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Orthogonal equations for the detection of hidden archaeological remains de-mystified

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ABSTRACT

Spectral variations of vegetation, known as crop marks, have been widely used for archaeological research as a proxy to detect buried archaeological remains. Such marks can be recognized using space-borne data and image analysis techniques supported by the existing archaeological knowledge of the area under study. Orthogonal equations for the enhancement and detection of crop marks using multispectral satellite images have been recently proposed in the literature. The proposed equations are linear transformations of the initial spectral bands of multispectral datasets aiming to the improvement of the satellite images. For the calculation of the n-space coefficients of this linear transformation a four-step methodology was followed, separately for each sensor. This paper aims to provide the fundamental concept of the development of these equations as well as some aspects related with the application and accuracy assessment. Spectral characteristics of the sensor, atmospheric effects, and spectral calibration of the datasets as well as the selection of the appropriate period for applying these equations for the enhancements of crop marks are also discussed. Such orthogonal equations may be further developed and applied for any kind of sensor either hyperspectral or multispectral for the detection of buried archaeological remains. An example of the applicability of the orthogonal equations at Stonehenge archaeological site is also demonstrated.

1. Introduction

Crop marks have been widely used as a proxy for the exposure of archaeological remains (Gojda and Hejcman, 2012; Alexakis et al., 2009, 2011; Cavalli et al., 2007; Wilgocka et al., 2015; Agapiou et al., 2012). Crop marks are frequently observed in agricultural fields where crops overlay near-surface archaeological remains. The latest tend to retain different percentage of soil moisture compare to cultivate crops that do not cover archaeological remains and therefore the crops can either be stressed or enriched (Winton and Horne, 2010). Consequently, crop marks are formed as an indirect effect of the buried archaeological remains.

The detection of crop marks had attracted the interest of archaeologists especially in the beginning of the 21st century, mainly due to the new capabilities of the satellite and airborne sensors which could provide higher spatial and spectral resolution. However, several researches tend to agree that such marks are difficult to be detected since they constitute a complicated phenomenon (Kaimaris and Patias, 2012). As a result, the recognition of crop marks using remote sensing data is still considered to be extremely challenging.

In the literature a variety of remote sensing techniques are usually applied in satellite datasets for the detection of crop marks. These techniques include amongst other vegetation indices, histogram enhancements, Principal Component Analysis (PCA). Recently, Agapiou et al. (2013a, 2015) have proposed orthogonal equations for a variety of multispectral satellite datasets that can directly applied for the enhancement of multispectral images and therefore the detection of crop marks. In detail, Agapiou et al. (2013a, 2015) have suggested linear equations for QuickBird; IKONOS; WorldView-2; GeoEye-1, ASTER; Landsat 4 TM; Landsat 5 TM and Landsat 7 ETM+ sensors. Further details regarding the orthogonal equations as well as the evaluation report can be found there (Agapiou et al., 2013a, 2015). Although these equations have been initially developed for archaeological sites of the eastern Mediterranean, they have been also exploited in other regions as well (Wilgocka et al., 2015; Rączkowski and Ruciński, 2015; Pagés and Calleja, 2015).

The aim of this paper is twofold: from one hand the paper intends to provide the basic concept and some critical issues related with the applicability of these orthogonal equations, while on the other hand it aims to assist researchers for developing new equations for other kinds of sensors for supporting archaeological research in other areas beyond the eastern Mediterranean. The latest may push further archaeological research to automatic or semi-automatic procedures for the detection of crop marks in vast areas (i.e. archaeolandscapes) and therefore assist archaeological research in a landscape level. In addition, the identification of crop marks which in turn can be linked with the presence of the archaeological remains can be used to protect still unknown and un-excavated cultural heritage sites.

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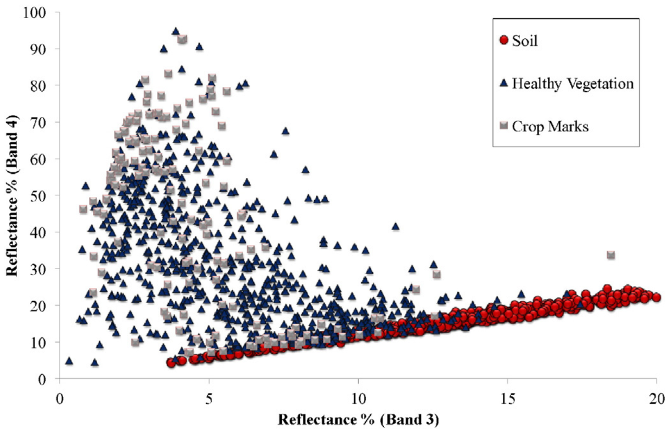

Fig. 1. Reflectance values for the Red and NIR band over the simulated archaeological site (Alampra case study, see Agapiou et al., 2013a, 2013b). The measurements were separated into three main categories: soil spectral signatures; healthy crop spectral signatures and crop marks spectral signature. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

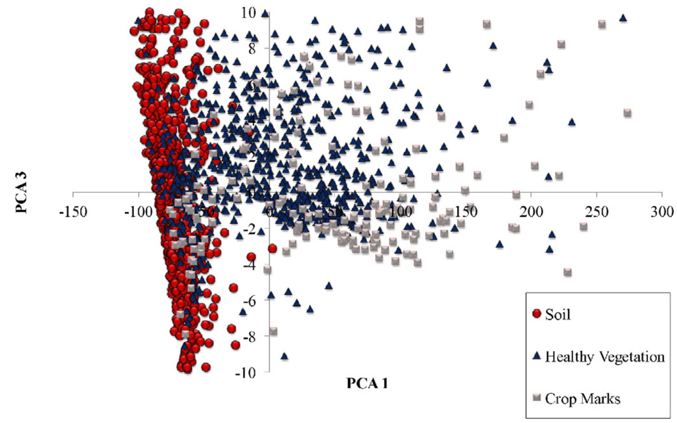

Fig. 2. PCA 1 and PCA 3 components after the transformation of the reflectance values (Alampra case study).

