Surface Reflectance Calibration of Terrestrial Imaging Spectroscopy Data: a Tutorial Using AVIRIS

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This tutorial is designed to help others understand how we calibrate terrestrial imaging spectroscopy data. This paper, along with the full resolution images can be found at:
http://speclab.cr.usgs.gov/PAPERS.calibration.tutorial
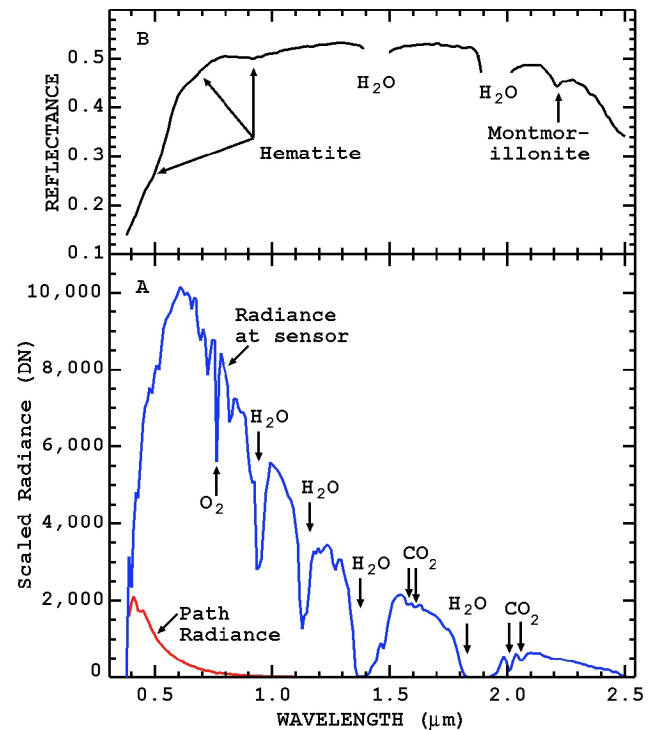
1. Introduction

Remote sensing data are routinely used to characterize vegetation, minerals and other materials on the surface of the Earth. The demands for better characterizations have increased as the technology of remote sensing, the complexity of biophysical models, and the sophistication of scientific studies and land management applications have advanced. As a result, there is a need for accurate correction of atmospheric effects and conversion from radiation measured at the sensor to reflectance arising solely from the imaged surface materials. Sensors known as imaging spectrometers have the capability of resolving the intensity of atmospheric absorption features and the shapes of scattering curves and, thus, allow for a better correction of remotely sensed spectra to values of reflectance.

Calibrating imaging spectroscopy data to surface reflectance is an integral part of the data analysis process, and is vital if accurate results are to be obtained. The identification and mapping of materials and material properties is best accomplished by deriving the fundamental properties of the surface, its reflectance, while removing the interfering effects of atmospheric absorption and scattering, the solar spectrum, and instrumental biases. Calibration to surface reflectance is inherently simple in concept, yet it is very complex in practice because atmospheric radiative transfer models and the solar spectrum have not been characterized with sufficient accuracy to correct the data to the precision of some currently available instruments, such as the NASA/JPL Airborne Visible and Infra-Red Imaging Spectrometer (AVIRIS, see Green *et al.*, 1998).

The objectives of calibrating remote sensing data are to remove the effects of the atmosphere (scattering and absorption) and to convert from radiance values received at the sensor to reflectance values of the land surface. Figure 1a shows a sample radiance spectrum from an imaging spectrometer. The overall level and shape of this radiance spectrum is strongly a function of the solar illumination and absorption by atmospheric gases. The advantages offered by calibrated surface reflectance spectra (e.g., Figure 1b) compared to uncorrected radiance data include: 1) the shapes of the calibrated spectra are principally influenced by the chemical and physical properties of surface materials, 2) the calibrated remotely-sensed spectra can be compared with field and laboratory spectra of known materials, and 3) the calibrated data may be analyzed using spectroscopic methods that isolate absorption features and relate them to chemical bonds and physical properties of materials. Thus, greater confidence may be placed in the maps of derived from calibrated reflectance data, in which errors may be viewed to arise from problems in interpretation rather than incorrect input data.

The consequences of poor surface reflectance calibration can be costly. For example, an artifact in the calibration could be seen as a dip in the derived surface reflectance spectra, and that dip might be interpreted as representing a material that does not really exist at that location. Such an error could have serious implications, for example, if the misidentified material has hazardous properties indicating a need for environmental cleanup, or if it indicated a new mineral deposit discovery. Investigating such a false lead could result in wasted time and money.

Figure 1. A typical radiance spectrum of a non-vegetated area (Figure 1a) is strongly influenced by the solar function and absorption features caused by atmospheric gases. After calibration to surface reflectance, the spectrum (Figure 1b) reveals the absorption feature(s) caused by minerals on the surface. Subsequently, lab spectra of minerals can be examined to identify the mineral(s) causing the absorption feature(s), in this case hematite and montmorillonite. The water features in the radiance spectrum in (A) is due to gaseous atmospheric water, while that in the surface reflectance in (B) is due to liquid water in the soil. The gaps in (B) are where the Earth's atmosphere is too opaque to derive surface reflectance in from the radiance spectrum in (A).

The following tutorial documents the methods used by scientists at the USGS Spectroscopy Lab to provide the best calibration given the technology available. This tutorial is based on methods and experience developed from calibrating dozens of AVIRIS data sets. While the discussion here is focused on the calibration of AVIRIS data, the concepts apply to other sensors as well. Because AVIRIS data are delivered to the investigator calibrated to radiance at the sensor, instrumental biases are already removed and will not be discussed in this tutorial.

2. Review of Calibration Approaches

Many approaches have been developed for atmospheric correction and calibration to surface reflectance of imaging spectroscopy data. These approaches may be grouped into four broad categories: scene-derived corrections, radiative transfer models, ground-calibration methods, and hybrid radiative-transfer-ground-calibration procedures.

The appeal of the scene-derived and modeling approaches is the potential ability to atmospherically-correct remote sensing data without the dependence on external information or measurements. The Internal Average Reflectance (IAR) approach of Kruse (1987) uses the mean radiance of all the pixels in the image as a correction factor. The individual radiance values in each pixel are divided by this mean radiance to estimate reflectance. The flat field correction method (Roberts *et al.*, 1986, and Carrere and Abrams, 1988) assumes that there is an area in the scene that is spectrally neutral (no variation in reflectance with wavelength). The average radiance of this "flat field" may then be used as an estimate of irradiance. As with IAR, this average radiance is used as a correction factor to convert the radiance in each pixel to reflectance. While essentially independent of external information or measurements, these approaches rely on assumptions about the surface materials in the scene which are rarely encountered and, thus, result in apparent reflectances which show deviations from spectra of comparable materials measured in the field or laboratory (Clark and King, 1987, and Kruse, 1987).

The calibration of remote sensing data using physics-based radiative transfer models has been the subject of vigorous research efforts. Theoretically, models may be developed which describe the radiative transfer of sunlight in its physical interaction with the gases and particles in the atmosphere, its interaction with the surface, and its transmission along a different path upward through the atmosphere to the sensor (e.g., Gao *et al.*, 1993, Leprieur *et al.*, 1995, Zagolski and Gastellu-Etchegorry, 1995, Adler-Golden *et al.*, 1999, Schlapfer *et al.*, 2000, and Qu *et al.*, 2000). These models describe the solar irradiance function, the absorption and scattering processes of atmospheric gases, and the reflection from surface materials, all

as a function of the wavelength of electromagnetic radiation and the directional angles of the sun and sensor with respect to pixels of remote sensing data as they are located on the Earth's surface. The full solution of the equations which describe the physics of this radiative transfer problem are complex and, thus, numerical models of radiative transfer use simplifying assumptions to achieve results in reasonable computation times.

Although theoretically well-described, the methods of radiative transfer calibration produce apparent surface reflectance values which show residual atmospheric absorptions and scattering effects. These residual errors may affect the identification, characterization, and/or mapping of surface materials. Indeed an examination of the results of radiative transfer models show errors in the calculated reflectance (see Clark *et al.*, 1993 and 1995). These errors arise from inadequate definition of the solar irradiance function, variations in the source illumination, and simplified assumptions in the physics that describe absorption by atmospheric gases. While the models have been steadily improving with time, they are not yet at the level where artifacts are smaller than sensor noise.

The use of field and/or laboratory measurement of reflectance from surfaces and materials within an image of remote sensing data represents another approach to atmospheric correction and calibration. The need for such measurements to be made during a field survey of the study area places demands on the conduct of a remote sensing study. The field measurements require the availability of an appropriate field spectrometer and a field crew to use the instrument to measure an area of ground within the image at the time that the remote sensor passes overhead, or, at least, at a time close to the overpass. The empirical line calibration (Conel *et al.*, 1987) was applied to an early imaging spectrometer, the Airborne Imaging Spectrometer (AIS). This approach uses field measurements of two or more areas within an image in order to correct the radiance data using a linear equation. The average field measurements of reflectance for the calibration areas are used in a linear relationship with the corresponding average radiance values over the calibration areas in order to derive additive and multiplicative correction factors. Conel *et al.* (1987) describe the application of the procedure using calibration areas of differing albedo, at least one bright target and one darker target.

A similar approach, but using only a single calibration site, described by Clark *et al.* (1988, 1993, and 1995) has been applied to Airborne Visible/InfraRed Imaging Spectrometer (AVIRIS) data over a wide range of study sites. This approach uses both an additive correction factor (an estimate of path radiance) and a multiplicative correction factor derived from the ground measurements of reflectance of the single calibration site. These empirical approaches based on field measurements result in well-calibrated surface reflectance values near the calibration sites. The drawbacks of these methods include the increase in atmospheric residual absorptions for pixels remote from the calibration site and for pixels with different path lengths through the atmosphere as caused by a changing scan angle of the sensor.

This paper describes a hybrid approach that uses ground measurements and radiative transfer models. First described by Clark *et al.*(1993 and 1995), this method uses a combination of the ATmosphere REMoval Program (ATREM; CSES, 1997) and field spectral measurements of a single ground calibration site. The use of the ATREM model allows better atmospheric correction at elevations that are different from the calibration site, while the ground calibration removes the residual errors common with most radiative transfer approaches. We have termed this method "radiative-transfer-ground-calibration (RTGC)." In a comparison of several methods, the use of field measurements in conjunction with radiative transfer models has been found to give the best calibration results for imaging spectrometers by Clark *et al.* (1993 and 1995).

