A Set of Spectral, Radiometric and Spatial Measurement Requirements for Imaging Spectrometers that Operate in the 400 to 2500 nm Spectral Range

Robert O. Green and Thomas G. Chrien
NASA / Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA., 91109

ABSTRACT

New spaceborne and airborne imaging spectrometers are being proposed and developed to derive properties of the Earth's surface from measurements of the upwelling radiance in the solar reflected spectrum. To achieve these objectives the measurements must meet a minimum set of spectral, radiometric, and spatial requirements. Based on experience with the AVIRIS sensor since 1987, a set of baseline spectral, radiometric, and spatial requirements are offered.

1. INTRODUCTION

Imaging spectrometers measure spectra as images for a wide range of science research and applications objectives. There are a number of existing and planned airborne and spaceborne imaging spectrometers with objectives to derive properties of the Earth's surface using measurement from the solar reflected portion of the spectrum. The primary measurement requirements for these instruments may be viewed in terms of spectral, radiometric and spatial characteristics. Requirements for these primary properties may be described in terms of range, sampling, response, stability, uniformity, precision and accuracy. For example many of the existing and planned imaging spectrometers have spectral ranges from 400 to 2500 nm, radiometric ranges from 0 to max Lambertian reflected radiance, and spatial ranges from 5 to 50 km. This paper offers a set of baseline spectral, radiometric, and spatial measurement requirements for imaging spectrometers that operate in the solar reflected spectrum. These requirements are based in large part on the experience with the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) (Green et al, 1998a).

2. SPECTRAL REQUIREMENT

The basis for many of the spectral measurement requirements for imaging spectrometers that operate in the solar reflected spectrum derive from the nature of the upwelling spectral radiance arriving at the instrument. Figure 1 shows a MODTRAN (Berk et al 1989) modeled upwelling spectral radiance spectrum from 400 to 2500 nm at 1 nm spectral resolution. The upwelling spectral radiance is dominated by narrow absorptions caused by the molecules in the Earth's atmosphere. The spectrum output by an imaging spectrometer is the result of a convolution of the input upwelling spectral radiance with the imaging spectrometers spectral channel sampling and response functions. Errors in the knowledge of the spectral channel sampling and spectral response functions cause errors in the output radiance spectrum. Figure 2 shows the errors in output radiance that are induced by errors in the spectral sampling of 10, 5, and 1 percent magnitude. These errors mimic and distort the spectral signatures of materials that are the science research and applications objectives of imaging spectrometers. This sensitivity to the ubiquitous atmospheric absorption causes the spectral requirements for an imaging spectrometer to be most critical in the solar reflected portion of the spectrum (Green 1998b). In the context of this sensitivity a set of spectral measurement requirements are offered.

Measurements with laboratory spectrometers, field spectrometers, and airborne imaging spectrometers have shown that spectral sampling range from 400 to 2500 nm is appropriate for objectives in a variety of science research and applications. Molecular absorptions and constituent scattering properties provide spectral signatures that are relevant spanning the disciplines of ecology, geology, coastal and inland water, the atmosphere, environmental hazards, snow and ice hydrology, biomass burning, urban environments, and others. These spectral absorption and scattering are well resolved with spectral sampling of 5 to 15 nm. A spectral response full width at half maximum (FWHM) of 5 to 15 nm matching the sampling is sufficient to record and allow separation of the signatures of materials found on the Earth's surface. In addition are requirement that the spectral response function be easily modeled such as a Gaussian offers an important advantage during spectroscopic measurement analysis. Additional flexibility in spectral re-sampling is obtained if the sampling interval is half the spectral response function interval. However, for data rate, optical design, signal-to-noise ratio reasons, imaging spectrometers are typically designed with spectral sampling intervals matched to the spectral response function intervals. Spectral stability is viewed as the variation of spectral channel position and response function between different image acquisitions. A sensitivity analysis has been performed on the requirement for spectral calibration for imaging spectrometers in this portion of the electromagnetic spectrum (Green 1998b). This work implies a baseline stability requirement of 3% and a goal of 1 % for change in spectral properties from image to image. Spectral uniformity is viewed as the known variation in spectral sampling and spectral response throughout an image. Again a requirement of 3% and goal of 1% is derived from the spectral calibration sensitivity analysis. This level of uniformity allows spectra from one portion of an image to be compared with spectra from another portion of the same image. Spectral precision is viewed as the unknown variation in spectral sampling and spectral response throughout an image. Because precision error is expressed as an error in spectral calibration the requirement is at minimum 3% with a 1% goal. Spectral accuracy is described as the knowledge of the spectral sampling and spectra response function through time. A spectral accuracy requirement of 3% and goal of 1% is essential to achieve objectives of imaging spectrometers measuring spectra in the solar reflected spectrum for science research and applications at the Earth's surface.

