3D Recording and Modelling in Archaeology and Cultural Heritage

Theory and best practices

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2.1 AIRBORNE LASER SCANNING FOR ARCHAEOLOGICAL PROSPECTION

R. BENNETT

2.1.1 INTRODUCTION

The adoption of airborne laser scanning (ALS) for archaeological landscape survey over the last decade has been a revolution in prospection that some have likened to the inception of aerial photography a century ago. Commonly referred to as LiDaR (Light Detection and Ranging)[1], this survey technique records high resolution height data that can be modelled in a number of ways to represent the macro and micro topography of a landscape. Arguably the most exciting aspect of this technique is the ability to "remove" vegetation to visualise the ground surface beneath a tree canopy (Crow *et al.*, 2007; Crow, 2009), but its value has also been shown in open landscapes and as a key component of multi-sensor survey (Bennett *et al.*, 2011, 2012).

The increased interest in and availability of ALS data has ensured its place in the tool kit of historic environment professionals. Increasingly, archaeologists are not just recipients of image data processed by environmental or hydrological specialists but are taking on the task of specifying and processing ALS data with archaeological prospection in mind from the outset. Despite this shift, the information and issues surrounding the capture, processing and visualisation of ALS data for historic environment assessment remain less well recorded than the applications themselves.

This chapter attempts to provide a balance of technical knowledge with archaeological application and to explain the benefits and disadvantage of ALS as a tool for archaeological landscape assessment. The aim here is not to overwhelm with detail (readers should look to Beraldin *et al.*, (2010) for an excellent technical summary of ALS systems) but to provide historic environment professionals, researchers and students with the questions, and answers, that will aid effective and appropriate use of ALS data. This information is paired with and refers to the ALS if the case study isn't going to be at the end of the chapter.

[1] Lidar is a broader term that can be used to describe a range of space, airborne and ground-based laser range measuring systems, while ALS relates to a particular type of airborne sensor which uses a rotating mirror to scan beneath the aircraft.

2.1.2 TECHNICAL BACKGROUND – HOW ALS DATA ARE COLLECTED AND PROCESSED

Unlike aerial photography or digital spectral imaging, ALS is an active remote sensing technique, meaning that measurements are taken using light emitted from the sensor unit rather than the reflection of natural light thus enabling night-time collection of data. The principle of laser scanning as a survey tool relies on the ability to calculate the time taken by a beam of light to travel from the sensor to the reflecting surface and back. The sensor scans in a direction perpendicular to the direction of flight creating a swath of points (Figure 1). Points are collected in a zig-zag or saw-tooth pattern resulting in an uneven distribution of spot heights along the swath. In addition, as the rotating mirror reaches the edge of each oscillation it slows down, resulting in a cluster of more-tightly spaced points at the edges of each flight-line.

Combining this with the information about the sensor's real-time location via Global Positioning System (GPS) and the roll, pitch and yaw of the plane via the Inertial Measurement Unit (IMU), it is possible to precisely calculate the distance of the sensor from the ground (Figure 2). Although airborne laser systems were known to be able to record height to less than 1m accuracy in the 1970s, it was advancements in GPS and IMU technology throughout the 80s and 90s and the removal of signal scrambling by the US military in 2000, that enabled ALS sensors to be used for topographic mapping to an accuracy typically in the order of 0.1-0.2 m (Beraldin *et al.*, 2010:20). This resolution means that features of archaeological interest that are represented in the macro-topography of a landscape can be captured in detail by ALS.