3. Method Summary

Our calibration process involves two steps. In the first step, the flight data are corrected using a radiative transfer algorithm that examines the imaging spectroscopy data pixel by pixel, adjusting atmospheric absorptions in the model and removing the absorptions from the data. This step also includes characterizing and removing the effects of Rayleigh and aerosol scattering in the atmosphere (called "path radiance") and a correction for the solar spectral response relative to wavelength. However, the resulting surface-reflectance-corrected spectra have residual artifacts due to imperfect radiative transfer models,

and the imperfect knowledge of the detailed spectral response of the sun. A second step is necessary to remove these artifacts.

The second step requires *in situ* spectral characterization of an area that is also measured by the sensor, *i.e.* a ground calibration site. The reflectance of a ground calibration site may be characterized using a field-portable spectrometer and/or the careful collection of samples of the materials covering the surface of the site and their subsequent measurement with a laboratory spectrometer. A comparison of the field or lab spectral measurements with the corresponding spectra from the imaging spectroscopy flight data may show differences which indicate that additional corrections are necessary. On the basis of this comparison, a set of multipliers (a multiplication factor for each spectral channel) can be derived. When the correction is applied to the data, the resulting spectra are similar in quality to laboratory reflectance spectra. Additional areas in the data set can be used to verify and further refine the accuracy of the multipliers and to derive any residual path radiance correction.

Achieving a high quality calibration is difficult. It requires careful planning, multiple visits to the field, time to reduce field and laboratory data, examination of flight data and comparison to the field data, and verification of the results. Our experience has shown that the high signal-to-noise of recent AVIRIS data (since 1995) typically requires 1 to 2 person months per study site to achieve a quality calibration. Table 1 shows a summary of our calibration steps, and the following presentation shows how a quality calibration can be achieved.

Table 1. Summary of Calibration Steps

Planning for calibration.
Include at least one calibration site as part your flight data set.
Near the time of data acquisition, characterize the calibration site using field portable spectrometers.
Collect samples and measure their spectra in the laboratory to back up the field data.
Numerically convolve field and lab spectrometer data to the bandpass and sampling of the flight data.
After data receipt, remove solar and atmospheric response using a radiative transfer algorithm.
Derive residual path radiance correction and subtract it from the flight data.
Trick: Use vegetation in shaded areas to determine residual path radiance issues.
Derive a set of multipliers as a function of wavelength to correct residuals from the radiative transfer algorithm.
Apply the offset correction and multipliers to the flight data set.
Examine spectra and large averages of spectra from the flight data set for artifacts. If artifacts are discovered, trace their origin and repeat the above analyses.

4. Planning for Calibration

An important preliminary step, before the calibration process is even started, is in planning for the acquisition of the imaging spectroscopy data. The planning should be conducted with these important considerations in mind in order to select good calibration sites.

1) It is important to visit the study area *before* establishing the exact location of the flight lines to ensure inclusion of at least one suitable calibration site.

2) If at all possible, the region of data coverage should include some spatially uniform, "spectrally bland" area. A spectrally bland area is one that does not have strong absorption features in the wavelength region to be measured.

3) High reflectance level is required. A high reflectance gives the best sensitivity to multiplicative corrections. A target with low reflectance will be more sensitive to additive offsets such as atmospheric scattering (which will be discussed later).

4) The site should be large enough so that many sensor pixels cover the site; thus, many spectra can be averaged to minimize noise in the flight data calibration. Regardless of the number of pixels averaged, some noise will remain in the average spectrum. The larger the calibration site, the more pixels that can be averaged to reduce that noise level. The noise decreases as the square root of the number of pixels averaged. So, for example, averaging 16 pixels results in a fixed pattern residual noise of 1/4th of the noise in any one pixel. A 100 pixel average reduces the pattern to 1/10th of the pixel noise. The high signal to noise of AVIRIS data since 1995 requires at least 25 pixels in the average for good corrections, and many more is certainly better. This many pixels implies large, spatially uniform calibration sites for accurate AVIRIS calibration.

5) The site should be accessible to a ground crew.

6) The site should be at a similar elevation to the prime study area.

The considerations of high reflectance and large area for the calibration site affect the overall signal-to-noise of the spectra that will be used to derive a set of multipliers, one for each spectral channel, to correct the flight data to surface reflectance (examples will be shown below). This set of multipliers will be applied to each pixel in the imaging spectroscopy data set. A residual noise pattern in the calibration site reflectance spectrum will propagate into the set of multipliers which are derived from the field data. Because the same set of multipliers are applied to the spectrum for each pixel, the noise pattern will impart a fixed residual pattern into the entire final data set. Thus, care must be taken to minimize noise, and that can be best achieved by averaging numerous measurements.

We have used playas, salt flats, dam faces, dirt or gravel parking lots, rock outcrops, sand beaches, building construction sites, rock talus slopes, plowed fields (free of vegetation), building roofs, and dry grass fields as calibration sites, with varying degrees of success (the list is in approximate order of best to worst in our experience). Figures 2a-n show some of these sites.

5. Atmospheric Correction Using A Radiative Transfer Model

Because imaging spectroscopy data sets are typically large, organization for easy use is an important preliminary step. We divide the data into manageable chunks to fit on our removable optical media. For AVIRIS studies, we divide the data into 1024- line Vicar-format data cubes which are 282 megabytes in size (Appendix A).

We assume in this report that the flight data are delivered to the user already calibrated to radiance (e.g. Figure 3). If that is not the case, the data must be corrected to radiance before radiative transfer calculations are performed.

The next step in calibrating imaging spectroscopy data is to remove the solar spectral response, atmospheric absorptions and atmospheric scattering using a radiative transfer program. Initially, the calibration is applied to the 1024-line data cubes that contain the ground calibration site(s). Currently we are using ATREM (Gao *et al.*. 1990, 1992, 1993) from the University of Colorado, with custom modifications to read Vicar headers, to perform this radiative transfer calibration step. ATREM estimates the average O_2, CO_2, ozone and others gases in the scene, but does not adjust the amounts on a per-pixel basis. Thus as the atmospheric path length changes with elevation, residual features caused by these gases will be observed in the ATREM-corrected data.

