

# **A COMPARISON OF IMAGE PROCESSING METHODS FOR ALTERATION MAPPING**

## **AT BODIE, CALIFORNIA, USING 1992 AVIRIS DATA**

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### **1. INTRODUCTION**

Hyperspectral remote sensing, or imaging spectrometry, has been under development for more than a decade since the first experimental sensor of this type, the Airborne Imaging Spectrometer, became operational in 1983. With the appearance of the Advanced Visible/Infrared Imaging Spectrometer (AVIRIS) in 1987 and its continued development by JPL since then, together with development of commercially operated imaging spectrometers such as those built and operated by Geophysical & Environmental Research Corp. (GER), a number of applications have been shown to benefit from this technology. Among these applications is the discrimination of superficial materials for mineral exploration, in particular, mapping hydrothermal alteration minerals. However, the unavailability of hyperspectral sensors and lack of data covering a diverse geological environments in different regions restricted the use of this type of data operationally. Also, hyperspectral data required the development of new image processing algorithms specifically designed to take advantage of the high spectral resolution and to cope with the much larger amount of data than those used with conventional multispectral data (e.g. Landsat TM).

With the continued deployment of AVIRIS in different regions of North America, Europe (1991) and South America (1995), and the continued operation of GER scanners, progressively more data has become available. The development of new algorithms for processing hyperspectral data came next, including those for identifying surface materials. Some of these algorithms have recently been incorporated into commercial image processing software.

Development of new hyperspectral imaging sensors marks a third stage toward operational applications for mineral exploration. In 1994 the Multispectral Infrared and Visible Imaging Spectrometer (MIVIS) was developed by Daedalus and in 1995 two new imaging spectrometers started collecting data: the Hyperspectral Digital Imagery Collection Experiment (HYDICE) and the SWIR Full Spectrum Imager (SFSI). Two other airborne imaging sensors are currently under development: GER's Digital Airborne Imaging Spectrometer-7915 and the Wedge Imaging Spectrometer (WIS) by Santa Barbara Research Center of Hughes Aircraft. TRW was selected by NASA to build the Hyperspectral Imager (HSI), a spaceborne imaging spectrometer to be launched by the end of this decade and which will provide 384 spectral bands with a 30 meter IFOV. All these developments, summarized by Taranik and Crósta (1996), indicate a clear trend toward operational use of hyperspectral data in geological remote sensing in the near future.

This paper examines and compares two different algorithms recently developed for identifying superficial materials in imaging spectrometry data. The objective was to assess the performance of these algorithms and their ability to map alteration minerals for precious metals exploration. Unlike previous mineral mapping studies such as those done at well known localities like Cuprite, Nevada, this exercise tried to simulate a situation often encountered in mineral exploration, in which remote sensing is used as the first tool for defining targets before the geologist sets foot on the ground. Therefore, techniques that do not require the a

*priori* input of ground data were favored for converting the image data to ground reflectance and for identifying superficial materials.

The area selected for this study is the Bodie mining district and part of the neighboring Paramount district, both located in Mono County, California. AVIRIS data for this area was acquired in October 1992 by NASA's ER-2 aircraft.

## **2. GEOLOGY AND MINERALIZATION OF THE BODIE AND PARAMOUNT DISTRICTS**

Bodie was an important gold-silver mining district in the second half of the nineteenth century, whereas only a mercury mine was exploited in the Paramount district. Tertiary (7.8 to 9.4 Ma) intermediate to basic volcanic rocks (dacitic, andesitic and sometimes rhyolitic lavas, plugs, tuffs and breccias) underlie both districts. Hydrothermal alteration associated with precious metal concentration at Bodie is probably the result of intense thermal spring activity, some of which can still be found in this region along fault zones (Silberman et al., 1995).

Bodie has characteristics of a bonanza-type lode quartz vein deposit and a large-scale stockwork system, with gold occurring in quartz veins and quartz-adularia-chalcedony stockworks in the center of the district. Petrographic work by Herrera et al. (1993) showed vertical and lateral zoning in the alteration with silicification in the center surrounded by zones of potassic, argillic and sericitic alteration and an outer zone of propylitic alteration. Not much information is available for the Paramount district due to the lack of important mineralization, but the district has recently been prospected for bulk tonnage precious metal mineralization (Herrera et al., *op. cit.*). Geological characteristics observed at Paramount are very similar to those in Bodie and the origin of the alteration is believed to be similar (Silberman et al., 1995).

