

Airborne spectral imagery for archaeological prospection in grassland environments—an evaluation of performance

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The new generation of aerial photographers is using different wavelengths to sense archaeological features. This is effective but can be expensive. Here the authors use data already collected for environmental management purposes, and evaluate it for archaeological prospection on pasture. They explore the visibility of features in different seasons and their sensitivity to different wavelengths, using principal components analysis to seek out the best combinations. It turns out that this grassland gave up its secrets most readily in January, when nothing much was growing, and overall the method increased the number of known sites by a good margin. This study is of the greatest importance for developing the effective survey of the world's landscape, a quarter of which is under grass.

Keywords: aerial photography, remote sensing, multi-spectral, TCC, FCC, NVDI, PCA

Introduction

The use of multispectral data in the form of satellite imagery is a relatively well-established technique for archaeological prospection and has been shown to be a powerful tool for site recognition and landscape scale analysis (Philip *et al.* 2002; Beck *et al.* 2007; Turner & Crow 2010). Applications of satellite data vary from palaeogeography (Khadkikar *et al.* 2004) to the identification of settlement areas in support of field investigations (Gheyle *et al.* 2004; Beck *et al.* 2007) or the looting of sites following the Iraq war (Stone 2008). However, to

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date, the use of airborne spectral sensors in historic environment research has been very limited, which is perhaps surprising given both the finer spectral and spatial resolution they can provide when compared with satellite-based sensors and their widespread use in the environmental sciences to detect vegetation and soil properties (Govender *et al.* 2007; Xie *et al.* 2008; Ben-Dor *et al.* 2009; Mulder *et al.* 2011).

Airborne spectral data was first used to detect archaeological remains over 20 years ago (Donoghue & Shennan 1988), since when a number of projects have shown the potential for the use of airborne digital spectral imagery for detection of archaeological features and its complementarity to other airborne and ground-based survey techniques (Winterbottom & Dawson 2005; Challis & Howard 2006; Powlesland *et al.* 2006; Challis *et al.* 2009). An emerging body of archaeological research into identifying features through soil spectral response is being undertaken in the Mediterranean region and the Fertile Crescent (Ben-Dor *et al.* 2002; Traviglia 2005; Rowlands & Sarris 2007). However, despite showing some promise, digital spectral imaging has not been widely applied by historic environment professionals, and research in the UK to date has focused almost exclusively on arable landscapes. For example, while digital spectral data was collected for the Stonehenge World Heritage Site, its analysis was secondary to that of airborne laser scanning (ALS or lidar survey) (Bewley *et al.* 2005). The single published example of the analysis of airborne spectral data for the non-arable, coastal Machair environment of Coll and Tiree, Argyre and Bute, Scotland (Winterbottom & Dawson 2005) showed the potential of these data for identification of archaeological features but was not able to provide a quantitative comparison with the results of aerial photographic transcription. Therefore while the identification in airborne spectral data of crop marks in cereals has been illustrated, there has been little assessment of the performance of this type of sensor in comparison to established techniques. This is particularly true for non-arable environments where the change in vegetation properties caused by surface or sub-surface features can be more subtle than in landscapes dominated by arable cultivation.

This paper assesses the potential use of *archive digital spectral data* for the detection of archaeological features in non-arable landscapes using a case study on the calcareous grassland of Salisbury Plain, Wiltshire, UK. The research makes use of archive spectral data collected in 2002 by the Environment Agency of England and Wales (EA) on behalf of the Ministry of Defence for the purposes of land-use mapping (Barnes 2003). The results are compared with those of the National Mapping Programme's (NMP) transcription of archive aerial photography.

Airborne digital spectral imaging

The identification of changes in vegetation patterns as proxy indicators for archaeological features is a long-held tenet of aerial photographic survey and transcription. Vegetation (crop) marks, along with soil marks and topographical anomalies, can be mapped using standard monochrome or colour photography, given favourable conditions. However, standard photographic techniques are only sensitive to a small portion of the visible electromagnetic spectrum of reflected energy at wavelengths between 450–650nm. In contrast to standard photography, digital spectral imaging (commonly referred to as multi- or hyperspectral

imaging) can capture the breadth of the electromagnetic spectrum, including the near infrared (NIR) region, which is of particular interest for the analysis of vegetation.

Airborne sensors collect radiance data in much the same way as satellite sensors. In contrast to active survey systems such as lidar, reflected radiance is captured passively through a lens onto a line of detectors in the spectral sensor as the aeroplane moves along the direction of survey. This type of sensor allows for the collection of many narrow spectral bands, giving coverage of the ultraviolet (UV), infrared (IR) and thermal regions of the spectrum depending on the instrument type. As such, airborne digital spectral imagery has been a mainstay of landscape analysis in the environmental disciplines in the UK and elsewhere since the 1980s, building an archive of airborne spectral data that also has potential for archaeological analysis. Although features of crop stress and soil change in the UK have frequently been collected with environmental management in mind, archaeological features may also be captured by these data. Moreover, increased spectral sensitivity has the potential to broaden the narrow window of ideal conditions required for the capture of vegetation marks in aerial photography (Wilson 2000; Beck 2011).

