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Near-Infrared Aerial Crop Mark Archaeology: From its Historical Use to Current Digital Implementations

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Abstract Even though most archaeologists are aware of the crop mark phenomenon and its possible archaeological nature, the information on its occurrence and specific character is, in most cases, obtained by imaging in the visible spectrum. After the Second World War, the occasional use of near-infrared (NIR) sensitive emulsions attributed this kind of invisible imaging with a great potential. However, archaeological NIR imaging always remained restricted due to several reasons not, at least, its complicated workflow and uncertain results. This article wants to delve deeper into the subject, looking at the conventional film-based approach of NIR aerial reconnaissance and its historical use in archaeological crop mark research, after which a current straightforward digital approach will be outlined. By explaining the spectral properties of plants and using examples of recently acquired NIR imagery in comparison with visible frames, it should become clear why the detection and interpretation of crop marks can benefit from low-cost digital NIR imaging in certain situations.

Keywords Aerial archaeology · Crop mark · Digital photography · Near-infrared photography · Spectral response · Vegetation stress

Introduction

It is generally known to most archaeologists that subsurface archaeological remains can reveal themselves as crop/plant marks, soil and shadow marks as well as less

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common snow, water or wind marks (Wilson 1982). Although these marks are usually discovered and recorded with small- or medium-format hand-held photo cameras sensitive to visible light, some aerial archaeologists have been taking near-infrared (NIR) sensitised media in their low-flying airplane to capture such archaeological signs utilizing this less conventional invisible waveband. Notwithstanding the response was often reported to be good—particularly for crop marks—the use of such beyond-visible techniques has never reached high peaks in archaeological reconnaissance. Before tackling this issue and looking at the historical and current use of the NIR spectrum, there is certainly the "need for a fuller understanding of the formation processes for cropmarks" (Shell 2002: 181), in order to sensibly evaluate these (pre)historically related vegetation patterns and understand why archaeology should be concerned with acquiring aerial NIR data in the first place. Therefore, both the physical characteristics and corresponding spectral properties of healthy and stressed vegetation need to be understood on both leaf and canopy level because the successful archaeological application, visualisation and interpretation of optical remotely sensed vegetation data (more in particular visible and NIR information) is fundamentally based on this understanding.

Crop Marks and Related Plant Reflectance

Buried features can often be identified because they cause some anomalous growth in the plants that overlie them. Subsurface archaeological remains such as pits or trenches will often be filled with organic material and/or new soil, having a greater moisture retention and more nutrients than the surrounding matrix. In periods of drought, these humous soils have a positive, favourable effect on the crops, allowing the plants to grow more luxuriantly and for an extended period of time. These resulting vegetation patterns are commonly called positive crop marks. In unfavourable situations (*e.g.* plants growing over buried stone walls or floors), weaker and shorter plants might occur, in which case, negative crop marks are yielded (Allen 1984; Evans 2007; Riley 1980; Wilson 1982). These plants' divergent physiology and morphology—positive or negative—often allow them to be distinguished in the visible and/or NIR domain. Both visible and NIR radiation are small parts of the so-called electromagnetic (EM) spectrum radiated by the sun and other sources. This EM spectrum is a very large continuum of varying waves, the latter characterised by a certain wavelength (λ) (Slater and Frank 1974). Visible light is characterised by wavelengths between circa 400 and 750 nm, hence covering only a very small part of the complete EM range. The radiation with slightly longer wavelengths is part of the NIR waveband (between 750 and 1,400 nm), comprising the first, short wavelength part of the broad IR spectrum (750 nm to 1 mm). It remains important to note that NIR has nothing to do with heat imaging, which uses completely different portions of the IR waveband (more in particular, the mid wavelength infrared from 3 to 6 μm and long wavelength infrared from 6 to 15 μm).

From the moment visible or NIR energy encounters a healthy green leaf, this radiation can be absorbed, reflected or transmitted, but only the reflected wavelengths will be used to create the aerial image. In the visible range of wavelengths, the photosynthetic pigments chlorophyll *a* and *b*, both residing in the chloroplasts of mainly the long *palisade parenchyma* mesophyll cells of all green plants (Fig. 1), absorb the incident radiation to a great extent (Gitelson *et al.* 2003; Hendry *et al.* 1987; Lichtenthaler 1987). By complementing each other, as much as 70% to 90% of the incident light might be absorbed, principally in the blue (centred on 450 nm) and red (around 670 nm) spectral regions (Knipling 1970; Rabideau *et al.* 1946; Woolley 1971). The slightly decreased absorptivity of chlorophyll in the 500 to 600 nm zone makes the human visual system perceive healthy leaves as green.

This behaviour changes completely in the NIR spectral band, where absorption by pigments is extremely low (Chappelle *et al.* 1992) and the leaf's internal cellular structure (more in particular the structure of the *spongy* parenchyma mesophyll which features a lot of intercellular air space (Fig. 1)) affects a very high and diffuse reflectance in the NIR spectrum (Gausman 1974; Gausman *et al.* 1969; Myers *et al.* 1970; Peterson and Running 1989; Slaton *et al.* 2001; Woolley 1971). As soon as NIR radiation—to which the upper leaf layers are largely transparent—reaches the spongy mesophyll tissue, heavy scattering takes place at the numerous air–water–cell wall interfaces, due to the differences in refractive index (Gates 1970; Gausman 1974; Knipling 1970; Slaton *et al.* 2001; Zwiggelaar 1998). Quantitatively, NIR reflectance attains values of about 40% to 60% in a healthy leaf. As only about 5% to 10% of this incident energy is absorbed internally (to counteract possible plant damage—Gates 1970; Gates *et al.* 1965), individual leaves still actively transmit

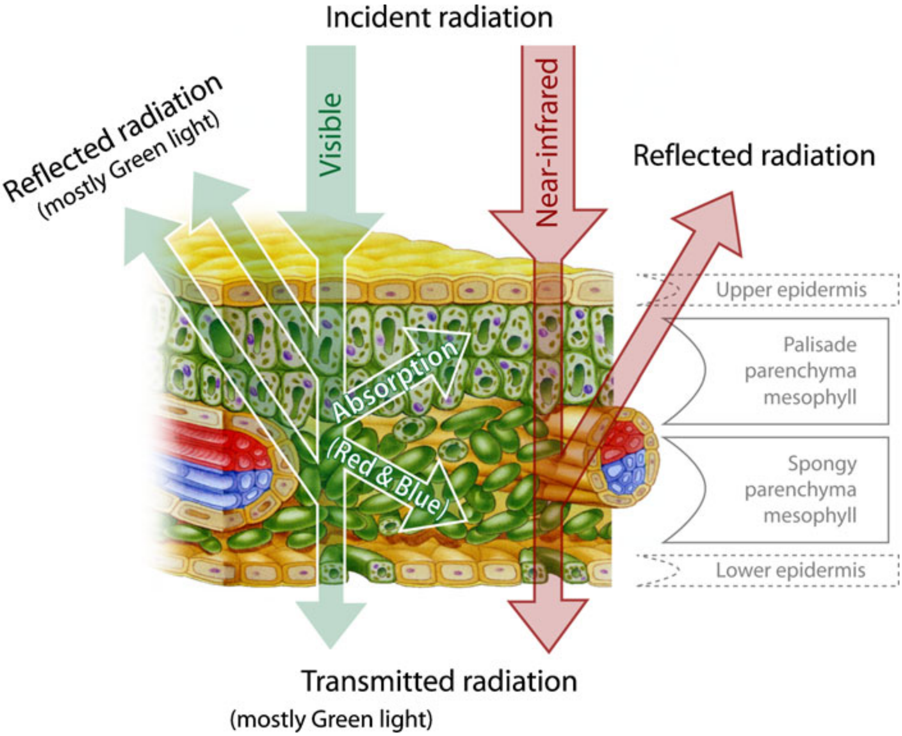


Fig. 1 Structure of a plant leaf and its interaction with incident visible and NIR radiation (adapted from Solomon *et al.* 2005, Fig. 32–3 and Summy *et al.* 2003, Fig. 2)

NIR to the underlying leaves and ground. This spectral behaviour is visualised in Fig. 2. From this graph, it is obvious that healthy vegetation typically reflects low in the blue band (circa 400 to 500 nm), more in the green band (circa 500 to 600 nm), again less in the red (circa 600 to 700 nm), after which it becomes very bright in the NIR. The very steep increase in the reflectance of radiant energy at the edge of the visible spectrum and the beginning of the NIR spectrum (between 700 and 750 nm), is the so-called red edge (Horler *et al.* 1983). It is the most prominent characteristic in the reflectance spectrum of healthy vegetation and one of the most extreme slopes to be found in reflectance spectra of natural materials (Clark *et al.* 1995). Notwithstanding, various crops will display slightly different reflectance curves due to their dissimilar cell structure and leaf inclination (Gitelson *et al.* 2002), these spectral features are typical of all mature and healthy green leaves (Carter and Knapp 2001; Goillot 1980; Woolley 1971).

