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Using spectrum differentiation and combination for target detection of minerals

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ABSTRACT

Among the techniques that have been developed in spectroscopy, derivative analysis is particularly promising for use with remote sensing data. In the first step of this research we apply the derivative spectrum in a real hyperspectral image and introduce a new target detection approach called "DCEM". For this purpose, 1st to 5th orders of derivative spectrum were applied to the DCEM. The outcome of this research has shown that the application of derivative spectrum in target detection is perfectly advisable in a specific derivative order for each target. This order can be introduced as an optimized order or the Best DCEM. The spectrum differentiation eliminates low frequency components of the spectrum. Despite the little information included in those low frequency components of a signal or spectrum, their complete elimination cause an information loss problem. Hence, in the second step of this research an ensemble classifier approach was employed for the combined use of both spectra and the best derivative order. This simultaneous use of the derivative and zero order spectra is introduced as "ECEM". Experiments were conducted via a HyMap hyperspectral airborne image in eastern Iran. The detection results show that both proposed methods significantly outperform CEM in ROC and AUC values. The best performance upgrade in DCEM detection was about 24% for Kaolinite target and about 28% for Alunite target in ECEM.

1. Introduction

Imaging Spectrometry takes the advantage of contiguous spectral channels to unveil signal sources that usually cannot be resolved by multispectral sensors (Chang, 2003, 2007; Clark, 1999). In hyperspectral data exploitation, most targets of interest are those with small spatial presence and low probability existence in either form of mixed pixel or sub pixel (Chang, 2007; Chang and Heinz, 2000; Schowengerdt, 2007). Therefore, literal based image processing techniques (Chang, 2007; Van der Meer, 2006; Van der Meer et al., 2012; Zhang and Pazner, 2007) are not effective in hyperspectral images even if they can be applied. Derivative spectroscopy and spectral analysis, on the other hand, offers a valuable alternative in this area.

Numerical differentiation is a common tool used in analytical chemistry for processing one-dimensional signals since a derivative is sensitive to important yet subtle details in a spectrum. Hyperspectral data nature allows the implementation of such techniques in this kind of image data (DemetridesShah et al., 1990). Application of this technique in remote sensing is due to its ability for resolving complex spectra of several target species within individual pixels (DemetridesShah et al., 1990), and the fact that derivatives of second or higher order are insensitive to illumination variations caused by sun angle, cloud cover, or topography (Tsai and Philpot, 1998, 2002). Additionally, it is worth considering that the spectral shape information is one of the most important measures in evaluation of the spectral similarity between two spectra (Clark et al., 2003; Hungate et al., 2008; Van der Meer and De Jong, 2011). As it was mentioned in (Dehnavi et al., 2014; Tsai and Philpot, 1998; Zhang et al., 2010 Tsai and Philpot, 1998; Zhang et al., 2010), derivatives of different orders contain various levels of spectral shape information in a spectrum. Therefore, it is not unexpected to have better detection on signal sources in an individual pixel by the usage of derivative spectrum and consequently its spectral shape information. Moreover, spectrum matching techniques are sometimes ruined, in as much as the library spectrum is less fitted to the field spectrum in contrast to its derivative (Kim, 2011). Taken together, it is of great value applying information content of derivative spectrum in target detection.

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Several investigators hinted that employing derivative signature has improved the results of their research in different application areas, including but not limited to the following: Torrecilla et al. took the advantage of derivative spectrum for identification of water constituents in oceanographic regions (Torrecilla et al., 2009). Algal chlorophyll concentration was estimated in (Han, 2005) by application of derivative analysis. The first derivatives were computed and correlated with the chlorophyll-a concentration in a shallow water in (Jensen, 2009). Second derivative approximation was applied in (Becker et al., 2005) in order to help identifying spectral regions where the spectral bands are the most botanically explanative. Partial abundances of spectrally similar minerals in complex mixtures were estimated in (Debba, 2009; Debba et al., 2006), applying first and second orders of derivative spectra. Toxic algal bloom was detected in (Craig et al., 2006) from the analysis of the fourth derivative of phytoplankton absorption spectra, estimated from in situ hyperspectral measurements of reflectance. First and second orders of derivative spectrum were also used in previous researches for un-mixing purposes (see (Bieniarz et al., 2012; Hengqiana et al., 2012; Zhang et al., 2004)). In an earlier research, second order derivative spectrum was applied in linear spectral mixture model (LSM) aimed to estimate minerals' abundance (Zhang et al., 2004). Results of their research suggested an increase in the accuracy of the abundance estimates. However as is clear, the usage of higher order derivatives is neglected in these researches, specifically in target detection.

The spectrum differentiation concept was also previously employed in binary encoding (Kim, 2011), spectral derivative based feature coding (SDFC) concepts (Chang, 2013; Chang et al., 2009), and also the determination of absorption features by using gradient changes in the spectral reflectance curve (Rezaei et al., 2012) for endmember extraction purposes. However, in such coding methods the information content of whole derivative signature was not applied.