The biological understanding of vegetation and soil reflectance across the electromagnetic spectrum is a feature of Verhoeven's work on NIR and UV photography (Verhoeven 2009; Verhoeven & Schmitt 2010), and a recent publication reviewed the methodology (Verhoeven 2011). However, the basic principles are repeated briefly here with a focus on the non-visible wavelengths used to detect changes that may be caused by archaeological features.

Healthy photosynthetically active vegetation absorbs as much as 70–90% of incident radiation, most strongly in the blue and red wavelengths (centred on 450nm and 670nm respectively), which is why it appears green to the human eye. Senescent or stressed vegetation exhibits different spectral properties, due to the rapid decay of the chlorophyll pigment, loss of absorption properties and changes in internal structure. There is some debate over exactly how visible the signs of early stress are in this spectral region, particularly when using 4-band NIR aerial photography (Verhoeven 2009: 199), but stress, particularly drought, causes a significant drop in NIR reflectance due to changes in leaf structure. This allows the NIR region to be used as an indicator of the state of vegetation vigour, making it easier to detect changes in this region over the visible wavelengths.

Recent work has also broadened our understanding of the biochemical and biophysical properties that differentiate vegetation marks from the surrounding canopy (Hejcman & Smrz 2010; Hejcman *et al.* 2011), providing insight into a subject predominantly left untouched since the work of Evans & Jones (1977). Digital spectral data can allow the mapping and quantification of parameters such as biomass that have been positively linked to vegetation mark formation, thus potentially providing archaeologists with a tool for analysing features as well as locating them.

Winterbottom & Dawson (2005) and Challis *et al.* (2009) have offered technical discussions of the archaeological use of airborne spectral sensor data, highlighting a number of techniques that can be applied, particularly for the identification of geoarchaeological features. While general visualisation techniques such as true and false colour composites (TCC and FCC), red/NIR vegetation ratios (such as the Normalised Difference Vegetation Index, NDVI) and compression techniques in the form of Principal Components Analysis (PCA) were employed by both studies, as yet there has been no attempt to assess their

Table 1. Airborne digital data sources for the Everleigh pilot area.

Data type	Source	Spatial resolution	Date flown	Source
Digital spectral imagery (CASI)	Environment Agency	1.5m	1 January 2001	NEODC
Digital spectral imagery (CASI)	Environment Agency	1.5m	1 January 2001	EA
Airborne laser scanning data	Environment Agency	1m	2005	EA
Aerial photography (oblique)	Various (collated and transcribed by NMP)	0.15m	Archive (c.1950–2002)	Wiltshire HER

relative effectiveness or tailor the analysis of airborne spectral data to specific vegetation zones or archaeological feature types (as per Traviglia 2006). Additionally, there has been scant opportunity for repeat acquisition of spectral data and therefore no analysis of the impact of seasonal variation on feature visibility.

The aims of this paper can be summarised as follows: **1)** to assess the viability of a variety of visualisation techniques for a grassland environment; **2)** to develop a greater understanding of the sensitivity of the visible-NIR wavelengths for visualising archaeological features; **3)** to contribute to our understanding of seasonal variation by assessing data collected by the same sensor at different times of year; and **4)** to assess the relative value of digital spectral data in non-arable areas when compared with aerial photography.

Study area

The Salisbury Plain Military Training Area (SPTA) is an area of approximately 39 000ha of chalk grassland in Wiltshire, England, that lies on Upper and Middle Chalk (Figure 1). Topographically the area is dominated by rolling hills and dry valleys and its vegetation is typified by extensive areas of unimproved calcareous grassland with occasional areas of woodland and scrub. The area contains a palimpsest of prehistoric, Roman and medieval features, totalling more than 2300 known archaeological sites, most of which were mapped through the NMP campaign and attendant field survey (Crutchley 2000; McOmish *et al.* 2002). The quality and quantity of previous investigations in the area provided an excellent baseline record from the Wiltshire Historic Environment Record (HER) with which to compare the digital spectral data. An area of 4km² between the village of Everleigh and Sidbury Hill was selected for the study based on the availability of archive data (Table 1).

Data and methods

Two spectral datasets collected using the ITRES Compact Airborne Spectrographic Imager (CASI) in January and May 2001 (Figure 2) were compared with the archaeological feature data provided by Wiltshire HER (incorporating the results of the Salisbury Plain NMP