Once the data are radiative transfer corrected, spectra from the AVIRIS data set are extracted from pixels over the ground calibration site covering the same area as was measured with the field spectrometer (e.g. Figure 4). These ATREM-extracted pixels are averaged (Figure 5) and compared to the average field spectrum (Figure 6). Because the solar irradiance function has not been modeled with sufficient accuracy to correct imaging spectroscopy data to surface reflectance, and because the radiative transfer corrections are imperfect, the ATREM-corrected data contain significant artifacts (Figure 6). The magnitude of residual features caused by imperfect water corrections by ATREM depends on the wavelengths selected to characterize the 0.95 and 1.15 micron water absorptions in the ATREM user command file. We use a different set of wavelengths in our ATREM corrections which give a more consistent correction than the wavelengths in the command file distributed by the University of Colorado.
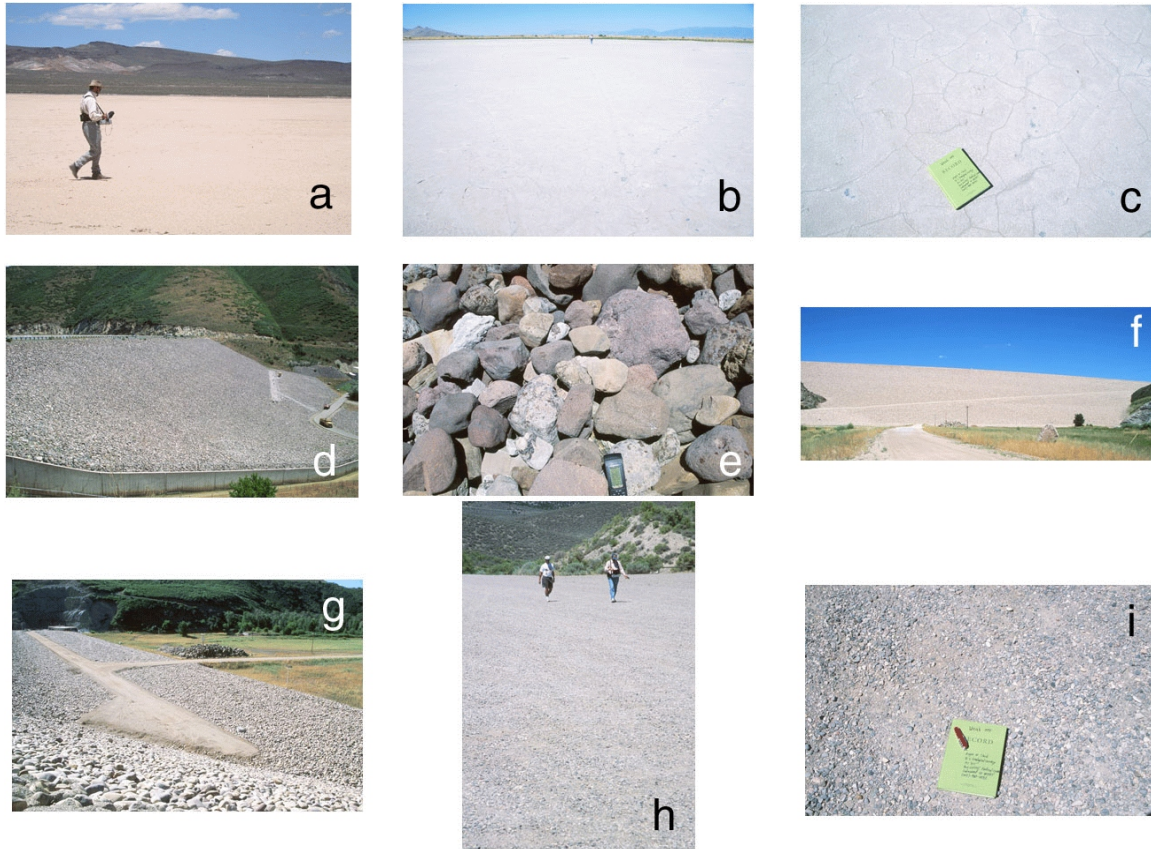
Figure 2a - Cuprite Calibration. Stonewall Playa, located southeast of the main hydrothermal centers at Cuprite, Nevada, is very large and uniform and provides an excellent calibration site, but must be characterized well because of weak Fe^{3+} absorptions in the visible and a weak montmorillonite absorption at 2.2-microns. **2b - Salt Flat Calibration A**. The shores of the Great Salt Lake provide for excellent calibration sites. This area, located next to Old Saltair west of Salt Lake City, Utah, is very large and uniform. High reflectance and no significant absorptions make this one of the best calibration sites we have encountered. Eric Livo is in the distance with the field spectrometer, walking a grid over the calibration area and obtaining hundreds of spectra. **2c - Salt Flat Calibration A**. Close up of the Old Saltair salt flat. The surface is so uniform that field sampling and measurement of the samples on a laboratory spectrometer should be able to give a good representation of the surface. Contrast this surface to the Deer Creek dam face. **2d - Deer Creek Dam Calibration A.** The Deer Creek dam, southeast of Salt Lake City, Utah, provides an excellent calibration site, if it can be characterized well. **2e - Deer Creek Dam Calibration B.** Close up of the Deer-Creek dam face. One can see large variations from rock to rock, making it difficult to collect rocks in the correct proportions for measurement on a laboratory spectrometer. A field spectrometer is required to accurately characterize the site. **2f - Jordanelle Dam Calibration A.** The Jordanelle dam face, located east of Salt Lake City, Utah, is much larger and appeared to be more uniform than the Deer Creek dam face. **2g - Jordanelle Dam Calibration B**. The toe of the Jordanelle dam appears excellent as a calibration site. The rocks are bright. The area is just barely large enough for AVIRIS coverage, giving only about 10 pixels on the toe. Despite appearances in the field, and with the field spectrometer, it turned out that the reflectance levels from spectrum to spectrum and weak absorptions in the field spectra were quite variable. Also, the spectra of the toe and dam face were slightly different. Thus, the Deer Creek dam face turned out to be a better calibration site than the Jordanelle dam face. **2h - Piute Parking Lot Calibration A.** An example of a gravel parking lot calibration site: the Piute reservoir boat launch parking lot in central Utah. Ray Kokaly (left) walks with Eric Livo (right, with the field spectrometer) to provide the Spectralon reflectance standard for re-calibration as soon as the spectrometer calibration begins to drift. **2i - Piute Parking Lot Calibration B.** Close up of the Piute Reservoir boat launch parking lot in central Utah. The average spectrum (in Figure 3) shows the mixture of muscovite in the rocks and the clay montmorillonite in the dirt.
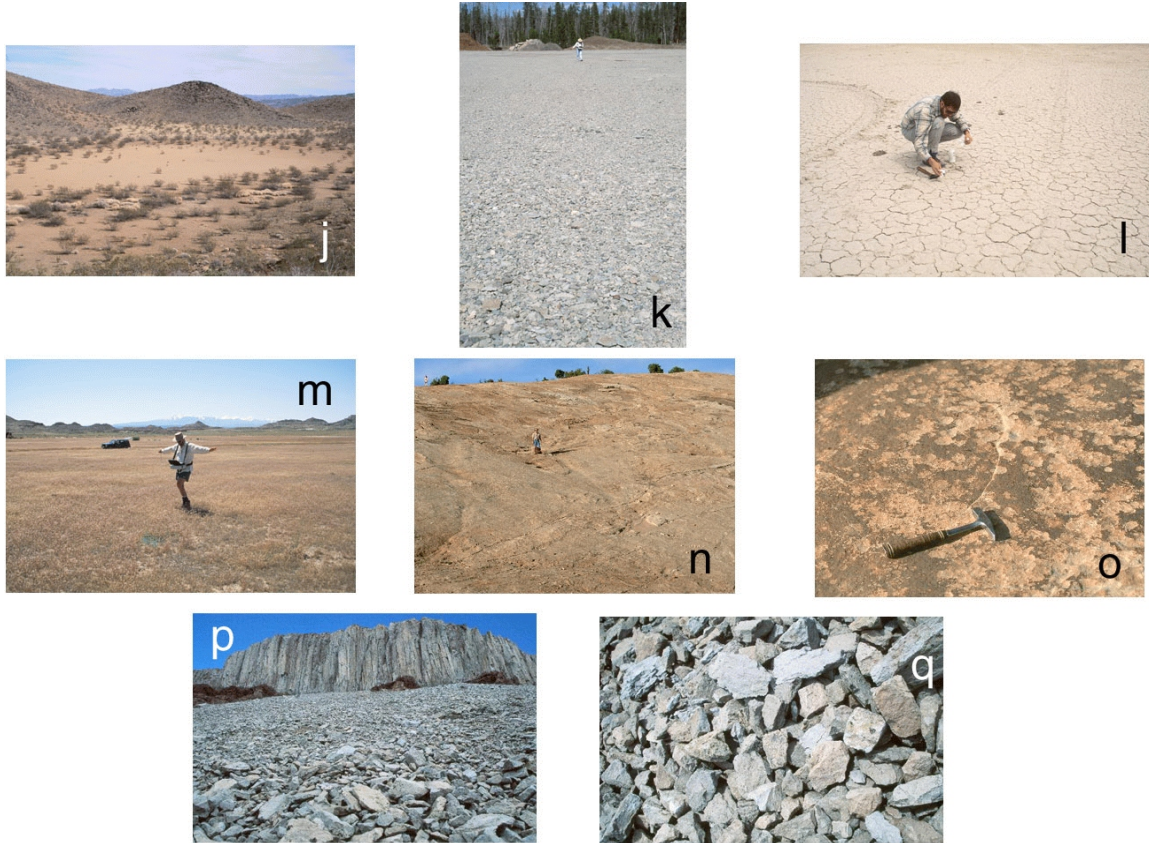
Figure 2j - Joshua Tree Calibration. This small playa was the most vegetation-free area we found to calibrate the 1995 AVIRIS data. **2k - Yellowstone Calibration.** At Yellowstone National Park we used a road construction gravel staging lot for calibration. Ray Kokaly is in the distance with the field spectrometer. While the area is large and uniform, the source rock for the road construction periodically changes, and thus the site must be re-measured near the time of each flight. **2l - Arches Calibration A.** The calibration for the 1995 AVIRIS data acquisition at Arches National Park was particularly well planned. This image shows Gregg Swayze collecting a sample of the Yellow Cat Flat playa, just outside of the Park boundary, on April 27, 1995. The site was well characterized with our field spectrometer. The flight was tentatively planned for May to July. **2m - Arches Calibration B.** On June, 19, 1995, the day of the flight, we arrived at the Yellow Cat Flat playa and found that in the previous month and a half, weeds had grown all over the playa, rendering it unusable as a calibration site. Nearby was the cheatgrass field shown here. While the field was uniform enough to work as a calibration site, cheatgrass (see Figure 3) has strong absorption features. If the site was not well characterized, residual cheatgrass features would appear in all the calibrated AVIRIS data. Because of this potential difficulty, additional calibration sites were characterized. Gregg Swayze is shown operating the field spectrometer. **2n - Arches Calibration C.** The calibration site used for the Arches 1995 data was this large outcrop of Moab Tongue Formation in Arches National Park just north of the Wolf Ranch parking lot and along the Delicate Arch trail (shown). **2o.** Closeup of the rock in Figure 2n. **2p.** Site used for AVIRIS animas Colorado calibration. The rocks are andesitic and spectrally bland, meaning they have few spectral features. **2q**. Closeup of the rocks in Figure 2p. While the rocks show variability on a small scale, on the large scale of many AVIRIS pixels, the site is relatively uniform.

Figure 3. A typical AVIRIS radiance spectrum. The general shape, including the peak near 0.5 microns and the overall decrease toward 2.5 microns, is due to the solar spectrum. Major atmospheric water absorptions occur at 0.95, 1.15, 1.4 and 1.9 microns. Oxygen absorption occurs at 0.76 micron, and CO_2 at 2.0, 2.08, and the weak doublet near 1.6 microns. The 1.9 to 2.5 micron region is scaled a factor of 2 higher relative to the data at shorter wavelengths to better show the details. Sixteen-bit AVIRIS data are distributed with this scale factor applied to avoid data number (DN) quantization errors.

Average AVIRIS radiance spectrum of Deer Creek Reservoir dam face calibration site

Figure 4. The AVIRIS pixels sampled to characterize the Deer Creek dam calibration site for comparison with the ground field spectra.

Note in Figure 6 the difference in reflectance level between the field and the ATREM spectra. Because the dam face consists of large boulders, shadowing plays a significant role. If the field spectrum was obtained under lighting conditions different from that of the AVIRIS flight, the levels could be different. In the case shown in Figure 6, however, the levels match closely near 0.8 to 1.1 microns, but differ more beyond 1.4 microns. This is due to some calibration difference with the AVIRIS and/or the solar spectrum used in the ATREM software. For the August 1998 Utah AVIRIS flight, we observed similar discrepancies at all our calibration sites, including those such as the Old Salt Air salt flat where shadowing is negligible. However, the ground calibration step removes these discrepancies.
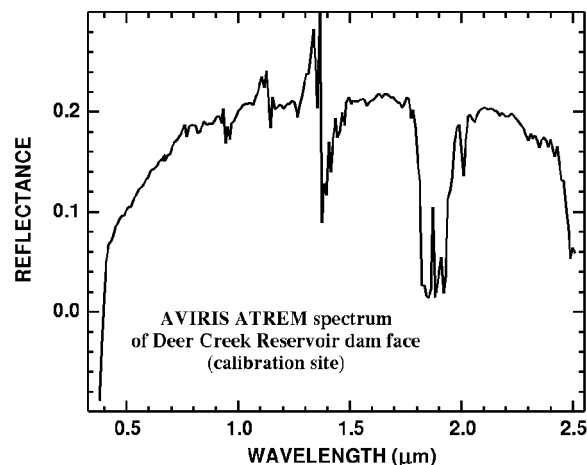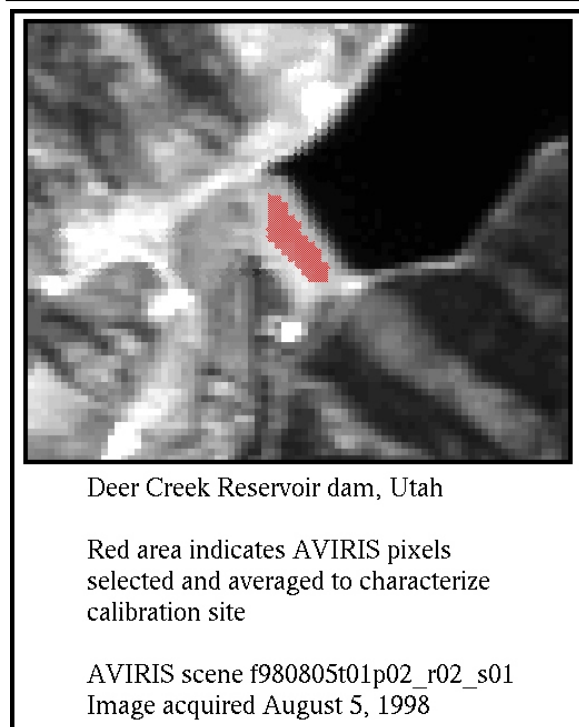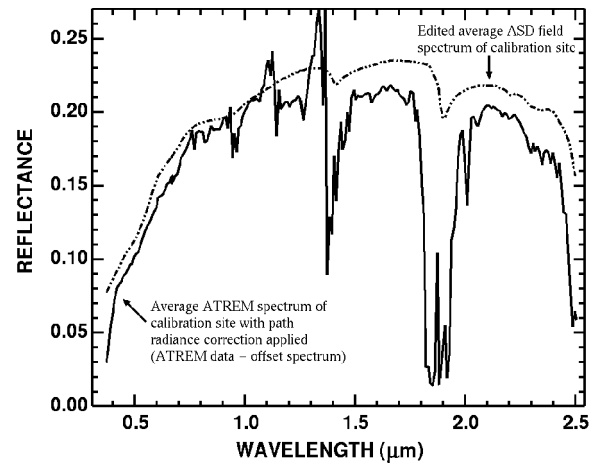

