Hyperspectral Imagery for Trafficability Analysis

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Abstract—This paper presents a summary of a project assessing the utility of hyperspectral imagery to determine cross-country trafficability in support of military operations. Hyperspectral imagery offers new capabilities to assess cross-country trafficability remotely. Development of recommended methodologies and procedures is the major thrust of this research. The use of spectral signature libraries is planned to help define areas to be avoided, such as areas with significant clay content. Likewise, other more compactable soils such as sandy loam can be located and used as preferred routes. This study develops methodologies and provides demonstrations of how hyperspectral imagery can be applied.

The results indicate that accurate detection of specific soils in an unfamiliar area is far from easy. Soils, being mixtures of minerals and organic material, have spectral signatures that are subject to variation. The components of soil are sub-pixel entities that must be identified, separated, and unmixed in the right proportions. Additionally, the dominant spectral feature may not represent the overall dominant physical characteristic of the soil being studied.

Both AVIRIS hyperspectral data and Landsat TM multispectral data were used. The principal results confirmed that areas in the data exhibiting spectral characteristics similar to the kaolinite reflectance spectrum, were successfully mapped using the Spectral Angle Mapper (SAM) algorithm. This conclusion is based on reference soil maps, ground truth observation, sample collection, and laboratory analysis. Closely corresponding areas were also spectrally mapped using a band ratio procedure that has historically been used to define clays in Landsat TM data.

Comparison of the hyperspectral and multispectral mapping results, clearly illustrates the advantage of hyperspectral data. The areas identified using hyperspectral data are much more precisely mapped. Multispectral data resulted in larger areas being mapped that included more

heterogeneous soil features. This same difference in spatial detection pattern is true for both the SAM and ratio analysis techniques.

INTRODUCTION

This project was initiated by the DoD Spectral Information Technology Applications Center (SITAC) in response to a request from the U.S. Army Space Command (USARSPACE). They requested assistance in developing methods to use hyperspectral imagery for determining cross-country trafficability for both wheeled and tracked vehicles. The mission of SITAC is to provide an applied research center for the investigation of the science and technology of spectral information, and an assessment of its utility in support of the Department of Defense. The purpose of the project was research and development of methodologies suitable for the use of hyperspectral data to improve military capabilities for assessing trafficability remotely. Current approaches rely on historical maps, multispectral imagery (such as LANDSAT and SPOT), Digital Terrain Elevation Data (DTED), and other resources. The primary goal of the study was to identify exploitation algorithms, data types, and procedures best suited for cross-country trafficability assessment.

Army Space Command provided 1994 AVIRIS hyperspectral data and June 1996 Landsat TM imagery over an area southeast of Colorado Springs, Colorado. USARSPACE also funded laboratory analysis of ground truth soil samples. Other materials provided included a 71/2 minute quadrangle geologic map of the Hanover NW Quadrangle[1]; soil maps of the area from the United States Department of Agriculture (USDA), Soil Conservation Service[2], and 1993 SPOT panchromatic imagery over the area of interest. The USDA soil maps used an aerial photography base from 1974 - 1975.

2. BODY

Methodology

The methodology is discussed as part of the body of this paper. Development of recommended methodologies and procedures is the major thrust of this research. The following paragraphs outline the procedures and algorithms used. In addition, the discussion will include a segment on lessons learned that is important for planning and conducting follow-on research.

Atmospheric Correction—The AVIRIS data provided was reflectance data. Therefore, it needed to be modified to account for atmospheric effects. These changes are necessary to enable the software to find a match to the spectral library sample. A clay mineral known as kaolinite was selected as the reference spectrum to be used. Kaolinite has a unique spectral absorption feature at about 2200 nanometers (nm) called the kaolinite doublet. The atmospheric correction process is considered an essential procedure except where targets or materials within the scene are used as the source for the reference spectra. An atmospheric correction algorithm called ATREM was used to remove atmospheric induced anomalies[3]. The algorithm calculates the amount of water vapor present and combines these values with measured solar irradiances. It then applies simulated, model-based light transmission values that incorporate representative molecular and aerosol scattering data.