From a quantitative point of view, reflectance from the canopy might be seriously modified from that of an individual leaf, due to reflectance from non-green canopy components, the anisotropic behaviour of the canopy, the spectral properties of shadows and the variations in soil background reflectance, together determining the overall canopy reflectance (Broge and Mortensen 2002; Colwell 1974; Curran 1980, 1983; Guyot 1990; Myneni *et al.* 1995; Peñuelas and Filella 1998). Canopies with a high biomass or leaf area per unit of ground (called leaf area index or LAI) can be characterised by a large increase in NIR reflectance due to the process of leaf additive reflectance. However, the latter process levels off when the vegetation fraction (VF) exceeds 60%, while a further VF increase can even generate a decrease of NIR canopy reflectance—a process which can be attributed to several reasons and generally occurs at or near the midseason (Gitelson *et al.* 2002). The spectral contribution of the soil can, however, be negligible in cases where the canopy

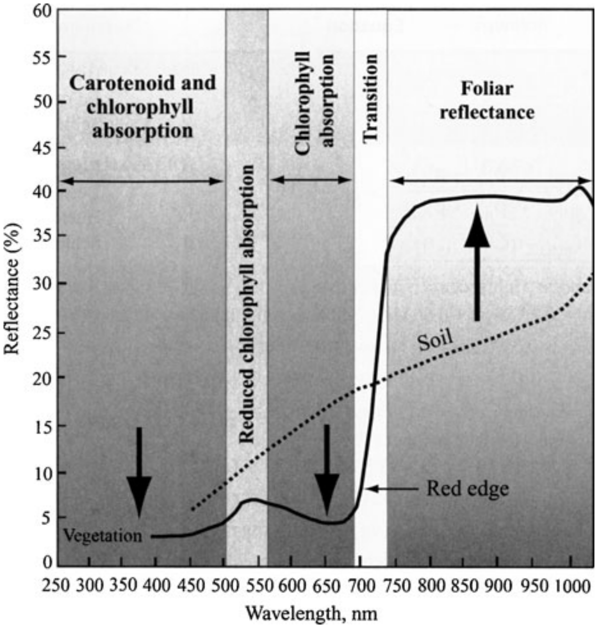


Fig. 2 Spectral reflectance characteristics of healthy green vegetation (after Jensen 2007, Fig. 11–21a)

features a large number of healthy, mature leaf layers (Curran 1980; Guyot 1990; Jensen 2007; Myers *et al.* 1970). These phenomena clearly show that individual, leaf-based reflectance spectra are not directly (and as a whole) transferable to the canopy level, although the best correlation generally is found within the NIR region (Asner 1998; Baret *et al.* 1994), with the strength of this expression being related to LAI and leaf angle (Asner 1998).

At a certain stage in its growth, the spectral properties of chlorophyllian vegetation change considerably due to senescence or stress, where stress is considered any (a)biotic factor affecting or blocking the growth, development or metabolism of the plant (Lichtenthaler, 1998), a process attributed to a whole variety of anthropogenic and natural stressors. In such cases, the chlorophyll pigment rapidly decays (Carter 1993; Carter *et al.* 1995; Hendry *et al.* 1987; Knipling 1970; Merzlyak and Gitelson 1995; Peñuelas and Filella 1998), additionally losing its absorption properties (Carter 2001). This results in an increased reflectance in the visible region, particularly in the red chlorophyll absorption band, as the other pigments do not absorb strongly there (Merzlyak and Gitelson 1995; Young and Britton 1990). Moreover, chlorosis—a yellowing discoloration of the leaf due to the lost chlorophyll dominance over the carotenoids (Adams *et al.* 1999; Hendry *et al.* 1987)—often occurs. In aerial archaeology, this changing spectral quality of the reflected light has always been used as a plant stress indicator. Hence, it is the stress-induced loss of chlorophyll that gives crop marks their altered colour, although the exact physical vegetation properties still depend on the type and amount of environmental stress as well as plant species and soil. Nevertheless, some archaeologists reported a clear relation between a crop mark's first occurrence and the water content in the topsoil, soil moisture deficit being the chief cause of vegetation's diminished growth vigour (Crawford and Keiller 1928; Evans and Jones 1977; Jones 1979; Jones and Evans 1975; Webster and Hobley 1964) besides factors as vegetation type, soil depth and type of soil (Evans and Jones 1977; Jones 1979; Jones and Evans 1975; Scollar 1964).

In the NIR beyond 750 nm, the reflectance values are not related to concentrations of wavelength-dependent absorbing pigments, but might change because senescence as well as biotic (pests, weeds, disease, fungi) and abiotic constraints (drought, floods, high light intensity, chilling, mineral deficiency, ozone) alter the internal structure of the foliage and/or the water content (Carter 1991; Estep *et al.* 2005; Hatfield *et al.* 2008; Jackson 1986; Maas and Dunlap 1989; Sinclair *et al.* 1973; Slaton *et al.* 2001). This means that any spectral change becoming apparent might give clues to the plant's stress condition and/or senescence. Very often, healthy green leaves respond to short-term, acute (a)biotic stressors with increased NIR reflectance. This certainly holds when plants suffer from dehydration (Bowman 1989; Carter 1991, Carter 1993; Guyot 1990; Hunt and Rock 1989; Schepers *et al.* 1996; Woolley 1971) due to a decreased water absorption of NIR radiation and internal structural leaf changes; the increased intercellular air space originating from the dehydration induced collapse of mesophyll cells, generates larger quantities of air, water, and leaf material interfaces. As the cell wall–water interface has a lower angle of refraction than the air–cell wall and air–water interfaces, an increase in multiple reflections inside the leaf is observed (Aldakheel and Danson 1997; Carter 1991; Carter and McCain 1993; Estep *et al.* 2005; Foley *et al.* 2006;

Schepers *et al.* 1996). In these early stages of stress, the NIR reflectance gradually changes, while the alteration in the visible region happens abruptly, but only at the time wilting is observed (Foley *et al.* 2006). Hence, previsual symptoms might be observed by monitoring the NIR reflectance (Carter and Estep 2002). In some older research, stress damage was indeed reported to be discernable in these invisible wavelengths prior to any pigment-related visible clues (Agache 1968; Blakeman 1990; Colwell *et al.* 1970; Donoghue and Shennan 1988b; Heller 1970). However, these results often remain questionable as it is unlikely that such small alterations in the NIR reflectance could be sufficiently captured by the NIR-sensitive films (which are confirmed by several researchers who concluded that NIR imaging is not able to record previsible stress symptoms, *e.g.* Totterdell and Rains 1973).

The positive NIR results are most likely obtained where water shortage is chronic and a complete vegetation canopy is considered, as these conditions make NIR reflectance drop significantly in the photographic NIR region (Heller 1970; Lelong *et al.* 1998; Moran *et al.* 1989; Shakir Hanna and Girmay-Gwahid 1998, 1999) (see Fig. 3), partially related to lower LAI (Carter and Estep 2002; Lelong *et al.* 1998).

