VALIDATION OF SPECTRAL UNMIXING METHODS USING PHOTOMETRY AND TOPOGRAPHY INFORMATION

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ABSTRACT

In this work the performance of spectral unmixing procedures applied on hyperspectral images of granular mixtures are compared. For that purpose we consider a laboratory image and synthetic images, the latter being created using an original algorithmic process while borrowing some aspects of the real data. The nonlinear effects of light multiple scattering within the mixture can be partially compensated by transformation of the image using the Hapke model under different levels of injected information regarding topography and photometry of the scene. The validation of the different methods and deconvolution processes is established by comparing the results with a "ground truth" through the mean Spectral Angle for the extracted endmembers and the mean Abundances Root Mean Square Error for the estimated abundances. Interpretation of the results indicates that is safer to extract the endmembers from the original version of image unless topography and most importantly photometry are precisely known. On the other hand better distribution maps are obtained in general from the transformed version of the image.

Index Terms— spectral unmixing, planetary regolith, Hapke’s model, photometry, topography, synthetic images.

1. INTRODUCTION

Spectral unmixing methods aim at detecting, mapping, and quantifying the planetary components by separating the different contributions that form the remote signal. It is quite common that spectral unmixing methods assume that the mixture is linear due to a macroscopic mixture. However, intimate mixture occurs extensively on planetary mineral or icy surfaces. For such kinds of mixtures the spectral signatures of the endmembers are combined nonlinearly according to the laws of radiative transfer within dense, scattering and absorbing granular media.

Physical models require a priori information such as the nature of the components and their optical properties -rarely available for the minerals- for simulating the spectra and evaluating the abundances. As a result, unsupervised spectral unmixing methods are promising but they need to take into account these nonlinearities.

Thus, the main goal of the present study is to evaluate the added value of nonlinear spectral unmixing compared to the classical linear unmixing under different level of injected a priori information regarding topography and photometry based on Hapke’s model.

2. DATA AND METHODS

2.1. Hapke’s Model

The semi-empirical radiative transfer model of Hapke expresses the bidirectional reflectance as a function of the single scattering albedo, the photometry and the geometry [1]. Thus, reflectance can be expressed as

\[ R = \frac{w}{4(\mu_0 + \mu)} [(1 + B(g, h, B_0))P(g, h, c) + H(\mu_0, w)H(\mu, w) - 1]S(\theta) \]

where \( R \) is the reflectance, \( w \) is the single scattering albedo, \( \mu_0 \) is the cosine of SZA, \( \mu \) is the cosine of VZA, \( g \) is the phase angle, \( B \) is the opposition effect function, \( P \) is the phase function, \( H \) is the isotropic multiple scattering function and \( S \) is the function for macroscopic roughness [2].

Point 1: in the case of a granular mixture of pure components, the single scattering of the media is the linear combination of the single scattering albedo of the endmembers, the "abundance" of any of them being the proportion it occupies in the total geometrical cross section per unit volume. Point 2: considering point 1, we note that classical linear unmixing methods could be used in the \( w \) space provided that we can invert the Hapke formula \( R \rightarrow w \) knowing the geometry (SZA, VZA, phase angle) and the photometry (\( b, c, h, B_0 \) and \( \theta \)). This is not possible analytically but numerically. In that framework, the nonlinearity of the mixing is treated by this inversion and change of space.

2.1. Images

2.1.1. Crater Image

The Crater image [2] is a multispectral image (16 bands) of a simulated crater made at the Midi-Pyrénées Observatory in Toulouse, France (Fig. 1). The interest of the image lies on its regolithic nature, the different angles of acquisition for different pixels and because craters are a typical geological accident in the study of planets.
The image was produced with an incidence angle (SZA) of 30°, an emergence angle (VZA) of 0° and an azimuth angle (DPHI) of 0° as referred to a coordinate system attached to the sample [2].