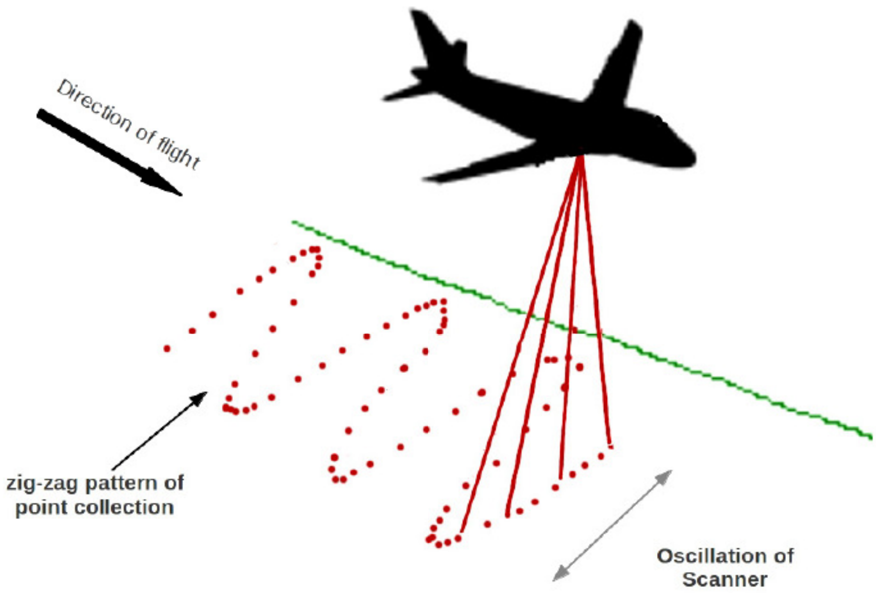


Figure 1. Demonstration and example of the zig-zag point distribution when ALS data are collected using an oscillating sensor

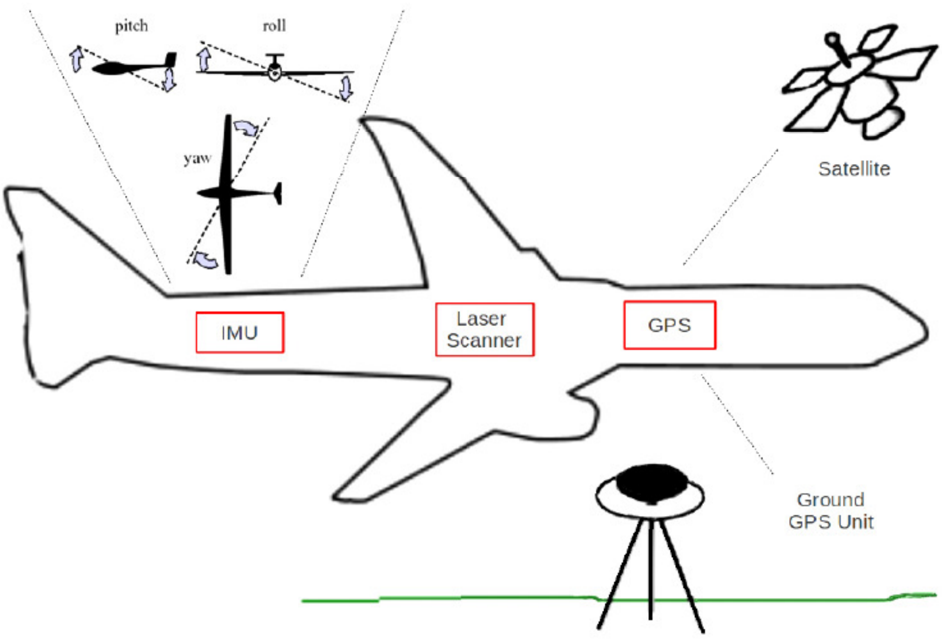


Figure 2. Schematic of the key components of the ALS system that enable accurate measurement of height and location

The reflected data from the laser beam can be recorded by the sensor in one of two forms: Discrete Return or Full-Waveform (Figure 3). Discrete Return systems record individually backscattered pulses when the beam encounters an obstacle from which it partially reflects, such as vegetation as can be seen in Figure 3. A return is only recorded when the reflection exceeds a manufacturer-defined intensity threshold and there is typically a discrete time interval before any subsequent return can be recorded. Between four and six returns can typically be recorded, forming the basis for identifying and removing vegetation (see below).

Full-waveform sensors record the entire returning beam allowing the user to specify the "pulse points" that they wish to use to define vegetation after the data is collected. This method has been shown to improve the accuracy of vegetation filtering (Doneus and Briese, 2010). However this type of sensor is less common than the discrete return systems and applications are hampered by the computational power required to process the data, which poses a challenge for many applications.