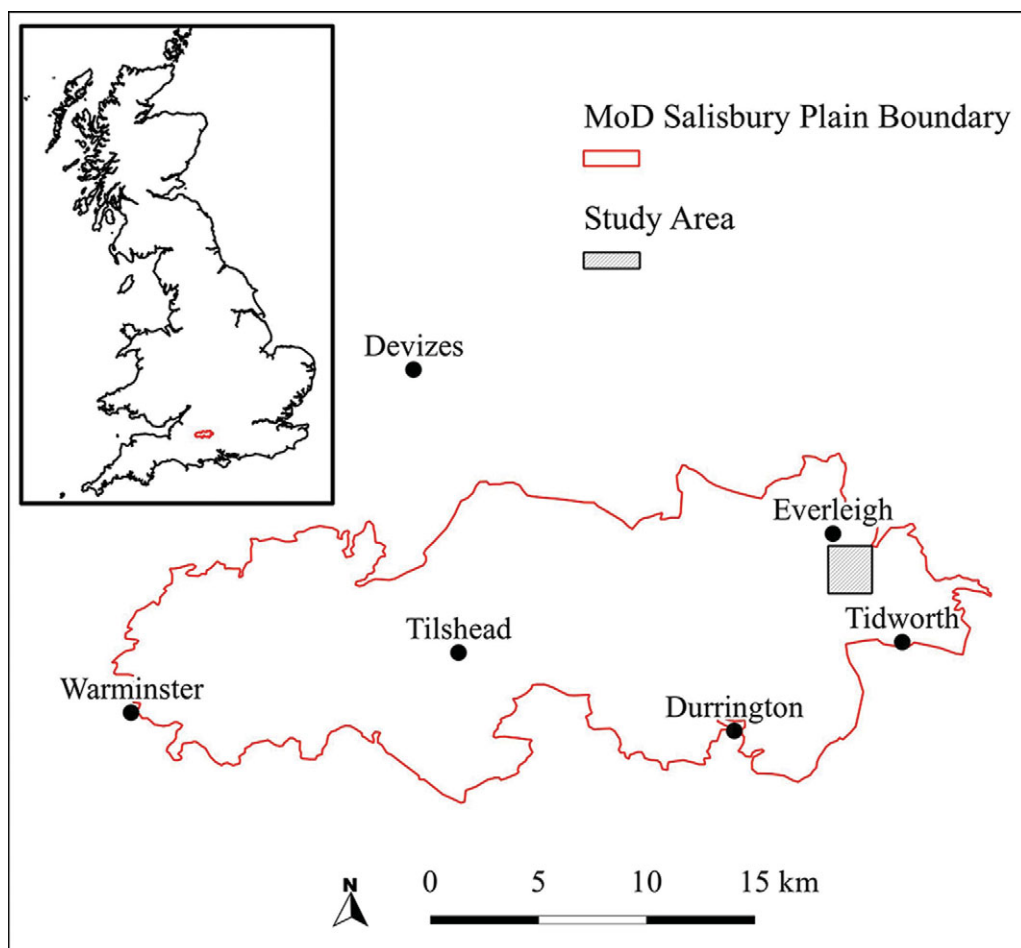


Figure 1. Location of the Salisbury Plain study area.

project [Crutchley 2002]). The CASI data were collected in 14 bands ranging from 440–891nm and had a ground resolution of 1.5m and a radiometric resolution of 12 bits (Table 2). Although no ground observations contemporary to the CASI data were available, the study area was subject to intensive walkover survey both before and after the feature mapping exercise.

The archaeological features visible in each of the 14 spectral bands were mapped following NMP protocol from greyscale images at a scale of 1:4000 or less. The process of identification of features followed a top-down approach where every anomaly of potential anthropogenic origin was initially recorded including modern routeways, tank tracks and agricultural features. Modern features were then identified following walkover survey and removed from the subset. The remaining features were then categorised by form and topography before being interpreted archaeologically with reference to the existing understanding of features in this landscape from the NMP/HER data. Hereafter these non-modern anthropogenic features will be referred to as archaeological features.