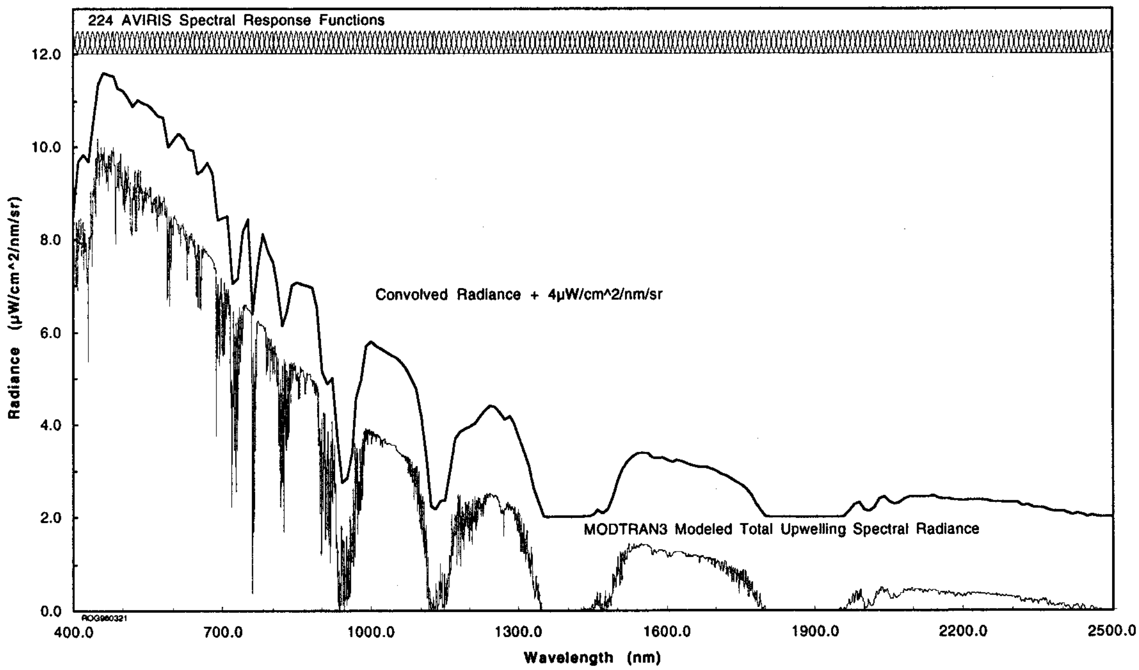

Figure 1. Model and convolved upwelling spectral radiance for an imaging spectrometer.