Spectral Signature Matching Algorithm—An algorithm called Spectral Angle Mapper (SAM) was used over the entire AVIRIS image and over a subset area of the Landsat image. The AVIRIS data set of 224 bands with 20 meter resolution was 140.8 megabytes. Total ground area covered was a strip 10.2 km wide and 36.8 km long with a total area of 377 square kilometers. Processing time was slightly more than 15 minutes.. The SAM algorithm is a physically based method that matches image spectra in n -dimensions. It is part of the ENVI hyperspectral software package produced by Research Systems, Inc. located in Boulder, Colorado[4]. ENVI is written entirely in IDL (Interactive Data Language). This software was selected because of its open architecture so custom algorithms can be added as they are developed and tested.

Band Ratio Approach—An adaptation of the traditional LANDSAT TM band 5 divided by TM band 7 ratio was also investigated. This approach has long been an accepted method for detecting altered clay soils. A study goal was to determine if the high spectral resolution from AVIRIS data provides improved detection capability compared to that provided by broad-band TM data.

Spectral Analysis Results

Spectral Angle Mapper (SAM)—Results from the SAM analysis indicated the presence of pixels matching the kaolinite signature. In order for these pixels to be selected, the “tolerance” level for the SAM algorithm had to be manually set at 0.25 for the AVIRIS data. Since the ENVI default setting is 0.10, it is apparent that the spectral match with the kaolinite signature was only in the “fair to good” range. This somewhat low correlation level of signature matching, implies that while clay may be detected, other minerals or materials are also likely to be present. Additional study is underway to spectrally identify the associated substances. Ground truth analysis (to be discussed in detail in a following section) did, in fact, show that a major component of the soils detected was quartz (sand)!

The green areas in Figure 1 show where the algorithm detected matches with the kaolinite spectrum. Other “tolerance” ranges (0.20 and 0.30 for example) resulted in lesser and greater amounts identified as having matching signatures. The 0.25 point was selected as most likely representing those areas where a kaolinite clay component of the soils would be found.. Selection of 0.25 was based on experience and knowledge of an experienced image processor and a trained geoscientist. These areas represented the most likely areas containing kaolinite clay soils in that portion of the image. Several areas were spectrally detected, but those highlighted by the circles identify sites where ground truth was collected to verify the spectral analysis results.

The white areas in Figure 2 show where the ratio analysis approach also detected clay-type features on the AVIRIS data. Careful examination shows that while there is a good correlation between many selections from the two approaches, some features seen on one result are totally absent on the other. It appears that differences in pixels detected may be largely due to the levels of tolerance or sensitivity applied to the processing algorithms.

Figures 3 and 4 show a comparison of the SAM and ratio mappings from the Landsat data. Notice that the amount, size and number of areas selected are greater than those shown on the AVIRIS imagery. The SAM default tolerance level of 0.10 was suitable for processing the Landsat data. The software more easily matched the broader spectral bands of Landsat with corresponding spectral features on the ground.

The Site A location, shown in Figure 5, provides comparative results between the two processing approaches for both AVIRIS and Landsat data. The primary feature

Figure 1. AVIRIS Data with Spectral Angle Mapper (SAM) Analysis Results

Figure 2. AVIRIS Data with Band Ratio Analysis

Figure 3. LANDSAT Data with Spectral Angle Mapper (SAM) Results

Figure 4. LANDSAT Data with Band Ratio Results

Site A - Sandstone Bluff

AVIRIS Data - SAM Classification

AVIRIS Data - Ratio Classification

LANDSAT Data - SAM Classification

LANDSAT Data - Ratio Classification

Figure 5. Spectral Angle Mapper (SAM) and Ratio Analysis on AVIRIS and LANDSAT Data

Figure 6. Site A - Ground Photo of Sandstone Bluff Looking East

at Site A turned out to be a large sandstone bluff or outcropping along a wash area labeled Squirrel Creek on the Hanover map. Examination of a geologic map of this and other areas, identified the formations as Laramie sandstone that contain 10-20 % silt and clay[1]. (See Figure 6)

The feature at Site B, shown in Figure 7 turned out to be an irregularly shaped area called a “borrow pit” Borrow pits are areas where soil or gravel is dug up and often used as fill and surfacing material for road construction. This feature answered our question as to why many of the dirt roads and driveways in the area exhibited a clay signature. The El Paso County Department of Transportation also verified that material from the borrow pit had been used for Squirrel Creek Road[5].