Deer Creek Reservoir dam, Utah

Red area indicates AVIRIS pixels selected and averaged to characterize calibration site

AVIRIS scene f980805t01p02_r02_s01
Image acquired August 5, 1998

AVIRIS ATREM spectrum of Deer Creek Reservoir dam face (calibration site)

Figure 5. The ATREM-corrected spectrum sampled from the area shown in Figure 4. While ATREM corrects the data to approximate surface reflectance, there are too many artifacts for detailed surface material identifications and mapping. Note the reflectance is negative in the UV (<0.4 micron). ATREM overcorrects for the path radiance (described below).

Figure 6. The ATREM-corrected spectrum from Figure 5 is compared to the edited average field spectrum for the Utah Deer Creek dam face. Note the field spectrum is smooth, as would be expected for the minerals present in the rocks, as compared to the ATREM-corrected spectrum. The ATREM-corrected spectrum has had the over-correction of the path radiance fixed using the methods described below. Besides the artifacts around atmospheric water absorptions, there are many small-scale spikes in the ATREM-derived spectra which must be corrected before material identification can begin.

After seeing the ATREM-derived surface spectra, one might ask why use ATREM at all? Water vapor in the atmosphere is highly variable, even over dry desert sites. Changes in elevation result in large variations in the atmospheric gas absorption depths. If a radiative transfer program was not applied first, the artifacts would be much greater than seen in Figure 6. The artifacts from ATREM are largely consistent between all pixels, and include those caused by the imprecisely known solar spectrum, possible errors in the AVIRIS radiance calibration, and relatively repetitive errors in the radiative transfer code in deriving the atmospheric water absorption profiles. Thus, these artifacts can be satisfactorily removed. Of course it would be better to use more accurate models, and we will test them when they become available.

6. Path Radiance Correction.

We have found that ATREM overcorrects for the path radiance scattering in the atmosphere at blue to UV wavelengths. The atmosphere scatters more light at shorter wavelengths (blue to UV--that is why the sky appears blue), so the path radiance portion of the measured signal that a radiative transfer routine must correct is largest in the UV. This type of scattering is called Rayleigh scattering and is caused by light scattering from molecules and particles much smaller than the wavelength of light. The information to derive the necessary correction can be found in the imaging spectroscopy data of a spectrally dark target whose reflectance is known. Larger particles, such as dust and water droplets (aerosols), cause Mie scattering at UV as well as at longer wavelengths (sometimes there is significant scattering in the infrared at 2.5 microns), but such conditions have not been a significant factor in our study areas in the western United States to date.

There is a simple strategy for deriving the UV path radiance levels. The main problem is in separating the surface reflectance component from the atmospheric path radiance. An accurate surface reflectance level is critical for determining the path radiance component. Ideally, a spot on the ground with zero reflectance would give a direct measurement of the path radiance. Traditionally, water has been used as a spectrally dark target. However, water also scatters blue light more than longer wavelengths (deep water also looks blue), so water is not usually UV-dark. The best UV-dark target we have found is green plants. From about 0.4 microns and shorter wavelengths, plant reflectance is very low, about 2% or less, and is either flat or decreases toward shorter wavelengths (e.g. Clark *et al.*, 1993, and Figure 7a). The north side of a hill or mountain (in the northern hemisphere) will be in shadow or at least lower solar intensity, so the apparent reflectance is lower than vegetation in full sunlight. It is common to find vegetated north sides of mountains with apparent reflectance in the UV of < 0.2% (Figure 7a&b). This provides an excellent UV dark comparison for the path radiance correction. Such areas are simply found by choosing a channel at UV wavelengths from the data (e.g. AVIRIS channel 3) and stretching the image brightness to show the darkest areas.

In some desert areas, where there is no vegetation in shadow areas in the imaged area, the above method cannot be used. In such cases an accurate measurement in the field is required. For example, some dark rocks on the north side of a hill might be used. It is important to make such measurements under the same lighting conditions as the flight data so the shadows will be the same.
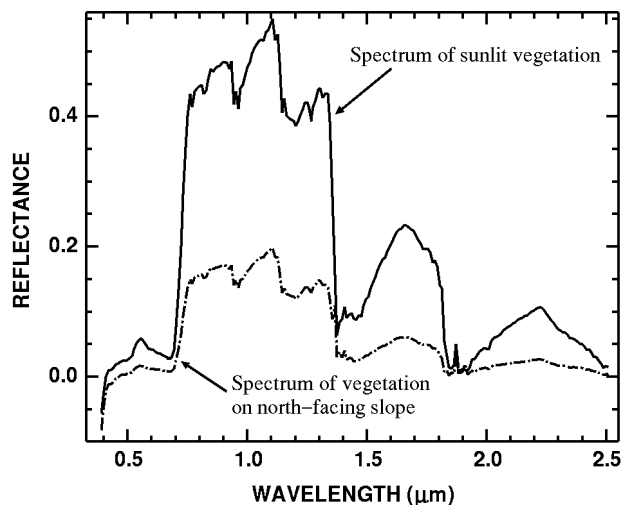
Figure 7a. Vegetation spectra from ATREM-corrected AVIRIS data. Two spectra are shown: one in sunlight, and another on the north side of a hill, largely in shadow. The reflectance in the UV is low and decreasing toward shorter wavelengths. ATREM has overcorrected the reflectance at wavelengths shorter than about 0.45 microns, and the data are negative at wavelengths short of 0.4 microns, which is not physically possible.

Figure 7b. Same two spectra as in Figure 7a, except showing details in the visible and ultraviolet portions of the spectrum.

The ATREM-corrected data typically are negative in the UV, so the UV spectrum of vegetation in shadow is used to estimate the ATREM over-correction (Figure 8a). The difference between ATREM derived spectrum and the estimate (Figure 8a) becomes an offset correction to the ATREM data (Figure 8b). The offset correction is typically zero at wavelengths longer than about 0.5 microns (Figure 8b). This is called the "offset spectrum."

Figure 8a. Estimate of a normal vegetation-in-shadow spectrum shown in Figures 7a and 7b. This estimation is used to remove the effects of the ATREM overcorrection for path radiance as shown in the un-edited vegetation spectrum.
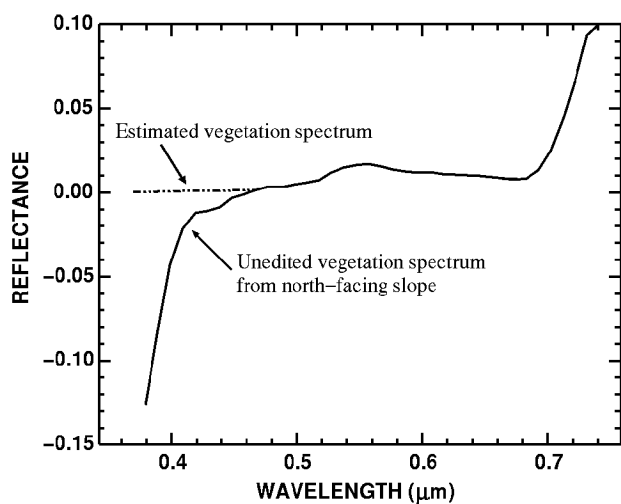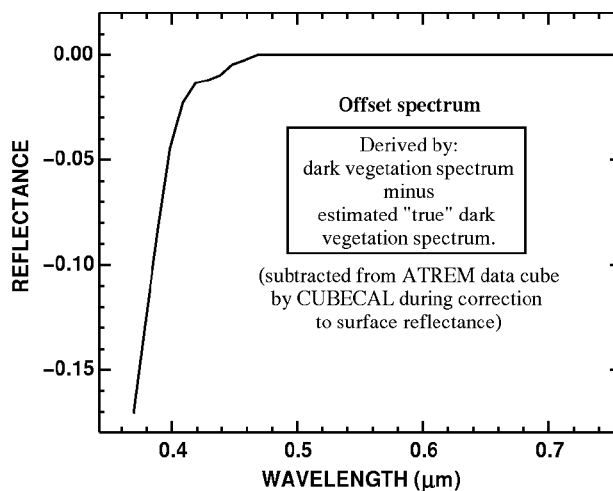

Figure 8b. The derived ATREM offset spectrum: the difference of the two spectra shown in Figure 8a.

7. Correction Using A Calibration Site
7.1 Calibration Site Surface Reflectance Characterization

At the time of data acquisition, it is very important to characterize the calibration site with a field spectrometer. Examples of field measurement activities at some calibration sites are given in Figures 2a-n and Figures 9a-d. A calibration site can change in a relatively short time (e.g. with rain or vegetation growth). For example, as a part of our calibration of the AVIRIS 1995 data over Arches National Park, we located an excellent playa just outside the park in April. It was a site we had used for calibration of previous AVIRIS data sets. While vegetation growth in the region seemed to be at its peak (relatively lush for that year), the playa had essentially no vegetation on it, and we had not seen significant vegetation on it during our previous visits. We measured it with our field spectrometer and sampled it for measurement on our lab spectrometer. However, on the day of the flight in mid-June, we went to the site and found it covered with weeds. As a result, it would no longer serve as an adequate calibration site. Fortunately, we had backup sites, and scrambled to characterize them. First we characterized a cheatgrass-covered field near the Playa (Figure 2m), and a rock outcrop just after the flight (Figure 2n).

