ANALYSIS OF SUB-PIXEL MIXING IN HIGH-ALTITUDE AVIRIS DATA OVER VIRGINIA CITY, NEVADA, USING SYSTEMATIC FIELD-BASED OBSERVATIONS

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1. Introduction

In 1995 AVIRIS data were acquired over Virginia City, Nevada at a 20-km altitude above sea level. The average elevation of the scene is about 2 km, so the resultant size of a pixel is 18 x 18 m^2 - about the size of a tennis court. One of the important questions to ask about such remote sensing data is how the effects of sub-pixel scale mixing will affect the ability to create an accurate mineral map. Pixel-scale mineralogic heterogeneity results in a spectrum that is a function of all the different materials that make up that pixel. Additionally, heterogeneity at the hand-sample scale can be recognized with field spectrometer analyses in the field or in the laboratory. This report describes methods used for the systematic sampling of a field site and the results of modeling the spectra of a heterogeneous area with linear mixtures of measured end-member spectra.

2. Study Area and Data Set

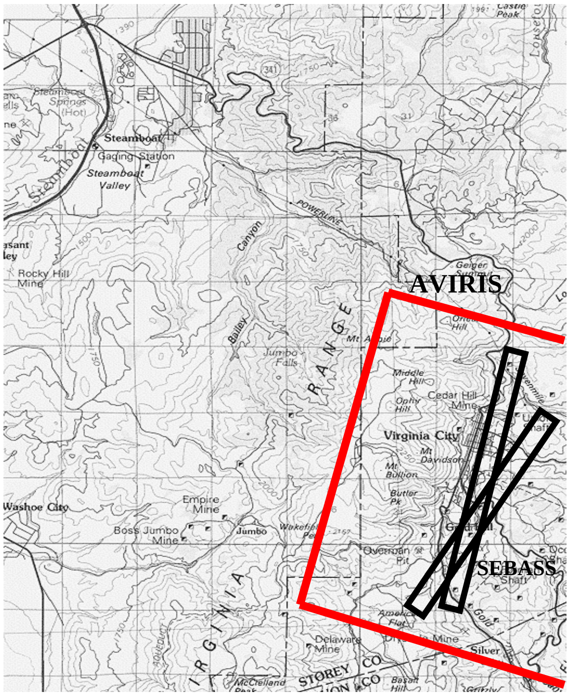

Figure 1. Location and data coverage.

Virginia City, Nevada is located on the east flank of the Virginia Range about 30 km southeast of Reno, Nevada (figure 1). Within the Virginia Range precious metal mineralization is associated with hydrothermal alteration of Tertiary volcanic and intrusive rocks. Virginia City, home of the historic Comstock Mining District and a source of Au, Ag and Hg since the 1850's, has been the focus of many geologic and remote sensing studies (Thompson and White, 1964; Whitebread and Hoover, 1968; Hudson, 1983; Hutsinpillar and Taranik, 1988; Vickre, 1998). As a result of ancient acid-sulfate style hydrothermal alteration, surface rocks now exhibit widespread propylitization, extensive bleaching, iron staining, kaolinitization, and alunitization.

High-altitude AVIRIS data were acquired over Virginia City in a group shoot in September 1995 (Kruse and Huntington, 1996). AVIRIS is an airborne imaging spectrometer that acquires data in 224 continuous spectral bands between 0.38 and 2.5 µm with a 10-nm spectral resolution. It uses a whiskbroom scanner with a FOV of 33° and an IFOV of 1 mrad, resulting in a swath of about 10.5 km (614 pixels) and a spatial resolution of 20 m when flown on the ER-2 platform at 20 km (Vane et al., 1993). Figure 1 shows the extent of the AVIRIS coverage.

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3. Field Methods

The specific field area was chosen based on preliminary analysis of the AVIRIS data. Near the center of the image, just south of the Virginia City town site, there is an easily identifiable landmark: Wheeler Reservoir. Comparing the AVIRIS image to a Digital Orthophotoquad (DOQ) image with 1-m spatial resolution, it appears that the southwest corner of the reservoir is very nearly coincident with the corner of an AVIRIS pixel. Figure 2 shows a subset of the AVIRIS image and a DOQ of the same area.