Similar decreases in NIR reflectance spectra of plant canopies are to be found in diseased, senescent and/or heavily nutrient-deficient vegetation (Carter and Estep 2002; Curran 1985; Krinov 1971; Murtha 1978; Peñuelas *et al.* 1994; Tahahoto *et al.* 1991; Wiegand *et al.* 1972), corresponding to a combined effect of internal tissue changes in single leaves, the general canopy geometry and the additional low soil reflectance due to a decreased LAI (Baret and Jacquemoud 1994; Carter and Estep 2002; Curran 1985; Girard and Girard 2003; Guyot 1990). Very often, these very large NIR decreases can reveal the plants' state of vigour (Colwell *et al.* 1970; Jensen 2007; Wells and Holz 1985), with an absolute change in the NIR reflectance that is far more noticeable with respect to the visible band (Fig. 3). Considering this, one can imagine that at a certain point, NIR wavelengths make it easier to discern negative crop marks, areas where plants are severely exposed to moisture shortage and/or nutrient deficiency. Conversely, growing plants will reflect more NIR radiant flux, which means that also positive crop marks—due to a large vegetation biomass (Koch *et al.* 1990)—might be distinguished in these invisible wavelengths.

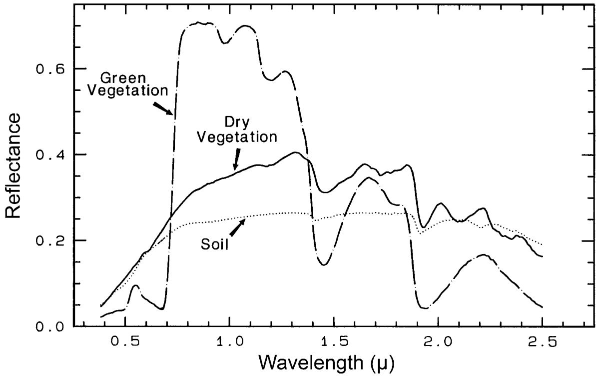


Fig. 3 Reflectance spectra of photosynthetic (*green*) vegetation, non-photosynthetic (*dry*) vegetation and a soil (after Clark 1999, Fig. 1.18)

Conventional NIR Aerial Archaeology

Research and Applications

Since its origin more than a hundred years ago, archaeological aerial reconnaissance has been imaging all kinds of marks almost exclusively in the visible part of the EM spectrum, using true colour or panchromatic photography. Although this visually based data acquisition approach might be justifiable for most types of archaeologically related anomalies, acquiring non-visible NIR wavelengths could sometimes be a better choice for revealing the vigour of crops. This idea is certainly supported by older, mostly non-archaeological literature (*e.g.* Colwell *et al.* 1970; Murtha 1978). On the other hand, more recent research claims the leaf reflectance response to acute plant stress in the visible spectrum to be more consistent (Carter 1993, 1994; Carter and Estep 2002; Carter and Knapp 2001; Carter and Young 1993). Nevertheless, the aforementioned physiological and morphological state-related spectral differences in the NIR canopy reflectance clearly indicate that archaeological NIR photography might, in some occasions, be very fruitful in detecting and monitoring negative and positive crop marks (although it will be hardly possible to correlate changed NIR reflectance to a particular stressor, a problem also characteristic for visual imaging—Carter 1993, 2001; Chapin 1991; Murtha 1978).

Besides, NIR photography can also be an important archaeological tool because of its haze penetrating capacity (Dorrell 1994; Rinker 1975). As aerial archaeology largely concerns high and low oblique photographs, parts of the image can become obscured due to severe atmospheric scattering in the visible region. NIR photography offers a solution here, yielding imagery with a high contrast ratio and enhanced clarity of detail (Rawling 1946), allowing the application of aerial photography even on early, hazy mornings (Scollar *et al.* 1990). Albeit this large potential in aerial reconnaissance, very little and mostly unsystematic effort has been made to incorporate NIR radiation in archaeological aerial frames, even though NIR photography by means of black and white and false-colour infrared (FCIR or more commonly CIR) film proved, in a lot of different areas, its capability to detect archaeological traces.

John Hampton, the director of the Air Photographs Unit of the Royal Commission on the Historic Monuments of England from 1965 to 1985, stated in the 1970s that normal film emulsions and filter combinations can often hardly detect the very small colour and/or height differences in crops (Hampton 1974). At early stages of cereal growth and late in the season, he found a Kodak Ektachrome CIR film to be very useful in the detection of crop marks (Hampton 1974). Besides hypothesising about its advantages (Conlon 1973; Hammond 1963), other archaeologists also empirically noted the—sometimes striking—advantage of NIR imaging (whether using pure NIR or conventional CIR photography, airborne multispectral approaches or satellite imagery) can have on the detection of archaeological (crop) sites (Agache 1968; Aqdus *et al.* 2007; Backe Forsberg *et al.* 2008; Bassani *et al.* 2008; Braasch 2007; Bradford 1957; Cameron 1958; Donoghue and Shennan 1988a, b; Edeine 1956; Fowler 1995, 1996; Fowler and Fowler 2005; Goguey 1977; Gumerman and Neely 1972; Jalmain 1970; Lasaponara and Masini 2006a, b, 2007; Lyons and Avery 1977; Petit 1977; Powlesland 2001, 2006; Powlesland *et al.* 1997; Rigaud and Hersé 1986;

Shell 2002; Shennan and Donoghue 1992; Strandberg 1967; Tartaglia 1977)—although the objectiveness of some observations needs to be questioned, as a systematic and rigorous assessment of the true archaeological potential was mostly impossible due to the lack of simultaneously acquired normal colour photographs and reconnaissance in dissimilar conditions. Nevertheless, these researchers indicated the potential field crop monitoring through the acquisition of reflected NIR radiation. Consequently, it might seem strange that the archaeological potential of pure or false-colour NIR photography was never more widely explored and generally practised. However, several possible explanations can be identified.

Drawbacks

Although some lack of knowledge about the subject certainly played an important part, the fact that some scholars—of whom the majority happened to have captured comparative frames in the visible spectrum—stressed that CIR imaging is not all revealing (Crawshaw 1995; Due Trier *et al.* 2008; Gumerman and Neely 1972; Hampton 1974; Harp 1968; Itek Data Corporation 1965; Matheny 1962; Strandberg 1967) most likely made the extremely error-prone film-based NIR workflow too much of an obstacle to be applied more often; both reversal and transparency film needed to be stored cooled and developed by specialised labs directly after exposing them (Eastman Kodak 2004, 2005); moreover, determining the right exposure was not as straightforward as with conventional photography (Buettner-Janusch 1954), and any inconsistency in emulsion or film development yielded different results (Benton *et al.* 1976). Being sensitive to about 900 nm, NIR-sensitive film also had a narrow exposure latitude and a rather small dynamic range (Gibson 1978), whereas its relatively weak sensitivity made it unusable with poor lighting conditions (Blakeman 1990; Bobbe 1997; Brooner and Simonett 1971; Hampton 1974). Finally, the spectral fidelity of CIR film was rather low, as the NIR-sensitive band also took large portions of the visible spectrum into account (see *infra*). Luckily, the digital (r) evolution of photography supplied new tools and methods to deal with most of these issues.

Digital NIR Archaeological Reconnaissance

Camera Modification

Since the early twenty-first century, archaeology has been witnessing an ever increasing role of and significant interest for airborne digital photography (Doneus 2005; Driver 2004), as do other disciplines (Petrie 2003). The advantages are clear: taking more photographs at a lower cost, without the need of loading and unloading film and scanning the resulting negatives/positives; the storage and retrieval is much easier and the resolving power of current digital still cameras (DSCs) is equal or even surpassing the 135 (or 35 mm) format. Besides, such a camera or DSC—to be defined as a camera equipped with both a digital image sensor for capturing photographs and a storage device for saving the obtained image signals in a digital way (Toyoda 2006)—offers another big advantage: its digital imaging sensor is essentially made of silicon (Si, atomic number 14) and very sensitive to NIR wavelengths to about 1,100 nm (Eastman Kodak Company 1999; Nakamura 2006; van de Wiele 1976). To cut out the image-degrading effect of this invisible radiation and only allow visible light to create the digital photograph, camera manufacturers place an NIR-blocking/cutoff/cut filter (also called hot mirror) in front of the sensor, which absorbs and/or reflects most NIR waves that pass the lens (Busch 2007; Koyoma 2006; Ray 2002). Replacing this filter with an optical element that completely blocks all visible radiation, makes the DSC only responsive to incoming NIR wavelengths (for a technical outline of digital imaging sensors and a detailed overview of this DSC modification, the reader should consult Verhoeven 2008). The resulting spectral response of such a modified DSC is given in Fig. 4a, showing a DSC's sensitivity to NIR. Moreover, such a modification still allows viewing through the lens, something that was impossible in the film-based approach of pure NIR imaging (because of the opaque filter mounted in front of the lens). Besides the sensitivity to NIR wavelengths, Fig. 4a illustrates the channel-specific spectral response due to the construction of the complete imaging array. The latter comprises also a colour filter array (CFA) between the sensor and the block filter. This mosaic pattern of coloured filters (Fig. 4b) is the most widespread method to give colour sensitivity to image sensors. Every individual photodiode (*i.e.* a very small radiation-sensitive area of the sensor which creates one pixel of the final digital image) is covered by a specific coloured filter, allowing only one particular range of EM radiation to be collected. Besides transmitting the red, green and blue visible waveband, all three red, green and blue filters are clearly characterised by a specific NIR transmittance, generating a waveband-specific charge in the photodiode.

