Evolution in Imaging Spectroscopy Analysis and Sensor Signal-to-Noise: An Examination of How Far We Have Come

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Imaging spectroscopy is a relatively new field whose instrumentation and analysis methods have grown in sophistication over the last decade. We have studied the signal-to-noise of the NASA/JPL AVIRIS instrument from 1990 to 1995 along with the improvements in our own analysis methods using the Cuprite, Nevada data available each year. The advantage of becoming familiar with a single test site, by studying both the data obtained, as well as conducting field trips to verify results, helps to understand the complexity of the surficial mineralogy at the site. The desert environment of Cuprite provides a relatively stable environment from year to year, which is important for assessing progress in algorithms and sensors.

Because the surficial geology of Cuprite is well understood (Swayze, 1996, Ph.D. thesis, near completion), as are several other AVIRIS sites we have studied, including areas near Barstow, CA (Clark *et al.*, 1996a), the Summitville mining region in Colorado (King *et al.*, 1995a, b, c), and sites on the Colorado plateau (e.g. Clark *et al.*, 1992), we have used our knowledge of the surficial minerals and their mixtures to derive a strategy for analysis. A spectral library of minerals (Clark *et al.*, 1993a), amorphous materials, vegetation, and mixtures of each has been compiled in the last few years, and their spectral features studied to design spectral identification algorithms capable of distinguishing more complex situations.

There are two conditions that have improved the level of detail in what we have been able to map: sensor signal-to-noise, and algorithm sophistication. We examined the effects of these two conditions separately and combined for the Cuprite test site.

We produced maps of materials at Cuprite using 1990, 1993, and 1995 AVIRIS data. For each data set, we produced two materials maps. The first map contains materials whose spectra show electronic absorptions. These absorptions generally occur in the ultraviolet to near infrared (~1 μm), and include iron-bearing minerals. The second map contains materials whose spectra show vibrational absorptions. Such absorptions generally occur in the near-infrared, where many diagnostic features occur in the 2 to 2.5-μm region. These maps include clays (and other phyllosilicates), carbonates and sulfates.

1990 AVIRIS Data

In 1990, the AVIRIS system achieved a signal-to-noise at 50% reflectance over Cuprite of about 150 in the visible, and about 80 at 2.2 μm. In 1993, AVIRIS isignal-to-noise improved to about 600 in the visible and about 140 at 2.2 μm. In 1995, with new detectors, the AVIRIS signal-to-noise improved to about 800 in the visible and about 360 at 2.2 μm. Swayze and Clark (1995), and Swayze et al., (1996) have shown that mineral discrimination ability is directly proportional to the signal to noise with shape-matching algorithms like those we use. Thus, improvements in signal-to-noise of the AVIRIS system directly leads to improved materials maps and the ability to discriminate more complex possibilities.

As AVIRIS signal-to-noise improved, we refined our algorithm, which we call Tricorder. Clark et al. (1990, 1991, 1993) analyzed AVIRIS 1990 data for Cuprite using Tricorder version 1.0 which had the ability to map up to about 30 materials at one time. However, separate spectral regions required different runs of the program. The algorithm analyzed multiple spectral features, without continuum constraints. Continuum constraints are additional information, such as level and slope. Calibration for these early studies included only ground targets, resulting in residual atmospheric absorptions as a function of elevation, thus complicating any analysis. Mapping methodology and results were verified with field mapping and X-ray diffraction analysis of hand samples (Swayze et al., 1992).

The mapping results (Clark et al., 1993b) shows 10 phyllosilicates, sulfates, and carbonates and three Fe-bearing oxides and sulfates (goethite, hematite, and jarosite). The vibrational-absorption maps show eastern and western bull's-eye patterns of hydrothermal alteration with their characteristic concentric zoning. The western center consisted of an alunite interior zone, surrounded by a kaolinite zone, in turn surrounded by a muscovite (or sericite) zone. The eastern center shows only the interior alunite zone surrounded by a kaolinite zone. The electronic-absorption map shows the eastern center bleached of Fe-bearing minerals with a hematite-rich halo encircling the bleached areas. The western center has appreciable jarosite and goethite indicating that erosion has exposed a deeper pyrite-rich level of the underlying hydrothermal system.