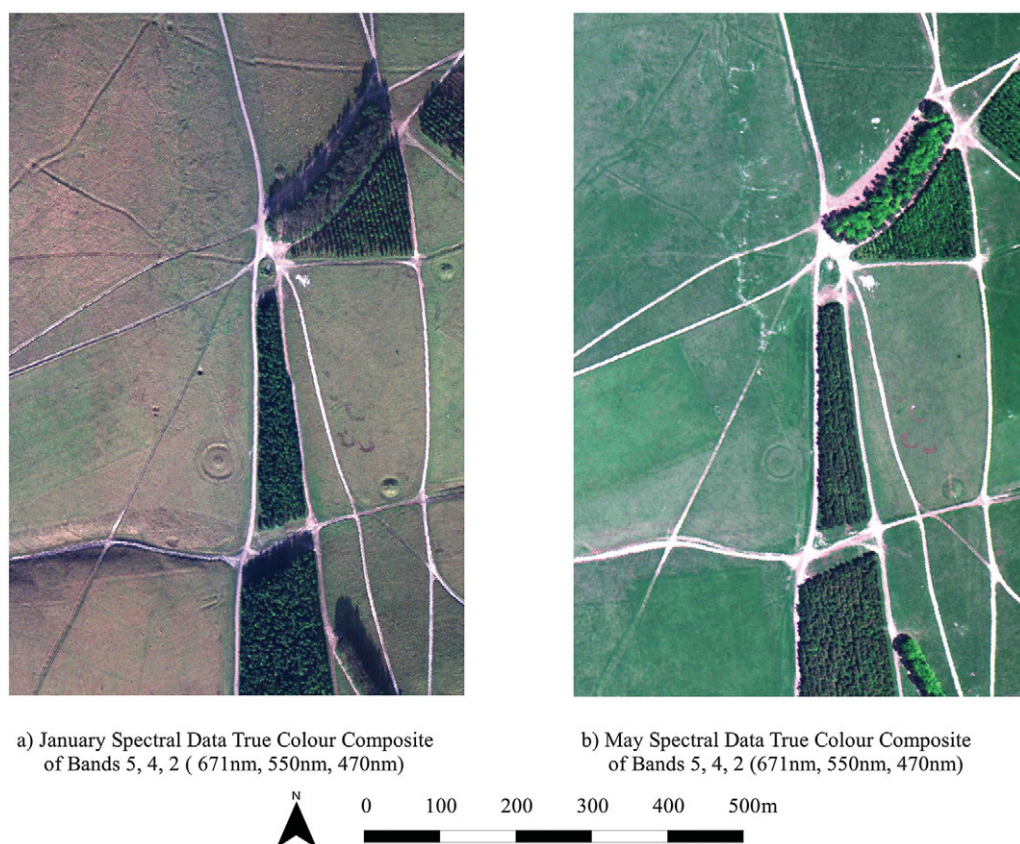


Figure 2. True colour composites of the January and May spectral data showing features relating to the archaeological landscape.

The features were then mapped from true and false colour CASI images. True colour images comprised bands 5 (around 671nm), 4 (around 550nm) and 2 (around 490nm) to approximate red, green and blue wavelengths respectively, providing the closest image to standard photography, albeit at a significantly reduced spatial resolution. The false colour composite (FCC) images were selected from the three bands that provided the combination of spectral diversity and high feature uniqueness (i.e. features not recorded in other bands from the results of the visual inspection). In January, this was bands 3 (around 490nm), 7 (around 700nm) and 14 (around 880nm) and in May bands 3 (around 490nm), 8 (around 711nm) and 12 (around 780nm). Principal Components Analysis (PCA) was undertaken on all 14 bands and on the three bands comprising the FCC for each date (Figure 3). Details of the percentage variation represented by each of the principle components are presented in Table 3.

Results

In total 110 archaeological features were mapped from both spectral datasets in the study area, of which 56 were known from the HER. Of these 56 known features, 81% were

Table 2. Wavelengths of the vegetation bandset of all the digital spectral data supplied for the Everleigh study area.

CASI band	Wavelength range (nm)	Mid-point wavelength (nm)	Interpretation
1	446.2±6.6	446.2	Blue vegetation response
2	470.1±6.6	470.1	Blue vegetation response
3	490.4±6.7	490.4	Green vegetation response
4	550.1±6.7	550.1	Green vegetation response
5	671.1±6.8	671.1	Vegetation absorption maximum
6	683.5±4.0	683.5	Red edge
7	700.7±5.9	700.7	Red edge
8	711.2±4.9	711.2	Red edge
9	721.7±5.9	721.7	Red edge
10	751.3±6.8	751.3	Near infrared plateau
11	763.7±4.0	763.7	Vegetation reflection
12	780.9±5.9	780.9	Water absorption
13	860.2±6.8	860.2	Near infrared plateau
14	880.2±11.6	880.2	Near infrared plateau

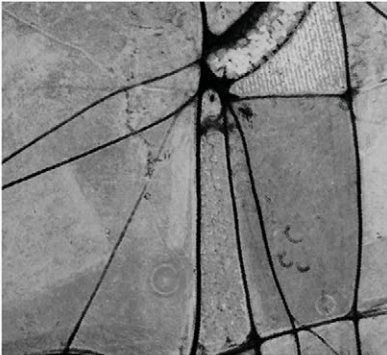
re-recorded from the January data and 69% from the May flight (Figure 4). In total, 54 features were recorded from the spectral data that were not known from the existing record of archaeological sites. The majority of features recorded in the study area were associated with Iron Age/Romano-British agricultural intensification in the area, including extensive systems of lynchets (both well preserved and heavily plough-damaged), banks, ditches and holloways. Although no geomorphological features were recorded in the study area, a sedimented post-medieval dew pond was detectable, indicating that palaeochannels or other features where sediments had been affected by the retention of water in this otherwise free-draining landscape could be identified in the airborne spectral data. In comparison with contemporary lidar data (Bennett 2011), 73% of features detected in the spectral data had some element of topographic representation, which compares favourably with the rate of 76% of features in the HER for which topography was detectable.

Combining the results from all the visualisation techniques, 82 features were mapped from the January data and 69 from the May data (Table 4). In all 7% more features were recorded in January than May with Figure 5 illustrating the variability in feature detection across the wavelengths of the archive data. While the visibility of features varied depending on the wavelengths viewed, the pattern of recovery followed that of a typical vegetation response with a peak in visibility over the red edge (680–730nm). In May this was also accompanied by a small peak in the green wavelengths (470–490nm), which again resembles growing vegetation spectra (as measured by chlorophyll quantity) at this time of year. This peak in the green region was not visible in the January data as the vegetation was dormant at this time.

