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A novel bilinear unmixing approach for reconsideration of subpixel classification of land cover

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ABSTRACT

Hyperspectral mixing depends on a variety of factors such as the instantaneous field of view of observation device, the height of the image capturing platform from the scene, the properties of materials in the pixel, and the interaction structure of these materials with incident light in the scene. Different unmixing models have been considered to model the hyperspectral mixing. The simplest one is the linear mixing model. Nevertheless, it has been recognized that mixing phenomena is usually nonlinear. Bilinear and linear–quadratic models have become popular recently, and also the bilinear polynomial post-nonlinear model shows promising results. Most of these nonlinear models consider only the reflection interaction. However, especially in regions like vegetated areas, absorbance and transmittance are also important facts which affect the mixture. So, they should be taken into account when dealing with physics of hyperspectral mixing. In this study, an enhanced bilinear mixing model is proposed for analyzing the physics of hyperspectral mixing. The model takes into account the transmittance, absorption and reflection. The results show that our enhanced bilinear viewpoint is superior, in terms of pixel reconstruction error, when compared to that of linear and other bilinear models which consider only the reflection interaction.

1. Introduction

Spectral unmixing problem is valid since 1960s when the multispectral scanner first emerged. Spectral mixing for hyperspectral images result due to mixed pixels from insufficient spatial resolution of the scanner. These mixed pixels are decomposed into spectrally pure members which are called end members. Many unmixing approaches have been performed in order to handle more accurate abundance maps. A detailed and very useful review of unmixing methods is conducted in (Heylen et al., 2014).

The basic model is the LMM (Linear Mixture Model) which assumes that the incoming light to the sensor is coming directly from each material. So the mixed spectrum is assumed as the linear combination of each material that physically exists in the pixel. As S is the mixed spectrum, a_m is the abundance value for the materials, s_m is the spectrum of each material. M is the number of end members, LMM model can be formulated as (1) with the constraints in (2). The constraints are ASC (Abundance sum-to-one constraint) and ANC (Abundance non-negativity constraint).

$$S = \sum_{m=1}^{M} a_m s_m \tag{1}$$

$$\begin{aligned} &\textstyle\sum_{m=1}^{M} a_m = 1 \\ &a_{\mathrm{m}} \geq 0 \ \text{ for all } \ m \end{aligned} \tag{2}$$

Though LMM is a fast and basic unmixing method, real world is mostly nonlinear. The physics of spectral mixing exhibits some complexities. Light usually has many interactions between the materials. This leads to nonlinear mixing which cannot be solved accurately just using LMM. This situation is largely considered by many researchers in the literature. The researchers came up with generally two approaches: intimate mixture model and bilinear model. Intimate mixture model assumes that light has many interactions between the materials in microscopic dimension. For this model, the distance between each mixing materials is shorter than the distance between the reflected photons and sensor. End members' abundance values are solved from the mixed spectrum by using the method in (Hapke, 1993). In Hapke model, for mixed surface, (3) is given between end members' wavelength based spectrum and single reflection albedo value. Albedo value can be calculated for any end member (m) by using (3).

$$\sqrt{1-\propto(\lambda)_m} = \frac{[(\mu + \mu_0)^2 s(\lambda)_m^2 + (1 + 4\mu\mu_0 s(\lambda)_m)(1-s(\lambda)_m)]^{\frac{1}{2}} - (\mu + \mu_0)s(\lambda)_m}{1 + 4\mu\mu_0 s(\lambda)_m} \tag{3}$$

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Here $\propto(\lambda)_m$ is the wavelength-based single reflection albedo value and $s(\lambda)_m$ is the spectrum of an end member. On the reflection plane as the angles between incident light and surface normal is θ_i and the angle between reflected light and surface normal is θ_e, $\mu_0$and μ is given as $\mu_0 = \cos(\theta_i)$ and $\mu = \cos(\theta_e)$. After calculation of albedo, abundance values a_m can be found by using (4). Here albedo mixture ($\propto(\lambda)_{mix}$) is considered as LMM, because albedo only depends on the first reflection case, even if many materials are in interaction.

$$\propto(\lambda)_{mix} = \sum_{m=1}^{M} a_m \propto(\lambda)_m \tag{4}$$

Since intimate mixture model has many calculations and requires the knowledge of many terms, the model is simplified down to two interactions only. This case is called bilinear model. In bilinear model there may be many end members however, it is assumed that, at maximum, two interactions are valid between any end members. This approach is logical, because the reflection values get smaller and converges rapidly to zero when multiplying more than two reflectance spectrums. So the contribution of interaction spectrums which have multiplication more than two may be ignored. Many studies such as (Nascimento and Bioucas-Dias, 2009; Fan et al., 2009; Halimi, 2011; Altmann et al., 2011; Altmann et al., 2012; Luo et al., 2016; Yang et al., 2017) have shown bilinear modeling gives accurate unmixing results. The mixing equation for bilinear modeling is given in (5) with the constraints in (6). It has 2 parts. First is the single reflection and the second part is the twice reflection cases. First part is the classical LMM. In second part, $s_i$is the spectrum of one end member, $\odot$means Hadamard product and $b_{mk}$is the abundance of m.and k.end member's interaction terms. The second part is the abundance-weighted linear combination of multiplied spectrums of each two end members.

$$S = \sum_{m=1}^{M} a_m s_m + \sum_{m=1}^{M} \sum_{k=1}^{M} b_{mk} s_m \odot s_k \tag{5}$$

$$m \geq k \tag{6}$$

For two end member case, the mixing equation reduces to (7)

$$S = a_1 s_1 + a_2 s_2 + b_{11} s_1 \odot s_1 + b_{21} s_2 \odot s_1 + b_{22} s_2 \odot s_2 \tag{7}$$

All bilinear models develop different solutions to Eq. (5) under the constraint in (6).