1993 AVIRIS Data

In 1993, Tricorder was improved to version 2.3, which had the ability to map up to about 120 materials, but separate spectral regions still required multiple runs of the program. Analysis used multiple spectral features, simple continuum constraints and some mineral mixtures. A good spectral library (Clark et al., 1993a) was complete. Calibration improved to include a combination of radiative-transfer-atmospheric modeling and ground-calibration targets (Clark et al, 1993c, 1996b) to achieve near laboratory quality surface reflectance spectra from AVIRIS. Verification continued with field mapping, X-ray diffraction analysis of hand samples from the field, and data from portable field spectrometers.

The Tricorder 2.3 results showed multiple iron-bearing minerals, including discrimination of the grain sizes of hematite, and several different Fe^{2+}-bearing minerals, mainly chlorites and muscovites. Our vibrational-absorption materials map shows 16 minerals, including a subdivision

of the solid solutions series of alunites and muscovites. Mapping also showed that most mineral-mixtures occurred on the alluvial fan surfaces as expected.

1995 AVIRIS Data

In 1995, the AVIRIS signal-to-noise was improved to the level of producing spectra equalling the quality of many laboratory-obtained spectra. Extraction of spectra from the calibrated data set showed spectral complexities that were hidden by noise in previous years. Fortunately, improvements in software allowed for a more sophisticated analysis (Clark *et al.*, 1995a). Tricorder 3.3 now has the ability to map for thousands of materials, including simultaneous analysis of spectra of solids, liquids, and gases. Analysis of multiple spectral features in all spectral regions are done simultaneously. Sophisticated shape matching constraints, preprocessing, and specific algorithm selections are done for each analysis. Tricorder does an artificial-intelligent-expert-system analysis and makes decisions on a case by case basis. Algorithms include thresholding of parameters, "not" spectral features (see Clark *et al.*, 1995a), and additional, selectable analyses based on answers to previous analyses. The spectral libraries are improved with spectra of amorphous materials, environmental materials, vegetation, snow, water, and some man-made materials. The analysis uses many mineral mixtures. Calibration is the same as with the 1993 data, but better field-portable spectrometers were used to characterize the ground calibration targets. Previously, samples were returned to the laboratory for analysis, and included only a few square centimeters of sample.

Results of mapping using the 1995 data show amazing complexity. Out of about 160 categories mapped, about 70 were found! The electronic-absorption map shows 16 categories of iron oxides, Fe^{2+}-bearing minerals, and weathered-Fe^{2+}-bearing minerals. The vibrational-absorption map shows 25 categories, including finer discrimination than before of the solid-solution series of alunites, muscovites, and mixtures of these with kaolinites and smectites. These two maps together show 36 categories. More maps would be needed to show the other materials found, which are generally in small spots, or scattered at a low level, or are trace vegetation types, and could not be readily distinguished amid the complexity of the first two maps.

Conclusions

JPL engineers have improved the AVIRIS signal-to-noise remarkably over the last few years and our analysis capabilities have similarly evolved to the point that sophisticated materials maps can be derived with high confidence in the results. Beyond the phenomenal increase in capability is our astonishment at the complexity of the surficial mineralogy expressed at Cuprite. Mineral maps derived from imaging spectroscopy data now convey mineralogic detail which exceeds that of conventional published geologic maps. The superb signal-to-noise of the 1995 AVIRIS system is a two-edged sword: the data have enough precision to show very subtle spectral detail; but that detail is showing us how complex the world really is. Spectra extracted from the Cuprite 1995 data set show more complexity than we have so far mapped, and we must continue to refine our analyses to handle that complexity.

Further Information

The USGS Spectral library, the images referenced in this paper, and additional information on spectroscopy can be found at the web site: "http://speclab.cr.usgs.gov" using a standard web browser.

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53