Figure 9a - Salt Flat Calibration. Spectralon calibration.

Figure 9b - Deer Creek Dam Calibration A. Ray Kokaly operates the field spectrometer on the Deer Creek dam face. Obviously, such a measurement is tricky because walking on large boulders is difficult.

Figure 9c - Deer Creek Dam Calibration B. Frequent calibration of the field spectrometer is important. The constantly changing atmosphere and heat load on the instrument from sun and shadow as one moves around making measurements cause continual drifts. Here, Ray Kokaly operates the field spectrometer while Eric Livo holds the Spectralon reflectance standard. Eric hold the standard high and away from his body to reduce secondary reflections, and tries to position the standard so the shadow side of his body is seen by the standard.

Figure 9d - Jordanelle Dam Calibration. Calibration of the reflectance target with the field spectrometer is important. Roger Clark holds the target high to minimize reflections from clothes, and makes his shadow side face the target. Roger's green Gortex hat has distinctive and sharp absorption bands. If any light from the hat contributed to the signal, inverse Gortex features would be seen in the spectra of the dam face, but no such features are seen in the data. Such checks are important to verify the accuracy of the calibration.

It is also important to characterize the sky conditions at the time of the flight. While the water, oxygen, and carbon dioxide contents of the atmosphere are derivable from the imaging spectroscopy data, cirrus or other thin cloud formations are harder to assess. While clouds might be recorded by the sensor in the image area, clouds outside the edges of the imaged area may reflect light into the scene, resulting in increased water features

apparent in the data. Thus it is important to record sky conditions (note sky conditions in Figures 2a-n) at the time of calibration site field characterization. Also record sky conditions overhead at the time of the overflight (e.g. Figure 10).

Figure 10. This photo shows the AVIRIS ER-2 aircraft flying over Arches National Park on June 19, 1995, and illustrates sky conditions at the time of the overflight. The rest of the sky was similarly clear. The photo was taken with a tripod-mounted 300 mm lens, Fujichrome Velvia (ISO 50) film, by Roger Clark. The aircraft velocity is so fast and the airplane is so high that the sound appears to come from about 60 degrees behind the plane. A quiet location is required to find the plane in the sky at the time of the overflight. Listen for the engines, and then, keeping in mind the flight line directions, look about 60 degrees ahead of the sound.

7.2 Spectrally Uniform and Spectrally Bland Sites

A calibration site is ideally spectrally uniform and spectrally bland. A site that is not spectrally uniform requires more thorough sampling. For example, the above discussion regarding the playa calibration for the Arches National Park AVIRIS flight illustrates a spectrally non-uniform site: weeds with strong green vegetation spectral signatures on a playa spectral background. While it is possible that an adequate field spectrometer measurement strategy could have been devised to characterize such a variable site, the possibility of residual artifacts is nevertheless increased.

Imaging spectroscopy pixels are almost always much larger than what you can measure in the field, and certainly larger that what can be measured in the lab. For example, AVIRIS pixels are about 20 meters square (area = 400 square meters). Our field spectrometer has about a 20 degree field of view so it measures a spot only about 0.5 meters in diameter from a distance of shoulder height. Such a spot corresponds to an area of only 0.2 square meters, or only 0.05 % of the area of an AVIRIS pixel. Even if one measures 300 spots, the equivalent area covered is only about 15% of an AVIRIS pixel (although the field spectra could be statistically scattered over many AVIRIS pixels). Thus, if the calibration site has spectral features which vary across the site, even 300 (or 3000) field spectra may not be representative of the large area seen by the AVIRIS instrument.

An improved method of spectrally sampling a calibration site involves the use of a rapid sampling spectrometer, which acquires a spectrum every fraction of a second. With such an instrument, hundreds of spectra can be obtained during a continuous traverse of the site. For example, at the USGS we use a field spectrometer that obtains a spectrum every 0.1 second. We typically configure the field computer to average 60 0.1-second integrations before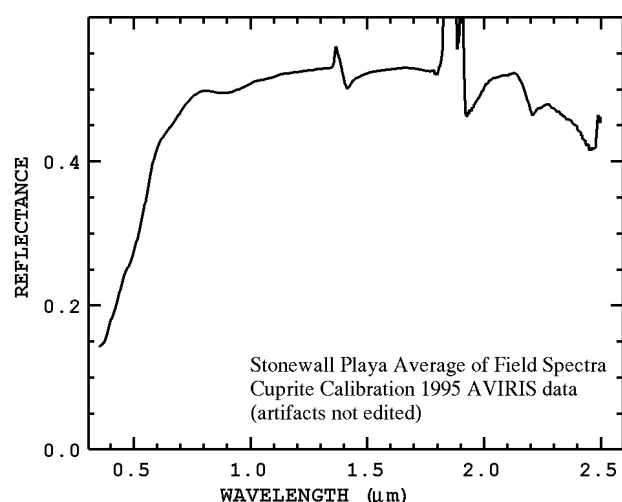 recording the spectrum (6 seconds). Six seconds reduces the recorded data volume while still providing feedback often enough for the operator to evaluate data quality. During those six seconds, the spectrometer operator is traversing the calibration site (note the operators in Figures 2a-n). Depending on the roughness of the terrain, a person will traverse from 1 to 8 meters every six seconds. Assuming an average of 4 meters traversed per six seconds, and a 0.5 meter spot for the spectrometer field of view, one integration covers about 2 square meters. Thus, 300 field spectra cover about 600 square meters, or about 150% of an AVIRIS pixel. If those spectra are spread over the large area of a typical multi-pixel calibration site, then it can be assumed that a reasonable representation of the site has been recorded.
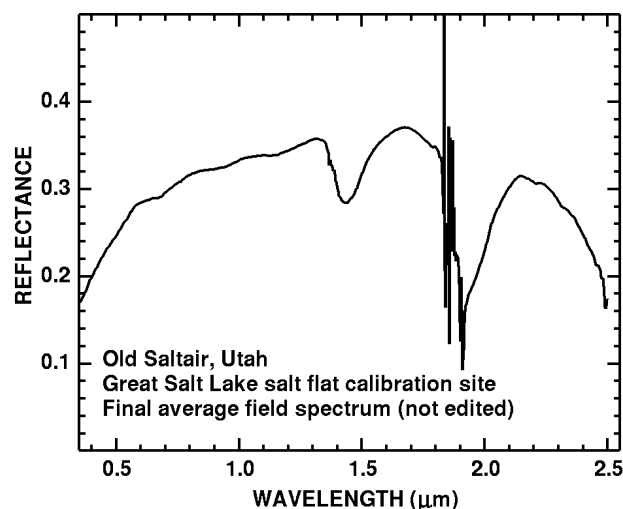

Figure 11a - Cuprite. Stonewall playa calibration site average field spectrum.

Stonewall Playa Average of Field Spectra
Cuprite Calibration 1995 AVIRIS data
(artifacts not edited)

Figure 11b - Salt Flat. Calibration site average field spectrum near Old Saltair west of Salt Lake City, Utah. The high reflectance and relatively bland spectral nature of the salt flat make it one of the best calibration sites we have encountered.
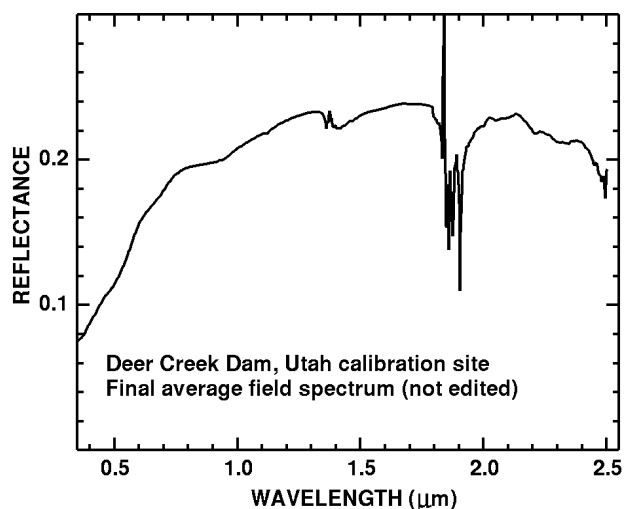

Figure 11c - Deer Creek Dam. Deer Creek dam face calibration site average field spectrum.
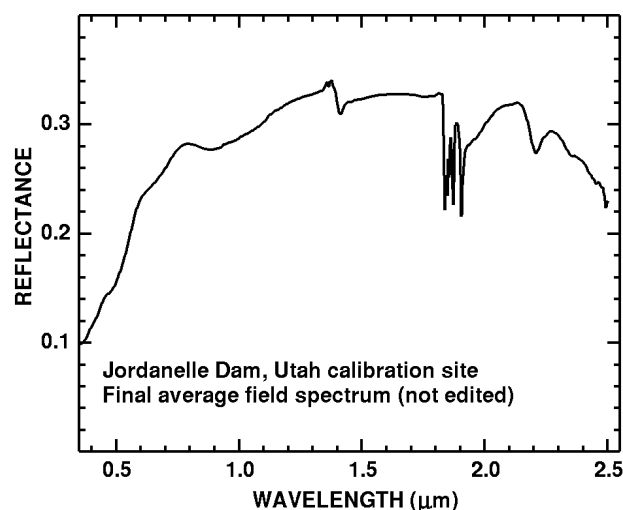

Figure 11d - Jordanelle Dam. Jordanelle dam calibration site average field spectrum. In the field, the dam appeared quite uniform and we thought it would be better than the Deer Creek dam site. However, note the strong muscovite feature at 2.2 microns, and the strong iron Fe^{3+} absorptions in the visible and NIR regions of the spectrum compared to the Deer Creek dam spectrum. The Jordanelle dam spectra had more variability than was obvious in the field. The Deer Creek dam is the better calibration site despite the variability in visual color between cobbles (Figures 2d-e).