2. Basic concept

The proposed orthogonal equations as those have been proposed by Agapiou et al. (2013a, 2015) have been calculated using a four step methodology -for each sensor- as this is briefly indicated below. It should be noticed that the methodological framework of the work was based upon the fundamental work of Kauth and Thomas (1976) applied for the development of Tasseled-Cap transformation. The basic idea for the development of the new orthogonal equations is to rotate the linear transformation of ground truth datasets after a PCA analysis into a new vector space.

•Step 1: In situ spectral signatures have been systematically collected over simulated archaeological environment using a handheld spectroradiometer (see Agapiou et al., 2013b). The spectral range of the measurements was limited to the visible and infrared part (NIR) of the spectrum (i.e. 450–900 nm) with a span of 1.5 nm interval. Measurements were retrieved during a complete phenological cycle of the crops. Using the appropriate Relative Spectral Response (RSR) filters of each sensor under study (i.e. QuickBird; IKONOS; WorldView-2; GeoEye-1, ASTER; Landsat 4 TM; Landsat 5 TM and Landsat 7 ETM+ sensors) the ground hyperspectral measurements have been re-calculated to the appropriate broadband reflectance. Fig. 1 shows the simulation final outcomes for the red and NIR band for Landsat 5 TM sensor after the spectral up-scaling of the ground spectroradiometric measurements. As it is demonstrated, detection of crop marks can be a very difficult task using reflectance values without any post-processing and further analysis of the data. Indeed, crop marks and healthy vegetation tend to give very similar reflectance spectral profiles and therefore their distinction can be problematic.

•Step 2: Then, the PCA was applied for each dataset for each sensor in order to create the initial eigenspace. PCA was applied to the whole dataset and the first three principal components (PC) have been used. Therefore from the initial four bands of each sensor (B-G-R-NIR) the dataset was limited to three PCs and eigenvectors. The results have shown that the first three components of PCA analysis can explain 99% of the variance of the initial data: PCA 1 = 72.63%; PCA 2 = 25.08%; PCA 3 = 1.43%. The coefficients for the PCA transformation are given in Table 1 for Landsat 5 TM sensor:

Table 1
PCA coefficients for the Landsat 5 TM sensor. The first three PCA coefficients could explain more than 99% of the total variance of the data.

	PCA 1	PCA 2	PCA 3	PCA 4
Band 1	−0.076	−0.396	0.304	0.863
Band 2	−0.023	−0.505	0.713	−0.486
Band 3	−0.142	−0.752	−0.630	−0.136
Band 4	0.987	−0.150	−0.051	0.036
Explained	72.83%	24.32%	1.84%	1.02%

Fig. 2 present the new values for Landsat 5 TM after the PCA transformation. As it is shown, soil and vegetation targets (i.e. healthy vegetation and crop marks) can be separated in the 2D space of PCA 1 – PCA 3, while crop marks could then be recognized from the rest of the vegetation especially in the phenophase (time-window) where the crops are photosynthesize.

•Step 3: After the PCs have been defined, the authors have identified three axes in the new 3D space of the dataset (i.e. PC1-PC2-PC3) as following: soil, vegetation and crop marks. The selection of crop marks axes was made upon the best phenophase of the crops, where from previous studies (Agapiou et al., 2013b) it was found to be the most promising period for detection of crop marks. These axes were defined as vectors in this new 3D space with a position vector at the point (0, 0, 0). Then the relative angles between these new axes and the PCs eigenvectors have been calculated.

•Step 4: The final step includes the 3D rotation of the PCA values into the new 3D orthogonal space of the new axes (soil; vegetation; crop marks). The new coefficients have been calculated after a 3D rotation of the eigenvalues based on the relatives angles calculated is Step 3. Therefore new linear coefficients (using the PCA coefficients of Table 1) have been calculated, for the different sensors as indicated for instance for Landsat 5 TM:

$$
\begin{aligned}
CC1 &= -0.04 * \rho_{\text{Band 1TM}} + 0.02 * \rho_{\text{Band 2TM}} \\
&\quad -0.04 * \rho_{\text{Band 3TM}} + 1.00 * \rho_{\text{Band 4TM}} \\
CC2 &= -0.47 * \rho_{\text{Band 1TM}} - 0.67 * \rho_{\text{Band 2TM}} \\
&\quad -0.57 * \rho_{\text{Band 3TM}} - 0.03 * \rho_{\text{Band 4TM}} \\
CC3 &= 0.19 * \rho_{\text{Band 1TM}} + 0.56 * \rho_{\text{Band 2TM}} \\
&\quad -0.81 * \rho_{\text{Band 3TM}} - 0.04 * \rho_{\text{Band 4TM}}
\end{aligned}
\tag{1}
$$

where CC1 (i.e. Crop Coefficient) corresponds to the vegetation axis; CC2 to soil and CC3 to crop mark axis. Such equations are expected to enhance crop marks, vegetation and soil pixels for each specific sensor selected. The proposed equations have been evaluated in different archaeological sites of Cyprus and Greece (i.e."*Nea Paphos*"; "*Ilis*"; "*Thesallian Plain*") with success. Further details from these applications can be found in Agapiou et al. (2013a, 2015).

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