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Review

A review on spectral processing methods for geological remote sensing

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A B S T R A C T

In this work, many of the fundamental and advanced spectral processing methods available to geologic remote sensing are reviewed. A novel categorization scheme is proposed that groups the techniques into knowledge-based and data-driven approaches, according to the type and availability of reference data. The two categories are compared and their characteristics and geologic outcomes are contrasted. Using an oil-sand sample scanned through the sisuCHEMA hyperspectral imaging system as a case study, the effectiveness of selected processing techniques from each category is demonstrated. The techniques used to bridge between the spectral data and other geoscience products are then discussed. Subsequently, the hybridization of the two approaches is shown to yield some of the most robust processing techniques available to multi- and hyperspectral remote sensing. Ultimately, current and future challenges that spectral analysis are expected to overcome and some potential trends are highlighted.

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1. Introduction

Spectroscopy is the measurement of light as a function of wavelength reflected or emitted from a material (Clark, 1999; Hapke, 1993). A spectral curve conveys information about the state of a target that in geology is usually (but not necessarily) composed of rocks and minerals. Pioneering work of John Hunt and Ronald Lyon in the early 70s paved the way for the interpretation of spectral data using quantum mechanics concepts (e.g., Hunt and Salisbury, 1971; Lyon and Burns, 1963). Their work established a link between observed variation in reflectance/emittance spectra and chemical and physical properties of minerals and significantly demonstrated their potential use in remote sensing (Hunt, 1977, 1979). Minerals, rocks, and other terrestrial compounds like hydrocarbons exhibit diagnostic absorption features in either the visible-near infrared (VNIR) (0.4–1.0 μm), shortwave infrared (SWIR) (1.0–2.5 μm), mid infrared (MIR) (3–5 μm), and/or longwave infrared (LWIR) (8–14 μm) wavelength ranges due to electronic and vibrational processes, as well as overtones and combinations of the fundamental (Clark, 1999; Gaffey et al., 1993; Hapke, 1993; Hook et al., 1999; Hunt and Salisbury, 1971, 1974).

Historically, remotely sensed multispectral imaging (MSI) has been used to produce colorful photographs for visual interpretation of lithologic units and geologic structures (Goetz and Rowan, 1981; Gregory and Moore, 1975). Meanwhile, their multispectral content has been processed by simple techniques, like band arithmetic, to discriminate broad alteration patterns (Goetz and Rowan, 1981; Rowan et al., 1974; Sabins, 1999). Early experiments with airborne imaging spectrometer (AIS) prototypes revealed its potential for remote mineral detection, which subsequently led to the development of NASA's airborne visible-infrared imaging spectrometer (AVIRIS) hyperspectral imaging (HSI) sensor (Goetz et al., 1985; Vane and Goetz, 1991). HSI has matured to such extent that advanced systems of this kind are currently orbiting Earth and Mars (e.g., Hyperion and OMEGA) (Bell, 2008; Pearlman et al., 2003). This technology has also evolved as a tool for field spectroscopy (Goetz, 2009; Thompson et al., 1999), drill core and chips logging (Mason and Huntington, 2012; Roache et al., 2011; Tappert et al., 2011), wall-rock imaging (Kruse et al., 2012; Kurz et al., 2012; Murphy and Monteiro, 2013; Ragona et al., 2006), and sensor-based mineral sorting (Goetz et al., 2009). Overall, proximal and distal sensing technologies in the VNIR-SWIR have been matured and are readily available (Goetz et al., 1985), whereas the LWIR hyperspectral data are only now becoming routinely available (Hook et al., 2013; Mason and Huntington, 2012; Vaughan et al., 2003).

HSI with hundreds of contiguous spectral bands has resulted in plethora of near laboratory-quality spectra for every pixel of the image (Clark and Swayze, 1996; Goetz, 2009; Goetz et al., 1985), thus creating its own breed of spectral analysis methods (e.g., Adams et al., 1986; Vane and Goetz, 1991). Spectral processing (also known as spectral mapping, or spectral analysis) refers to "the extraction of quantitative and/or qualitative information from remotely sensed reflectance (or emittance) spectra based on the albedo-, and wavelength-dependent properties of the material" (Mustard and Sunshine, 1999). It encompasses most of the techniques proposed for detection, classification, discrimination, identification, characterization, and quantification of materials in a given hyper- or multispectral scene (Chang, 2003, 2007; Schott, 2006).

There are numerous review papers devoted to the topic of spectral analysis and geologic remote sensing in the last two decades. In a tutorial paper on spectral unmixing by Keshava and Mustard (2002), linear versus nonlinear mixing is clarified and algorithms for linear unmixing are discussed. Recent advances in this subject including geometrical, statistical, and sparse regression-based approaches, along with unmixing challenges are highlighted in Bioucas-Dias et al. (2012) and Plaza et al. (2011). There are also papers concentrated on very specific themes like subpixel detection algorithms (Chang, 2003), nonlinear unmixing (Heylen et al., 2014), image classification (Lu and Weng, 2007; Richards, 2005), support vector machine (Mountrakis et al., 2011), or the evolution of HSI technology (Goetz, 2009; Schaepman et al., 2009; Vane and Goetz, 1991).

On the other hand, a wealth of review papers are dedicated to the application of remotely sensed imagery for natural resource assessment (Agar and Coulter, 2007; Bedell et al., 2009; Gregory and Moore, 1975; Rajesh, 2004; Sabins, 1999). van der Meer et al. (2012) provided a balanced review of multispectral and hyperspectral remote sensing data, the common products, and their applications to different geologic areas, with a brief discussion on historic and current processing techniques used for both data types. More in-depth evaluation of analytical techniques for extraction of compositional mineralogical information from hyperspectral remote sensing data was provided by Cloutis, some two decades ago (Cloutis, 1996).

While these review papers are seminal and have made science impacts, they either focus on the application of remote sensing in geology, or take stock in specific algorithmic research areas, or are not wide-ranging and up-to-date. None of them provide a categorization strategy for the vast spectral processing methodologies, nor study them in a comparative manner.

In this paper, many of the known and off-the-shelf spectral analysis methods currently available to geologic remote sensing are reviewed. According to the availability and usage of reference data, a categorization scheme is proposed that groups the techniques into knowledge-based and data-driven approaches. The two categories are compared and their outcomes in terms of geologic information are discussed. The methods used to bridge the spectral data and mineralogical, lithological and geochemical datasets are considered. Subsequently, current and potentially new hybridization concepts are discussed, and future challenges that spectral processing methods are expected to overcome are highlighted.

2. Test dataset

Throughout this paper, a hyperspectral datacube of an oil-sand sample is processed and used to illustrate the effectiveness of selected processing techniques discussed within the text. The sample was taken from an exhumed hydrocarbon reservoir located in the eastern edge of the Paraná basin, some 170 km to the NW of São Paulo city, Brazil. The area consists of bitumen accumulations in early Triassic sandstones (De Araújo et al., 2006). XRD analysis shows that the sample is dominated by quartz and montmorillonite, plus titanomagnetite, brushite, and orthoclase as minor phases. Montmorillonite is present as inter-layers and small spots in the sandy matrix, probably as a result of alteration due to hydrocarbon migration (Fig. 1a). The sample was scanned using the sisuCHEMA-SWIR hyperspectral imaging instrument (Roache et al., 2011). Using a 31 mm lens, a spatial resolution of 390 μm in length