The characterization of a calibration site becomes more difficult with a laboratory spectrometer, which measures an area of only about a square centimeter (~3×10^{-7} of the area of an AVIRIS pixel). If the ground characterization does not exactly agree with the spectral features observed by AVIRIS, there will be residual features in all the reflectance-calibrated imaging spectroscopy data. Such artifacts can produce errors in identification and mapping of materials, as mentioned above.

A spectrally bland calibration site is ideal because any spectral features that are not well characterized might result in residual spectral features added to all pixels in the final calibrated data set. For example, montmorillonite (clay) and
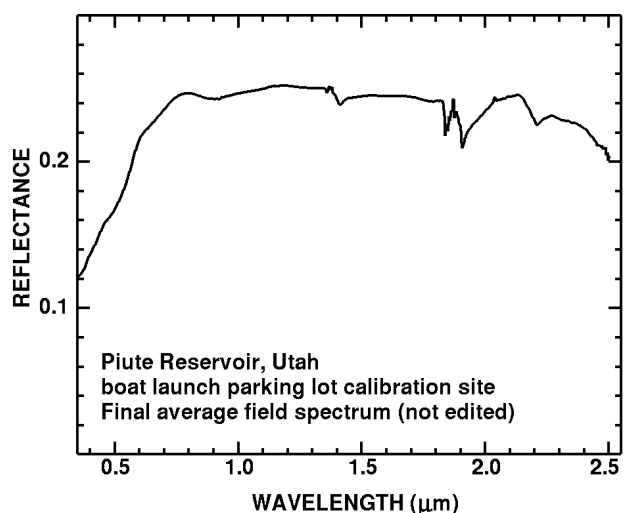

Figure 11e - Piute Parking Lot. The Piute Reservoir boat launch parking lot calibration site average field spectrum.
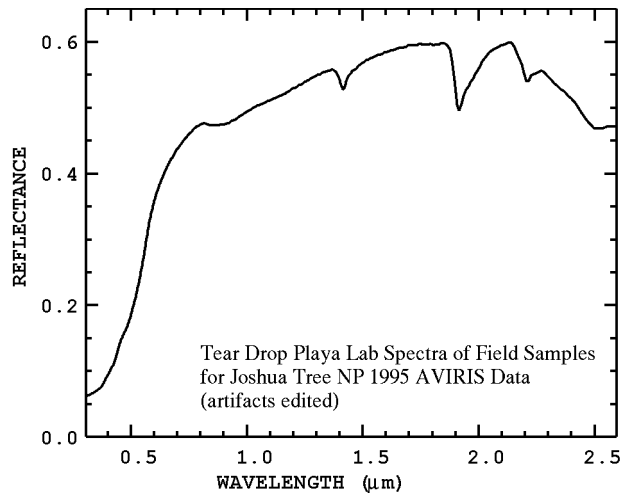
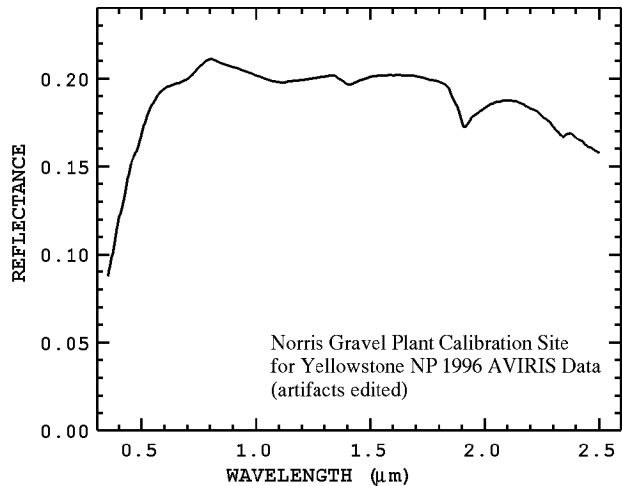**Figure 11f - Joshua Tree Playa.** Calibration site average field spectrum.

Figure 11g - Yellowstone. Yellowstone National Park road construction gravel staging lot calibration site average field spectrum.
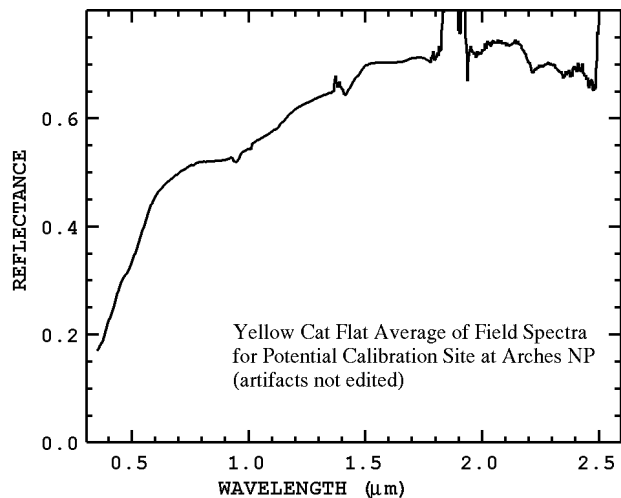
t

Figure 11h - Arches A. The Yellow Cat Flat playa calibration site average field spectrum acquired on April 27, 1995, about 2-months before the AVIRIS flight.
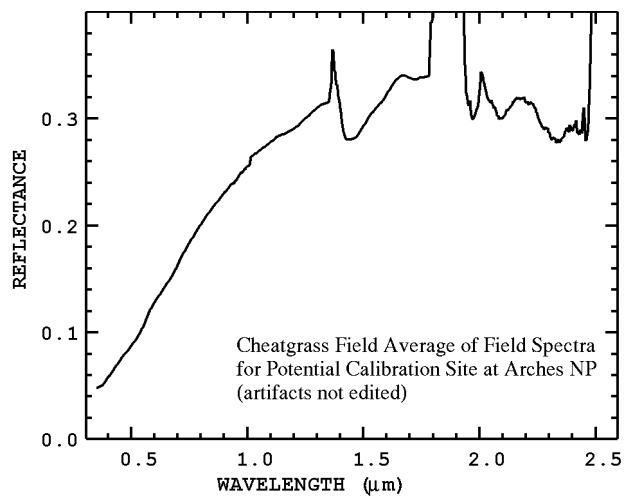

Figure 11i - Arches B. Calibration site average field spectrum of cheatgrass field, located just outside of the Arches national Park boundary.

trace iron oxide (or iron hydroxide) are common components of playa surfaces (see Figure 11a). If the field spectral measurement of the playa does not accurately characterize the site, there could be a residual spectral signature imparted to the final calibrated data that is either not enough of a particular absorption feature, or too much of a feature. Such residuals are a result of different sampling between the remote sensing instrument and the ground study. If the site has no spectral features (e.g. no 2.2 micron montmorillonite absorption, and no iron absorption in the ultraviolet or visible), then there would be no error in sampling.

The probability of residual spectral artifacts is reduced if the calibration site spectrum has few or no spectral features. If the spectrum is flat, and thus there are no residual features to impart to the data, then even a laboratory spectrometer could be effectively used (assuming disturbing the surface to take the sample to the lab does not change the spectral characteristics). For the AVIRIS spectral range (0.4 to 2.5 microns), quartz sand is ideal: it has high reflectance at all wavelengths and no significant absorption features. Playas often have high quartz content and usually only weak clay or iron absorption bands, thus they are usually spectrally bland. Bright white rocks or sandy areas are often ideal if not covered with

vegetation (even sparse vegetation). Feldspar-bearing rocks also have little to no absorption features in the AVIRIS spectral range. Figures 11a-j show spectra of the calibration sites shown in Figure 2. Note that just because a site appears bright and white does not mean it is a good spectral calibration site. It may have strong UV or infrared spectral features (such was the case with the Jordanelle dam spectra, Figure 11d).

A spatially uniform calibration site is an area on a scale which can be characterized in the field, on the ground and by the remote sensor, where the pixel to pixel variations in the reflectance spectra are low. If a site is composed of many different pebbles, for example, but both the field spectrometer and the flight data measurements average many pebbles together, the site is most likely acceptable and can be considered spatially uniform. Many dam faces are composed of large boulders, some larger than a person's head, but a field spectrometer with a half-meter diameter spot can average over many boulders, thus providing a uniform site. Such was the case of the Deer Creek dam site shown in Figure 2d-e.
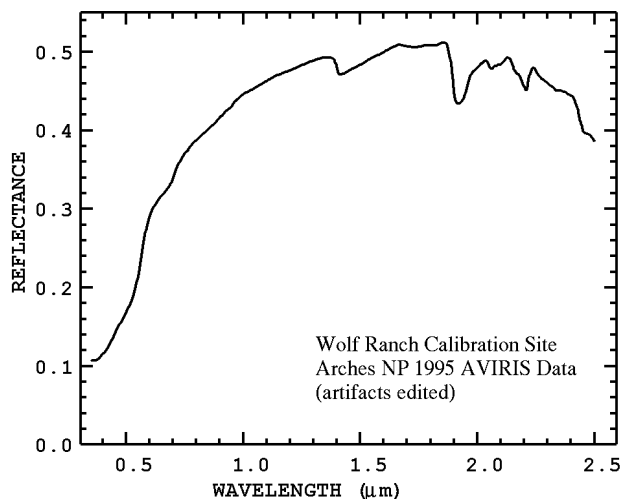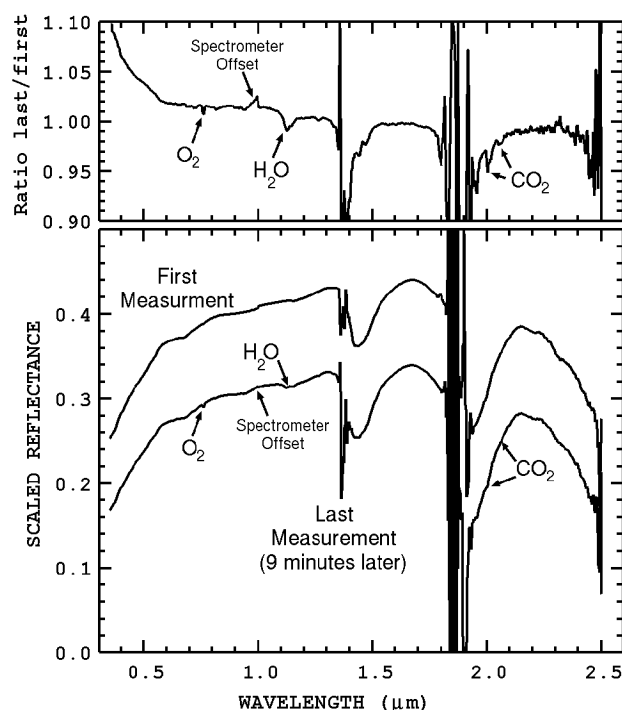

Figure 11j - Arches C. Calibration site average field spectrum of Moab Tongue Formation in Arches National Park.