Benefits

Using NIR-modified DSCs deals with most of the aforementioned film issues, while the inherent properties of digital imaging as well as modification-specific characteristics offer additional benefits. First of all, a DSC's linear response to incoming

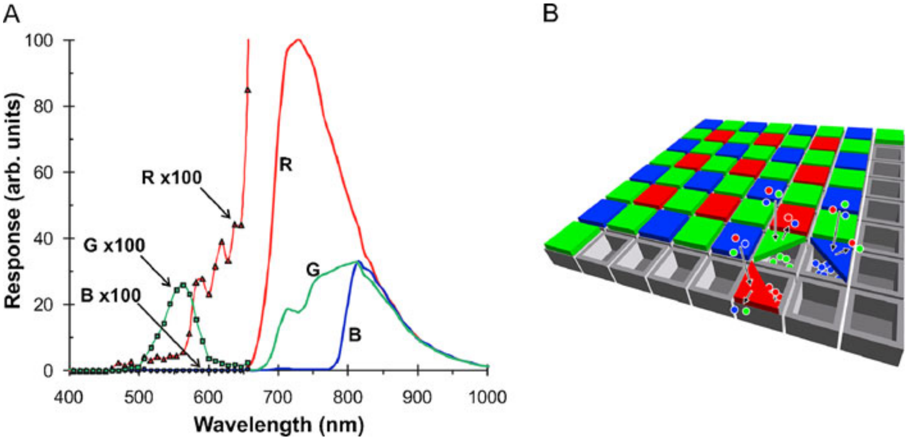


Fig. 4 **a** Relative response *versus* wavelength of the Nikon D50$_{\mathrm{NIR}}$ with Nikkor 20mm f/3.5 AI-S (Verhoeven *et al.* 2009b); **b** The layout and principal of a Bayer CFA (Verhoeven 2008, Fig. 7)

radiant intensity, its larger dynamic range as well as the direct feedback about accurate exposure and focusing, mean that more consistent results can be generated when compared to a film-based solution. Secondly, the substantial NIR sensitivity allows their use in far from optimal operational conditions, while the possibility to embed geographic coordinates into the photograph's metadata header should also not be underestimated.

Furthermore, the fact that all three spectral channels are created by taking the reflected EM radiation of a very specific waveband into account, allows for very useful arithmetic channel operations (see *infra*). Finally, DSCs are very suited for mapping purposes, as they do not suffer from geometric film distortions (King *et al.* 1994, 1997). Despite these advantages, the use of NIR-modified DSCs was never fully explored in aerial archaeology.

NIR Aerial Crop Mark Archaeology: Applications and Examples

To indicate some possible situations where NIR imaging might be very fruitful, some real-world examples are presented. The imagery shown was generated in the framework of the Potenza Valley Survey, a geo-archaeological research project conducted by the Archaeology and Geography Departments of Ghent University (Belgium) in the Regione Marche, one of the contemporary Italian regions situated on the central Adriatic part of the country. To study the urban and rural occupation patterns in the Potenza river valley through (pre)history, aerial archaeology has been playing a very substantial role from the very beginning of the project (Verhoeven and De Vliegher 2004; Verhoeven and Vermeulen 2004; Vermeulen 2002a, b, 2004; Vermeulen and Boullart 2001; Vermeulen and Verhoeven 2004, 2006; Vermeulen *et al.* 2002; 2005) even though the possible flying time has always been limited due to the practical reason of working abroad. Till now, several flights have been performed in which perfect simultaneous visible and NIR image acquisition was made possible by the use of a two-DSC rig. Almost all reconnaissance flights were performed around noon, previously being revealed as the optimum period for NIR photography (Tartaglia 1977). Besides, NIR imagery has been generated from a radio controlled low-altitude aerial platform based on a Helikite (a combination of a helium balloon with kite wings), allowing for very targeted and large-scale (1/500 to 1/5,000) aerial imaging (Verhoeven and Loenders 2006; Verhoeven *et al.* 2009a). Because the platform currently allows only one DSC to be mounted, the imagery generated by this apparatus will not be used in the following comparison.

For reasons explained previously (Verhoeven 2007), most of the presented NIR imagery was captured by a modified Nikon D50, a digital single-lens reflex camera that is hereafter called 'D50_{NIR}', and whose spectral characterisation (Fig. 4a) was described by Verhoeven *et al.* (2009b). Since 2008, a modified Nikon D80 has been taken aloft (D80_{NIR}), as it generates digital frames with a higher pixel count and accepts larger memory cards.

Before getting airborne, an AF Nikkor 50mm f/1.8D lens, of which the focus was fixed on infinity, is mounted on both the normal as well as NIR-enabled DSC. Afterwards, the white balance of the modified DSC is user-defined by pointing it to a patch of green grass. This operation normalises the dissimilar NIR response of the three channels (Verhoeven 2010), as the highly NIR-reflective grass can be considered an NIR-neutral target. To make sure only pure NIR imagery was used for the following comparison, the blue channels were extracted from both the $D50_{NIR}$ and $D80_{NIR}$ imagery, as the red and green channels still take small portions of the red edge region into account (see Fig. 4a and Verhoeven *et al.* 2009b)—although it needs to be stressed that in normal, daily working practice, the complete RGB image is used because the output is almost identical.

All conventional visible colour photographs were generated by a Nikon D200 or Canon EOS 300D. To compare the two data sets by objective means, both the visible and pure NIR frames were subjected to histogram stretching to optimise the images' global contrast.

Pure NIR Channel

Figure 5—acquired above the central Potenza valley—gives an overview of a visible frame's (Fig. 5a) altered appearance in the NIR (Fig. 5b) and illustrates the typical behaviour of ground features. As healthy, green vegetation (1) reflects huge amounts of NIR, it appears very bright in Fig. 5b, while soils (2) generally reflect much lower amounts of NIR (cf. Fig. 3). Consequently, they are rendered much darker. When both are combined ((3), *i.e.* a soil with a scarce vegetation cover) an intermediate greyscale value results. Water (4), on the other hand, always appears blackish on an NIR photograph due to its very high absorption of these invisible wavelengths (Curcio and Petty 1951). The potential of NIR to discriminate between plants on the basis of their species and/or health status is revealed by the trees (5) at the bottom of the frame, showing a much larger variation in brightness compared to the visible record. Contrary to the visible record where stress is visualised by an increase in brightness (*e.g.* yellow crop marks), NIR vegetation stress patterns will be darker compared to the surrounding non-stressed plants. Finally, the increased clarity of detail in distant scenes is also visible to a certain extent. Due to the longer wavelengths, atmospheric scattering is much less in the NIR region than it is in the visible part, allowing NIR radiation to largely penetrate haze (Conlon 1973; Ross 1933), yielding imagery with a larger contrast (Rawling 1946).

