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Lithological mapping from hyperspectral data by improved use of spectral angle mapper

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ABSTRACT

The spectral angle mapper (SAM), as a spectral matching method, has been widely used in lithological type identification and mapping using hyperspectral data. The SAM quantifies the spectral similarity between an image pixel spectrum and a reference spectrum with known components. In most existing studies a mean reflectance spectrum has been used as the reference spectrum for a specific lithological class. However, this conventional use of SAM does not take into account the spectral variability, which is an inherent property of many rocks and is further magnified in remote sensing data acquisition process. In this study, two methods of determining reference spectra used in SAM are proposed for the improved lithological mapping. In first method the mean of spectral derivatives was combined with the mean of original spectra, i.e., the mean spectrum and the mean spectral derivative were jointly used in SAM classification, to improve the class separability. The second method is the use of multiple reference spectra in SAM to accommodate the spectral variability. The proposed methods were evaluated in lithological mapping using EO-1 Hyperion hyperspectral data of two arid areas. The spectral variability and separability of the rock types under investigation were also examined and compared using spectral data alone and using both spectral data and first derivatives. The experimental results indicated that spectral variability significantly affected the identification of lithological classes with the conventional SAM method using a mean reference spectrum. The proposed methods achieved significant improvement in the accuracy of lithological mapping, outperforming the conventional use of SAM with a mean spectrum as the reference spectrum, and the matching filtering, a widely used spectral mapping method.

1. Introduction

Hyperspectral remote sensing with high spectral resolving properties provides great potential to accurately identify and map the constituents of the earth's surface (Goetz et al., 1985; Vane and Goetz, 1988). Mineral/lithological mapping has been one of the important applications of hyperspectral remote sensing in the past two decades (e.g., Bowers and Rowan, 1996; Budkewitsch et al., 2000; Rowan et al., 2000, 2004; Harris et al., 2005, 2010; Chen et al., 2007; Gersman et al., 2008; Waldhoff et al., 2008; Leverington, 2010). Different methods have been developed and have produced very promising results of lithological mapping. Generally, the mineral/lithological mapping using hyperspectral data can be generalized as a comparison of an unknown spectrum (target spectrum) to a reference spectrum, either in absorption features or over the full wavelength range (Mustard and Sunshine, 1999). The comparison in absorption features (e.g., position, strength and shape) is also called feature mapping or absorption mapping, which exploits the fact that many constituent materials (e.g., minerals) exhibit unique absorptions that are diagnostic of their composition (Mustard and Sunshine, 1999; Clark et al., 2003). Although feature (or absorption) mapping is very powerful, it can be problematic for many materials whose spectra are characterized by their continuum shape and/or very broad absorption (e.g., rocks). In such cases, methods of full spectral mapping (i.e., spectral comparison over full wavelength range) have been developed to address some of these concerns (Mustard and Sunshine, 1999).

One of the most widely used lithological mapping methods is the spectral angle mapper (SAM) (Kruse et al., 1993; Crosta et al., 1998; Murphy et al., 2012), which quantitatively compares two spectra over full wavelength range. Specifically speaking, the SAM measures the similarity of a target spectrum to a reference spectrum by a spectral angle (Kruse et al., 1993). The spectral angle is an average fit over entire spectral range (or a subset of it) of the dataset used in classification (Hecker et al., 2008). It was found that the performance of the SAM algorithm depends upon the choice

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of the reference spectrum (Harris et al., 2005; Hecker et al., 2008). Hecker et al. (2008) evaluated the influence of different sources of reference spectra on the performance of SAM classification using synthetic spectral data. They found that the spectra from image data themselves (i.e., image spectra) outperformed the other sources of reference spectra (i.e., field spectra and spectra from a standard library) in SAM classification. Although in many existing lithological mapping studies, image spectra were also used as reference spectra (e.g., Bowers and Rowan, 1996; Chen et al., 2007; Harris et al., 2005, 2010), how to select the appropriate reference spectra from training samples (i.e., image spectra) is still an issue to be addressed (Hecker et al., 2008).

In existing lithological mapping studies using SAM, each lithological class is assumed to have a unique spectral signature (Crosta et al., 1998; Rowan et al., 2000; Debba et al., 2006) and the mean spectrum of training samples of the class, which is considered as the representative of spectral feature of the class, is used as the reference spectrum. The assumption of a unique spectral identity for each lithological class and the use of the mean spectrum as the sole reference spectrum imply that the spectral variability of the lithological type is not taken into account in the SAM based mapping process (Bateson et al., 2000; Cho et al., 2010). However, it is very common that many rocks show spectral variability (e.g., the difference in whole spectral shape, the variations in position, strength and shape of absorption features) (Sgavetti et al., 2006; Murphy et al., 2012). On the one hand, rocks comprise a mixture of minerals in varying proportions (Harris et al., 2010). The spectral variability of rocks is intrinsic to the involved rock-forming geologic process and the spectral properties of rocks are affected by many factors, such as mineral chemistry and structure, mineral composition, grain size, and rock texture (e.g., Sgavetti et al., 2006). On the other hand, remote sensing data acquisition process also contributes to and further magnifies the spectral variability of rocks, such as viewing geometry, incident illumination and atmospheric conditions (e.g., Murphy et al., 2012). As a result, the use of the mean spectrum as the sole reference spectrum in SAM based mapping results in a loss of valuable information from individual samples and undistinguishable mean spectra for rock types with spectral variability. This could lead to a low accuracy of classification for rock types and other materials with spectral variability (Angelopoulou et al., 1999; Bateson et al., 2000; Song, 2005; Somers et al., 2011; Murphy et al., 2012). Therefore, the exploration of methods to address spectral variability in SAM based lithological mapping is urgently required.

