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New ways to extract archaeological information from hyperspectral pixels

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ABSTRACT

Airborne remote sensing for archaeology is the discipline that encompasses the study of archaeological remains using data collected from an airborne platform by means of digital or film-based aerial photography, airborne laser scanning, hyperspectral imaging etc. So far, airborne hyperspectral scanning or – more accurately – airborne imaging spectroscopy (AIS) has occupied only a very small niche in the field of archaeological remote sensing: besides reasons of cost, the common archaeologically-insufficient ground-sampling distance can be considered the main limiting factor. Moreover, the technical processing of these data sets with a high level of potential redundancy needs specialized software. Typically, calculation of band ratios and a principal component analysis are applied. As a result, the few practical applications of archaeological AIS have not been entirely convincing so far. The aim of this paper is to present new approaches for analysing archaeological AIS data. The imagery under study has a ground-sampling distance of 40 cm and covers the Roman town of *Carnuntum* (Austria). Using two algorithms embedded in a specifically developed MATLAB® toolbox, it will be shown how the extracted archaeological information can be enhanced from high-resolution hyperspectral images. A comparison with simultaneously acquired vertical photographs will indicate the specific advantages of high-resolution AIS data and the gain one can obtain when exploiting its potential using any of the newly presented methods.

1. Introduction

The practice of aerial photographic reconnaissance in which the archaeologist acquires predominantly oblique images from a manned, low-flying aeroplane is still the mostly applied archaeological remote sensing approach. Although this survey approach did not witness major changes over the past century (Verhoeven, 2009), its success lies mainly in its straightforward execution, while its capacity to cover large areas turns it into one of the most cost-effective methods for site discovery. The non-invasive approach also yields easily interpretable imagery with abundant spatial detail (Palmer, 2005; Wilson, 2000). The latter characteristic should never be underestimated, as the spatial resolution of the acquired datasets, which typically is between 5 cm and 10 cm, enables the assessment of small, but often abundant features such as post holes and pits. It can, therefore, be considered one of the main reasons that this type of aerial survey is still so intensely practiced.

Oblique aerial photography does, however, exhibit shortcomings (discussed below in more detail), mainly due to its limited spectral resolving power. Therefore, a growing number of archaeologists are investigating in other aerial archaeology techniques providing images with increased spectral resolution. Although airborne multi-spectral imaging is one of these approaches (e.g. Winterbottom and Dawson, 2005), truly increased spectral resolution is only obtained by airborne hyperspectral scanning (AHS) also called airborne imaging spectroscopy (AIS) (Aqdus et al., 2007, 2008, 2012; Barnes, 2003; Bassani et al., 2009a, 2009b; Bennett et al., 2012, 2013; Cavalli et al., 2007, 2012; Cavalli, 2013; Cavalli and Pignatti, 2001; Challis et al., 2009; Coren et al., 2005;

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Emmolo et al., 2004; Forte et al., 2011; Merola, 2005; Merola et al., 2007, 2008; Pietrapertosa et al., 2008; Traviglia, 2005, 2006a, 2006b, 2008; White, 2003). The success rate in terms of detection of archaeological subsurface structures is varying, however, and less successful applications seem to be connected with the lower spatial resolution of the acquired datasets (in most cases ranging from 4 m to – at best – 1 m). Since the current generation of AIS sensors does enable the acquisition of relatively high spatial resolution data (i.e. ground-sampling distance (GSD) below 50 cm), they seem to be promising for archaeological applications.

The high spectral resolution of AIS sensors is generally not easily handled in standard image processing software. Indeed, hyperspectral scans result in huge datasets of hundred and more spectral bands, which are moreover to a high degree correlated and often affected by noise. Processing of these image cubes, i.e. reducing the data to only a few layers containing a high degree of archaeologically relevant information is therefore an important part of the AIS workflow.

In this article, we will present two new approaches that have been developed and tested on comparatively high spatial resolution hyperspectral datasets (GSD ≤50 cm). They are implemented in an open MATLAB®-based toolbox called ARTCIS (see Atzberger et al., 2014) and make use of the spectral features stored in the AIS data cube. Therefore, a basic introduction into airborne hyperspectral imaging is provided in the next section (chapter 2), before chapter 3 delves deeper into the two new processing approaches. The proposed approaches are consequently tested on a high-resolution dataset from a case-study area detailed in chapter 4. The results are analysed and discussed in chapters 5 and 6.