The ground truth photographs in Figure 8 provide a detailed view of the Site B features. Soil samples were collected in close proximity of both locations except for the sandstone bluff. The bluff was on private property and access was not possible. All samples were taken from nearby locations that exhibited the kaolinite signature on the imagery.

Sieve analysis by Terracon Consultants Western, Inc., Colorado Springs, CO, of soil samples collected in the vicinity of the Laramie outcrop, indicate a mixture of 86.4% sand, 8.6% silt, and 6.4% clay[6]. These percentages correspond closely with the composition percentages describing the Laramie formation in USGS papers[7].

Furthermore, the sandstone bluff that comprised the lower member of the Laramie formation, is described as containing a number of clayrock subunits[7]. Other samples collected in the study area ranged from 84.5 - 92.2% sand, 1.1- 3.8% silt, and 2.0 - 4.0% clay.

Optical vs. Composition Dominance—The phenomenon of Optical vs. Composition Dominance explains why the soils, while feeling like and being verified as 90% sand, exhibit a clay-like spectral (optical) signature[6]. The reason is that the small clay particles tend to adhere to and coat the larger sand particles. Sunlight is reflected from this outer layer and exhibits the kaolinite signature. The illustration in Figure 9 provides a visual example of Optical vs. Composition Dominance. Separately, the flour and the drumstick exhibit their own unique spectral and spatial signatures. The drumstick covered with flour, however, exhibits the spectral dominance of flour. We know from our spatial experience that the “white” drumstick is, in fact, a drumstick that just happens to be covered with flour. To a 20 or 30 meter resolution sensor, however, an area totally covered by flour-covered drumsticks is going to be spectrally (optically) identified only as flour. The same principle applies to the soils of the study area, and the outcrop of the Laramie formation.

SAM analysis of the Landsat data that is shown mapped in green on Figure 3, was obtained using the Landsat spectral

Site B - Borrow Pit

AVIRIS Data - SAM Classification

AVIRIS Data - Ratio Classification

LANDSAT Data - SAM Classification

LANDSAT Data - Ratio Classification

Figure 7. Comparison of Site B Analysis Results

Figure 8. Site B - Ground Photo of Borrow Pit and Dirt Road

Figure 9. Example of Dominance Characteristics

signature of the sandstone bluff. Due to the reference library spectral matching requirements in SAM, the ENVI hyperspectral library spectrum for kaolinite could not be used with the 6-band Landsat data file. The mapped area shows that the Landsat data resulted in larger area and less precise discrimination of kaolinite-like areas.

Band Ratio Results—Two AVIRIS bands located at the mid-point of TM bands 5 and 7 were selected. AVIRIS bands 140 (1679 nm) and 195 (2217 nm) were chosen. The generic ratio expression used was: $A \cdot A/B$. The squaring of the numerator mathematically expands or enhances the final results to ensure greater discrimination of the target material (in this case “clay”). The approach was initially developed to detect vegetation stress. For vegetation, the expression is: $TM4 \cdot TM4/TM5$. For this study however, using AVIRIS data to detect clay-type soils, the expression is: $Band\ 140 \cdot Band\ 140/Band\ 195$.

Result of the analysis is displayed as part of a three-band color composite image. Colors are assigned as follows:

Red = Results of the enhanced ratio

Green = The numerator band (140)

Blue = The denominator band (195)

The data is then manipulated (stretched) as illustrated by the histograms in Figure 10:

Blue = linear stretch

Green = linear stretch with the line rotated counter-clockwise and placed vertically next to the right y-axis.