The AVIRIS scene used in this study covers the Bodie district almost entirely and the eastern portion of the Paramount district, between Atastra and Rough creeks.

## **3. DATA CALIBRATION TO SURFACE REFLECTANCE**

Identification of surface materials using hyperspectral data is based on quantitative comparisons between pixel and library spectra. In order to make such comparisons, imaging spectrometer data need to be pre-processed for retrieving ground reflectance values from radiance measurements. A number of methods have been proposed for such conversion, some of which require the input of ground data preferentially collected simultaneously with the sensor's overflight. Radiative transfer methods rely on the use of atmospheric models and allow the retrieval of apparent ground reflectance from the radiance values provided by AVIRIS. A comparison of several methods by Clark et al. (1995) showed that a hybrid method which combines simultaneous ground-based data and the radiative transfer method developed by Green et al. (1993a), provides the best results for reflectance retrieval in hyperspectral data, followed by the sole use of the Green's radiative transfer method.

Green's radiative transfer method was selected because it suits the objectives of this study. This method uses the AVIRIS laboratory-calibrated radiance (Chrien et al, 1990) in conjunction with in-flight calibration data obtained over Rogers Dry Lake at the beginning of the 1992 AVIRIS data acquisition season (Green et al., 1993b) and the MODTRAN radiative transfer code. The method requires no *in situ* measurements and compensates for AVIRIS derived estimates of water vapor, aerosol and surface on a pixel by pixel basis. Compared to other radiative transfer methods, it provides a better correction for H<sub>2</sub>O and other atmospheric gases, as a function of elevation throughout a scene (Clark et al., 1995). Disadvantages of this method include: (i) errors in the ground measurements during the in-flight calibration at the beginning of the season will propagate into the derived surface reflectance; (ii) computation time is considerable and (iii) the method is still under development at JPL and not yet available for general use.

#### **4. IMAGE PROCESSING METHODS FOR MINERAL MAPPING**

Two different methods have been compared for mineral mapping at Bodie and Paramount: the Spectral Angle Mapper (Kruse et al., 1993) and Tricorder (Clark et al, 1990; Clark and Swayze, 1995). Both methods rely on a spectral comparison between pixels from the scene and reference spectra from a spectral library, using different algorithms to compare and measure the similarity between spectra extracted from pixels and reference library spectra. The two methods are insensitive to illumination differences due to topographical shadowing and therefore can be used in all sorts of terrain. The library used for this assessment was the public domain USGS Spectral Library which contains nearly 500 reference spectra of minerals, vegetation and other surface materials (Clark et al., 1993).

##### **4.1 Spectral Angle Mapper Classifier**

The Spectral Angle Mapper (SAM) is a supervised classification technique that measures the spectral similarity of image spectra to reference spectra which can be obtained either from a spectral library or from field and laboratory spectra. SAM defines spectral similarity by calculating the angle between the two spectra, treating them as vectors in  $n$ -dimensional space, with  $n$  being the number of bands used. The angle is the arc-cosine of the dot product of the two spectra. Small values for the angle represent higher spectral similarity between pixel and reference spectra.

This method is not affected by gain (solar illumination) factors, since the angle between two vectors is invariant with respect to the lengths of the vectors. SAM produces an image with the pixels it manages to classify assigned to the respective reference minerals, constrained by a user-specified threshold, together with a set of "rule images", one for each reference mineral used. DN values in these "rule images" are the expression of the angle itself (smaller DNs indicate greater similarity to the respective reference mineral), and these images can be used to assess individual results for each reference mineral. The advantages of SAM are that it has already been implemented in commercial imaging processing packages, it is easy to use and it is computationally fast.

##### **4.2 USGS Tricorder Algorithm**

Tricorder is still under development by the U.S. Geological Survey Spectroscopy Laboratory and is expected to be released in early 1996 for general use. It was designed to compare spectra of materials from the USGS Digital Spectral Library to image spectra from hyperspectral sensors, analyzing simultaneously for multiple minerals using multiple diagnostic spectral features for each mineral.