The results of the TCC and FCC mapping are shown in Figure 6, compared with the best performing single band and NDVI for each month. It can be seen that mapping from TCC alone led to a significant reduction in the number of features recorded in both January and



a) May best performing single band
(band 8 - 711nm)



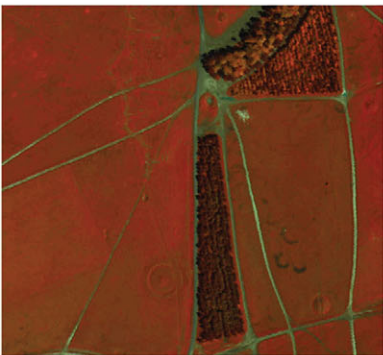
d) May NDVI



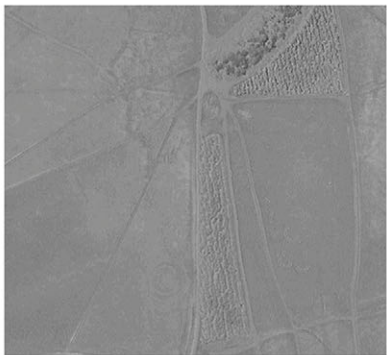
b) May True Colour Composite
of Bands 5, 4, 2 (671nm, 550nm, 470nm)



e) May 14-band PCA (First Component)



c) May False Colour Composite
of Bands 3, 8, 12 (490nm, 711nm, 780nm)



f) May False Colour Composite (3-band) PCA
(First Component)



Figure 3. The different visualisation techniques employed in this study.

Table 3. Variation and Eigenvectors (relative contribution) represented by each of the Principle Components Analysis of the Everleigh spectral date: a) 14-band PCA; b) January false colour composite; c) May false colour composite.

	a)	14-band PCA			b)	January FCC			c)	May FCC		
		PC1	PC2	PC3		PC1	PC2	PC3		PC1	PC2	PC3
% variance		90.63%	8.56%	0.33%		89.75%	9.88%	0.37%		94.38%	5.22%	0.40%
Eigenvectors by CASI band	1	−0.10	−0.22	−0.29	3	0.23	−0.55	0.81	3	0.13	−0.71	0.69
	2	−0.11	−0.26	−0.25	7	0.43	−0.68	−0.59	8	0.42	−0.59	−0.69
	3	−0.10	−0.27	−0.16	14	0.87	0.49	0.08	12	0.90	0.38	0.22
	4	−0.16	−0.26	−0.10								
	5	−0.13	−0.43	−0.07								
	6	−0.13	−0.42	−0.07								
	7	−0.19	−0.34	0.13								
	8	−0.26	−0.24	0.29								
	9	−0.26	−0.08	0.31								
	10	−0.44	0.21	0.38								
	11	−0.16	0.09	0.09								
	12	−0.45	0.24	0.16								
	13	−0.40	0.21	−0.41								
	14	−0.39	0.21	−0.51								

