament lamps (~3400;K color temperature) in housings with aluminum reflectors about 1 meter above the surface being measured.

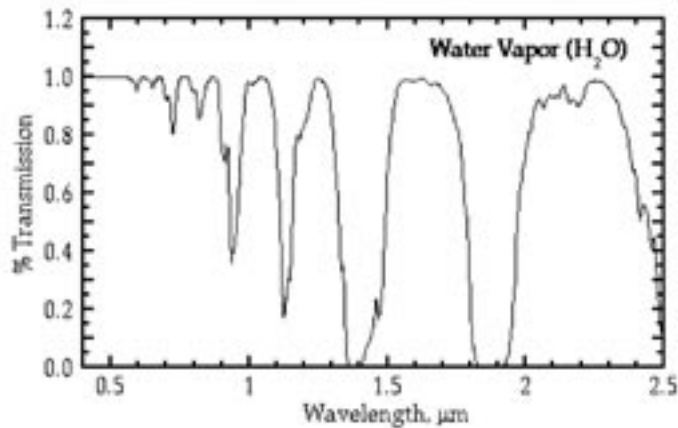


Figure 3. Transmission spectrum of water vapor under typical atmospheric conditions.

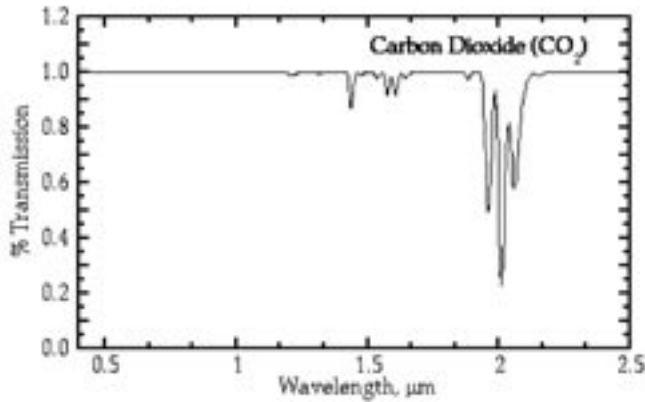


Figure 4. Transmission spectrum of carbon dioxide under typical atmospheric conditions.

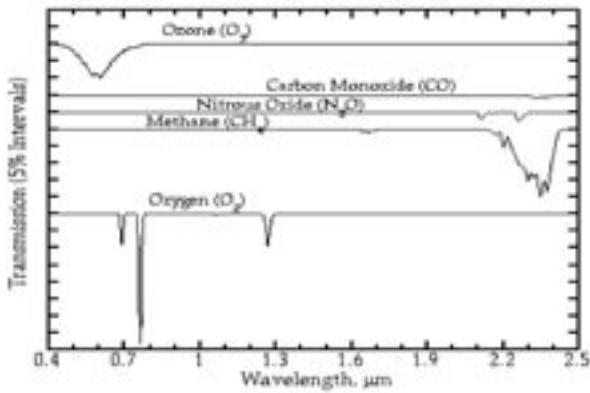


Figure 5. Transmission spectrum of various gases under typical atmospheric conditions.

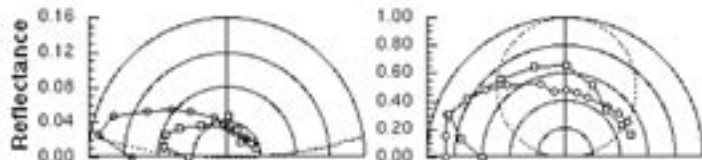


Figure 6. Bi-directional reflectance functions (BRDF) of a conifer, Mugo Pine, (circles) and a broadleaf shrub, Viburnum, (squares). For reference, the BRDF of a Lambertian reflector is plotted as a dashed line. The plot on the left is for a red band (650 nm) and that on the right is for a near infrared band (850 nm). Both canopies were illuminated from the left at an elevation of about 30°.

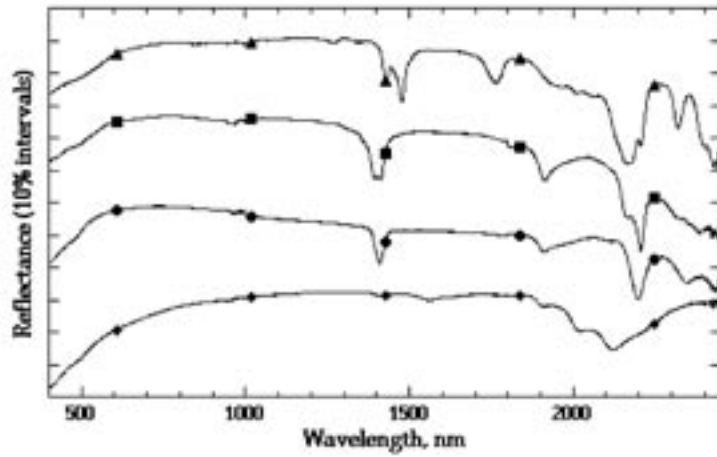


Figure 7. Reflectance spectra of alunite (triangles), kaolinite (squares), illite (circles), and buddingtonite (diamonds) measured with a FieldSpec FR field portable spectroradiometer.