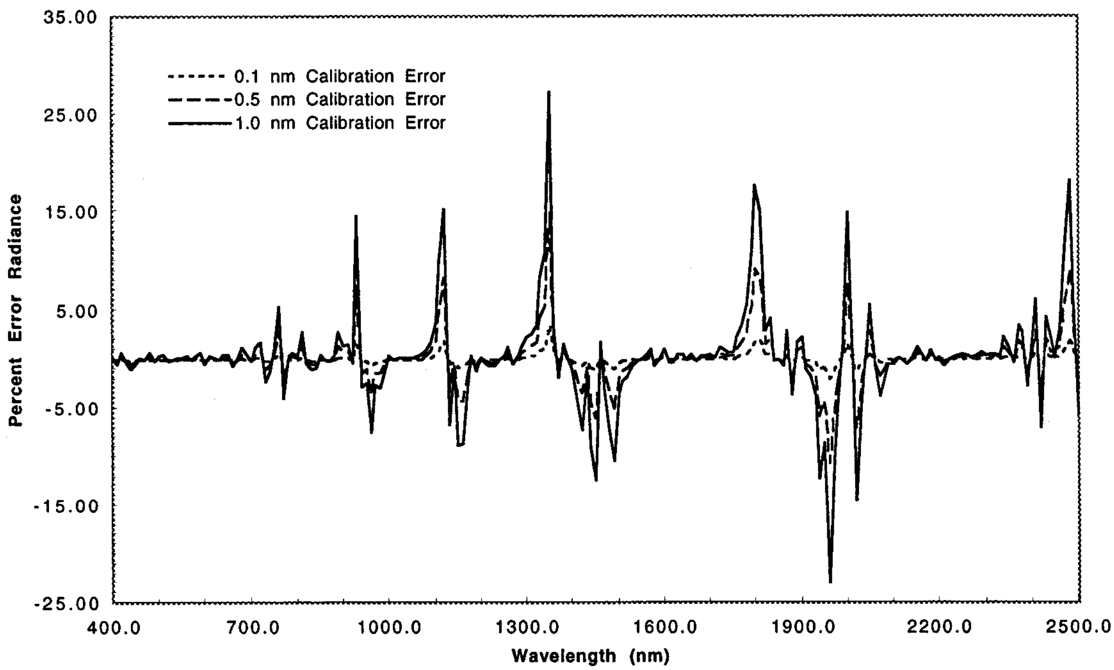

Figure 2. Error induced in measured radiance due to error in knowledge of spectral channel position.

3. RADIOMETRIC REQUIREMENT

The radiometric requirement for imaging spectrometers generally derives from the objective to measure many different surface constituents in isolation and in mixtures under a range of illumination conditions. A baseline radiometric range requirement for imaging spectrometers is from 0 to the maximum Lambertian reflected radiance. Figure 3 shows the maximum Lambertian reflected radiance from 400 to 2500 nm. This range is appropriate for almost all Earth materials. However, a greater radiometric range is required for hot targets such as fires and for materials with strong peaks in their bidirectional reflectance distribution function. Fine radiometric sampling is required to measure dark surface materials. Dark materials include water, vegetation in the visible and short wavelength infrared portion of the spectrum, as well as an material with low illumination intensity. To measure most dark targets radiometric sampling interval of better than 0.05 μW/cm^2/nm/sr is required. This radiometric sampling requirement leads to 12 bits or greater signal digitization. The radiometric response requirement is that the response be linear with radiance or a well known function. Radiometric stability is viewed as the variation in radiometric sampling and response for image to image. With complex and mixed spectral signatures found within a signal image the radiometric stability must approach 1%. Onboard calibrators may be used as a strategy to bring relative radiometric knowledge to the 1% level. However, on board calibrators may themselves vary through time. Radiometric uniformity refers to the variation in radiometric sampling and response throughout an image. The more uniform the system, the more easily characterized and calibrated. Variation in radiometric uniformity may be accepted only to the level it may be measured and compensated to near the 1% level. Radiometric precision refers to the variation in radiance output from consecutive measurements of the same stable target. Precision may by reported as the signal-to-noise ratio or noise equivalent delta radiance. The desire to measure the spectral properties of dark materials and make useful measurement in non optimal illumination conditions drives the precision requirement. A precision requirement consistent with current spectroscopic analysis algorithms is given in terms of signal-to-noise ratio in Figure 4. This precision requirement is based on a signal-to-noise ratio of 500:1 in the continuum regions for the surface reflected radiance from a 0.25 reflectance target illuminated with a 45 degree solar zenith angle through a mid latitude summer atmosphere. Figure 5 shows the modeled radiance for these conditions. In the visible portions of the solar reflected spectrum only a fraction of the total radiance arriving at the imaging spectrometer has been reflected from the surface. This raises the precision requirement for surface materials in the visible portion of the spectrum. A high signal-to-noise ratio is increasingly being shown as critical for separating and measuring the subtle molecular absorption and component scattering signatures of materials found on the Earth's surface. Radiometric accuracy is the knowledge of the relationship between the imaging spectrometer output radiance and the actual radiance. Current systems are exceeding 5% absolute radiometric accuracy. For model based analyses of high signal-to-noise ratio data an absolute radiometric accuracy of 1% or better is needed. Currently, empirical methods are used to achieve better than 1% apparent accuracy. These methods often involve acquisition of ground measurements and forcing agreement with the imaging spectrometer data for the ground targets. To move beyond these empirical methods, a radiometric calibration accuracy approaching 1% is required.