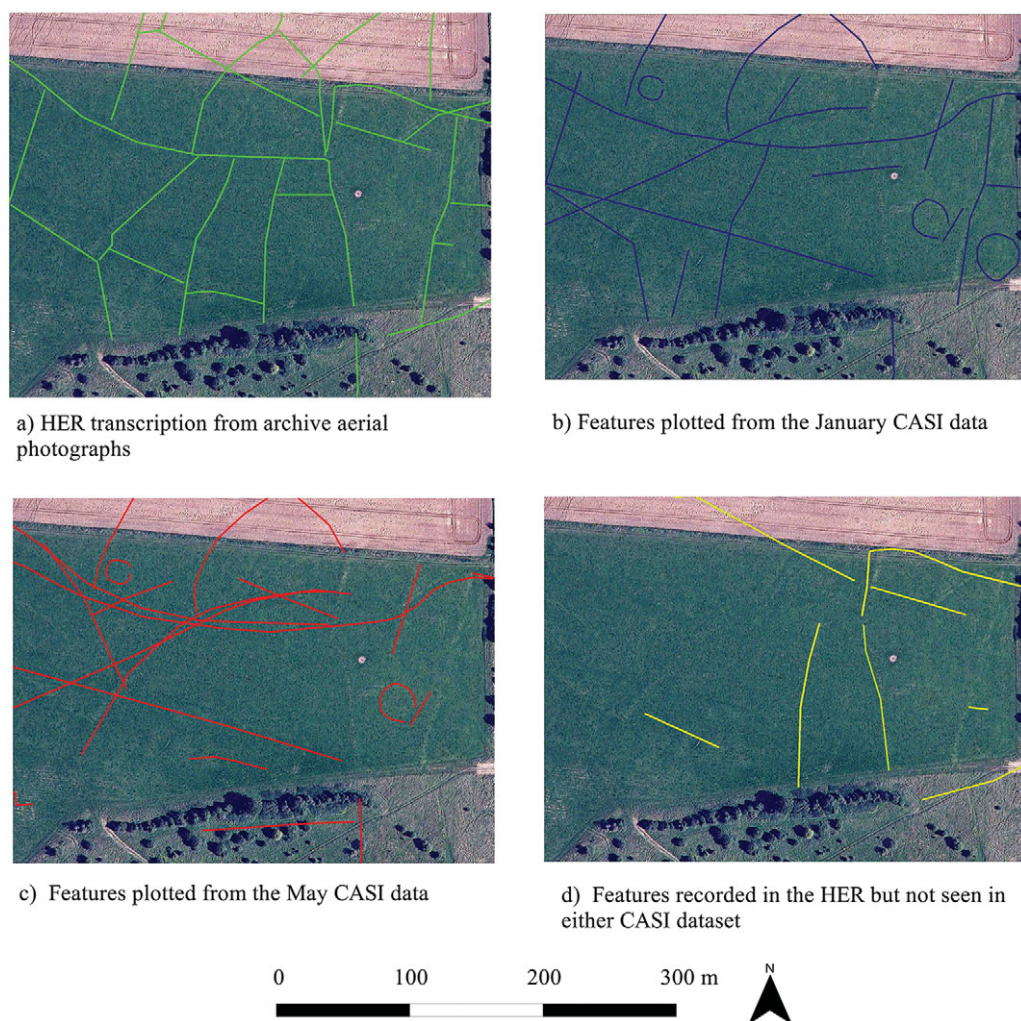


Figure 4. Features mapped from the January and May spectral data compared with the Historic Environment Record.

May. By contrast, the FCC led to a marginal increase in the number of features mapped for each flight but returned less than three-quarters of the number of features recorded across all bands (70% and 74% of features recovered respectively). This indicates that neither the FCC nor TCC provided optimal visualisation of archaeological features in this instance. Detailed analysis of the application of vegetation indices to these data (Bennett *et al.* 2012b) also showed the NDVI ratio was a poor index for detecting archaeological features.

The use of PCA improved the visibility of features when compared with true and false colour composites. Combining the results of PC 1–3 of all bands (viewed as individual greyscale images) gave recovery rates of 84% and 72% for January and May respectively. No archaeological features were visible in Principle Components 4–14.

Table 4. Summary of features mapped by single band analysis of the spectral data.

Month of flight	Number of features mapped	Percentage of total number of features	Number of features unique to month (not mapped in other spectral data)
January	82	48%	37
May	69	41%	34
January and May total	110	65%	
Both January and May	41	24%	

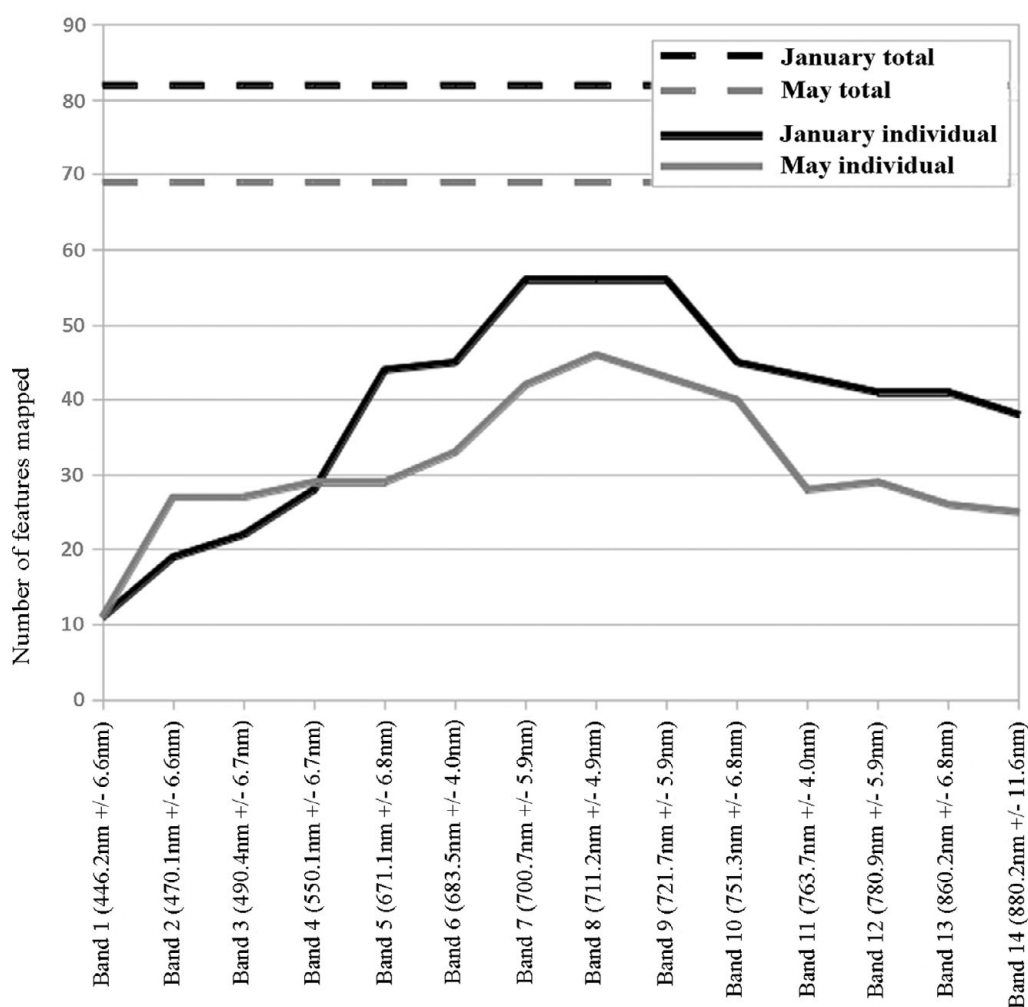


Figure 5. Chart showing the number of features recovered from individual bands of the spectral data.