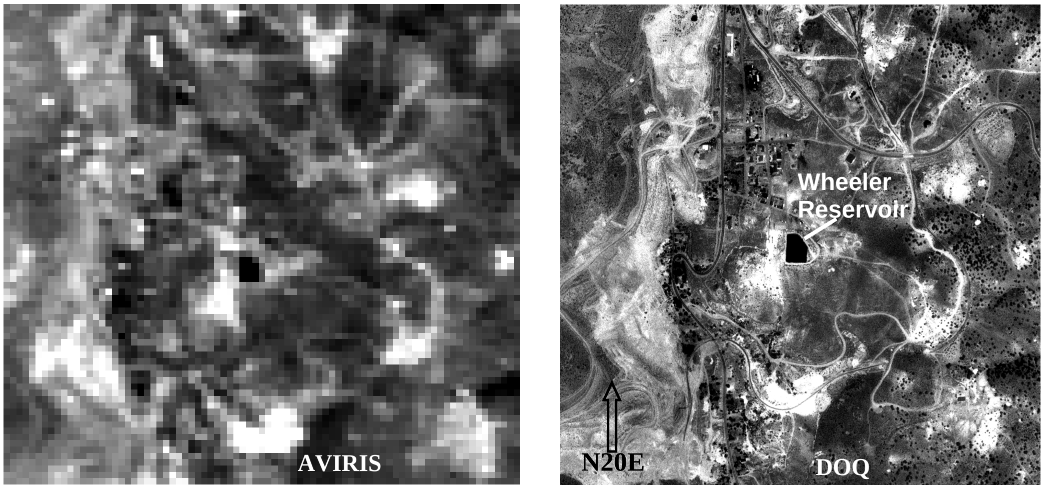

Figure 2. Comparison of spatial resolutions for AVIRIS (18-m) and DOQ (1-m). The SW corner of Wheeler Reservoir is coincident with the corner of an AVIRIS pixel.

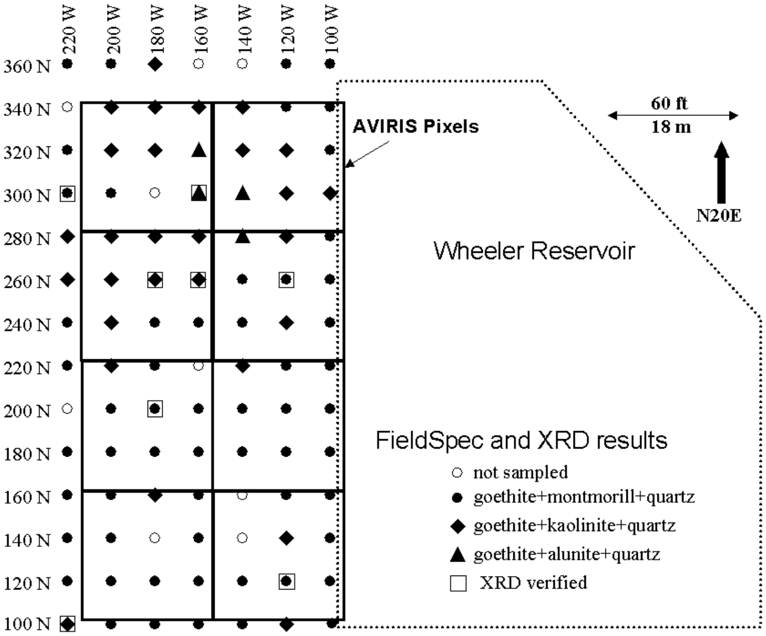

Figure 3. Diagram of field site with location of AVIRIS pixels, Wheeler Reservoir, and sample locations. Sample mineralogy identified with field spectrometer and XRD analyses are indicated with symbols.