Tricorder works by first removing a continuum from spectral features in the reference library spectra and also from each spectrum in the image data set. Both continuum-removed spectra are then compared using a modified least square procedure. The algorithm uses a linear correlation coefficient to determine the fit by individually fitting all diagnostic absorption features of all reference spectra in the library to each pixel spectrum. The algorithm then calculates an overall fit by weighting each individual fit based on the area under its continuum-removed spectra. The overall fits are then compared and the mineral from the library with the highest fit is assigned to the image pixel.

One of the strengths of Tricorder is that it considers several attributes in the analysis: the depth for particular absorption features, the goodness of fit and the reflectance level of the continuum at the center of the feature. By doing this, it can analyze feature shapes using all data points and therefore resolve even complex feature shapes such as doublets in minerals like kaolinite, dickite and halloysite. The method, like SAM, is also not affected by illumination differences.

#### **5. ALTERATION MAPPING AT BODIE AND PARAMOUNT**

Both methods, SAM and Tricorder, were applied to the Bodie/Paramount reflectance-calibrated AVIRIS scene (512 x 614 pixels) in order to identify and map alteration minerals in both districts and to compare results.

Two spectral regions were processed separately in SAM: the visible/near-infrared (VNIR) region (0.4 to 1.3  $\mu\text{m}$ ) and the shortwave infrared (SWIR) region (2.0 to 2.4  $\mu\text{m}$ ). The VNIR bands were analyzed for minerals with diagnostic electronic transition features (hematite, goethite, jarosite, etc.) using 9 reference spectra, and the SWIR bands were analyzed for hydroxyl-bearing minerals and carbonates using 15 reference spectra. These spectra were from the USGS Digital Spectral Library and were convolved to AVIRIS bandwidths prior to running the SAM classification. The threshold value used for the maximum angle between spectra vectors was established empirically at 0.065 radians. Values above this produced too many classified pixels in only one or two classes and values below it produced images with almost entirely "non-classified" pixels.

In the SWIR, SAM classified most of the alteration at Bodie as Na-montmorillonite with some pixels classified as a mixture of kaolinite+smectite at Silver Hill, near the center of the district, and at Bodie Bluff in the northern portion. At the Paramount district, most of the western part was classified as a mixture of kaolinite+smectite with some pixels as Na-montmorillonite, whereas the eastern part of the alteration was classified as Na-montmorillonite plus a very few pixels classified as either poorly crystalline kaolinite or well-crystalline kaolinite. Two of the reference spectra, illite and Ca-montmorillonite, were mapped in a great number of pixels scattered throughout the scene. They were treated as misclassifications and removed from the final result. Computation time for the SWIR 15-mineral classification using 40 AVIRIS bands on a low-end Unix workstation (Sun IPX) was 8 minutes.

In the VNIR, 99 AVIRIS bands were used with nine reference spectra of common  $\text{Fe}^{2+}$ - and  $\text{Fe}^{3+}$ -bearing minerals. The results presented by SAM were not satisfactory because it classified most of pixels of the image as a mixture of hematite and quartz. Even after experimenting with different values for the minimum angle and removing the hematite+quartz spectrum from the reference spectra, SAM would classify most of the pixels as a single reference spectrum. It was then decided to use only three reference spectra: hematite, goethite and jarosite. Some empirical work had to be done to find the threshold value for the maximum angle which was 0.31 radians. The results showed goethite in altered areas at Bodie Bluff and Silver Hill together with jarosite in mine dumps and in a tailing pond. A few pixels were mapped as hematite at Silver Hill and in an area to the north of the major alteration. Goethite was also mapped in the Paramount district as well as jarosite which also appeared scattered throughout the western part of the scene and along dirt roads. It took 15 minutes to run SAM using 99 AVIRIS bands and 3 reference spectra on a low-end Unix workstation (Sun IPX).

Tricorder is run through command files which are pre-set to analyze specific groups of minerals. The command file used in this study included 126 materials including minerals, vegetation and ice. All the minerals analyzed using SAM were included in Tricorder's command file. Tricorder also analyzes separately for multiple minerals in the VNIR and SWIR spectral regions. Therefore, the analysis of the whole spectrum for a single pixel may find two different minerals, one for each spectral region, showing that the pixel contains diagnostic features for two minerals in different spectral regions.