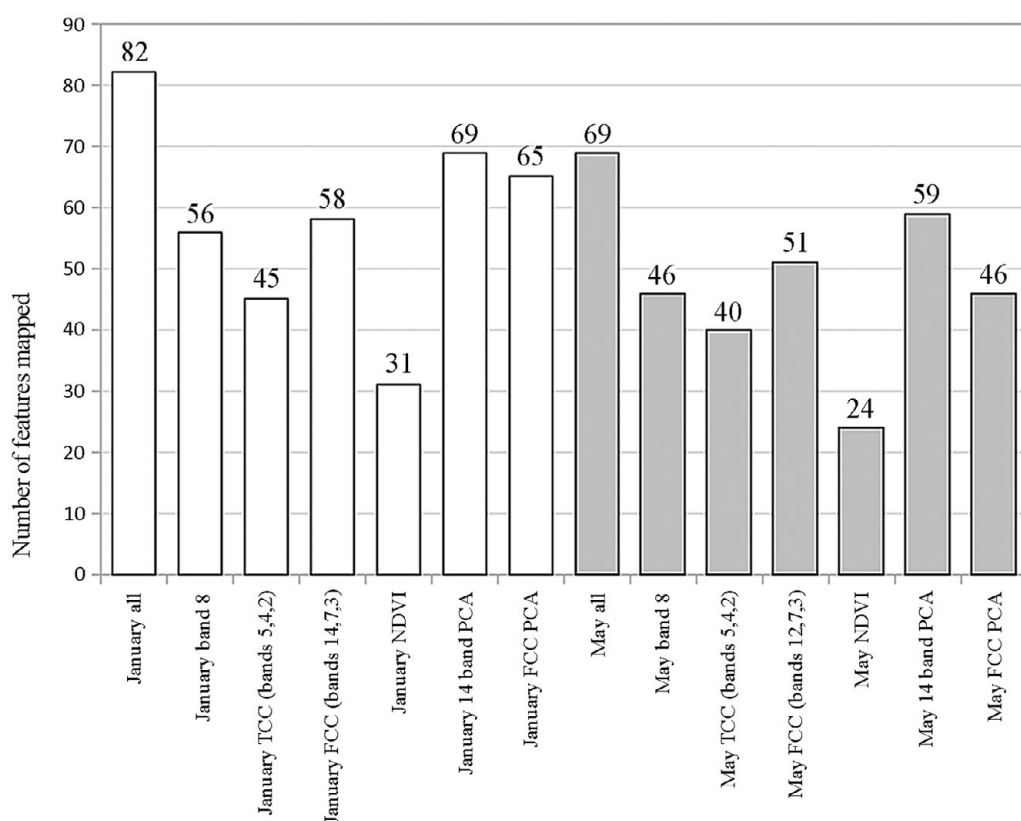


Figure 6. Relative feature recovery rates from the true and false colour composites and NDVI of the January and May spectral data.

Discussion

This assessment of airborne spectral data for archaeological prospection in a grassland environment showed that a range of individual features could be detected. All the features were in the order of 2–3 times the spatial resolution of the spectral data (around 3–6m). The definition of features on this scale is different from that of the scale of most satellite-based spectral prospection performed to date, where geomorphological and large-scale settlement activity covering areas of 10–50m² have dominated the types of features recorded (e.g. Mumford & Parcak 2002; Philip *et al.* 2002; Ur 2003; Khadkikar *et al.* 2004; Beck *et al.* 2007), although there have been specific instances where using a pan-sharpening technique to improve the apparent resolution of multi-spectral satellite imagery has allowed the detection of features in the order of 1–2m (Beck *et al.* 2007: 169, fig. 4).

Both the January and May data compared favourably with the HER record derived from archive aerial photographic mapping. Individually, each spectral dataset recorded a smaller proportion of features than were known from the HER, however the two flights combined recorded significantly more. In terms of feature recovery, a single pass with the

CASI sensor in January recorded 81% of all previously known features. This is a promising result given the lower spatial resolution of the imagery (1.5m compared with around 0.15m for aerial photography) and the fact that the existing HER record represents the culmination of information from many photographs taken over more than 60 years (Crutchley 2000).

By mapping individual bands it was possible to assess the visibility of archaeological features over different spectral regions. In both seasons it was shown that the wavelengths from 695–728nm are the best for visualising the archaeological features in this study area. In the January CASI data, detectability was equal throughout this range but in May visibility peaked markedly in the 706–716nm range. While no data were available for wavelengths lower than 440nm or higher than 891nm (so the analysis cannot be said to be exhaustive), it appears that the red-edge, a term used by environmental scientists to denote the red/NIR spectral range between 700–750 nm where there is a sharp increase in reflection associated with healthy vegetation, is a particularly important spectral region for the visibility of archaeological features. The best performing band for each dataset lay in this region and represented approximately 68% of all features recorded from the spectral data. This depth of sensitivity analysis, that is not yet possible using the broad spectral bands of satellite data, could prove key to developing spectral detection of archaeological features.