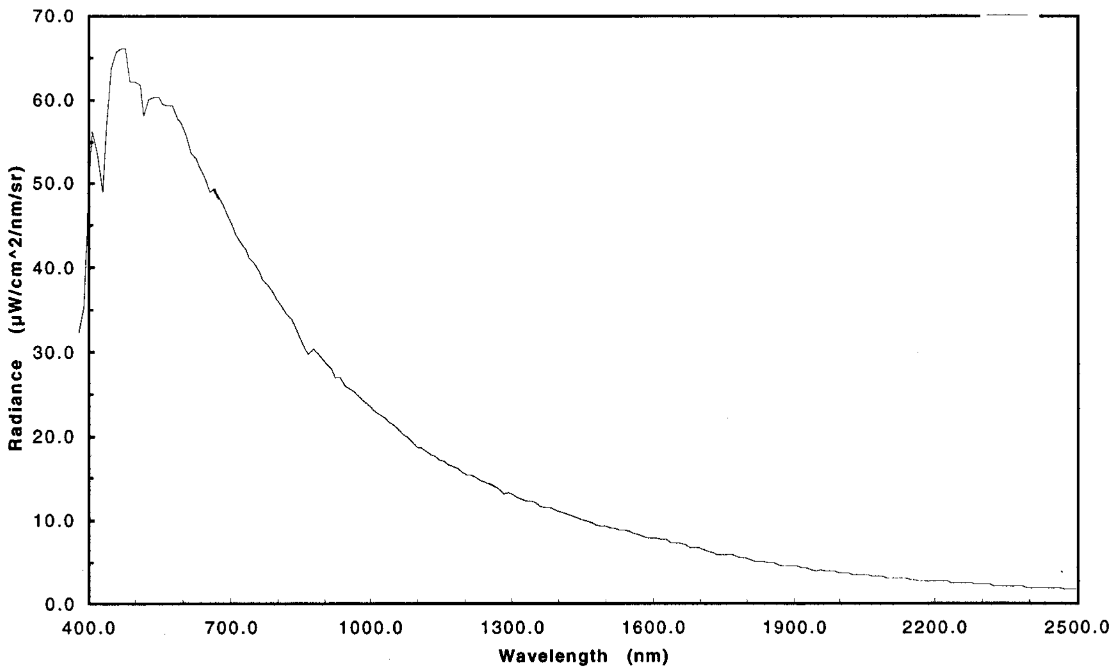

Figure 3. Maximum Lambertian reflected radiance in the solar reflected spectrum.