In addition, the AVIRIS flight line is oriented in a N20E direction, parallel to the long dimension of the rectangular reservoir. Thus, the west edge of the reservoir coincides with the edges of 4 AVIRIS pixels. Figure 3 is a diagram of the field site indicating where AVIRIS pixels are relative to landmarks. In reality the pixels along the west side of the reservoir may receive some component of reflected radiance from the water. Starting at the southwest corner of the reservoir, using the west edge as a baseline, a grid was established with a 6-m (20-ft) spacing between stations (see figure 3). Surface samples were taken at each grid station over an area that evenly covered approximately 2600 m^2 (8 AVIRIS pixels), and the surface features were mapped in detail. 90 samples were taken and analyzed under laboratory conditions with an ASD field spectrometer for mineral identification. Samples that were identified as being representative of a unique surface cover type were analyzed with X-ray diffraction for verification of mineral identification. For each sample discussed here, XRD analyses agree with the field spectrometer mineral identification. Systematic mapping and sampling of the subset area provides a quantitative way of estimating the percentage that each unique surface cover class should contribute to a single AVIRIS pixel.

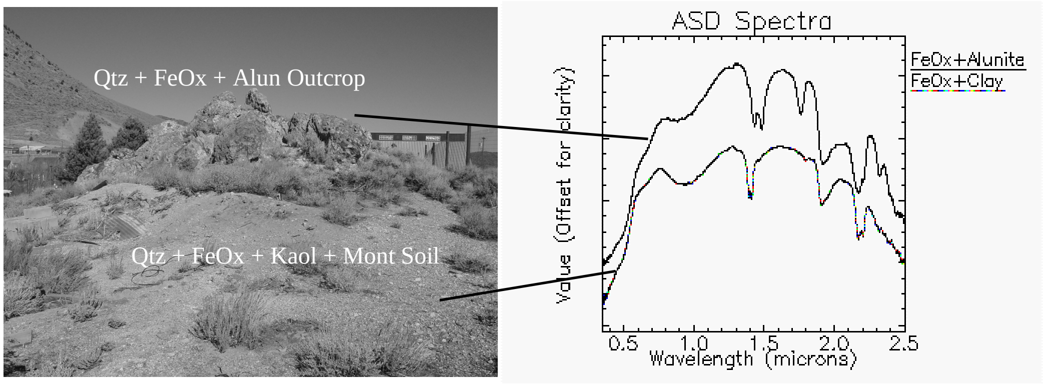

Figure 4. Spectra of selected field locations measured with ASD field spectrometer.

4. Image Processing

The raw AVIRIS data were calibrated to apparent reflectance using ATREM (ATmospheric REMoval program) and EFFORT (Empirical Flat Field Optimal Reflectance Transformation). ATREM is designed to retrieve “scaled surface reflectance” from hyperspectral image data. It uses an approximate atmospheric radiative modeling technique and corrects for scattering and absorption of atmospheric aerosols and gasses (H_2O, CO_2, O_3, NO, CO, CH_4, O_2). EFFORT is a routine that removes residual atmospheric and instrument artifacts from the apparent reflectance data. Numerous trial-and-error experimentation with the EFFORT routine suggests that if this smoothing algorithm is applied to the entire wavelength range together, some mineralogic spectral information is lost. Therefore, prior to applying the EFFORT transformation, certain wavelength regions are isolated to lessen the degradation of mineralogic absorption features. Extracting AVIRIS bands 1-29, 33-96 and 99-224 (0.383-0.657 µm, 0.663-1.268 µm and 1.273-2.509 µm, respectively) for the EFFORT transformation also eliminates the overlapping wavelengths between spectrometers inherent to the 1995 AVIRIS data sets. Finally, for the linear mixes, AVIRIS spectra are scaled to match the reflectance values of the sample spectra measured with the field spectrometer.

5. Linear Mixing

Natural surfaces are rarely composed of a single uniform material. Spectral mixing occurs when materials with distinct spectral properties are present within a certain area. Mineralogic heterogeneity can be present at many scales. At the scale of a tennis-court-sized AVIRIS pixel (18x18 m^2) different materials can be distributed over the area in a linear fashion, where each material can be examined macroscopically, and a percentage contribution determined. At a microscopic scale mixing is more intimate, and can not be modeled as truly linear. However, such small-scale non-linear mixing tends to be a second order effect and linear unmixing techniques appear to work well for approximating spectrally mixed areas (Boardman and Kruse, 1994).