Fig. 5 General comparison between the appearance of common ground features in the visible domain (**a**) and NIR spectrum (**b**): (*1*) healthy green vegetation, (*2*) soil, (*3*) low density canopy, (*4*) water, (*5*) trees and (*6*) distant objects. Images acquired in the middle Potenza valley (N 43°18′02″, E 13°16′12″—WGS84) with a Nikon D200 (**a**) and Nikon $D50_{NIR}$ (**b**) on May 15, 2008 at 11.40 h

When focusing more in detail on crop marks, several observations can be made. Figure 6, depicting the central part of the Roman coastal colony *Potentia* and acquired in the middle of May, clearly confirms what was already remarked by Everitt *et al.* (1997): Chlorotic vegetation is very difficult to distinguish in the NIR (compare visible Fig. 6a with NIR Fig. 6b). At moments this stress-related loss of chlorophyll pigment is rather moderate, the yellow discoloration of vegetation is not extremely pronounced, but the alteration of the NIR reflectance curve can even be smaller. Hence, the very common negative crop marks are often better discernable in the visible domain, an observation also made by Hampton (1974). Pushing the local contrast in both frames (Fig. 6a, b) to the limits (Fig. 6c, d) does not alter this observation: even though the resulting tonal differences clearly prove the spectral NIR responses of chlorotic and healthy green vegetation to be dissimilar (Fig. 6d), the amount of features perceptible as well as the distinctness of the archaeological traces still remain superior in the visible spectrum (Fig. 6c).

On the other hand, pure NIR channels can clearly reveal the more severe drought and nutrient stress in the canopy reflectance (Dungan *et al.* 1996). Imagery taken during the hot summer of 2008, again above the Roman city of *Potentia*, clearly illustrates this physical fact. In the cereal field on the right side of Fig. 7a, little pieces of the street network in the southern part of the city are visible. The NIR record (Fig. 7b), however, allows much more traces to be seen, whereas the features

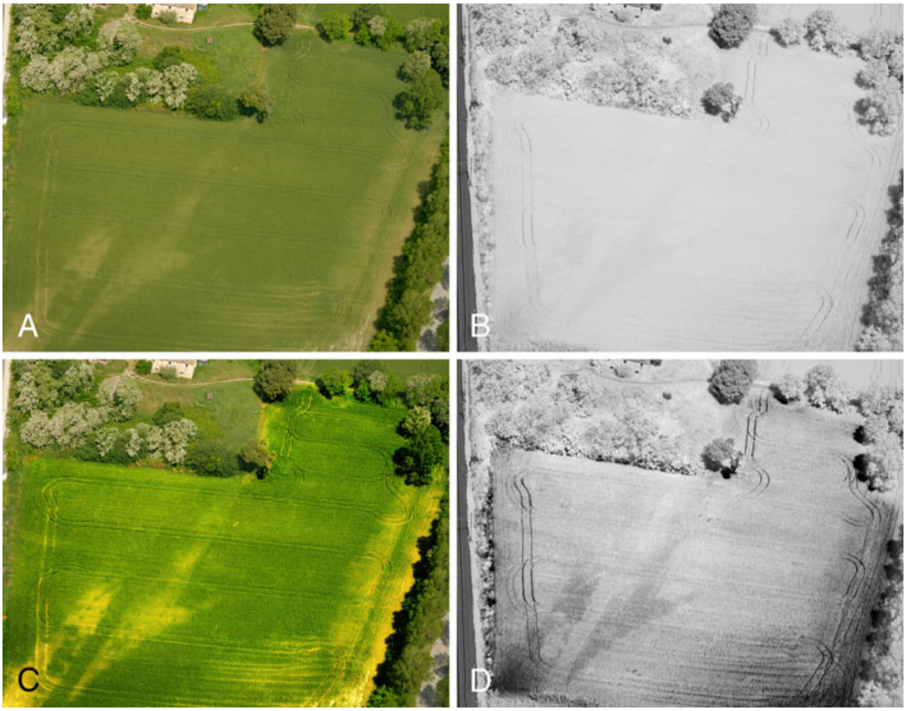
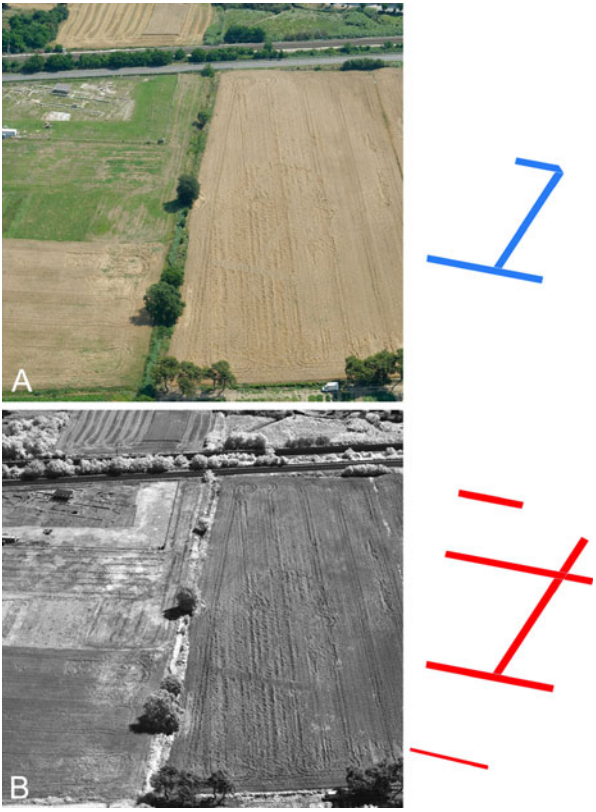


Fig. 6 **a** Visible image of the central part of the Roman town of *Potentia* (N 43°24′53″, E 13°40′14″—WGS84); **b** NIR image of the same scene. To obtain versions **c** and **d**, very extreme local contrast enhancement was applied to **a** and **b**, respectively. Images acquired with a Nikon D200 (**a**) and a Nikon D50$_{\mathrm{NIR}}$ (**b**) on May 15, 2008 at 11.14 h

are also more distinct when compared to the visible record. Because it is ripe, the overall visible reflectance response of the grain is higher and the human visual system perceives these crops as yellow-brown. Therefore, the reflectance increase of grain growing over a rocky subsurface can only be slightly larger in comparison with the adjacent crops. In the NIR, the global reflectance decreases significantly at this stage of the crop cycle, but the image in Fig. 6b proves the total reduction of NIR reflectance to be noticeably larger for the extremely stressed plants. After additional contrast enhancement had been performed, the traces of the street network that could be mapped were indicated on the right of Fig. 7a, b. These results nicely confirm the previous statements of Hampton (1974), who also empirically attested NIR imaging to be superior for cereal crop mark imaging late in the season.

Besides pigment variations, smaller plants and a less dense vegetation canopy can also be possible responses to subsoil variations. Figure 8 presents a last example of negative crop marks, showing that these particular canopy situations with a low LAI can benefit from an NIR approach as well. It is evident that both the visible and NIR image of the vegetation canopy reveal hidden ancient hydrographic features, although the most distinct result is yielded by the invisible wavelengths: the low biomass density and related high contribution of low background reflectance produce very explicit, dark traces in the field (*e.g.* the traces on the left and upper right part of the field).

Fig. 7 **a** Visible image of the southern part of *Potentia*, while **b** displays the same view in the NIR. Imagery was acquired with a Nikon D200 (**a**) and a Nikon D80$_{\mathrm{NIR}}$ (**b**) on July 03, 2008 at 11.02 h



In addition to these negative crop marks, positive crop marks might also be distinguished in the NIR, as these features are characterised by a larger vegetation biomass and, as a consequence, will reflect more NIR-radiant energy. This principle is illustrated in Fig. 9, showing a positive, non-archaeological crop mark in the centre of the Roman town of *Ricina*. The higher and denser number of plants is perceived in the visible domain as two squares, slightly darker green patches (1 and 2 in Fig. 9a). In the NIR (Fig. 9b), the same squares are brighter, as the larger quantity of plant tissue affects a higher reflectance. When comparing both frames against each other, the magnitude of reflectance dissimilarity is largely equal. Increasing the local contrast to a much larger extent clearly shows the greyscale NIR frame (Fig. 9d) to have the advantage over the normal colour image (Fig. 9c).

Although the above examples clearly indicate the spectral response in the NIR to be unrelated to chlorophyll pigment concentration, the most striking example is given in Fig. 10, which presents two different photographs of the central part of the Roman town *Trea*. Figure 10a again depicts the visible bands, together with the D50$_{\mathrm{NIR}}$-image (Fig. 10b) captured in the middle of April, 2007. Whereas the visible image only shows strange, non-archaeological positive vegetation marks (maybe due to differential manuring or a dissimilar kind of crop), the NIR image—being insensitive for these pigment variations—clearly reveals the outlines of a Roman temple.