Red = linear stretch with the line also rotated counter-clockwise and placed vertically next to the right y-axis.

(This process generates a moderately dark, blue-toned image)

Next Step: move the vertical line for the Red band (the ratio result) is moved to the left about 1/2 the distance towards the left y-axis.

(This results in parts of the image changing to red and magenta.) These areas define the pixels that lie on the right end of the histogram profile and have clay-type spectral characteristics.

Next; begin to move the vertical line for the Green band (the numerator) to the left in small increments, which is a form of density slicing.

(This results in bright white spots or areas beginning to appear inside the red and magenta areas. The white areas represent the locations that most closely spectrally resemble clays.

The white areas in Figures 2, 4, 5, and 7 show where the ratio approach identified clay locations. Locations of major clay-like sites are quite similar using the two techniques. Sites A and B were both detected, for example. The

relative amounts or size of the respective areas is largely a function of the tolerance setting used for the SAM algorithm or the Green band density level selected using the ratio approach. Both approaches require varying levels of subjective assessment to arrive at acceptable or reasonable tolerance thresholds

This study did not quantitatively compare the levels of precision of one approach vs. the other. Both approaches visually appear reasonably valid. The overall larger and less precise mappings using the Landsat data is believed to be a function of broader spectral band width differences of Landsat as opposed to the 10-meter difference in spatial resolution between AVIRIS and Landsat. If we were looking for targets that have unique spectral features in non-Landsat band spectral regions, much greater differences in mapped areas would almost certainly result. Further investigation using greater ranges of tolerance and density level enhancement may be accomplished depending on the results of additional tests including X-ray Diffraction analysis of the soil samples.

Spectral Signature Differences

Library and Image Spectral Signature Comparison—Figure 11 illustrates the differences in the USGS Spectral Library kaolinite signature and the AVIRIS image spectral signature from the large sandstone formation. The “doublet” absorption feature near 2200 nm shown enlarged in the two top spectra is a key attribute of the kaolinite spectral signature. The overall spectral shape comparison shown in the lower illustrations, however, show quite divergent spectral characteristics in other portions of their respective spectrums. These differences are largely the result of the presence of materials other than clay. The differences also may indicate why a rather broad tolerance range setting for the SAM algorithm was required. Figure 11 also shows the Landsat spectral signature from the sandstone bluff. Given the pronounced lack of spectral detail, it is remarkable that the Landsat mappings corresponded to the AVIRIS mappings as closely as they did. These similarities in results are believed to be a function experienced analysts knowing where logical processing thresholds should be established for each image type and for each processing technique.

3. LESSONS LEARNED

Ground Truth is Essential—Availability or collection of ground truth in unfamiliar areas is absolutely essential at our current level of hyperspectral analysis experience. Without the soil samples collected, availability of soil maps, and technical geological descriptions, analysis of the spectral and composition dominance phenomenon would not have been possible. A sudden rain and hail storm while we were in the field caused the dirt road to become extremely slippery.

Figure 10. Histograms Illustrating the Data Stretch Parameters used for the Ratio Analysis Products

Spectral Signatures

Figure 11. Comparison of Spectral Library and AVIRIS Image Spectra

Whether such road surface conditions would seriously effect tracked vehicles is to be determined. Wheeled vehicles using the roads, however, would be slowed considerably.

Spectral Information is Another Tool—Spectral information alone is often not sufficient to solve a problem. This study demonstrated that a wide range of skills and knowledge was required to even partially find an answer. The difference in the mapping precision of hyperspectral and multispectral data was expected. Detection of unique spectral signatures is much more successful when greater spectral resolution is available. Follow-up study to more accurately determine types and levels of abundance of soil materials, will definitely require hyperspectral data.