In sum, previous researches have proven the practical usefulness of derivative spectrum in different fields of research. However, many of the earlier works were carried at the laboratory level (see for example (Dehnavi et al., 2015), whereby some orders of derivative spectrum were introduced as good discriminators for mineral targets). On the other hand, they rarely or never discussed application of higher order derivative spectrum, i.e. 3rd to 5th orders, in target detection of hyperspectral images. The first idea of this work is thus, putting in various orders of derivative spectrum (1st to 5th orders) into CEM algorithm, introduced as "Derivative Constrained Energy Minimization" or "DCEM", and exploring the detection maps in available image data.

Moreover, one of the points that we have to pay special attention is that spectrum differentiation eliminates low frequency components of the spectrum. Despite the little information included in the low frequency components of a signal or spectrum, their complete elimination cause an information loss problem. Having a spectra and its best derivative order (as a result of DCEM) in a unified approach cause an increase in the information we could obtain from a spectral curve. Hence, in the second step of this research an ensemble classifier approach (Dietterich, 2000, 2002; Rokach, 2010; Zhang et al., 2010) was applied for the combined use of both spectra and the best derivative order. This combined uses of derivative and zero order spectra is introduced as "Ensemble Constrained Energy Minimization" or "ECEM". Thereupon, it can be claimed that the majority of the information contained in a target's spectral curve is used in ECEM.

To justify the above-mentioned frameworks, this study was carried out with an airborne hyperspectral data in comparison to the previous works whereby the standard laboratory images were applied (Zhang et al., 2004). Both proposed detection algorithms were used for identification of four mineral targets including alunite, kaolinite, epidote and hematite which were located in a hydrothermally altered mineral region in Iran east. Due to the possible economic importance of various minerals within the study area better mapping performance was required. To this end, our proposed method was used for better mapping of the region.

A description on the methods applied in this work and the evaluation methodology is presented in Section 2. Section 3 focuses on the study area, experimental and ground truth data; laboratory measurements, pre-processing step and experimental results are discussed in Sections 4–6 respectively. Finally, we draw out our conclusion in Section 7.

2. Method

This section provides a full description of the proposed three-step approach for target detection. First, derivative spectrum was used for target detection in the proposed DCEM approach. Second, one of the derivative orders was selected as the best order for the identification of each target. Third, a combination of both spectra and its derivative spectrum was applied in the proposed ECEM approach.

2.1. Derivative constrained energy minimization (DCEM)

There are various ways to compute derivative spectrum (Tsai and Philpot, 1998). Since hyperspectral images have many discrete contiguous spectral bands like Eq. (1),

$$\boldsymbol{r} = [r(\lambda_1), r(\lambda_2), \ldots, r(\lambda_L)] \tag{1}$$

in which ' r ' is a parameter of spectrum definition and $r(\lambda_l)$ is the reflectance value of l^{th} spectral band, a computationally efficient (Tsai and Philpot, 1998) finite approximation approach is the most widely used (Kim, 2011; Zhang et al., 2004). This numerical method introduces no artefacts, which may be the side effect of polynomial curve-fitting procedures (Tsai and Philpot, 1998). Three forms are commonly considered for finite difference approximation: forward, backward, and central differences. Backward difference (Iskandarani, 2014), which is proven to be efficient (Rezaei et al., 2012; Tsai and Philpot, 1998), was employed in this work.

Assuming that ' r ' is a parameter of spectrum definition and $r(\lambda_l)$ is the reflectance value of l^{th} spectral band, the first and the n^{th} derivatives of the spectrum can be represented as Eq. (2) and Eq. (3) respectively:

$$\frac{d\boldsymbol{r}}{d\lambda}\Big|_l \approx \frac{r(\lambda_l) - r(\lambda_j)}{\Delta\lambda} \tag{2}$$

$$\frac{d^n\boldsymbol{r}}{d\lambda^n}\Big|_l \approx \frac{d}{d\lambda}\left(\frac{d^{n-1}\boldsymbol{r}}{d\lambda^{n-1}}\right) = \frac{r(\lambda_l) - \ldots + r(\lambda_{l+n})}{(\Delta\lambda)^n} = \frac{\sum_l^{l+n} C_k r(\lambda_k)}{(\Delta\lambda)^n} \tag{3}$$

where, λ is the band separation which can be delineated as $\lambda = \lambda_j - \lambda_l$, $\lambda_j > \lambda_l$. Band separation for spectral differentiation of hyperspectral data, supposed to be equal to the band intervals (Zhang et al., 2004).

Employing the calculated derivative spectrum provides a new space called *Gradient Feature Space or "GFS"*. Derivative spectral features, as the basis-vectors of GFS, are vectors of shorter length in contrast to their original spectral features. This property is shown in Eq. (4) and is clearly evident from (Eqs. (2) and (3)). According to the fact that derivatives of different orders contain spectral shape information, GFS provides a space for an investigation on spectral shape. As fully described in (O'Haver, 2016), differentiation has some important properties. These properties give the GFS the ability for a better spectral discrimination between nearly identical spectra. Therefore, one of the main purposes of this research