![Fig. 1 Crater image](image)

In the scene, one can distinguish 3 different materials: Basalt, Palagonite and Tephra. Full photometric characterization of these 3 materials was performed based on goniometric measurements and their Hapke’s parameters (photometry) are given in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>b</th>
<th>c</th>
<th>h</th>
<th>B0</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basalt</td>
<td>0.42</td>
<td>0.32</td>
<td>0.14</td>
<td>0.16</td>
<td>25.0</td>
</tr>
<tr>
<td>Palagonite</td>
<td>0.44</td>
<td>0.40</td>
<td>0.13</td>
<td>0.25</td>
<td>25.0</td>
</tr>
<tr>
<td>Tephra</td>
<td>0.42</td>
<td>0.44</td>
<td>0.2</td>
<td>0.2</td>
<td>25.0</td>
</tr>
</tbody>
</table>

Besides, reference reflectance spectra of these 3 materials have been measured individually with the Imager Spectral pour l’Exploration Planétaire experiment (ISEP). On the other hand the single albedo spectra have been calculated by inverting Hapke’s model, taking into account the values of the photometric parameters and the angles of acquisition, i.e., SZA = 30°, VZA = 0° and DPHI = 0°. These spectra are shown in Fig. 2. Auxiliary maps of acquisition angles can be derived for the image from a simplified model of the crater topography (spherical bowl). Approximation of the abundances distribution of each of the 3 materials on the scene is available. The materials are poorly mixed and their distribution is correlated with the topography. These abundances are an approximation because it is not easy to control experimentally the distribution of the materials throughout the scene.

2.1.2. Synthetic Images

In order to distinguish between these uncertainties and inherent limitations of the proposed methodology, 2 synthetic reflectance images have been created, for which we have in the interest of knowing the absolute reference, having a better control of the image characteristics, while preserving a certain degree of realism since the image is calibrated using lab measurements.

First, the endmembers in the albedo domain are taken from fig. 2. Second, the abundances maps are created using a cellular automaton. Even, the abundance maps obtained in this way seems to have fractal properties as expected for real scenes in nature, being possible to control the level of fractal roughness (do not confuse with soil roughness), although it is not proved yet [3]. The used cellular automaton consists on an iterative process where each pixel in each iteration has 3 possible actions with 3 different p probabilities. The first action, mixing (p = 0.2), consists on mixing the abundance vector of the given pixel with some random neighbor pixels. The second action, exchange (p = 0.5), consists on changing the value of the abundance vector by the value of one of its neighbors. The third action, no-operation (p = 0.3), consists on keeping the previous abundance values of the given pixel.

The user can define the endmembers distribution seed, the different probabilities for each action, the size of the neighborhood window and the total number of iterations. With the probabilities it is possible to control the level of spatial heterogeneity and even the level of mixture in a qualitative way.

![Fig. 2 – Endmembers Spectra: Measured Reflectance (dotted) & Single Scattering Albedo (dashed)](image)

Once the albedo domain endmembers and the abundances are obtained, they are multiplied linearly so as to obtain the image in the albedo domain. Finally, the image in the reflectance domain is obtained by applying the Hapke’s model fed by the scene topography and a photometry.

The incidence, emergence and azimuth distribution maps used for the creation of the synthetic images are extracted from the auxiliary data corresponding to a real observation of the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) onboard Mars Reconnaissance Orbiter (MRO) [5] for the sake of being realistic. It is interesting to highlight the extreme geometries that are exhibited on some parts of the image, such as in a cliff. As regards to the photometry, the values used in each pixel are the expected values of the Hapke parameters of Table 1 weighted in terms of the abundances of the materials in the pixel.
The main characteristics of the 2 synthetic images are:

- **Synthetic Image 1**: (Random seed, 400 iterations) the endmembers are poorly mixed and the distribution of the materials is not correlated with the scene topography.
- **Synthetic Image 2**: (random seed, running until reaching 80% of maximum purity index) the endmembers are highly mixed and the distribution of the materials is not correlated with the scene topography.

2.2. Algorithms

The unmixing algorithms used in this work are: NFINDR [5], Vertex Component Analysis (VCA) [6], Negative Abundances Oriented (NABO) 1, Simplex Identification via Split Augmented Lagrangian (SISAL) [7] and Sparsity Promoting Iterated Constrained Endmember (SPICE) [8] for Split Augmented Lagrangian (SISAL) and Sparsity simplex, the replacement is performed.

