Mineral Mapping and Applications of Imaging Spectroscopy

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Abstract--**Spectroscopy is a tool that has been used for decades to identify, understand, and quantify solid, liquid, or gaseous materials, especially in the laboratory. In disciplines ranging from astronomy to chemistry, spectroscopic measurements are used to detect absorption and emission features due to specific chemical bonds, and detailed analyses are used to determine the abundance and physical state of the detected absorbing/emitting species. Spectroscopic measurements have a long history in the study of the Earth and planets. Up to the 1990s remote spectroscopic measurements of Earth and planets were dominated by multispectral imaging experiments that collect high-quality images in a few, usually broad, spectral bands or with point spectrometers that obtained good spectral resolution but at only a few spatial positions. However, a new generation of sensors is now available that combines imaging with spectroscopy to create the new discipline of imaging spectroscopy. Imaging spectrometers acquire data with enough spectral range, resolution, and sampling at every pixel in a raster image so that individual absorption features can be identified and spatially mapped (Goetz et al., 1985).**

Keywords-Imaging Spectroscopy; Minerals; Mapping

I. INTRODUCTION

Planetary surfaces are complex and the Earth's surface is probably the most complex in our solar system, showing varied geology, oceans, ice caps, abundant life and anthropogenic influences. Other planets have different geology and different surface compositions. In order to understand our own planet as well as others, we produce maps of materials and other measurable quantities. Maps of the Earth's surface can depict many themes, including those in geology, ecosystems, environmental hazards, land management and global change. Geologic mapping can include the depiction of geologic formations (thus providing information on ages and placements of units through geologic time), soils, mineral occurrences, faults, mineralized zones and aggregate for building materials. Environmental applications can include acid-rock drainage, oil or toxic waste spills, water quality and other distributions. Geologic hazards maps can include volcanic eruption potential, swelling clays, fault zones and landslide hazards. The need for accurate and more detailed maps has never been greater, which drives the requirement for more advanced information such as that from imaging spectrometers.

Imaging spectroscopy is a tool that can be used to identify and spatially map materials based on their specific chemical bonds [1]. Spectroscopic analysis requires significantly more sophistication than has been employed in conventional broad-band remote sensing analysis. In producing materials maps, robustness is vital. If a sensor is flown over the same site with minor changes to the instrument spectral sampling, spectral bandpass, and spatial resolution, the materials mapped should still be the same. If the sensor is flown over a geologically different region, and the same minerals exist as in other areas, those minerals should be similarly detected and accurately mapped. When mapping materials in response to environmental or other disasters where lives, health, and economic impacts play major roles, mapping accuracy becomes more important.

Despite numerous technical and theoretical difficulties, spectral unmixing methods have proven useful in the application of imaging spectroscopy to geological studies. It is clear that grain size effects intimate mixtures, mineral coatings, and other spectroscopic

realities of the remote measurement complicate the problem of unmixing and limit the absolute accuracy of a simple linear model. On the other hand, it is equally clear how pervasive spectral mixing is in imaging spectroscopy data, since every natural pixel is inevitably a composite of multiple components. For the past twenty years, spectral unmixing methods have been evolving in step with the evolution of the data collection systems. The early methods simply cast the problem as an overdetermined system of linear equations and required a complete and accurate library of appropriate spectral endmembers. It has become clear that derivation of this proper set of endmember signatures is a very challenging problem and often, at least partially, ill-posed. Nevertheless, modern unmixing methods and their associated endmember derivation techniques have been used to extract geologically meaningful endmembers from high-quality data sets. With the high signal-to-noise ratios and spectral fidelity of modern imaging spectrometers, it is not uncommon to have data sets with inherent spectral dimensionalities of up to fifty, each indicating the potential for a linearly separable endmember. In complex scenes with high-quality data, we regularly derive dozens of spectral unmixing endmembers using nothing but the mixed data themselves.

Spectral unmixing results provide a unique result for geological applications of imaging spectroscopy. The endmember derivation process, when coupled with a robust spectral identification tool, leads to the in-scene derivation of appropriate spanning spectra and their mineralogical make-up, all with no reference to filed data or ground truth. Beyond identifying which minerals are present, the unmixing methods also produce apparent abundance maps for each derived endmember material on a pixel-by-pixel basis. While these abundances can only be considered as semi-quantitative, they are clearly useful from a geological point of view. Unraveling spectral mixtures among various materials can provide insight into subtle geological and surficial processes that govern the distribution of the various materials. The combined spatial and spectral results, in the form of the abundance images and the spectral endmembers, represent a powerful exploitation of the rich information content inherent in imaging spectroscopy data. Leveraging the overdeterminacy of hyperspectral data, when the number of bands exceeds the number of endmembers, truly lets us see inside a pixel to identify and measure the presence of dozens of geologically important minerals.