On comparison of visualisation techniques, it was shown that true colour composites performed poorly for identifying archaeological features. Despite a rigorous method of band selection, false colour composites based on uniqueness and spectral diversity performed only marginally better than the best single band in both datasets. While PCA of the bands selected for false colour composites did not conclusively improve visualisation, PCA of all bands was a useful tool to aid visualisation and improved recovery over the analysis of any single band. It was also shown that the PCA allowed 84% of features in the January data and 72% of features in the May data to be detected, although it would appear that the greater spread of feature visibility across the spectra in May led to a reduction in the visibility of features using the PCA technique. Whether this level of return is appropriate depends of course on the aims of the research and must be weighed against the time required to assess many individual spectral bands for archaeological content.

The analysis also showed that there was seasonal variation in the visibility of archaeological features in the spectral data, with 7% more features being recorded in January than in May. This difference appears low, but is in contrast to what was hypothesised from previous studies. Virtually all previous spectral data that have been examined for archaeological purposes have been collected in the summer at the height of vegetation growth, on the principle that differential growth caused by archaeological features will most likely be visible at this time of year. May represents the peak of the grass growth season, so if this hypothesis was supported we would expect improved monument visibility in this flight compared with January, when the vegetation is dormant. It is hypothesised that in this chalk grassland environment, the sparser cover of dormant vegetation in January enhances detectability of archaeological features, potentially by allowing non-vegetation attributes such as variations in soil or topography to be detected in the spectral signature. In contrast the blanket cover of hardy vegetation in May exhibits few signs of stress. However, further work on this theme

requires simultaneous ground observations and an intensive focus on features that have no detectable topographic representation.

Conclusions

The UN estimates that grasslands account for almost half of the land area of the UK (48%) and over a quarter (26%) of global land use (compared with arable crops which comprise 11%). In many countries grasslands are under increasing threat from the agricultural intensification needed to feed the growing global population (Food and Agriculture Organization of the United Nations 2010). Given the known limitations of traditional archaeological prospection techniques in this environment, advances in large-scale airborne survey techniques are necessary. The systematic study of archive spectral data for an area of grassland in the UK has illustrated the viability of airborne spectral data for the detection of archaeological features in this environment.

The single acquisitions of spectral data increased the number of sites known from the NMP. The performance was seen to improve when a number of methods for visualisation were combined, although traditional true colour composites were shown to be the least effective visualisation method. Additionally, although further work is required to assess fully the impact of seasonal variation, the results of this study indicate that in areas such as grasslands, where the dominant vegetation is not prone to displaying stress or enhanced growth caused by underlying archaeological deposits, flights undertaken outside the peak season of vegetation growth may be of equal or greater value to those targeted to the summer months. This has important implications for the use of archive imagery, suggesting that the timing of acquisition for airborne hyperspectral data may not be as critical as previously observed for standard aerial photography. This broadens the potential archive for archaeological prospection from data collected at various times of the year.

As the cost of acquiring airborne data can be prohibitively expensive, historic environment applications can profit from the use of archive spectral data. In the UK, for example, this is predominantly collected by two bodies: the Natural Environment Research Council (NERC) Airborne Research and Survey Facility (ARSF), in support of environmental research, and the EA, largely for the purposes of flood mapping. Both these organisations hold archives of data that are accessible to researchers. Worldwide archives are held by a number of organisations including NASA (North America), Blom Italy (Italy, France, North Africa) and the Australian Geological and Remote Sensing Service (Australia, New Zealand, Bolivia and Brazil). The archaeological potential of these archives has yet to be explored, but this study has shown that the application of spectral data for archaeological prospection is perhaps less limited by environment and seasonality than previously assumed. It is also anticipated that advances currently being made in the acquisition of airborne spectral data using unmanned platforms have the potential to reduce costs, thus improving accessibility and flexibility for historic environment applications.

Although there are disadvantages to the use of archive data (including accessibility, lack of metadata, and lack of contemporary field observations), there are also opportunities, for example the comparison of multiple sensors or data collected in different seasons (Bennett *et al.* 2011, 2012a). Additionally, by more closely linking observed reflectance

with observable proxy features it is possible to broaden our understanding of the vegetation and soil properties that contribute to identifying surface or near-surface features in a variety of environments. This research has indicated that current models of the optimal environmental conditions for detection (based on visual recognition from aerial photographs) fall short of indicating the relative usefulness of spectral data in pastoral landscapes based on season of acquisition alone. Much more research needs to be undertaken—particularly in the areas of soil composition and plant physiology—to understand the processes underlying detection in spectral imagery, to which the archive of data collected for environmental survey could significantly contribute.

This paper has illustrated that archive data can be quarried to discover archaeological features in non-arable environments (specifically chalk grassland) from a single pass, as compared with several decades of aerial photography. The importance of reflectance ranges outside the visible wavelengths when prospecting for features is not a new discovery, but this paper has shown that the increased spectral sensitivity of airborne platforms when compared with the broad bands of satellite sensors is of particular advantage in environments where proxy vegetation features are scarcely observed. The key to moving forward our understanding of the global applications of these data for curators of the historic landscape in such environments will be to grow the body of research associated with them, both geographically to encompass other non-arable environments, and through localised, detailed experimentation to build the knowledge base from which our models of the detection of archaeological features in spectral data are based.

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