The initial processing steps for ALS data are most often done by the data supplier but are worth mentioning

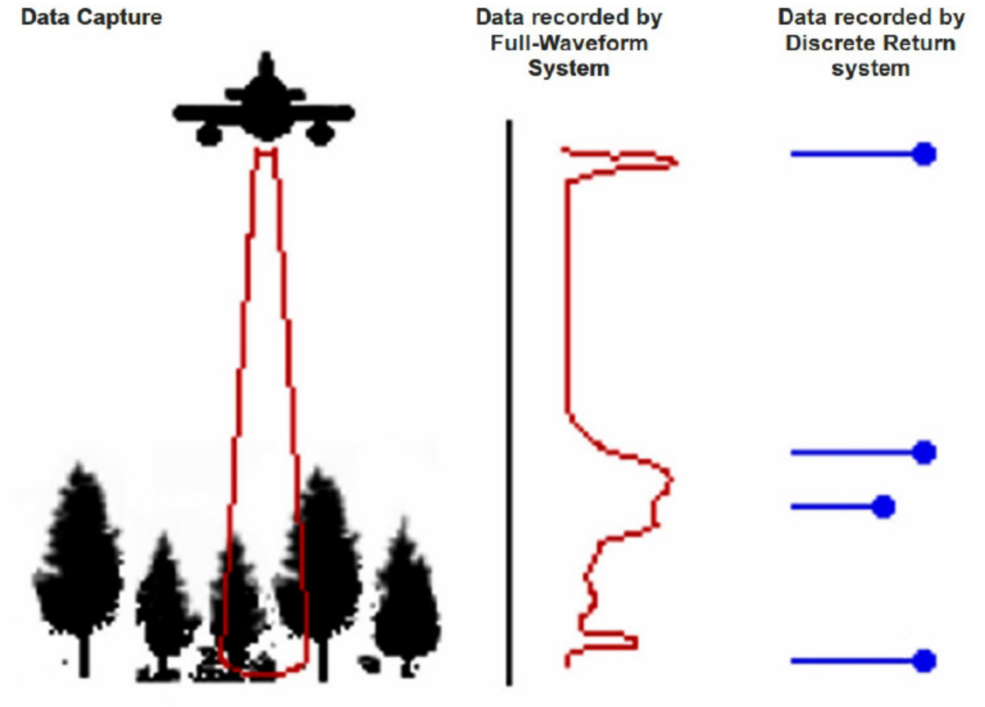


Figure 3. Schematic illustrating the differences in data recorded by full-waveform and pulse echo ALS sensors