The main objective of this paper is to determine appropriate reference spectrum in SAM mapping to improve the performance of lithological mapping. The specific objectives are twofold: (1) to experimentally examine the spectral variability and separability of lithological types and their effect on lithological mapping using SAM with a mean reference spectrum, and (2) to propose two methods of determining alternative reference spectrum for the improved use of SAM in lithological mapping with hyperspectral data by improving class separability and accommodating the spectral variability, respectively.

2. Methods

Given the spectral variability of many rock types, two methods were proposed for improving SAM based lithological mapping using hyperspectral data by choosing appropriate reference spectra for each lithological class. In the first method, original spectral data and the spectral derivative calculated from the spectral data were jointly used in SAM to improve class separability (Angelopoulou et al., 1999). In the second method, instead of using only the mean spectrum as the reference spectrum, multiple reference spectra from each lithological class were used, which accommodates spectral variability in SAM based lithological mapping. Furthermore, spectral variability and spectral separability were also examined before classification, in order to understand the effectiveness of the proposed methods. As in many lithological mapping studies (e.g., Harris et al., 2005; Hecker et al., 2008), the image spectra (i.e., spectra from training samples) were used as reference spectra.

2.1. Lithological mapping using SAM with mean reference spectrum

The SAM is a supervised classification algorithm, which utilizes spectral angular information for the classification of hyperspectral data (Kruse et al., 1993). It treats each pixel in a hyperspectral image as an n-dimensional vector, where n equals the number of spectral bands. The algorithm measures similarity of a target spectrum to a reference spectrum by calculating spectral angles between them. A smaller angle represents a closer match to the reference spectrum.

The angle between a target spectrum vector $\boldsymbol{a}$ and a reference spectrum vector $\boldsymbol{b}$ can be calculated by

$$\alpha = \cos^{-1}\left(\frac{\boldsymbol{a}^{\bullet}\boldsymbol{b}}{||\boldsymbol{a}||^{\bullet}||\boldsymbol{b}||}\right), \tag{1}$$

where $||\ ||$ is a norm function (Prugovečki, 1982). Eq. (1) can also be written as

$$\alpha = \cos^{-1}\left\{\frac{\sum_{i=1}^{n} a_i \cdot b_i}{\left[\sum_{i=1}^{n} a_i^2\right]^{1/2}\left[\sum_{i=1}^{n} b_i^2\right]^{1/2}}\right\}, \tag{2}$$

where n is the number of spectral bands, a_i denotes value of the target spectrum at ith band and b_i denotes value of the reference spectrum at ith band.

As mentioned previously, in existing lithological mapping studies, the mean spectrum of all sample spectra of a lithological type is used as the reference spectrum. If the spectral angle between an unknown spectrum (i.e., target pixel) and the reference spectrum of a specified lithological class (i.e., the mean spectrum) is less than a user-specified threshold, the pixel is assigned to the class. Otherwise, the pixel is assigned to the background or non-target class. When multiple lithological classes are to be identified using the SAM method, if a pixel is classified to more than two classes simultaneously, the final class label for the pixel is assigned to the class with the smallest spectral angle.

2.2. Lithological mapping by incorporating spectral derivatives

Spectral derivative analysis is a common and useful method in laboratory spectroscopy (Butler and Hopkins, 1970; Talsky, 1994) and has been used in hyperspectral remote sensing (Demetriades-Shah et al., 1990; Philpot, 1991; Chen et al., 1993; Tsai and Philpot, 2002) for eliminating background signals, detecting absorption spectral features and enhancing spectral contrast (Zhang et al., 2004). Harris et al. (2010) suggested that use of spectral derivatives is a promising technique for reducing effect of variable illumination. In recent years, spectral derivatives have been used both in isolation (Murphy and Monteiro, 2013) and in combination with original spectral reflectance data (Tsai and Philpot, 2002; Demir and Erturk, 2008; Chen et al., 2009; Kalluri et al., 2010) in land cover classification and material identification. In this study, spectral reflectance features and spectral derivatives were combined to express pixel characteristics and used in SAM based mapping.

Spectral derivative computation involves the change in dependent variables (reflectance) relative to independent variables (wavelength) (Tsai and Philpot, 2002). The spectral derivatives for hyperspectral imagery can be estimated by obtaining the slope information from the reflectance curve over available wavelengths.