2. Airborne imaging spectroscopy

2.1. Limitations of conventional aerial photography

Despite its many advantages and the capability to capture small landscape details, conventional oblique and vertical aerial photography is also characterised by some major spectral shortcomings. In oblique aerial photography, the survey working principles are governed by the human visual system which is only sensitive to the visible electromagnetic spectrum between 400 and 700 nm. Additionally, the majority of the aerial footage has been acquired with photographic media that were sensitised only to this visible radiation (e.g. normal colour photography). Although very striking and revealing images have been obtained in this way, the detection of vegetation marks (and to a certain extent soil marks) becomes impossible in less-optimal circumstances, as the slight differentials of height and colour in crops might exhibit too low a contrast with the surrounding matrix to be noticed through normal (colour) photography in the visible spectrum. Even though researchers have been experimenting with different filters and film emulsions (Crawshaw, 1995) and the application of digital cameras has enabled the easy application of beyond visible imaging in the Near-InfraRed (NIR) domain (Verhoeven, 2012a), visually imperceptible soil and crop disturbances will never be photographed. As an answer to this 'observer-directed' approach (Palmer, 2005), aerial archaeologists have also used photographs generated during strictly vertical sorties (e.g. Coleman, 2007; Doneus, 1997; Kennedy, 1996; Mills, 2005; Palmer, 2007). Although even NIR coverage becomes possible with such a vertical approach, both the standard oblique and vertical photographic strategies still capture reflected solar radiation in spectrally broad wavebands: a typical colour photograph records the visible spectrum in three approximately 100 nm wide channels (Red, Green, Blue), whereas NIR radiation is usually sampled in a 300 nm wide band. This is, however, far from optimal, because particular diagnostic spectral features are often only a few nanometres wide, which makes acquisition of data with a high spectral resolution necessary when one wants to assess small variations in – for example – the plants' physiology. Vertical and oblique photography, even when executed in the spectral range beyond the visible light, thus significantly reduce the diagnostic accuracy of vegetation investigation (Hampton, 1974). In other words, they hamper the detection of archaeological vegetation marks as the reflected radiation is spectrally undersampled and spectral characteristics that are too narrow to be distinguished get masked (Verhoeven, 2009).

Spaceborne data, consistently acquired over extended areas and often in invisible wavebands, have been used in a variety of archaeological surveys (Lasaponara and Masini, 2012). They repeatedly cover large parts of the Earth's surface, are often easily available, and tackle the observer-directed and visible-radiation-limited issues. However, the data are less (or not at all) suited for the discovery and detailed recording of small archaeological features, as the resolving power of the sensors is in all but a few cases more than one meter. Moreover, the spectral bands of older spaceborne imagers (i.e. those whose products are freely available) are generally too broad or misplaced spectrally to truly detect plant stress (Carter, 1994). Airborne multi- and hyperspectral sensors might acquire data in narrow wavebands, but cost, moderate temporal resolution, and low resolving power also significantly hampered their frequent use in archaeological research (Hanson, 2008). An ideal system that joins the best of these approaches by offering the cost-effectiveness as well as operating and post-processing flexibility of the oblique reconnaissance approach, while also allowing a total coverage in narrow visible and invisible spectral wavebands, does not exist so far. However, the current generation of hyperspectral sensors does enable the acquisition of relatively high spatial resolution data (i.e. a GSD below 50 cm) and due to the increased demand in non-archaeological fields, even the acquisition costs are steadily decreasing. However, some big hurdles still need to be taken before these high-resolution AIS data can become of real archaeological interest.

2.2. AIS – what's in a name?

Airborne hyperspectral imaging is a passive remote sensing technique as it digitizes the earth's upwelling electromagnetic radiation (reflected solar radiation or thermal radiation emitted by the objects themselves) in a multitude of small spectral bands. Just as normal photographs consist of a stack of three spatially co-registered two-dimensional images of which each represents the reflected radiation in a broad visible band, the final hyperspectral data product can be considered an extended stack of narrow-band images. Each image is a digitisation of the reflected and/or emitted radiation in a small spectral range (typically around 10 nm in the visible and NIR range). Commonly an airborne hyperspectral flight yields tens to hundreds of these narrowband images, which are captured in spectrally contiguous bands. The final product can therefore be considered a three-dimensional data cube (x, y, λ) in which the first two dimensions are the spatial dimensions, whereas the third dimension reflects the spectral dimension (Fig. 1). Thus many small bands of electromagnetic radiant energy are captured per pixel location. Just as a pixel of a common digital colour photograph contains three samples or Digital Numbers (DNs) at the same location to represent the amount of radiation captured in the three broad spectral bands, a hyperspectral image features N DNs, in which N equals the amount of spectral bands that are sampled. Every image is also characterised by a certain bit depth (e.g. integer 10-bit or values between 0 and 1023), which determines the resolution by which the at-sensor radiance L can be mapped onto a discrete set of digital values. From these DNs, reflectance (or emission) can be calculated. Through a combination of all these many