5.1 Micro-Scale Mixing

Sample #300-160 was taken from an outcrop of quartz-alunite in the northern part of the study area. The ASD-measured reflectance for this sample is shown in figure 4 (upper spectrum) and figure 5 (solid line). The sharp 1.76 and 2.32 µm absorption features, the broad 2.15 µm feature, and the doublet feature centered around 1.45 µm are all characteristic of alunite. In addition, the spectral structure between 0.5 and 1.0 µm is indicative of an iron oxide phase (goethite), and the 1.92 µm feature indicates the presence of a clay mineral (montmorillonite), or possibly adsorbed water on the sample.

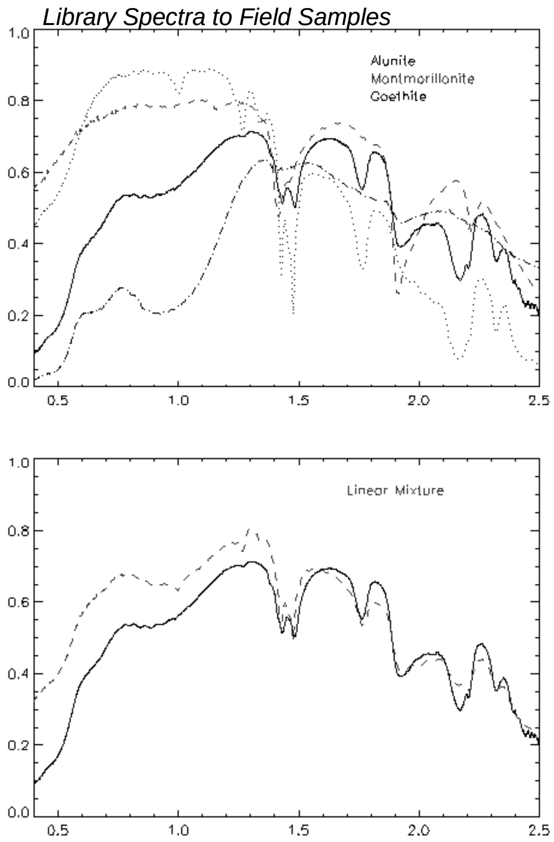

Figure 5. Weighted linear mixture of USGS library alunite (dotted), montmorillonite (dashed), and goethite (dash-dot) compared to ASD-measured spectra (solid line) for quartz + alunite field sample.

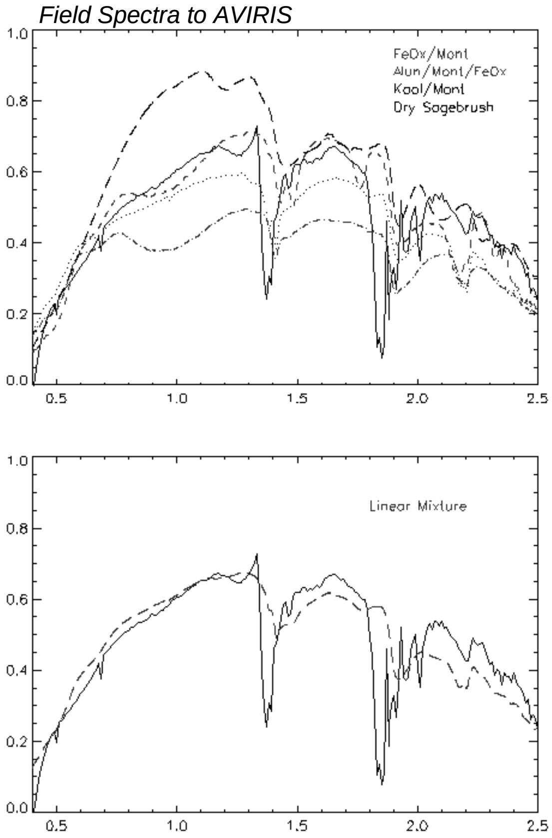

Figure 6. Weighted linear mixture of ASD-measured spectra of field samples FeOx/Mont (dash-dot), Alun/Mont/FeOx (dashed), Kaol/Mont (dotted), and USGS library dry sagebrush (long dashes) compared to AVIRIS spectrum for a single pixel (solid line).