II. EXAMPLES

Maps derived from imaging spectroscopy data have already proven their value. Examples include:

Oxidation of sulfides in the Leadville mining district in the central Colorado Rockies releases lead, arsenic, cadmium, silver and zinc into snow melt and thunderstorm runoff, which drains into the Arkansas River. The Arkansas River is a main source of water for Front Range urban centers and agricultural communities. Maps of pyrite and jarosite, derived from imaging spectroscopy data, showed the source regions of acidic water. The maps helped to accelerate the cleanup efforts by 2.5 years and saved $2 million in remediation costs [2].

Cuprite, Nevada is one of the premiere sites in the world for field testing the accuracy of new sensors and spectral mapping techniques. This site is ideally suited for remote sensing because of its diverse alteration mineralogy, excellent rock exposures, sparse vegetation, dry climate and easy access. The hydrothermal alteration at Cuprite consists of two barren advanced-argillic lithocaps, straddling U.S. Highway 95. These systems were active between 6.2-7.6 Ma [3][4][5], most likely a result of volcanic activity related to nearby Stonewall caldera, now a resurgent volcanic dome 5 km east of Cuprite. Mineral maps made from AVIRIS data [5][6][7][8][9] show a wide variety of alteration and rock-forming minerals including Na-K alunites, buddingtonite, calcite, chalcedony, chlorite, dickite, goethite, halloysite, hematite, jarosite, kaolinite, montmorillonite, muscovite (Al-Mg-Fe compositional series), nontronite, opal and pyroxene. The first natural occurrence of the NH_4-mineral buddingtonite was discovered with imaging spectroscopy at Cuprite [10]. Tetracorder mineral maps [5][8][9] reveal that the western relict alteration center lacks a siliceous cap, has a propylitic remnant surrounded by an advance-argillic alunite zone, and that the system was deeply eroded, exposing the high temperature kaolinite polymorph dickite and a pyrite-rich zone. Mineral maps indicate that the eastern relict alteration center has an extensive siliceous cap surrounded by an advance-argillic alunite zone, lacks a propylitic remnant (at least at the present level of exposure), has extensive kaolinite zones lacking dickite and has volumetrically insignificant jarosite, all consistent with present exposure near the top of the hydrothermal system. Apparently, the hydrothermal systems at Cuprite formed at different times with activity first in the western center and then spreading to the eastern center.

Rapid-response materials maps of the World Trade Center disaster were produced from imaging spectroscopy data that showed the location and temperatures of fires and also showed that there was no widespread distribution of asbestiform minerals or other toxic materials in the dust/debris from the collapse of buildings, in agreement with ground-sample analyses [11][12]. However, the dust was found to generate high pH, so maps of the dust indicate that hazard, which caused eye irritation and respiratory problems. The maps also showed asymmetric debris distribution indicating a non-symmetric collapse of the buildings.

Iron ore is the third-largest export earners in Australia and Port Hedland, located on the North West coast in the Pilbara region of Western Australia, which is one of the largest port handling facilities. The processing, blending, and handling of ores produces a considerable amount of dust. Given the proximity of the Port Hedland township to surrounding mangroves ecosystem, managing dust is a top priority for BHP Billiton Iron Ore (BHPBIO, the main user of the facility) and is a significant concern of the community and regulators. BHPBIO is required under its ministerial conditions for the operation of the facility to monitor the effects of dust on the surrounding ecosystem, and BHPBIO has invested heavily in monitoring and controlling dust emissions. This includes the implementation of a series of monitoring and suppression programs over the years, including the use of non-directional gauges to collect dust data from the mangroves in 1996. These gauges are currently accepted as the standard tool for monitoring ambient dust fallout even though they were developed in the 1920s. Ten sites, each with four gauges, were established, but the many risks and physical difficulties of working in the mangroves, such as deep mud and tides, the threat of Ross-River virus from disease-infested insects, the labor-intensive nature of regular checking, and especially, the questionable accuracy of the gauges prompted the search for a better method of monitoring and assessing the dust impacts on the mangroves.