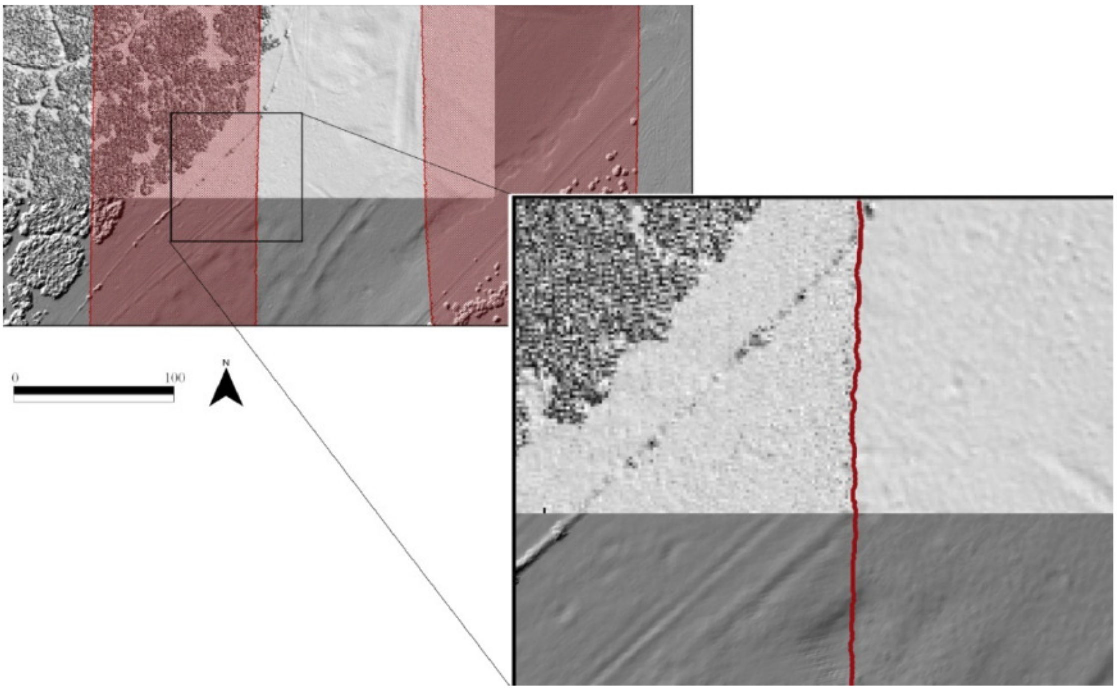


Figure 4. An example of "orange peel" patterning caused by uncorrected point heights at the edges of swaths. The overlay demonstrates uncorrected data which in the red overlap zones appears speckled and uneven compared with the same areas in the corrected (underlying) model

briefly here as the techniques used may affect the ALS data supplied and input to subsequent processing steps. In addition to reconciling the data from the ALS sensor, GPS and IMU to create accurate spot points, the processing must also correct for effects caused by the angle of the sensor at the edge of adjacent flightlines. The increased distance the laser has to travel at the edge of the flightline causes inaccuracies in the heights recorded. If left uncorrected, these inaccuracies result in an uneven "orange peel" effect of surface dimpling where flightlines overlap (see Crutchley 2010: pp. 26-27 and Figure 4). One of the most effective methods for correcting this is the Least Squares Matching (LSM) algorithm (Lichti and Skaloud, 2010:121), requiring.

2.1.3 BASIC AND ADVANCED PROCESSING

Filtering

ALS creates a dense point cloud of spot heights as the laser beam scans across the landscape, resulting in a zig-zag distribution of points each with an x, y and z value. The point cloud data can then be interpolated into two categories of terrain model: Digital Surface Models (DSM), give the surface of the topography (usually recorded from the first return per laser pulse), including buildings, trees etc.; and Digital Terrain Models (DTM) represent the bare earth surface stripped of vegetation, buildings and temporal objects such as cars (Briese, 2010) (Figure 5). For the purposes of disambiguation, both of these products can also be referred to as a Digital Elevation Models (DEM) as they represent elevation in its original units of height above sea level. Another common product is the Canopy Height Model (CHM) or normalised DSM (nDSM), which is defined as the bare earth surface subtracted from the first return DSM. In terms of the historic environment, while the DSM provides environmental context for the model and should always be viewed to identify areas where the data may be affected by dense vegetation, the DTM, or filtered model, is most commonly used to view the terrain that is otherwise masked by vegetation and as such it is worth discussing the processing required to create a DTM in more detail here.

The removal of non-terrain points is undertaken by classification of the point cloud into points that represent terrain and points that represent all other features. The non-terrain points can be identified and removed using a variety of algorithms that have been developed to automate this procedure. Sithole and Vosselman, (2004) provide a detailed evaluation of many filtering approaches with respect to their accuracy, which are found to be generally good for rural and level terrain but worse in complex urban or rough, vegetated terrain. This is because the simplest approaches apply only a local minimum height filter that leads to systematic errors in hilly or rough terrain (Briese, 2010:127). In addition, less sophisticated filtering techniques have been noted to remove archaeological features from the terrain model and add artefacts (Crutchley, 2010). Recently more sophisticated approaches have been developed, including segmentation-based methods and the identification of breaklines such as building edges as a pre-filtering step to improve the final interpolation, though as yet no fully automated procedure has been found that can be applied universally to all landscape areas (Briese, 2010:139). This means that manual checking and editing of the model is necessary to improve the results of the automated process, though this tends to be far more intensive in urban areas with complex local surface characteristics (ibid). It is worth noting that adaptive morphological methods such as those proposed by Axelsson (2000) and Chen *et al.*, (2007) are the filtering techniques used by Terrascan and LASTools software and so are likely to be the most common.