In (Nascimento and Bioucas-Dias, 2009) the self-interactions are not included and the constraint in (8) is used for solution to (5). This model can be solved with LSE (Least Square Estimation) method with the known end member spectrum.

$$\sum_{m=1}^{M} a_m + \sum_{m=1}^{M-1} \sum_{k=m+1}^{M} b_{mk} = 1 \tag{8}$$

In (Fan et al., 2009), the self-interactions are not included. Firstly the abundance values of linear part are calculated by using Eqs. (1) and (2). Then the constraint: $b_{mk} = a_m a_k$ is applied. The physical meaning of this model is that the probability of interaction with any material should be proportional to its abundance.

However, it is shown in (Halimi et al., 2011), and (Altmann et al., 2011) Fan model can be too restrictive, and it is proposed to add an additional free parameter at each bilinear interaction, leading to $b_{mk} = \Upsilon_{mk} a_m a_k$ with $\Upsilon_{mk} \in [0, 1]$. This GBM (Generalized Bilinear Model) has more degrees of freedom than Fan's bilinear model. In (Halimi et al., 2011), the GBM uses a hierarchical Bayesian technique to determine the Υ_{mk} term. Several experiments on synthetic and real data sets are conducted and reported that GBM provided better unmixing results in terms of reconstruction error than the LMM and Fan's bilinear model.

It is important to emphasize that Nascimento, Fan, and GMB bilinear models all assume that there are no bilinear self-interactions.

Another approach in the literature is PPNM (Polynomial post-nonlinear model) (Altmann et al., 2012) which uses nonlinear transformation of the spectrum generated by the LMM to introduce nonlinearities. It differs from Fan, Nascimento and GBM at two points: The first one is that self-interactions are included and the second one is all bilinear terms are scaled with the same constant such that $b_{mk} = c * a_m a_k$ where no restriction is specified while determining the value "c". Fan, GBM and PPNM all solve the linear part of bilinear model by using ASC and ANC approach.

In the case of nonlinear mixing, other methods such as neural networks, kernel methods, support vector machines, piecewise linear unmixing, database approach are studied (Foody, 1996). MLP (Multilayer perception) artificial neural network is also used by many studies (Foody, 1996; Licciardi & Frate, 2010; Licciardi & Frate, 2011; Atkinson et al., 1997; Plaza et al., 2008) and is still popular (Li et al., 2016; Mitraka & Frate, 2015; Mitraka et al., 2016).

2. Claims of originality

In this paper, some points and assumptions in the literature which are evaluated as having shortcomings are criticized and a novel enhanced bilinear model is proposed. The criticized issues and the claims of originality of this study are the following:

A. The unmixing methods mentioned may not produce fine results according to the case handled. Bilinear approach is much simpler than the others and it gives very promising results. However, most of the bilinear models have a problem that they consider that the light has only reflection interaction. In fact, three basis situations are valid for the interaction of any material with light. These are: reflection, transmission and absorbance. These interactions perform different characteristics for different materials. In spectrum mixing case, similar to reflection interaction, the light may reach the sensor by transmitting through one end member and reflects from the other one. Therefore, in this study, it is evaluated that bilinear models which consider merely the reflection will not be sufficient for accurate unmixing. The proposed enhanced bilinear model takes into account both reflectance and total transmission (absorbance affected transmission).

B. In literature, rare studies such as (Zhang et al., 1998) take into account the transmittance. However It does not measure or calculate transmission and assumes that reflection and transmittance spectrum is the same. (Zhang et al., 1998) also assumes that the bilinear interaction terms' abundance values are the same of each other. However, transmission spectrum is not the same as reflectance spectrum. Furthermore, the transmission is affected by the absorption also. The proposed enhanced bilinear model develops a smart way for calculating the absorbance affected transmission spectrum. The method which is not applied in the literature for bilinear modeling is based on measuring the ground truth spectral signatures of materials on black body and white body. It measures the spectrum and calculates the actual reflectance and total transmission (absorbance affected transmission) spectrum of materials by using snell law and Fresnel logic.

C. In literature, there is a common assumption which states each material has abundance value as much as its physical existence in the mixed pixel. This assumption is incomplete in many aspects. The physics of spectral mixing is not linear, and the physical structure and placing of the materials in the mixed pixel affects the mixing. Although one end member has not the majority of a pixel, it may contribute the mixing as much as the end member has the majority. For instance one cannot guarantee that the soil that is seen completely covered by leaves, does not contribute the mixed pixel captured by a sensor above. Basically, the transmitted light through leaf may reflect from soil, transmits from leaf again and reach the sensor. In the proposed bilinear method, the values of abundance of all end members are calculated together without any pre-