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SPECTRAL DECOMPOSITION OF AVIRIS DATA

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1. INTRODUCTION

A set of techniques is presented that uses only information contained within a raw Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) scene to estimate and to remove additive components such as multiple scattering and instrument dark current. Multiplicative components (instrument gain, topographic modulation of brightness, atmospheric transmission) can then be normalized, permitting enhancement, extraction, and identification of relative reflectance information related to surface composition and mineralogy. An expanded discussion of these analyses is now in review for submission to the Journal of Geophysical Research. The technique for derivation of additive-component spectra from a raw AVIRIS scene is an adaptation of the "regression intersection method" of Crippen (1987). This method uses two surface units that are spectrally homogeneous, spatially extensive, and located in rugged terrain. For a given wavelength pair, subtraction of the derived additive component from individual band values will remove topography in both regions in a band/band ratio image. Normalization of all spectra in the scene to the average scene spectrum (e.g., Kruse, 1988) then results in cancellation of multiplicative components and production of a relative-reflectance scene. The resulting AVIRIS product contains relative-reflectance features due to mineral absorptions that depart from the average spectrum. These features commonly are extremely weak and difficult to recognize, but they can be enhanced by using two simple 3-D image-processing tools. The validity of these techniques will be demonstrated by comparisons between relative-reflectance AVIRIS spectra and those derived by using JPL standard calibrations. The AVIRIS data used in this analysis were acquired over the Kelso Dunes area (34°55'N, 115°43'W) of the eastern Mojave Desert, Calif. (in 1987) and the Upheaval Dome area (38°27'N, 109°55'W) of the Canyonlands National Park, Utah (in 1991).

2. FUNDAMENTAL CONCEPTS

In simple terms, there are six major, wavelength-dependent components of a typical spectrum that must be dealt with to derive surface reflectance from measured DN values at visible and near-infrared wavelengths. They include solar flux (F); atmospheric transmission (T); surface reflectance (R); atmospheric scattering ($A\uparrow$ and $A\downarrow$, irradiance at the top and bottom of the atmosphere, respectively); and the instrument gain (G) and dark current (D). Solar flux is well known; atmospheric transmission has characteristic "windows" through which spectral observations can be made, but they vary in "clarity" with atmospheric gas and/or water vapor content. Surface reflectance (as related to mineral composition) is the quantity we seek; it is influenced by a variety of parameters, including terrain roughness and particle size, texture, composition, and moisture content of surface materials. Atmospheric scattering varies with the amounts and types of particulates and gas molecules in the atmosphere; its influence decreases with increasing wavelength. Instrument gain and dark-current values characterize the sensor response; here the gain is assumed to be linear and both the dark current and the gain are assumed to be constant over the imaging field. These components combine in additive and multiplicative ways to form a measured spectrum.

The largest portion of energy in a measured raw spectrum is the direct-reflected component, which is essentially the product of solar flux, two-way atmospheric transmission, surface reflectance, surface photometric function (P), and instrument gain. In rugged terrain, surface reflectance includes the effects of topography as it modulates incident and reflected sunlight. The photometric properties of the surface define its light-scattering behavior; they are a function of viewing phase (α), incidence (i), and emission (ε) angles. The direct-reflected component, written $FT^2RP(\alpha, i, \varepsilon)G$, contains the surface reflectance information that we seek.

A second major component in a measured raw spectrum is surface-reflected skylight, or the diffuse light scattered to the surface through multiple interactions with the atmosphere and surface and reflected directly back to the sensor. Surface-reflected skylight includes upward atmospheric transmission, downwelling scattered radiation at the bottom of the atmosphere ($A\downarrow$, which incorporates the solar flux and downward atmospheric transmission), surface reflectance, and instrument gain, and it can be written $TA\downarrow RG$. The other major additive component in a measured raw spectrum is upwelling diffuse skylight ($A\uparrow G$, where $A\uparrow$ incorporates the solar flux and two-way atmospheric transmission), is also called path radiance or haze. This diffuse skylight is mostly due to atmospheric scattering, although the surface is weakly involved where it contributes to multiple scattering at the base of the atmosphere. Together these two components compose the atmospheric scattering component, and they are not separable. The last major additive component of a spectrum is the instrument dark current (D), a measure of instrument background noise that serves to elevate the spectrum by a roughly constant amount. These relationships can be expressed as

(1) Raw spectrum = $(FT^2RPG)+[(TA\downarrow RG)+(A\uparrow G)]+D$

where the first is the multiplicative term we seek and the last three are additive terms.

3. ADDITIVE COMPONENTS

Our technique for derivation of additive-component spectra (an adaptation of the "regression intersection method" of Crippen, 1987) relies on selection of two units in a multispectral image that are spectrally homogeneous, spatially extensive, and located in rugged terrain. More explicitly, each selected unit must have a contrasting, dominant reflectance, must be larger than $\sim 10^2$ pixels, and must have a strong brightness modulation due to topography. We start with two spectral bands substantially separated in wavelength, and we produce 2-D cluster plots of pixel DN values for the two areas. Regression lines are fitted to these histograms for each area; their intersection point represents all additive terms for those wavelengths. In this manner intersection values are derived for all bands and are subtracted to remove additive components at all wavelengths. To correct for the effects of total additive components in an entire multispectral scene, we assumed that the atmosphere over the scene was homogeneous and that variation in surface reflectance as it affects the surface-reflected skylight can be neglected. Using ISIS software developed for spectral analyses of 3-D imaging spectrometer "cubes" (Torson, 1989), we applied these techniques to two units from an AVIRIS scene of the Mojave Desert, including parts of the Granite Mountains and the Kelso Dunes (Gaddis et al., 1992).