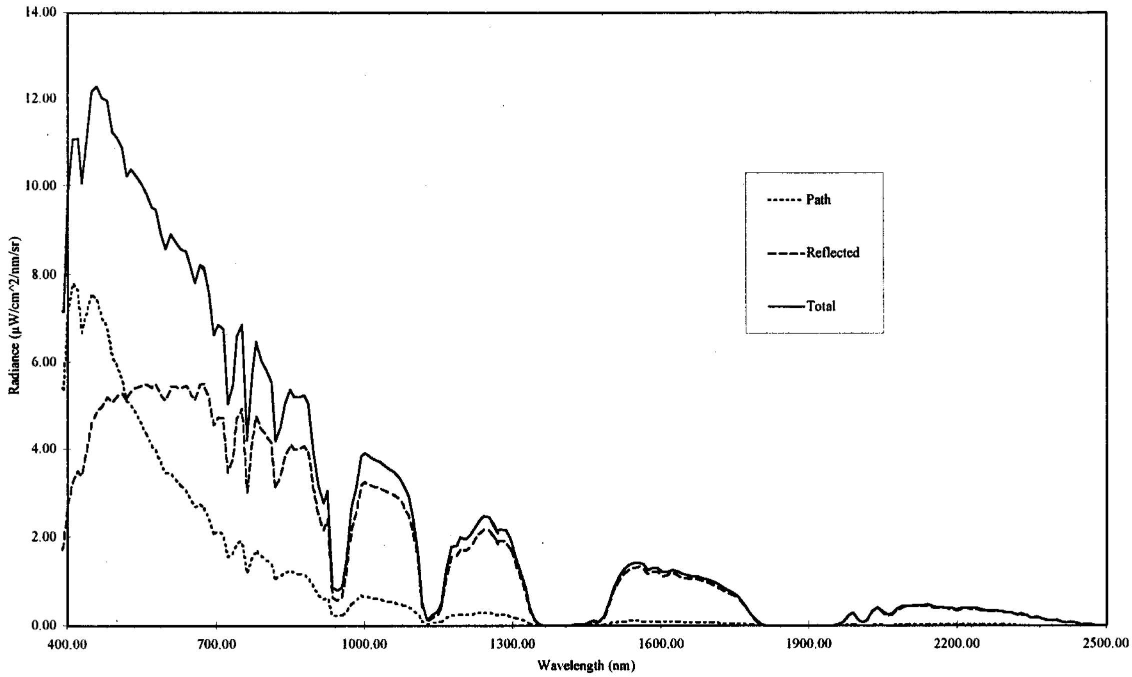

Figure 4. Radiance from a 0.25 reflectance surface illuminated from 45 degree solar zenith. The atmospheric path, surface reflected, and total radiance arriving at the instrument is shown.