7.3 Field Spectra Verification

Field spectra commonly have artifacts due to constantly changing conditions. The atmosphere and local air temperature can vary with time. Wind, sun, and shadow impacting on the instrument vary as the operator moves around making measurements, and battery power constantly decreases. Dark and gain levels also vary with time, producing offsets in measured spectra. Atmospheric water vapor varies with time resulting in residual water absorptions. The atmospheric path length constantly changes as the sun moves across the sky, necessitating continual re-measurements of local reference standards. Given these conditions, it is very difficult to keep the field spectrometer in a stable environment and therefore in good calibration. Example spectra with typical artifacts are shown in Figure 12.

Figure 12: Example sample spectrometer drift over 9 minutes is shown. The residual features after 9 minutes are small in this case because the atmosphere and the instrument were relatively stable. The features are small enough they would be barely noticed on a field spectrometer computer screen. However, when the first and last spectra are ratioed, one sees residual features several percent in strength. Each spectrum is a six-second integration. These residual features must be hand-corrected if present in the final average for the site (discussed below).

There is no simple solution to the above problem. Even if the field spectrometer remained in perfect calibration, the atmosphere will not remain constant. The best conditions in which to make field measurements are clear skies, near solar noon, at temperatures that do not stress the instrumentation (no extreme heat or cold). A field spectrometer that

measures a reference spectrum to provide continuous corrections to varying atmospheric conditions at the same time as measuring the surface is needed to avoid some of these problems, along with low sensitivity to temperature and power fluctuations.

Another way to reduce atmospheric effects is to use an artificial light source, powerful enough to measure a large spot in an enclosure to minimize solar and atmospheric effects. However, batteries to power lights and the spectrometer, which last long enough to measure many spots, would be cumbersome to carry, especially on rough terrain.

So how does one determine if a spectral feature in a calibration site spectrum is real or a field spectrometer artifact? One solution to this difficulty with field measurements is to sample the surface materials and measure their spectra in the laboratory. We have found that for some calibration sites, the laboratory spectra of field samples usually measure enough of the site's spectral characteristics to enable determination of what are artifacts and what are real features in the field data. Thus, the laboratory spectra provide a secondary check to establish the quality of the *in situ* field data (e.g. Figure 13). Multiple calibration sites also help answer this question. When compared to the airborne imaging spectroscopy data, multiple calibration sites should indicate the same residual differences between the flight data and the calibration site spectra. Ideally, those differences are zero for the flight data converted to surface reflectance and the field reflectance data.

Once artifacts are identified, the spectrum is corrected by numerous methods depending on the artifact. An offset in the spectrum might be corrected by multiplying one part of the spectrum by a constant to adjust the level. If the correction can be determined to be a zero-level error, a constant could be added or subtracted. Spikes and residual features can be interpolated across, or other the correct values can be estimated from a graph and the data values edited by hand. Laboratory comparison spectra are sometimes spliced into the field spectrum, most commonly where the terrestrial atmosphere is nearly opaque around the 1.4 and 1.9 micron water absorptions. There are no simple software packages for these manipulations. We commonly use the tools available in the SPECPR package (Clark, 1980, 1993).
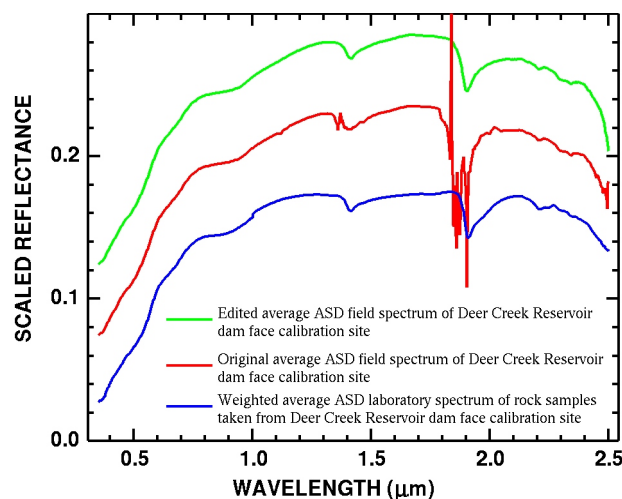

Figure 13. Example calibration site spectra and the correction of artifacts. Spectra are offset for clarity. The average field spectrum from the Deer Creek dam calibration site is shown (middle). Artifacts include residual atmospheric water features at 1.15, 1.4, 1.9, and 2.5 microns, and residual CO_2 features near 2 microns. A weak offset at 1 micron (a grating and detector change in the instrument) is also present but at a level too small to appear in this graph. Spectra of rock samples from the site were measured in the lab (lower spectrum) to confirm spectral features. Note the difference in the 2.2-micron feature depth between lab and field spectra. This is due to variation in the proportions of materials sampled in the field and lab. The lab spectrum is relatively smooth in the regions of atmospheric water, and was used to fix/interpolate the average field spectrum across the regions of atmospheric artifacts. The final edited spectrum is shown at the top. The quality of the final spectrum shows that field spectra can be of laboratory quality. This is the quality we try to achieve at each of our calibration sites.

7.4 Spectralon Correction.

Spectra obtained by both the field and laboratory spectrometers must be fully corrected to absolute reflectance before any analysis can be performed. Laboratory and field reflectance measurements are made relative to a "white" reference material, such as Spectralon (available from Labsphere, a commercial derivative of the reflectance standard developed by the National Institute of Standards and technology, NIST: Weidner and Hsia, 1981). However, no currently known material has a 100% diffuse

reflectance in the UV to near infrared (0.3 to 2.5 microns). The reflectance of Spectralon is shown in Figure 14, derived according to methods similar to that used by Clark *et al.*. (1990) to derive the reflectance of Halon. It is obvious from Figure 14 that Spectralon has a several percent absorption feature near 2.13 microns. Because reflectance with a field or laboratory spectrometer is derived by the ratio of sample / reference, the result with a Spectralon reference will result in a spectrum with a positive feature near 2.13 microns. Thus, the corrected reflectance, R_{absref} is:

$$R_{absref} = (I_{sample} / I_{ref}) R_{ref},$$

where I_{sample} is the light intensity measured by the instrument from the sample, I_{ref} is the light intensity measured by the instrument from the reference under the same incident lighting conditions, and R_{ref} is the absolute reflectance of the reference material (e.g. Figure 14 if Spectralon).
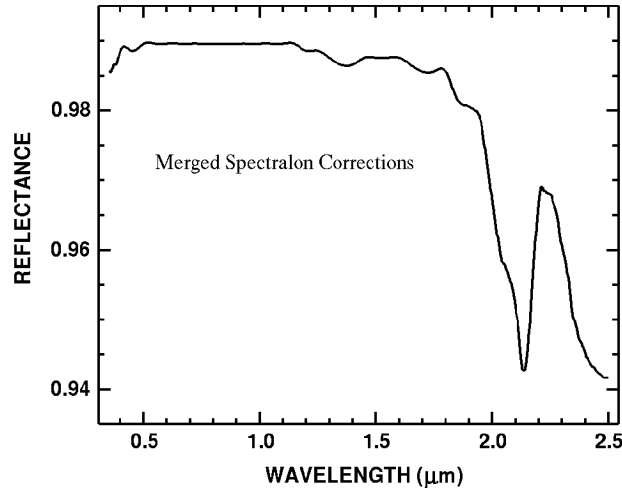

Figure 14. The reference used with the field spectrometer, Spectralon, is not a perfect 100% reflectance standard. The spectral features of the field reference standard must be removed, or residual reference material spectral features will be propagated into the imaging spectroscopy data.

7.5 Spectral Convolution.

Before actual comparisons are done between different spectrometers, the field spectra to be used in the comparisons should be convolved to the bandpass and sampling of the flight instrument. If there are absorption features in the spectra that are on the same order or less in width than the bandpass of the spectrometer, the spectrometer will broaden the feature and give a width wider by approximately the sum of the squares of the widths of the feature and the spectrometer. The measured width, W_m is

$$W_m = (W_f^2 + W_s^2)^{0.5},$$

where W_f is the width of the feature and W_s is the bandpass width of the spectrometer. Thus, the field and/or lab spectrometer should have narrower bandpasses than the flight instrument. Note, however, that if the spectra being compared have no spectral features, then all spectrometers will give the same answer. Spectral convolution software that tracks the finite bandwidth of spectrometers is available in the SPECPR package (Clark, 1980, 1993).

The variation of wavelength accuracy between instruments will result in disagreements between spectra measured by those instruments. Because field instruments get rough treatment relative to laboratory instruments that remain in the lab, the wavelength accuracy should be monitored often in the field and confirmed in the laboratory. We measure mylar plastic in the field with our field spectrometers and confirm the wavelength position of the mylar absorption features with our Fourier Transform laboratory spectrometer. The bandwidth of the spectrometer can also be monitored by use of the mylar absorption features and the above formula. The narrowest features in a spectrum provide for the highest accuracy when determining wavelength accuracy and bandwidth.