Research has been ongoing since 1998 to develop an operational method to generate accurate measurements of dust quantities on mangroves from airborne hyperspectral data. This research included field, laboratory and airborne components. The field and laboratory studies incorporated intensive field studies where independent measurements of dust quantities on the surface areas of leaves were collected concurrent with the reflectance of the leaves. A total of 212 samples were collected to be used in these experiments designed to develop a robust algorithm to generate measurements of quantities of iron oxide dust per area from surface reflectances. The analysis was performed using partial least squares analysis [13] and the algorithm was developed using spectral parameterization of iron oxide diagnostic spectral features. The algorithm was validated using two independent sets of mangrove leaves data collected in the field. The airborne component focused on the reduction of the airborne data to accurate surface reflectances and cross calibration issues between these airborne data and the field and laboratory reflectances to ensure that the results of the laboratory and field studies are transferable to the airborne data. A total of six airborne data sets had been collected over the Port Hedland Harbour from 1998 to 2005. Dust on mangrove maps have been generated for all these data sets and the maps have been validated with independent field measurements. This monitoring system has been recognised by the industry and regulators and is in the process of being incorporated into routine environmental management system of BHPBIO's port facility.

Satellite-based hyperspectral mineral mapping of the Earth is now possible using NASA's EO-1 Hyperion sensor, launched in November 2000. Hyperion covers the 0.4 to 2.5 micrometer spectral range with 242 spectral bands at approximately 10nm spectral resolution and 30m spatial resolution from a 705km orbit [14]. Comparisons of Hyperion data to airborne hyperspectral data (AVIRIS) show that Hyperion provides the ability to remotely map basic surface mineralogy. Minerals mapped using Hyperion include calcite, dolomite, kaolinite, alunite, buddingtonite, muscovite (several varieties), hydrothermal silica, and zeolites. Case histories demonstrate the viability of Hyperion as a means of extending hyperspectral mineral mapping to areas not accessible to aircraft sensors.

Imaging spectroscopy plays a key role in planetary exploration. The Mars Global Surveyor (MGS) is currently orbiting Mars with the Thermal Emission Spectrometer (TES)[15], which located deposits of hematite [16] that led to the selection of a Martian landing site with unique geology. The Cassini Visual and Infrared Mapping Spectrometer, VIMS, is currently mapping minerals in the Saturn system [17], and the Mars Express OMEGA is currently mapping Mars. The Mars Reconnaissance Orbiter is carrying a next-generation spectrometer, CRISM, to Mars to begin mapping in 2006 and NASA's Moon Mineralogy Mapper (M3) will begin assessing lunar resources in early 2008 on board the Indian satellite Chandrayaan-1. The planetary future of imaging spectroscopy is bright,

with entire planets being mapped. Similar coverage of the Earth with imaging spectrometers is needed.

REFERENCES

[1]   A. F. Goetz, G. Vane, J. E. Soloman, and B. N. Rock, Imaging Spectrometry for Earth Remote Sensing. Science, 228, 1147, 1985.

[2]   G. A. Swayze, K. S. Smith, **R. N. Clark**, S. J. Sutley, R. N. Pearson, G. S. Rust, J. S. Vance, P. L. Hageman, P. H. Briggs, A. L. Meier, M. J. Singleton, and S. Roth, 2000, Using imaging spectroscopy to map acidic mine waste, *Environmental Science and Technology*, .**34**. 47-54.

[3]   R. P. Ashley, and M. J. Abrams, 1980, Alteration Mapping Using Multispectral Images-Cuprite Mining District, Esmeralda County, Nevada: U.S. Geological Survey Open File Report 80-367, 17 p.

[4]   D. C. Noble, E. H. McKee, and S. J. Weiss, S.I., 1988, Nature and timing of pyroclastic and hydrothermal activity and mineralization at the Stonewall Mountain volcanic center, southwestern Nevada: Isochron/West, no. 51, p. 25 - 28.

[5]   G. A. Swayze, 1997, The hydrothermal and structural history of the Cuprite Mining District, Southwestern Nevada: an integrated geological and geophysical approach, Ph.D. Dissertation, University of Colorado, Boulder, Colorado, 399 p.

[6]   M. J. Abrams, R. P. Ashley, L. C. Rowan,, A. F. H, Goetz., and A. B. Kahle,., 1977, Mapping of hydrothermal alteration in the Cuprite mining district, Nevada using aircraft scanner images for the spectral region 0.46-2.36 μm: Geology, v. 5, p. 713-718.