Pre-planned Collections Can Maximize Levels of Information Acquired—The AVIRIS and Landsat data were already available, and selected as test case data sets to be investigated. Ideally, ground truth data is collected before, during and after collections are flown. In the future, perhaps higher spatial resolution hyperspectral data, available from 1-meter resolution HYDICE collections, can provide more complete target type and area information.

4. CONCLUSIONS

This Preliminary Study Did Not Satisfactorily Support Trafficability Analysis—The spectral algorithms tested performed satisfactorily, from a technical perspective. The spectrally derived results, however, did not adequately address the primary problem of locating clay soils that could interfere with cross-country trafficability. The results did, however, provide valuable lessons regarding the broad range of spectral and spatial factors that must be considered when applying hyperspectral or multispectral data to address technical problems. The only major cross-country trafficability obstacle identified, was the large sandstone bluff. Ground truth observation, soil sample collection, soil maps, and detailed topographic maps all were essential elements required in addition to spectral analysis results.

Hyperspectral Data is an Important Tool—This study demonstrates that hyperspectral data can isolate area soils that have similar reflectance characteristics to the kaolinite reference signature as processed by the SAM algorithm in ENVI. From the ground samples collected for this study, the clay portion assessed by X-ray diffraction revealed that all the samples included kaolinite clay.[8]

Results of The SAM and Ratio Methods Provide Both Similarities and Differences—

The study demonstrates distinct similarities in the areas defined by SAM and areas defined by the ratio procedure.

Many areas delineated on AVIRIS using the band ratio procedures corresponded reasonably well to areas defined by the SAM algorithm at a 0.25 tolerance level. One unexplained exception is worth noting. There is a T-shaped pattern of two intersecting asphalt roads that are mapped by the SAM as clay (See Figures 3 and 4). The ratio technique, however, shows the roads as having no clay characteristics at all; they appear black. The road is actually a dark, gray-toned, hard-top, paved road. The AVIRIS data spectrum of the road does not exhibit the characteristic clay “doublet” feature, yet SAM mapped it as clay. This serves as a good example to emphasize the point that while spectral information can have significant contribution to addressing a wide range of issues, caution and judgment are essential elements in applying spectral analysis results.

Thorough Analysis is Required

Different Soil Types Can Exhibit Similar Spectral Characteristics—Clays are known to constitute a portion of the lower member of the Laramie sandstone formation. Thus, it is not surprising to find the kaolinite “doublet” in a signature from the sandstone bluff. X-ray diffraction analysis substantiated the existence of kaolinite within the samples collected at ground truth locations corresponding to kaolinite signatures mapped in figure 1. This provides further corroboration for the optical dominance phenomenon[8]. Since the tolerance parameters were only in the fair to good range (for both the SAM and the band ratio procedures), it is not surprising that numerous areas in the AVIRIS data set were delineated as kaolinite.

Both Analysis Techniques Successfully Detected Major “Clay” Features—Further detailed study is required to determine a preferred methodology. The Spectral Angle Mapper (SAM) is technically more robust since it looks at all 224 bands and does a more detailed spectral match. The ratio technique, however, can perhaps provide a useable field expedient approach if sophisticated hyperspectral software or precise library spectral signatures are not available.

Spatially Precise Discrimination of Detected Spectral Signatures—As expected, the hyperspectral data more precisely identified areas that had spectral signatures corresponding to the reference spectrum.

More Sophisticated Spectral Unmixing Algorithms Should Be Investigated—It was beyond the technical scope and time deadlines for this paper, to investigate the utility of Spectral Unmixing Algorithms to aid in addressing the issue. Such a study represents a meaningful, technical challenge and merits serious consideration.

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Biographies

Alfred J. Johnson received a B.S. degree in Forestry from Michigan State University in 1962. He was employed by the Central Intelligence Agency for 28 years and held a number of positions dealing with visual and digital analysis of imagery from a wide range of platforms. Mr. Johnson is currently employed by Logicon Geodynamics Corporation in Fairfax, Virginia. This position involves verification and validation of hyperspectral imagery processing software, supporting DoD requirements.

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