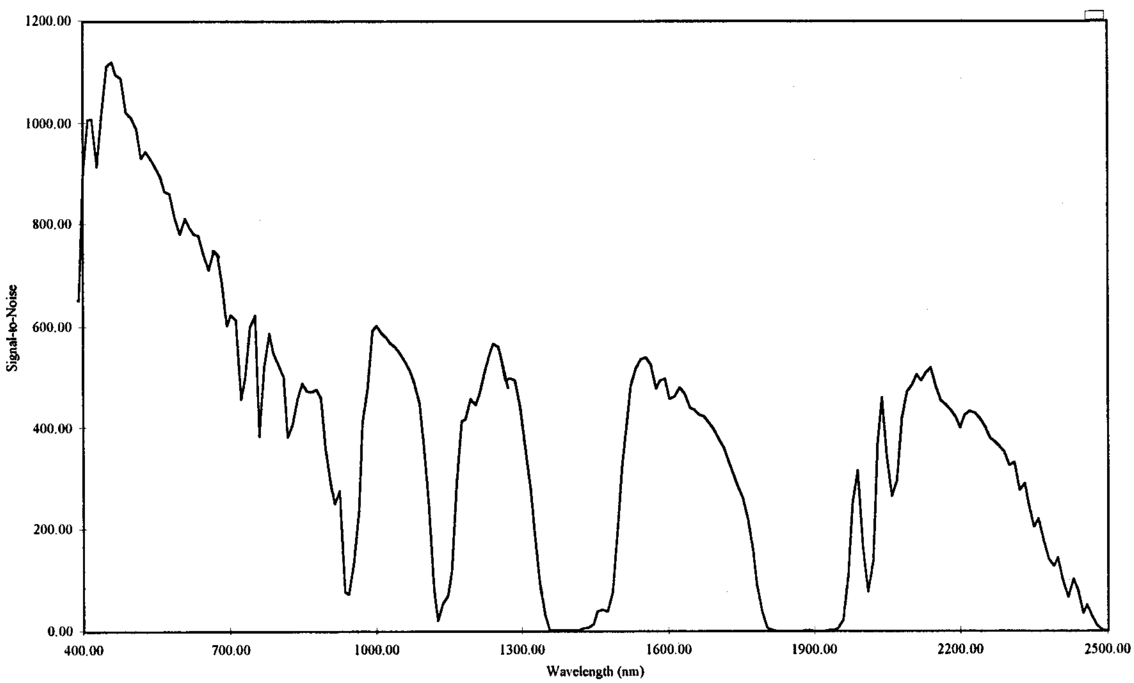

Figure 5. Signal-to-noise requirement for an imaging spectrometer in the solar reflected spectrum. This requirement is based on reaching 500:1 signal-to-noise for the reflected

radiance component of the total radiance in each of the continuum regions of the spectrum.

4. SPATIAL REQUIREMENT

The spatial requirements for imaging spectrometer are based on the objective to measure the Earth at surface scales similar to that of the SPOT and LANDSAT satellite sensors. An imaging spectrometer swath range from 5 to 50 km or greater is required for investigations at the local to regional scale. The requirement for spatial sampling of imaging spectrometer is from 5 to 50 m in the cross and along track. The exact range and sampling must be established for the specific mission based on the science research and applications objectives. The spatial response function is required to match the spatial sampling of the imaging spectrometer. As in the spectral domain, an over sampled spatial image enables more robust re-sampling and sub spatial element detection. However, over spatial sampling by a factor of 2 increases the data rate by a factor of 4 and is generally impractical. Spatial stability refers to the repeatability of the spatial sampling, and response from image to image. Spatial stability is required at the 5% level to enable comparison of derived material properties for place to place and time to time objectives. Spatial uniformity corresponds to the variation of the spatial sampling and response throughout the image. Complete uniformity allows every measurement to be compared directly with every other measurement in the image from the spatial perspective. In addition, uniform systems are comparatively straightforward to calibrate. A baseline spatial uniformity requirement of 5% across an image is appropriate. Spatial precision describes to the variation of spatial sampling and response from consecutive measurements of the same stable target. The baseline requirement is that the spatial sampling and response not vary in an undetermined manner by more than 5 % in an image. Spatial accuracy relates to the knowledge of the spatial sampling and response of the imaging spectrometer. Currently spatial information is rarely used to quantify the expressed concentration of components derived from imaging spectrometer data. However, in the future issues of concentration are likely to become important. This evolution towards deriving the expressed concentration of materials drives the spatial accuracy requirement toward the 5% level with a goal of 3%.

5. DISCUSSION

In addition to the baseline radiometric requirements given, there is often a need for a polarization sensitivity requirement. This is most critical for dark targets where the illumination signal may be polarized. For these targets strong instrument polarization sensitivity leads to degraded radiometric accuracy. For dark targets such as coastal or inland water a requirement of polarization sensitivity of less than 5 % is set.