NABO is a geometrical heuristic method for extracting endmembers under pure pixel assumption and linear mixing supposition. This approach iteratively selects the pixel with the most negative unconstrained abundance for a given set of endmembers, replacing alternatively each of these endmembers by this pixel and evaluating for each substitution a global energy function. This energy function consists on absolute value of the sum of the most negative unconstrained abundance for a given set of endmembers under pure pixel assumption and linear mixing supposition.

The experiments consist on unmixing the aforementioned crater and synthetic images using each endmember extraction algorithm under 5 different scenarios:

- **Linear model** Working in the reflectance domain.
- **Nonlinear model** Applying the Hapke inversion in order to transform the image in the albedo domain in 4 different deconvolution processes:
  - **(NO PHOTO & NO TOPO)** Assuming a lambertian photometry and applying a constant geometry when performing the Hapke inversion.
  - **(NO PHOTO & TOPO)** Assuming a lambertian photometry and applying the reference variable geometry.
  - **(PHOTO & NO TOPO)** Applying the mean of the reference photometry and applying constant geometry.
  - **(PHOTO & TOPO)** Applying the mean of the reference photometry and applying variable geometry.

The lambertian photometry consists on values equal to 0, except c = 0.5 and h=0.01. The reference photometry consists on the mean values of TABLE I. The constant geometry in the crater image case consists on the angles: SZA = 30°, VZA = 0° and DPHI = 0°; and in the synthetic images cases consists on the angles: SZA = 64.8628°, VZA = 17.8213° and DPHI = 75.7412°. Finally, the reference variable geometry for the crater and the synthetic images are taken in the auxiliary data described above.

For each image under test, under each considered scenarios, the endmembers are extracted using each algorithm of the section 2.2. Then, the extracted endmembers are transformed into the reflectance domain if needed (i.e., in case of nonlinear unmixing) using the laboratory geometry (SZA = 30°, VZA = 0° and DPHI = 0°) and photometry (Table I) in order to compare these extracted endmembers with the reference laboratory endmembers under the same conditions. On the other hand, the FCLS algorithm estimates the abundances of the extracted endmembers in the image under test.

In order to measure the unmixing quality, we have computed a number of indicators and derived quantities (means over the image). In this paper we choose to discuss two of them: the mean of the abundances Root Mean Square Error (RMSE) and the mean of the Spectral Angle Measurement (SAM) for the endmembers. In figures 3-5, we illustrate, in the form of boxplots, the statistics of two selected indicators over all the considered methods. Each image is treated separately.

3. EXPERIMENTS AND RESULTS

The results obtained for the synthetic image 1 show no ambiguities: performing the unmixing in the albedo space produce better results in most cases than working in the reflectance space. Excellent results of the endmembers and their abundance maps are achieved when full information is available (PHOTO & TOPO). Degradation on the mean abundance RMSE and to a lesser extend on the mean spectral angle occurs with partial information, especially if photometry is not known. In this case it is safer to extract the endmembers in the reflectance space even though abundances are better estimated in the albedo space.

Regarding the synthetic image 2, for endmember extraction there is no clear advantage of working in the albedo space except that the behavior of the unmixing methods is more homogeneous after inverting the spectra with the Hapke model when the photometry is known. Nevertheless abundances are unambiguously better estimated in the albedo space especially when full information is available.

We finish with the crater image for which our knowledge on the photometry and topography is degraded compared to the synthetic cases even when they are available. In that sense we assess the consequences of the data uncertainties.

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on the unmixing results. The first consequence is that the endmembers extraction is more accurate in the reflectance space regardless of the scenario for topography and photometry. Indeed the inaccuracies in the latter can introduce large errors during the inversion process, increasing the probability to produce outlier spectra in albedo (in particular in areas where geometry is extreme). However one has to bare in mind that the crater image displays large units made of one of the pure materials thus implying that nonlinear mixing is in a sense marginal in the image. Should the opposite occurs, the nonlinear method, despite its limitations due to uncertainties, could take the lead. As for the evaluation of the abundance maps, there is a clear advantage of using the albedo space provided that the photometry is known.

Fig. 3 - Synthetic image 1 results

![Synthetic image 1 results](image1)

Fig. 4 - Synthetic image 2 results

![Synthetic image 2 results](image2)

5. ACKNOWLEDGES

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6. REFERENCES