Figure 5 shows 2 plots with the ASD-measured spectrum for this sample as a solid line. The upper plot also shows mineral end-member spectra extracted from the USGS spectral library for alunite, montmorillonite and goethite. The lower plot shows that a weighted, linear mix of these library spectra reproduces the ASD-measured spectrum very well. Band positions, shapes, and relative band depths match particularly well throughout the wavelength range. The only place the mixture doesn’t match well is in absolute reflectance values at shorter wavelengths (below 1.5 µm).

5.2 Macro-Scale Mixing

The quartz-alunite outcrop is apparently divided by 2 AVIRIS pixels and spatially only covers about 15% of each. For one of the pixels that contains this outcrop (the one not bordered by the reservoir), a scaled linear mixture of measured spectra of samples from that pixel, yields a spectrum that fits the EFFORT-corrected AVIRIS spectrum for that pixel. Figure 6 shows 2 plots with the EFFORT-corrected AVIRIS spectra displayed as a solid line. The upper plot shows measured spectra of 3 rock samples from within the pixel and a spectrum for dry sagebrush extracted from the USGS spectral library. The lower plot shows a scaled, linear combination of these spectra (dashed line). The best match is produced by assigning weights to the "end-member" spectra in the mix, based on field mapping estimates of the percentage cover for each surface material. Approximately 40% of the pixel is covered with clay-rich (kaolinite + montmorillonite) gravel, 15% is iron oxide and clay-rich soil, 15% is oxidized quartz-alunite outcrop and 30% is covered with vegetation. In September, when the AVIRIS data were acquired, the vegetation was likely very dry, thus, it is important to include this component of the area because even sparse presence of dry vegetation can have a significant effect on the spectrum, particularly in the steepness of the spectral structure between 0.5 and 1.0 μm and in the suppression of the band depth of the 2.2 μm feature.

6. Conclusions and Future Directions

Linear mixing of library spectra appears to be successful in reproducing spectra measured of field samples particularly in matching band position, depth, and shape. Deviation in absolute reflectance at lower wavelengths (less than 1.5 μm) suggests a need for an intimate mixture model to account for albedo differences. At the scale of an AVIRIS pixel, linear mixing of spectra measured of field samples from within that pixel is successful in reproducing the EFFORT-corrected AVIRIS spectrum for that pixel. Weighting the sample spectra based on their fractional abundance mapped in the field and including the percentage of vegetation cover is important for producing the best matching result.

There are limitations to producing linear mixtures that accurately identify the contents of a pixel. The presence of at least 30% dry vegetation appears to degrade the spectral structure between 0.5 and 1.0 μm diminishing the ability of high-altitude AVIRIS to identify iron oxides. In addition, a notable outcrop like one composed of quartz-alunite mineralization will not contribute significantly to the spectra if the spatial extent is less than about 15% of the pixel. Low-altitude AVIRIS data, with finer spatial resolution, should be able to resolve such smaller features.

In the future, identification of sulfate minerals like alunite may be enhanced by the use of high-resolution hyperspectral thermal infrared (TIR) data in conjunction with hyperspectral VNIR/SWIR data. Sulfate minerals have abundant spectral absorption features throughout the VNIR/SWIR and TIR wavelength ranges. These features are diagnostic and exhibit measurable variations such as band shifts with cation substitution allowing for species identification. However, in the SWIR region, some non-uniqueness is introduced due to the overlap between the diagnostic spectral features of sulfates with those of clay minerals. In the TIR region, emissivity minima of sulfate and clay minerals are clearly separated in wavelength, and can be uniquely identified. The high spectral resolution images provided by AVIRIS and the Spatially Enhanced Broadband Array Spectrograph System (SEBASS) could be used as complementary data sets for the unambiguous identification of sulfates, clays and silicates.

7. References

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