The initial step in our derivation of the total additive spectrum for each wavelength in the AVIRIS Mojave Desert scene was to select a single reference band (e.g., band #177, λ=1.98 µm) and to derive corresponding intersections with every other band. We found the solution for band 177 to be consistent (e.g., DN=75) only when paired with bands at longer wavelengths (>1.4 µm). Using this solution and calculating an additive-component spectrum for each of the two selected units, we found the two spectra to be similar at longer wavelengths and different at shorter wavelengths. These differences at smaller wavelengths are attributable to differences in atmospheric column height between the two sites; the Granite Mountains site (elev. = ~6700') shows less atmospheric scattering than the Kelso Dunes site (elev. = ~2600'). The calculated additive spectrum for each of the two units in the Mojave AVIRIS scene clearly shows features of the atmospheric scattering spectrum and the detailed structure of an instrument dark-current spectrum. For validation of these techniques, the derived total additive spectra was deconvolved into Rayleigh, Mie, and instrument dark-current components.

4. MULTIPLICATIVE COMPONENTS

Subtracting the calculated total additive component from raw AVIRIS data removes the additive effects of atmospheric scattering and the instrument dark current, and the total direct-reflected component remains. In addition to the surface-reflectance information we seek, the direct-reflected component (FT^2RPG) contains the multiplicative influences of topography (including the effects of terrain roughness and of the geometry of instrument viewing and solar illumination), atmospheric transmission, and instrument gain. These influences can be removed through two normalization procedures to arrive at relative reflectance (c.f. "internal average relative" reflectance of Kruse, 1988). We applied these techniques to derivation of relative reflectance from a raw AVIRIS scene from Upheaval Dome and compared the derived relative-reflectance spectra to calibrated spectra from the same units. Here we summarize briefly those results.

Most differences in brightness among units in a direct-reflected component multispectral image are due to differences in unit albedo and in illumination due to topography. We used an equal-area normalization to scale the sum of all of the DNs in each spectrum to a constant, arbitrary value. Such an operation scales the variation in broadband albedo among the units in a scene to a common value of overall brightness, and thereby it mutes the influence of topography on the relative brightnesses of the units. To remove the remaining multiplicative terms (atmospheric transmission and instrument gain), we normalized the data again, dividing each spectrum by an average scene spectrum; the FT^2G term will cancel out, resulting in the reflectance of the surface relative to a scene-average spectrum.

To identify possible mineral-absorption features in the relative-reflectance spectra in this analysis, we first used a 3x3x3-pixel low-pass filter to suppress small-scale (high-frequency) "noise" and then a 1x1x15-pixel high-pass filter to enhance the strength of the relatively weak absorption features by removing long-wavelength variations. After features are visually identified with the enhanced filtered data, however, unfiltered data are then compared with laboratory spectra and can be used to derive images that are interpretable in terms of relative absorption-band strengths and positions, and thus serve as indicators of surface mineralogy.

These procedures for derivation of relative-reflectance information were applied to AVIRIS data for the Upheaval Dome. The dome (diameter~5 km), on the Colorado Plateau in Utah, consists of a series of complexly faulted sedimentary formations that have been uplifted in the center and surrounded by a structurally depressed ring of rocks (e.g., Shoemaker, 1956). Representative spectra from each of the five major geologic formations of the dome were extracted from the raw relative-reflectance (low-pass filtered) and calibrated (scaled intensity/solar flux, or I/F) AVIRIS data. The relative-reflectance spectra show a variety of absorption bands at wavelengths of 0.45-0.65 and 2.0-2.3 μm. In general, calibrated spectra show more complex, stronger absorption features in these wavelength ranges, but in all cases the spectra are comparable directly with features observed in the relative-reflectance spectra.

To identify mineral components, spectrum-matching was applied to spectra from major geologic formations at Upheaval Dome and used to search through the JPL SPAM spectral library (Grove et al., 1992) at wavelengths of 0.45-0.65 and 2.0-2.3 μm. Spectral band-depth analysis (e.g., Clark et al., 1990) was used to compute the band depth of an observed absorption feature relative to its continuum and to calculate a goodness-of-fit parameter for a given similarity threshold. We find mineral matches for the Upheaval Dome units that are broadly consistent both with the results of Clark et al. (1992) and with the major unit lithologies (Huntoon et al., 1982). An iron-bearing, carbonate-type composition for the Kayenta and Chinle Formations is consistent with the marine sandstones, limestones, and siltstones of these units, and a clay-bearing mineralogy is consistent with the compositions of the ripple-marked, cross-bedded shales and siltstones of the Moenkopi, White Rim, and Organ Rock Formations.

5. SUMMARY

These preliminary results demonstrate our success in extracting reasonable mineral signatures from complex AVIRIS data. Use of these techniques for derivation of additive-component spectra not only allows decoupling of atmospheric scattering from surface reflectance, but it also provides an independent check on the behavior of the instrument through analyses of instrument dark-current behavior. If the atmospheric-scattering component of the total additive spectrum can be decomposed into instrument dark-current and Rayleigh and Mie scattering components, then the instrument dark current can be studied. In addition, treatment of the multiplicative components of the measured AVIRIS spectra has allowed extraction of surface-reflectance data that can be interpreted in terms of surface mineralogy.

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