Besides the masking effect of the chlorophyll pigment in the darker vegetation zones, this striking difference might even be attributed to the anisotropic behaviour

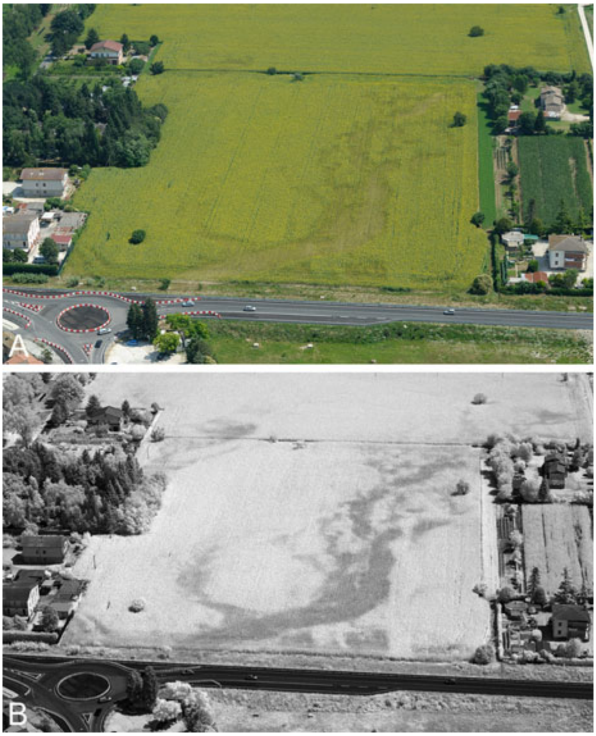


Fig. 8 Hydrographic features revealed by negative crop marks in the visible (**a**) and NIR (**b**) part of the spectrum. Imagery was acquired in the central part of the Potenza Valley (N 43°19′22″, E 13°25′26″—WGS84) with a Nikon D200 (**a**) and a Nikon D80$_{\mathrm{NIR}}$ (**b**) on July 03, 2008 at 11.23 h

Fig. 9 **a** Visible image of the central part of the Roman town of *Ricina* (N 43°19′41″, E 13°25′26″—WGS84); **b** NIR image of the same scene. To obtain versions **c** and **d**, very extreme local contrast enhancement was applied to **a** and **b**, respectively. Images acquired with a Nikon D200 (**a**) and a Nikon $D50_{NIR}$ (**b**) on May 15, 2008 at 11.27 h

of the vegetation canopy. Being a non-Lambertian surface, the reflectance of the vegetation canopy is not equal in all directions, but dependent upon the sun and sensor zenith/off-nadir and azimuth angle (Kimes 1983). As the canopy reflectance and its anisotropy will generally be higher when the sensor records back-scattered energy (Sandmeier and Itten 1999), the backward scattering component of the incident visible wavelengths—which is imaged in this situation—might be

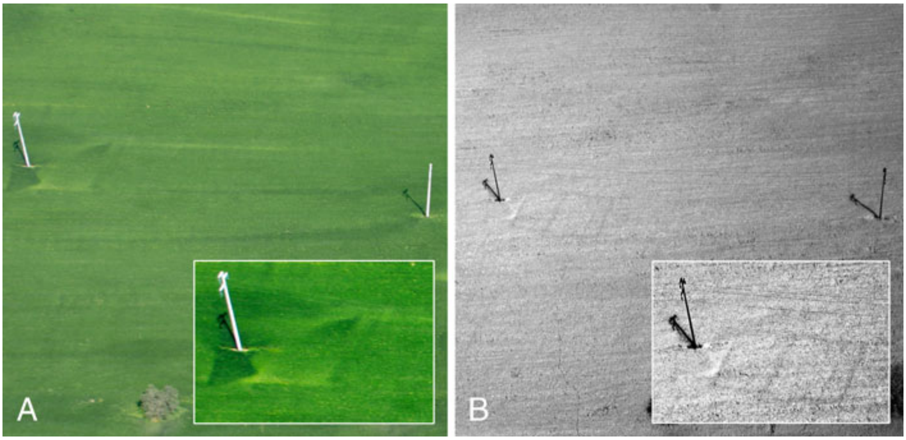


Fig. 10 A visible (**a**) and pure NIR image (**b**) of Roman *Trea*'s central part (N 43°18′40″, E 13°18′42″—WGS84). The *insets* are high-contrast enlargements of the same area around the left pylon. Images acquired with a Canon EOS 300D (**a**) and a Nikon $D50_{NIR}$ (**b**) on April 23, 2007 at 11.01 h

responsible for this lack of archaeological evidence in Fig. 10a, as reflectance anisotropy reaches a maximum at visible wavelengths. NIR radiation is relatively free of such directional reflectance effects (Guyot 1990; Sandmeier and Itten 1999) due to the multiple canopy scattering of NIR photons (Lobell *et al.* 2002). The phenomenon of crop marks being clearly visible from one specific direction of view is widely known among aerial archaeologists. Concerning this, the less critical angular view characteristic for the digital NIR approach might prove very useful, certainly in cases one would opt to fly a vertical coverage, trying to detect archaeological features afterwards.

NIR-Based Vegetation Indices

Capturing NIR with a modified DSC often allows to perform some arithmetic channel operations, as the channels generally acquire dissimilar wavebands of reflected EM radiation. This was illustrated by Fig. 4, which displays the channel-dependent spectral response of the Nikon $D50_{NIR}$. As described by Verhoeven *et al.* (2009b), these characteristic, unequal spectral responses of the $D50_{NIR}$ allow for the calculation of a simple ratio (SR): a Vegetation Index (VI) that has a large potential to indicate zones with a large amount of green biomass (Jordan 1969; Peñuelas and Filella 1998; Schlerf *et al.* 2005) and computed by dividing a pure NIR waveband by a part of the red spectrum. Applied to a frame of the $D50_{NIR}$, the following simple arithmetic operation can be executed: $F(i,j)=[R(i,j)-G(i,j)]/[G(i,j)+B(i,j)]$, in which $F(i,j)$ is the final pixel and R, G and B, respectively indicate the value of this pixel in the red, green and blue channels of the NIR image. The output equals a new array of greyscale pixels, of which the intensities represent the amount of chlorophyll pigment present at that particular spot. Figure 11 illustrates this principle. On the left (Fig. 11a), the visible frame indicates some negative, likely geomorphologically related, crop marks. The same traces are only weakly discernable in the NIR (Fig. 11b) for reasons explained previously. The plot on the lower right of the image is once more a very striking example of NIR's reflectance insensitivity to pigment content; although the red flowers are clearly distinguishable in Fig. 11a, the NIR record does not give a single clue about their presence. The SR image (Fig. 11c), however, indicates that Fig. 11b has all information embedded to clearly indicate the

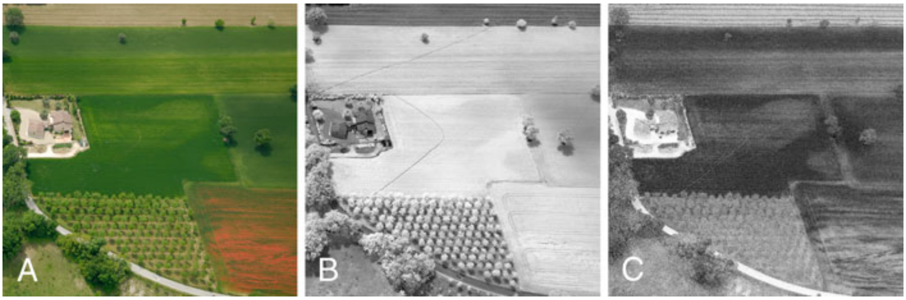


Fig. 11 A visible (**a**) and pure NIR image (**b**) of some agricultural plots. Image (**c**), which shows dark, chlorophyll-rich areas and white regions without biomass, was yielded by the SR described in the text. The imagery was acquired in the central Potenza valley (N 43°19′06″, E 13°17′16″—WGS84) with a Nikon D200 (**a**) and a Nikon $D80_{NIR}$ (**b**) on May 15, 2008 at 11.39 h

chlorophyll dense areas; houses and streets are completely white, the red flowers and negative crop marks have some middle grey value, whereas the dark areas correspond to the healthy green zones in the visible picture in Fig 11a. Even though this approach does not always work (Verhoeven *et al.* 2009b), there is a good chance for this SR to add relevant vegetation information to the spectral signals stored in the NIR photograph.