Tricorder produced more detailed results than SAM, mapping a greater number and variety of minerals. In the SWIR region, Tricorder distinguished Na- and Ca-montmorillonite in most of the Bodie district and in the eastern part Paramount, two types of kaolinite (well- and poorly-crystalline) in the western part of Paramount, a mixture of kaolinite+smectite in the central part of the Bodie district, halloysite in the western part of Paramount, plus a few pixels as Al-muscovite, mostly at Silver Hill and the center of the Bodie district, and illite in a mine tailing at Silver Hill. Dolomite was given a good fit by Tricorder, and a fair number of pixels were mapped as such, but these pixels were scattered all over the image without any meaningful geological pattern. They were treated as misclassifications and removed from the final result, together with a few other minerals with low fits and small number of pixels: dolomite, phlogopite, hectorite, diasporite, clintonite, palygorskite, elbaite and nontronite.

In the VNIR, Tricorder mapped two different types of hematite. One is a fine-grained variety which was mapped scattered around hydrothermally altered areas in the Bodie and Paramount areas, and the other is a

mixture of hematite and quartz distinctively associated with the alteration at Bodie Bluff, plus a few pixels in the western part of Paramount. It also mapped goethite in the center of the Bodie district and in a tailing pond nearby. A few pixels scattered across the district were mapped as K-jarosite, while some others were classified as Fe<sup>2+</sup>-bearing minerals in the center of Bodie district and at Silver Hill.

The algorithm took around four hours to complete the analysis for 126 minerals in the VNIR and SWIR running on a medium-performance Unix workstation (HP 9000).

A spatial comparison between the areas of major alteration identified by both methods reveals that in the SWIR, Na-montmorillonite was identified by both methods at approximately the same locations in Bodie and eastern part of Paramount. The mixture of kaolinite+smectite only shows good correlation between both methods at the center of the Bodie district, whereas another major area of occurrence for this mineral mapped by SAM at the western part of Paramount was mapped by Tricorder as well- and poorly-crystalline kaolinite and halloysite. The separation achieved by Tricorder between Na- and Ca-montmorillonite at Bodie, as well as between Na-montmorillonite, halloysite and poorly-crystalline kaolinite in the eastern part of Paramount, did not appear in the SAM results. SAM also mapped the western part of Paramount as a mixture of kaolinite+smectite and Na-montmorillonite, whereas Tricorder identified poorly-crystalline kaolinite, with subsidiary well-crystalline kaolinite and halloysite for the same pixels.

Comparing results obtained by the two methods only for those minerals that could be mapped by SAM (hematite, goethite and jarosite) in the VNIR reveals major differences. SAM did not find much hematite in the whole scene, whereas Tricorder mapped clusters of pixels as hematite in both districts. However, some of the pixels mapped as hematite by Tricorder were assigned to goethite by SAM. On the other hand, pixels that Tricorder mapped as goethite were assigned to jarosite by SAM.

## 6. CONCLUSIONS

We managed to recognize and map a variety of minerals associated with hydrothermal alteration processes using AVIRIS data at the Bodie and Paramount mining districts, California. The method selected for calibrating the data and for retrieving reflectance from radiance was found to be precise enough to allow mineral mapping without the use of ground data. This represents a major advantage for mineral exploration activities in which ground data acquisition is rarely possible.

Two algorithms were used and compared for mineral mapping: Spectral Angle Mapper (SAM) and Tricorder. In general, Tricorder was able to produce more detailed mineral maps than SAM. Results obtained for the SWIR region showed a relatively good coincidence between the two methods for alteration minerals of major occurrence (montmorillonite and kaolinite). Both methods were able to show a east-west zonation in the alteration at Paramount regarding these minerals, and also some zoning at Bodie. In addition, Tricorder was able to map two types of montmorillonite, two types of kaolinite, plus halloysite, muscovite and illite.

In the VNIR however, results from both methods were quite different. Some of the pixels mapped by SAM as goethite were assigned by Tricorder to hematite. Tricorder managed to map a greater number of pixels as some mineral with diagnostic spectral features than SAM.

Spectral analysis of samples to validate these results is still ongoing, but preliminary results appear to confirm the Tricorder results in the SWIR region. Some of the characteristics of SAM, such as the fact that it is available in commercial image processing packages, easy to use and relatively fast to compute make it a feasible alternative for mineral mapping in exploration activities. Tricorder on the other hand produced more detailed results than SAM, and will be available for general use in the near future, but its complexity will demand some training, basic knowledge of spectroscopy and considerably more computing time than SAM.

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