A special class of spatial and spectral uniformity requirement arises in the context of currently proposed spaceborne imaging spectrometers. This requirement is that the spatial sampling and response not vary by more than 5% through the 400 to 2500 nm spectral range. In other words, all the wavelengths of the spectrum should come from the same place on the ground at the 95% level. If the spatial sampling and response vary as a function of wavelength, large errors in output radiance and derived reflectance are induced. Figure 6 shows two pure spectra and a set of spectra that are mixtures as a function of wavelength. Figure 7 shows the errors in reflectance that results from this spatial-spectral shift. As important than the large errors is the result that the spectra output from a spatial-spectral shift are not physically real. In one part of the spectrum one material is measured in another part of the spectrum another material is measured. These non real spectra have the potential to overwhelm the current suite of anomaly detection algorithms.

An additional imaging spectrometer requirement is related to the location knowledge for the spectra in the image (Boardman 1999). A baseline requirement is set to know the location of a measured spectrum on the Earth surface at least at the spatial sampling scale. This requires a set of position and pointing knowledge requirements that must be calculated based on the instrument platform characteristics.

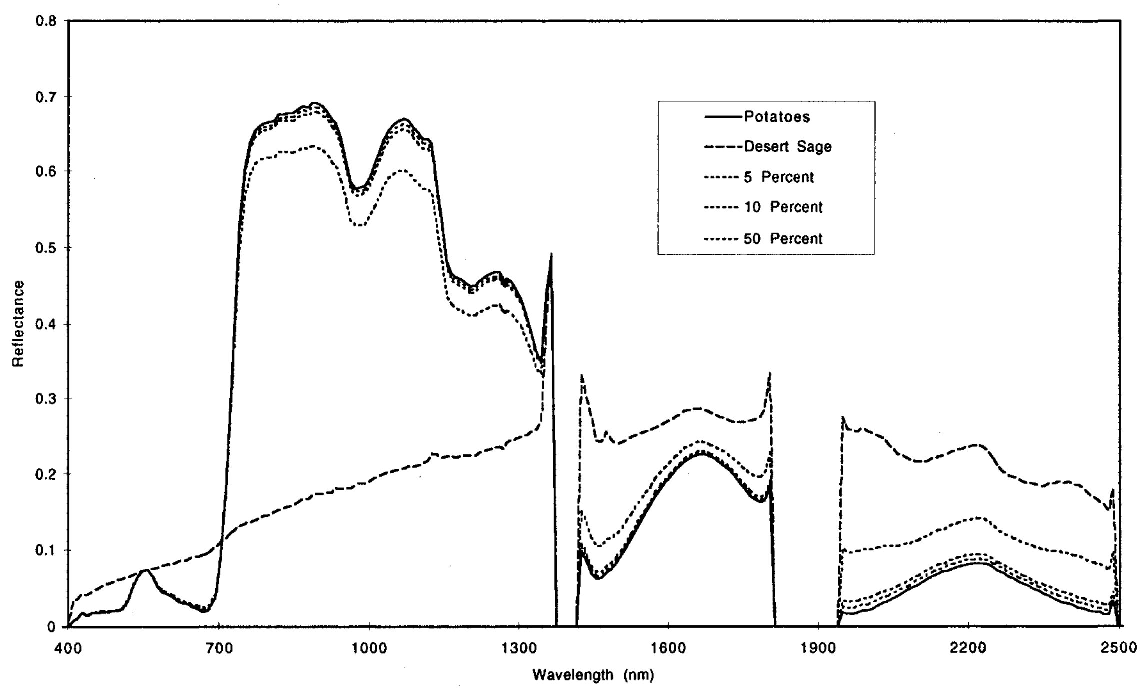

Figure 6. Measured reflectance spectrum of a potato field and adjacent area of desert sage. Spatial spectral mixture spectra of 5, 10 and 50 % from 400 to 2500 nm are calculated. This represents the measured area on the ground shifting as a function of wavelength.