[7]   F..A. Kruse, K. S. Keirein-Young, and J. W. Boardman, 1990, Mineral mapping at Cuprite, Nevada with a 64-channel imaging spectrometer: Photogrammetric Engineering and Remote Sensing, v. 56, no. 1, p. 83-92.

[8]   G. A. Swayze, , R. N. Clark, A. F. H. Goetz, T. G. Chrien, and N. S., Gorelick, 2003, Effects of spectrometer bandpass, sampling, and signal-to-noise ratio on spectral identification using the Tetracorder algorithm: *Journal of Geophysical Research*, v. 108, no. E9, 5105, doi:10.1029/2002JE001975, 30 p.

[9]   R. N. Clark, G. A. Swayze, K. E. Livo, R. F. Kokaly, S. J. Sutley, J. B. Dalton, R. R. McDougal, and C. A. Gent, 2003, Imaging spectroscopy: Earth and planetary remote sensing with the USGS Tetracorder and expert systems: The Journal of Geophysical Research, v.108, no. E12, 5131, doi:10.1029/2002JE001847.

[10] A. F. H. Goetz, , and V. Strivastava, 1985, Mineralogical mapping in the Cuprite mining district, *in* Proceedings of the Airborne Imaging Spectrometer (AIS) Data Analysis Workshop: Jet Propulsion Laboratory Publication 85-41, p. 22-29.

[11] R. N. Clark, R. O. Green, G. A. Swayze, T. M. Hoefen, K. E. Livo, B. Pavri, C. Sarcher, J. Boardman, and S. Vance., 2001, Images of the World Trade Center site show thermal hot spots on September 16 and 23, 2001: U.S. Geological Survey, Open-File Report 01-0405, http://pubs.usgs.gov/of/2001/ofr-01-0405

[12] R. N. Clark, G. A. Swayze, T. M. Hoefen, R. O. Green, K. E. Livo, G., Meeker, S. Sutley, G. Plumlee, B. Pavri, C. Sarture, J. Boardman, I., Brownfield, L. C. Morath, 2006, Chapter 4: Environmental mapping of the World Trade Center area with imaging spectroscopy after the September 11, 2001 attack: in *Urban Aerosols and Their Impacts: Lessons Learned from the World Trade Center Tragedy*, Jeff Gaffney and N. A. Marley (eds), *American Chemical Society*, Symposium Series 919, Oxford University Press, p. 66-83, plates 4.1-4.6.

[13] D. M. Haaland, and E. V. Thomas, , 1988. Partial Least Squares, Anal Chem, 60:1193-1200.

[14] J. Pearlman, S. Carman, P. Lee, L. Liao and C. Segal, Hyperion Imaging Spectrometer on the New Millennium Program Earth Orbiter-1 System, In *Proceedings, International Symposium on Spectral Sensing Research (ISSSR), Systems and Sensors for the New Millennium,* published on CD-ROM, International Society for Photogrammetry and Remote Sensing (ISPRS), 1999.

[15] P. R. Christensen, D. L. Anderson, C. C. Stillman, **R. N. Clark**, H. H. Kieffer, M. C. Malin, J. C. Pearl, J. C. Carpenter, N. B. Bandera, F. G. Brown, and S. Silverman, Thermal Emission Spectrometer Experiment: Mars Observer Mission, *Journal of Geophysical Research,* **97,** 7719-7734, 1992.

[16] P. R. Christensen, J. L. Bandfield, **R. N. Clark**, K. S. Edget, V. E. Hamilton, T. Hoefen, H. H. Kieffer, R. O. Kuzmin, M. D. Lane, M. C. Malin, R. V. Morris, J. C. Pearl, R. Pearson, T. L. Roush, S. W. Ruff, and M. D. Smith, 2000, Detection of Crystalline Hematite Mineralization on Mars by the Thermal Emission Spectrometer: Evidence for Near-Surface Water: *Journal of Geophysical Research*, **105**, 9623-9644.

[17] R. H. Brown, K. H. Baines, G. Bellucci, J. P. Bibring, B. J. Buratti, F. Capaccioni, P. Cerroni, P., R. N. Clark, A. Coradini, D. P. Cruikshank, P. Drossart, V. Formisano, R. Jaumann, Y. Langevin, D.J. Matson, T. B. McCord, V. Manella, E. Miller, R. M. Nelson, P. D. Nicholson, B. Sicardy, and C. Sotin, 2004, The Cassini visual and infrared mapping spectrometer investigation: *Space Science Reviews*, **115** (1-4), 111-168.