For full waveform data, the echo width and amplitude can be used to improve the classification and filtering process

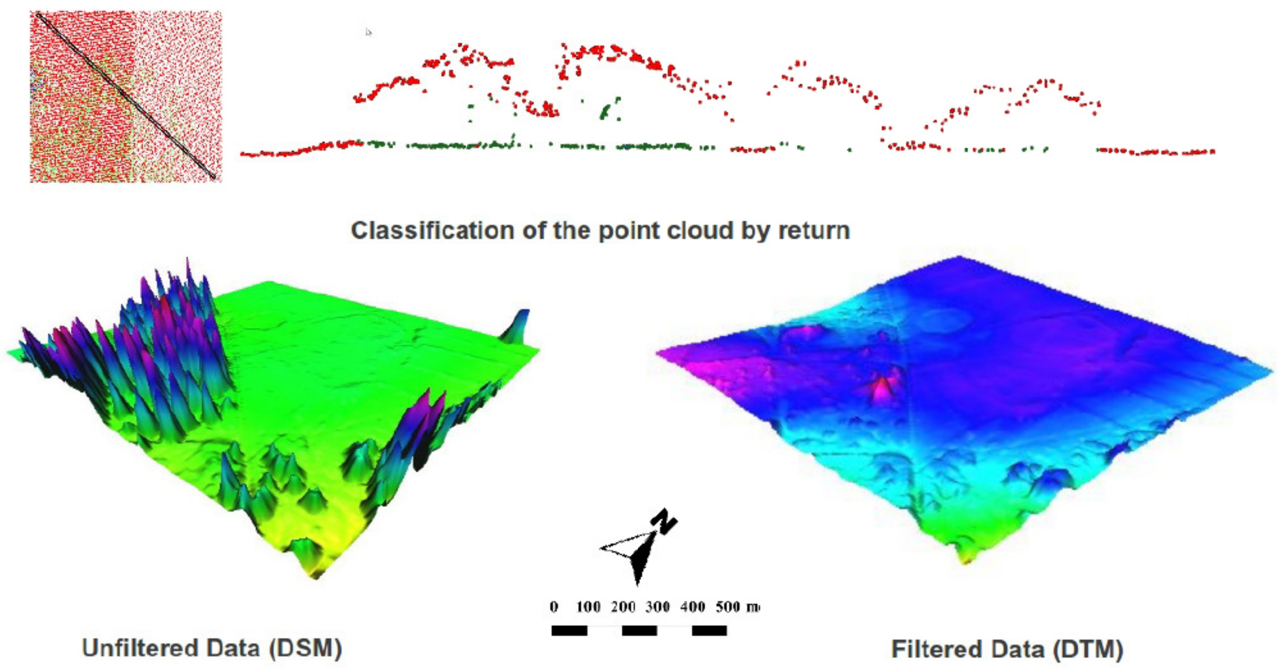


Figure 5. An example of classification of points based on return which forms the most basic method to filter non-terrain points from the DSM