7.6 Multiplier Correction.

The offset spectrum (e.g. Figure 8b) is subtracted from ATREM-corrected data (e.g. Figure 5) from the ground calibration area. The edited field spectrometer average of the ground calibration site (Figure 6) is spectrally convolved to the AVIRIS sampling and bandpasses and ratioed to the offset-corrected ATREM data. This ratio becomes the multiplier for the ATREM data cube to correct the data to surface reflectance (Figure 15).
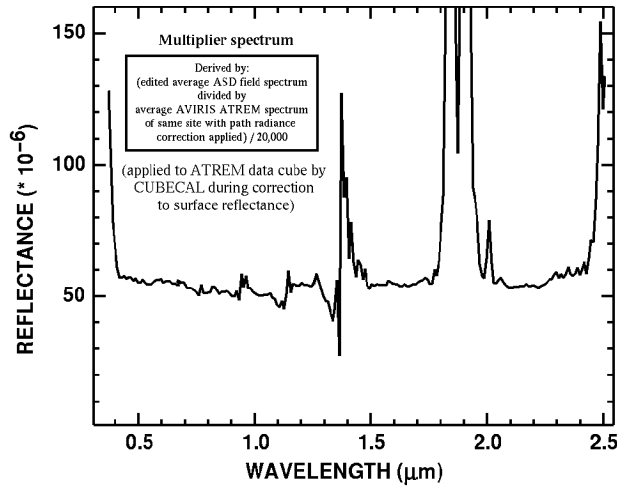
Figure 15. The derived multiplier spectrum. Our ATREM-corrected data are scaled integers where a reflectance level of 1 is a data number (DN) equal to 20,000. The multiplier corrects the DN back to reflectance in our software, so the multiplier should be approximately 1/20,000 (or 50×10^{-6}). If the ATREM data matched the field spectrometer data, the multiplier would be a flat line on this graph at 50×10^{-6}**.**

The imaging spectroscopy data are corrected by running a computer program that subtracts the offset and multiplies by the multiplier for each pixel. This simple math can be done with commercial software such as IDL or small custom programs or other public domain software such as REMAPP. We scale the AVIRIS data souch that a derived reflectance of 1.0 is scaled to a DN = 20,000, so the multiplier shown in Figure 15 should have a level approximately equal to 1/20,000. The resulting surface-reflectance-calibrated data set is called "radiative transfer ground calibrated" and we use a file extension of "rtgc" on the output file name.

The final "rtgc" data are stored as signed 16-bit integers so that the 0 to 1.0 reflectance range must be scaled. Because of the very high signal-to-noise of current AVIRIS data (which can be several thousand), with seemingly continuous improvements from year-to-year by the AVIRIS engineering team, we use a high scale factor, 20,000, to be sure we do not run into any DN quantization problems. Thus all "rtgc" calibrated data from our lab is scaled so a DN of 20000 is a reflectance of 1.0 (reflectance 0.5 has a DN=10000, a reflectance of 0 is DN=0). If any value in the data set is out of range, or the processing steps indicated bad data, the data point is marked deleted. Deleted point values are set to a value of -32767.

Example spectra from well-calibrated data cubes are shown in Figure 16a-c. Ignoring the regions of low signal through the Earth's atmosphere, near 1.4 and 1.9 microns, the derived surface reflectance data are excellent.
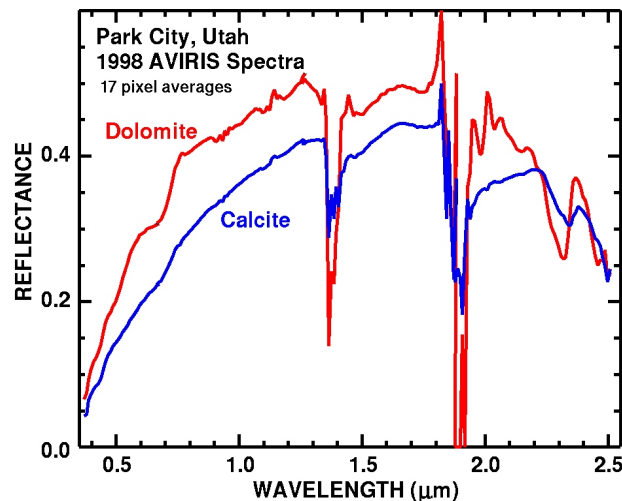

Figure 16a. Radiative transfer, ground calibrated (rtgc) calibrated AVIRIS spectra from the August, 1998 flight over Park City, Utah. Comparison of calcite and dolomite spectra. Ignore the 1.4 and 1.9 micron regions where the terrestrial atmosphere is mostly opaque. The dolomite spectrum shows residual CO_2 absorptions near 2-microns because the area from which it was sampled is at a much higher elevation than the calibration site and ATREM does not correct for localized CO_2 effects.

Figure 16b. Radiative transfer ground calibrated (rtgc) AVIRIS spectrum from the August, 1998 flight over Park City, Utah. The clay mineral montmorillonite shows a 2.2-micron absorption feature. Ignore the 1.4 and 1.9 micron regions where the terrestrial atmosphere is mostly opaque.
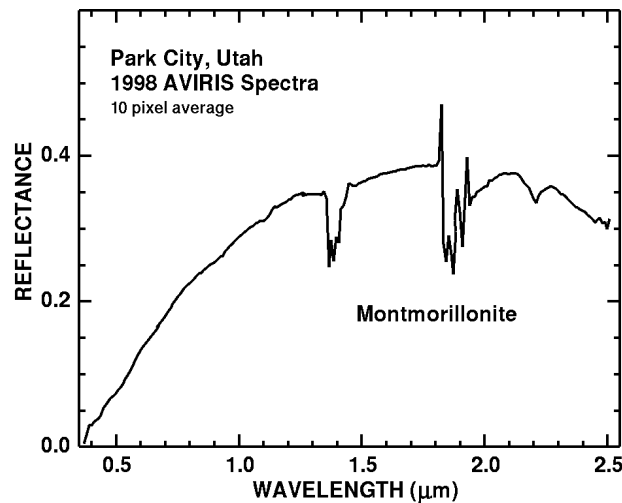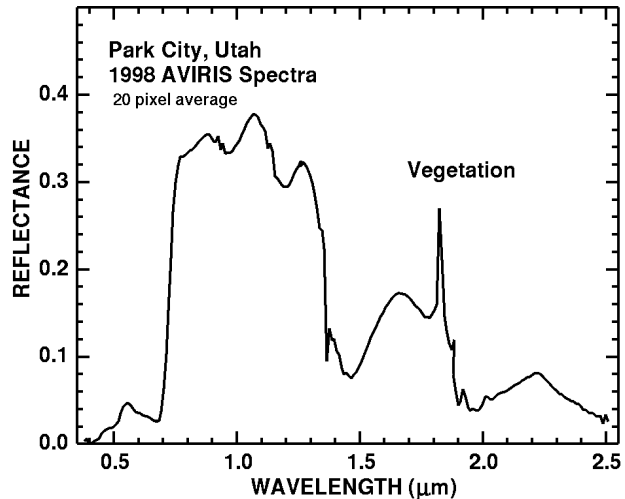

Figure 16c. Radiative transfer ground calibrated (rtgc) AVIRIS spectrum from the August, 1998 flight over Park City, Utah. Example vegetation spectrum. Ignore the 1.4 and 1.9 micron regions where the terrestrial atmosphere is mostly opaque.

8. Summary

Imaging spectroscopy data, such as AVIRIS, can be corrected to surface reflectance by using a two step correction. A radiative transfer correction tracks changing atmospheric water absorptions from pixel to pixel and removes the absorptions due to water and other atmospheric gases, scattering in the atmosphere and the solar spectrum. The second step uses the reflectance of known targets in the scene to correct the artifacts from the imperfect radiative transfer correction. Critical to the success of this method is the accurate reflectance characterization of field calibration sites.

The quality of the calibration to surface reflectance is important for accurately identifying materials. A small calibration artifact could distort an absorption feature, causing a misidentification. An accurate calibration shows the fundamental properties of surface materials, and is key to linking remotely sensed surface properties with laboratory data.

The effort to do the calibration is significant. The steps involved are many, including pre-assessment of calibration sites before the flight, measurements with a field spectrometer near the time of the flight, sampling of the materials at the site, measurement of those samples on laboratory spectrometers, reduction of the field data, radiative transfer corrections of the flight data, extraction of imaging spectroscopy data over the same area as the field measurements, comparison of the radiative transfer data with the field data, correction of artifacts in the field data, evaluation of path radiance scattering in the imaging spectroscopy data, derivation of offsets and multipliers to correct the radiative transfer calibrated imaging spectroscopy data, application of the offsets and multipliers to the flight data, and then evaluation of the resulting calibration to see if it is adequate. If the calibration is not adequate, the data need to be re-evaluated and some steps re-done. Our experience has shown that the calibration of one site involves about 1 to 2 person months to calibrate, and sometimes more. One of our recent experiences was with the Utah EPA study where a person week was spent pre-assessing calibration sites, 3 person weeks spent in the field making measurements near the time of the flight, and about 7 person months working in the lab and at the computer doing the above steps for 3 sites. The average is about 2.7 person months per site, and the calibration for all 3 sites is not yet complete.

While the effort is substantial, the results are worth the effort as the "radiative transfer ground calibrated" spectra are near laboratory quality. The remaining artifacts are mainly due to elevation differences because the current radiative transfer code we use does not correct elevation effects for all

atmospheric gases. More sophisticated code should result in even better corrections for all pixels in the imaging spectroscopy data set.

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APPENDIX A
Obtaining and Organizing Imaging Spectroscopy Data

The first step to organizing data is to acquire digital copies of the imaging spectroscopy data (e.g. AVIRIS data are obtained from JPL). The data may not come in a form that will be easy to work with and will have to be reformatted. For example, new AVIRIS data are sometimes shipped as one flight line per tape, with AVIRIS data in 512-line scenes (files) in band-interleaved-by-pixel (BIP) format. Our processing requires band interleaved by line (BIL) format. We read the data tapes onto disk, and convert the imaging spectroscopy data to BIL format and add ascii Vicar headers. Table 1 shows a sample Vicar header. Important for software use, including easy access by FORTRAN programs, the header should have a length equal to a logical record length. For example, AVIRIS has 614 pixels across one scan line and 2 bytes per pixel, thus the header is (2x614=) 1228 bytes. Note that a valid vicar header has at least two blank spaces between key words.

```
LBLSIZE=1228 FORMAT='HALF' TYPE='IMAGE' BUFSIZ=19648 DIM=3 EOL=0 RECSIZE=1228
ORG='BIL' NL=1024 NS=614 NB=224 N1=614 N2=224 N3=1024 N4=0 NBB=0 NLB=0 TASK='dd
to combine scene1,2' USER='rclark' DAT_TIM='Aug 19 19:35:05 1992 UTC'
TITLE='Chesler Park flight 920819B run 6 scene 1,2'
```

We concatenate the AVIRIS scenes into 1024-line segments because the size of a segment is about 281 megabytes, enabling convenient viewing on a terminal screen and so that two scenes plus some data products can fit onto a CD-ROM disk (650 megabyte capacity). Two scenes on an optical disk are required because the radiance data and the reflectance calibrated cubes are stored together so that they can both be used for mapping. In the future, the many-gigabyte capacity of Digital Versatile Disk (DVD) technology will allow archiving of an entire flight line on a single disk as one file each for the radiance and reflectance cubes.