However, the above approach should be followed only where one DSC can be taken aloft. In the PVS, it became a common approach to take a two-DSC system—based on an unmodified Nikon DSC and a Nikon $D50_{NIR}$ or $D80_{NIR}$—in the airplane, a tandem which is rather simple to construct and perfect for hand-held operation (Eastman Kodak Company 1985). Besides a more rigid and consistent application of the SR—which is also known as the Ratio Vegetation Index or Vegetation Index Number—this combination allows additional VIs to be calculated, thus dealing with situations in which the $D50_{NIR}$-based SR does not prove very useful (*e.g.* differentiating between moderate and very high chlorophyll content or LAI, Gitelson *et al.* 2002). As an example, Fig. 12 visualises the differences between the SR calculated by using the $D50_{NIR}$ only (Fig. 12a), while Fig. 12b displays the output of the D200's red channel after division by the $D50_{NIR}$'s blue channel. It is obvious that the second approach yields a superior result, due to the far better spectral placement of the red band (Verhoeven *et al.* 2009b)—although one must not forget that imagery from two different DSCs has to be co-registered (*i.e.* the process of geometrically aligning two or more images to allow them to be superimposed) before any mathematical operation can be performed. The latter is, of course, not needed when applying a single DSC.

CIR Film Emulation

Apart from the problems of aligning the optical axis and firing the shutters at the exact same time, creating—and flying—such a two-DSC system is easy and exploits the spectral characteristics of an NIR-modified DSC more fully, offering archaeologists a very affordable and manageable multispectral tool that suits both visual interpretation and mathematical spectral operations, aiding in the revealing of the

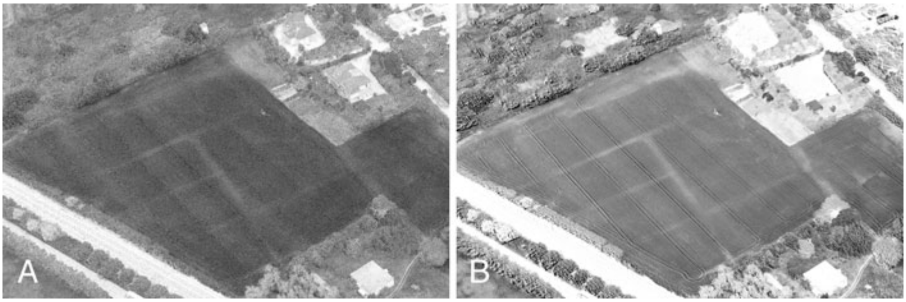


Fig. 12 **a** The output of an SR operation, using only the image channels of a Nikon $D50_{NIR}$; **b** this SR output was generated by utilizing the $D50_{NIR}$'s blue channel and the visible red band acquired by a simultaneously operated Nikon D200. The image shows the street pattern in the northern part of *Potentia* and was taken on May 15, 2008 at 11.16 h

archaeological subsurface, just by capturing whole parts of the landscape in several spectral bands with the ease of one single exposure.

In the ideal situation, several visible and NIR bands could be sampled by one DSC, hence also omitting the otherwise necessary co-registration step. Some years ago, such an approach was tried by the Eastman Kodak Company with their now discontinued Kodak DCS-200 CIR, DCS-420 CIR and DCS-460 CIR (Graham and Koh 2002). Although a number of complications clearly proved these models to be initially built for non-scientific work (Shortis and Beyer 1997), Fig. 13a, b shows that their spectral response approximately matched Kodak's NIR-sensitive emulsions (Bobbe and Zigaldo 1995; Graham 1995). As can be seen, both the film and digital approach acquired spectral information in very broad wavebands, hence taking significant portions of the other spectral bands into account (Dean *et al.* 2000; Graham and Koh 2002; Pouliot *et al.* 2002; Stow *et al.* 2000). From the response of the Kodak DSC-420CIR (Fig. 13b), it is obvious that the red sensitive diodes (and to a lesser extent also the green channel) take large portions of the NIR into account, a drawback Kodak counteracted by subtracting the NIR's Digital Numbers (DNs) from the initially captured green and red DNs (Graham and Koh 2002). However, this approach could never yield pure spectral information. Because the spectral response curves do not even coincide on the long wavelength side (Fig. 13b), it is impossible to remove the precise NIR-contributing part of the green and red channel. Moreover, the NIR and red channel still took a significant portion of the red edge region into account, which made these broad band imagers less suitable for quantitative spectral analysis as they masked unique spectral features to a large extent. As also the analogue media were characterised by a low spectral fidelity (Fig. 13a – *e.g.* consider the amount of visible radiation the NIR-sensitive band takes into account), Kodak's NIR-enabled DSCs emulated the Kodak CIR film rather well, and was therefore often used in several vegetation studies (*e.g.* Bobbe 1997; Bobbe and Zigaldo 1995; Dean *et al.* 2000; GopalaPillai and Tian 1999; King *et al.* 1997; Knapp *et al.* 1997; Olthof and King 1997; Pouliot *et al.* 2002; Stow *et al.* 2000).

A two-camera system based on a Nikon D50$_{\mathrm{NIR}}$ coupled with an unmodified DSC can, however, deal with these issues. Figure 13c illustrates the blue, pure NIR channel response from the D50$_{\mathrm{NIR}}$ normalised to the sensitivity of the D200's green and red channel. The spectral fidelity of the acquired information is, obviously, superior to the CIR film and Kodak's NIR-enabled DSCs. So, given the fact the CIR film proved in many study areas its capability to detect the effects of physiological plant changes (*e.g.* Everitt *et al.* 1997; Summy *et al.* 2003; Thomas and Oerther 1977), means that CIR imagery generated by less broad bands certainly will yield similar, if not largely superior and less debatable results (the latter, most likely, is also one of the reasons for its sparse archaeological application). Moreover, this approach is a cheap solution, cost being the main reason Kodak had to discontinue their models in the late 1990s (Graham and Koh 2002). The essential co-registration step can be considered a major drawback, slowing down the visualisation of the final output (Fig. 14b). However, several software packages for (semi-)automatic co-registration exist, meaning this disadvantage can be solved in a rather straightforward way.

A possible solution to capture CIR imagery with only one DSC is presented in the United States patent 20060066738, in which Hershey and Zhang proposed a CFA