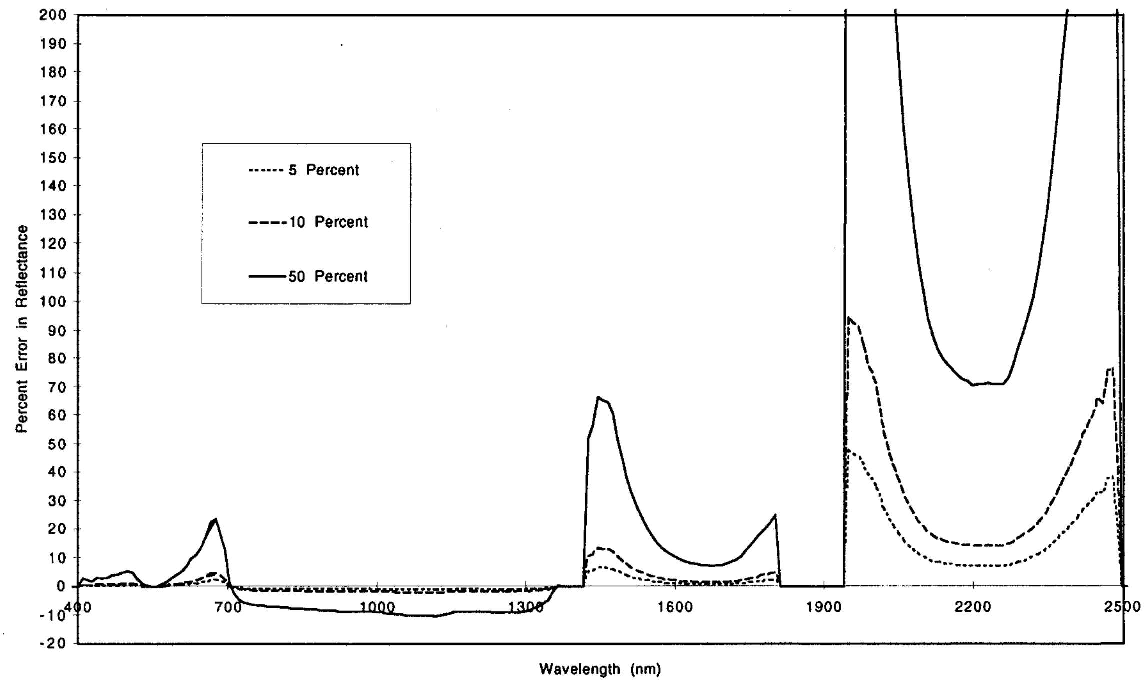

Figure 7. This plot shows the percent error in reflectance as a function of shifting spatial sampling through the wavelength range.

6. CONCLUSION

Airborne and spaceborne Earth look imaging spectrometer are being developed or planned to measure the upwelling radiance in the solar reflected spectrum at the spatial scales similar to that of the SPOT and LANDSAT satellite sensors. These imaging spectrometers are being pursued for a number of science research and applications objectives. Based on experience with AVIRIS, a set of baseline spectral, radiometric, and spatial requirements have been developed. These requirements have been presented in terms of range, sampling, response, stability, uniformity, precision, and accuracy. The spectral requirements of a imaging spectrometers in this portion of the spectrum have been established based on the ubiquitous absorption features of the atmosphere that will be present in every spectrum. The radiometric requirements are based on the objective to derive properties of both low and high reflectance targets under a range of illumination conditions. The spatial requirements are derived from the goal to determine the spatial distribution of materials on the Earth's surface at the spatial scales currently found with the SPOT and LANDSAT satellite sensors. In real systems it is often not possible to fully de-couple the spectral, spatial, and radiometric properties. An example has been given of combined spatial-spectral shift requirement. These spectral, radiometric, and spatial requirements are offered as a baseline. The requirements of a specific mission must be refined with respect to the mission.

7. REFERENCES

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8. ACKNOWLEDGEMENTS

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