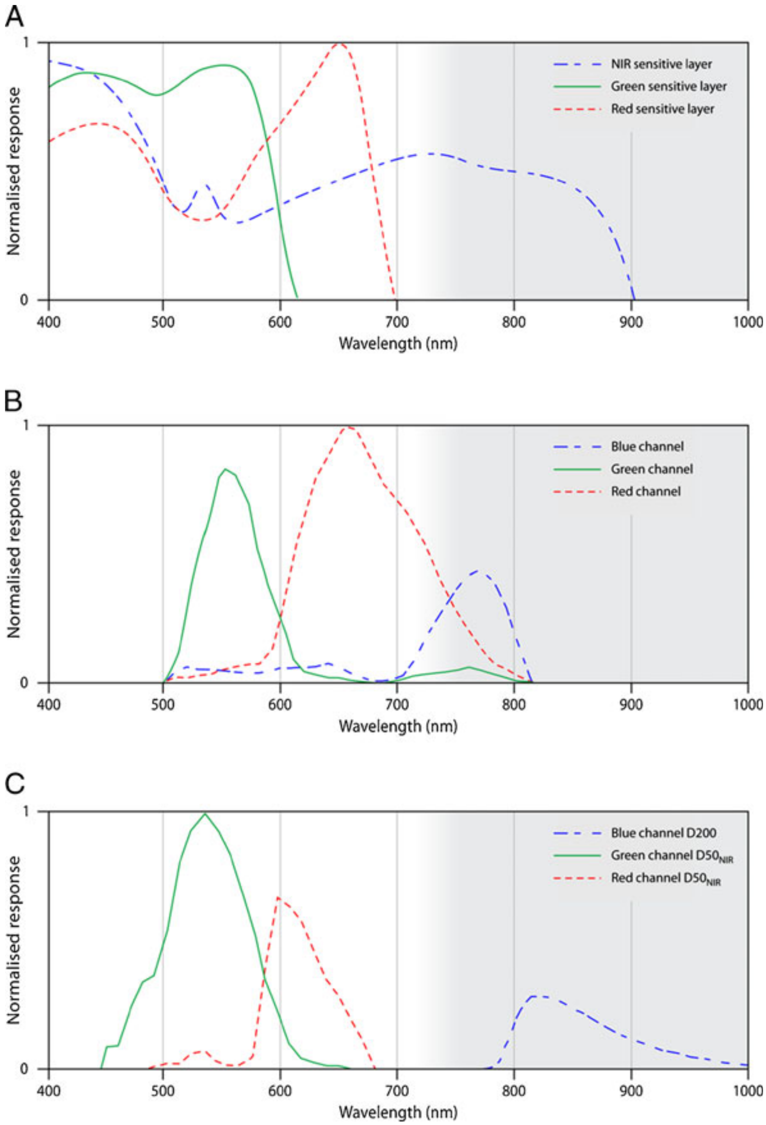


Fig. 13 **a** Spectral sensitivity curves of the Kodak Ektachrome Professional Infrared EIR film (adapted from Eastman Kodak Company, 2004); **b** spectral response of the Kodak DCS-420 CIR (adapted from Graham and Koh 2002, Fig. 5.7); **c** the green and red channel response of the Nikon D200 (adapted from Sigernes *et al.* 2008, Fig. 6b) with the spectral sensitivity curve of the Nikon D50$_{\text{NIR}}$'s blue channel. The *grey zone* indicates the NIR domain

pattern consisting of four different coloured filters, three passing the blue, green and red visible bands, while a fourth is dedicated to transmit pure NIR or UV radiation (Hershey and Zhang 2006). It is, however, highly questionable whether any company will ever market such a device, in which case a multispectral imaging system utilizing a multitude of DSCs would still offer a higher resolving power and more possibilities in choosing spectral combinations. The latter property is of crucial importance, as it allows the execution of mathematical spectral operations to indicate a number of archaeologically important vegetation parameters (*e.g.* canopy cover, biomass, chlorophyll and water content,…) better than can be revealed by either NIR or red alone (Lyon *et al.* 1998; Richardson and Everitt 1992). This clearly proves the highly complementary nature of NIR and visible reflectance data.

Finally, it remains to be seen whether or not digital CIR still has to be considered beneficial (let alone essential) for archaeological purposes. Even though the lack of simultaneously captured CIR (or pure NIR) and visible information made it previously very difficult to correctly assess the added value of such false-colour composites in aerial crop mark archaeology, Fig. 14b illustrates that the output does not always yield better results compared to the visible frame (as also noticed by Crawshaw 1995; Gumerman and Neely 1972; Hampton 1974; Harp 1968; Itek Data Corporation 1965; Matheny 1962; Strandberg 1967). Moreover, the digital workflow allows the individual examination of each captured spectral channel, whereas the calculation of specific VIs enhances the dissimilarities between these channels far more than a CIR image is able to do. From this point of view, merging several spectral channels into one false-colour photograph appears not to be essential anymore, except for creating a visually pleasing image. Because the analysis of the currently acquired data set confirms this suggestion, it seems more and more obvious that the creation of CIR photographs no longer offers direct archaeological benefits over the abovementioned techniques in revealing information on the vegetation's physiological and morphological conditions (cf. Fig. 14a *versus* Fig. 14b).

Conclusion

By using the reflected portion of incident EM radiation, the spatial perspective offered by aerial photography allows the remote assessment of the vegetation status over both small and larger areas (Benton *et al.* 1976; Nellis 1982). Notwithstanding accurate and cost-efficient monitoring and mapping of morphological and/or physiological crop changes is essential to study our hidden past, the slight differences of colour and height in crops are often very difficult to record through normal colour photography. Therefore, it might seem striking that relatively few aerial archaeologists have been exploring the limits of the human visual system, trying to incorporate NIR reflection in their photographs. This phenomenon can,

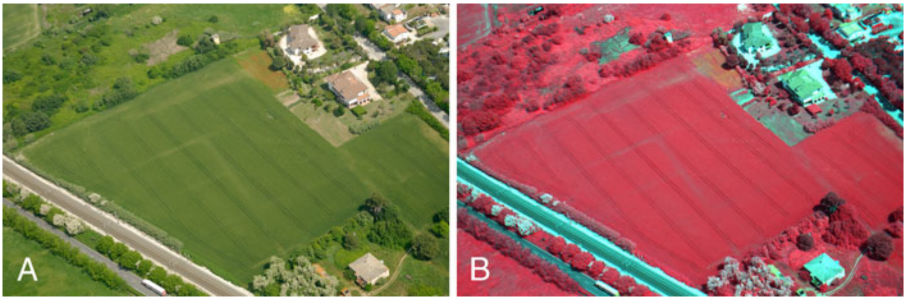


Fig. 14 Visible record (**a**) and CIR output (**b**) of the street pattern in the northern part of *Potentia*. The images were taken on May 15, 2008 at 11.16 h and generated by a Nikon D200 and a simultaneously operated Nikon D50$_{\mathrm{NIR}}$

however, largely be attributed to the error-prone, awkward film-based workflow of pure NIR or CIR imaging, some unfamiliarity with its principles and the fact that such a beyond-visible approach did not always prove successful or even useful—although a thorough assessment of the full archaeological potential has, in most cases, been problematic due to the usual lack of simultaneously acquired and geographically extended comparison material from the visible spectrum. Flying with two simultaneously operated DSCs, however, proves to be the way forward. Besides capturing the conventional and familiar visible radiation, a modified DSC can be triggered to record the pure NIR reflectance of the same scene.

Both the use of individual spectral channels as well as the arithmetic operations performed on a combination of channels (*e.g.* the calculation of an SR) offer a lot of opportunities to visually enhance archaeologically related anomalies and/or even reveal completely new features. Although archaeological NIR aerial imaging is by no means novel, the advantages modified DSCs can offer in the generation and interpretation of reconnaissance information is substantial: in addition to simplifying the complete workflow, the possibilities known from the film-based pure NIR or CIR approach are expanded and perfected, without the significant costs of the latter.

Since the summer of 2010, the author is working at the Ludwig Boltzmann Institute for Archaeological Prospection and Virtual Archaeology (http://archpro.lbg.ac.at), a novel and innovative research institution for the development and application of advanced non-destructive prospection methods and their integration within the theoretical and methodological framework of landscape archaeology (Doneus and Neubauer 2010). One of the aims of this research institute is to spectrally characterise positive and negative crop marks during their complete life cycle. Only by building such an archaeologically relevant spectral library, can crop mark detection be understood more thoroughly and convenient approaches be formulated. The spectral information collected will also permit the acquisition of a more complete and conclusive picture of the operational conditions of NIR, indicating the amount to which certain features can become more, less or equally visible in this invisible domain. Even though it has not been possible to perform in-site spectral measurements while taking the imagery presented here, it can already be stated that the archaeological potential of a complementary NIR-visible approach cannot be underestimated and that the results gained so far confirm the non-archaeological research performed in the field of biology.

Obviously, NIR imaging is not solely restricted to crop mark archaeology: the existing soil moisture differences that are characteristic for soil marks (Avery and Lyons 1981; Jones and Evans 1975) can benefit from an NIR approach as well (Itek Data Corporation 1965; Lyons and Avery 1977; Rinker 1975). This way, modified DSCs can be considered low-cost, convenient possibilities to yield additional, beyond-visible archaeological information that supports and speeds up the analysis of simultaneously captured visible spectral bands, while also aiding in the interpretations of existing data sources collected in previous years with different means—without making these other methods of data acquisition obsolete. As such, every single new piece of information, regardless of the instrument it was acquired with, can contribute to improve our understanding of (pre)historic landscapes. Therefore “it is extracting as much archaeological information from as many sources as possible that is the challenge for the coming century” (Bewley 2003: 286).

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