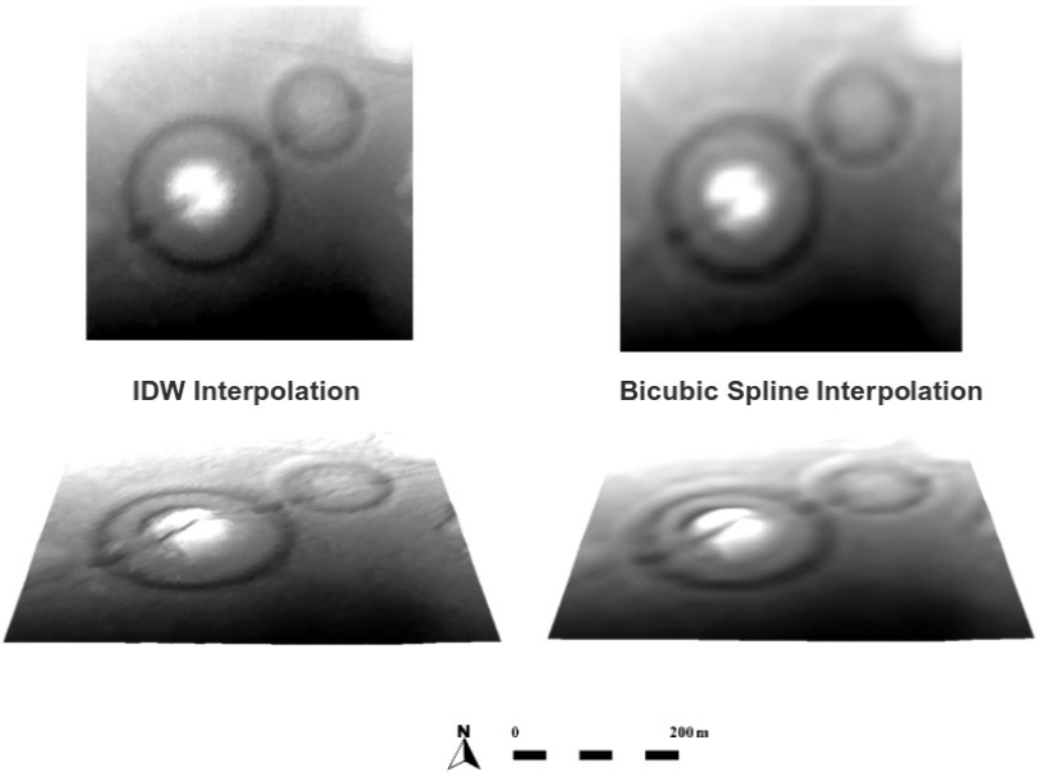


Figure 6. Two examples of common interpolation techniques: IDW (left) and Bicubic Spline (right)

particularly in areas of dense, low vegetation such as forest understory. Although these techniques are still in development they have been shown to be very effective at defining ground hits from low-level vegetation based on texture (Doneus and Briese, 2010).

Interpolation

Although the general morphology of a landscape is an important feature for archaeologists to observe, most individual sites and features representing past human interaction with the landscape can be observed as micro-topographic changes. Such features are difficult to visualise from the point cloud itself, so while the pre-processing steps described above use the point cloud, for visualisation the survey is most often processed by interpolating the x, y, z points into a 2.5D surface either as a raster grid or triangulated irregular network (TIN) format. Although a TIN or mesh is commonly used for terrestrial and object laser scanning (see Remondino this volume), for archaeological applications to date most ALS data are rasterised. Rasterisation is advantageous for the landscape researcher as it allows ALS data to be visualised, processed, interrogated and interpreted in a Geographical Information System (GIS) alongside a range of other geographical or archival data, such as historic mapping, aerial photographs and feature data derived from Historic Environment Records. The disadvantage of rasterisation is the loss of geometric complexity as described below.

The process of interpolating takes the data from a number of points to provide a height for a cell in the image (Figure 6). There are many methods of interpolation from the most basic operation of taking the mean, median, or modal height of the points within an area to complex weighting of points and incorporation of breaklines to negate the impact of smoothing when interpolating over sharp changes in topography (Briese, 2010:125). Any of the common interpolation methods can be used; typically nearest neighbour, inverse distance weighting (IDW), linear functions (regularised / bicubic or bilinear spline), or kriging are the most common. In practise determining the "best" interpolation method depends on the topography, so trialling a number of techniques on sample areas is often necessary. The accuracy of the interpolation models can best be assessed by the collection of ground-observation point via Real Time Kinetic (RTK) GPS survey. There is no 'standard' or 'best' method for the interpolation of point data to raster, but users should be aware that models created using different interpolation methods will represent micro-topography differently. Consequently if visualisation techniques are to be compared with each other they should all be based on the same interpolation technique.

2.1.4 INTENSITY DATA

In addition to height data, the ALS sensor also captures the intensity of the returned beam and there has been some speculation regarding the use of the intensity measure as a means to detect archaeological features with varying reflectance properties (Coren *et al.*, 2005; Challis *et al.*, 2011). While the intensity has been used for a number of studies including environmental applications

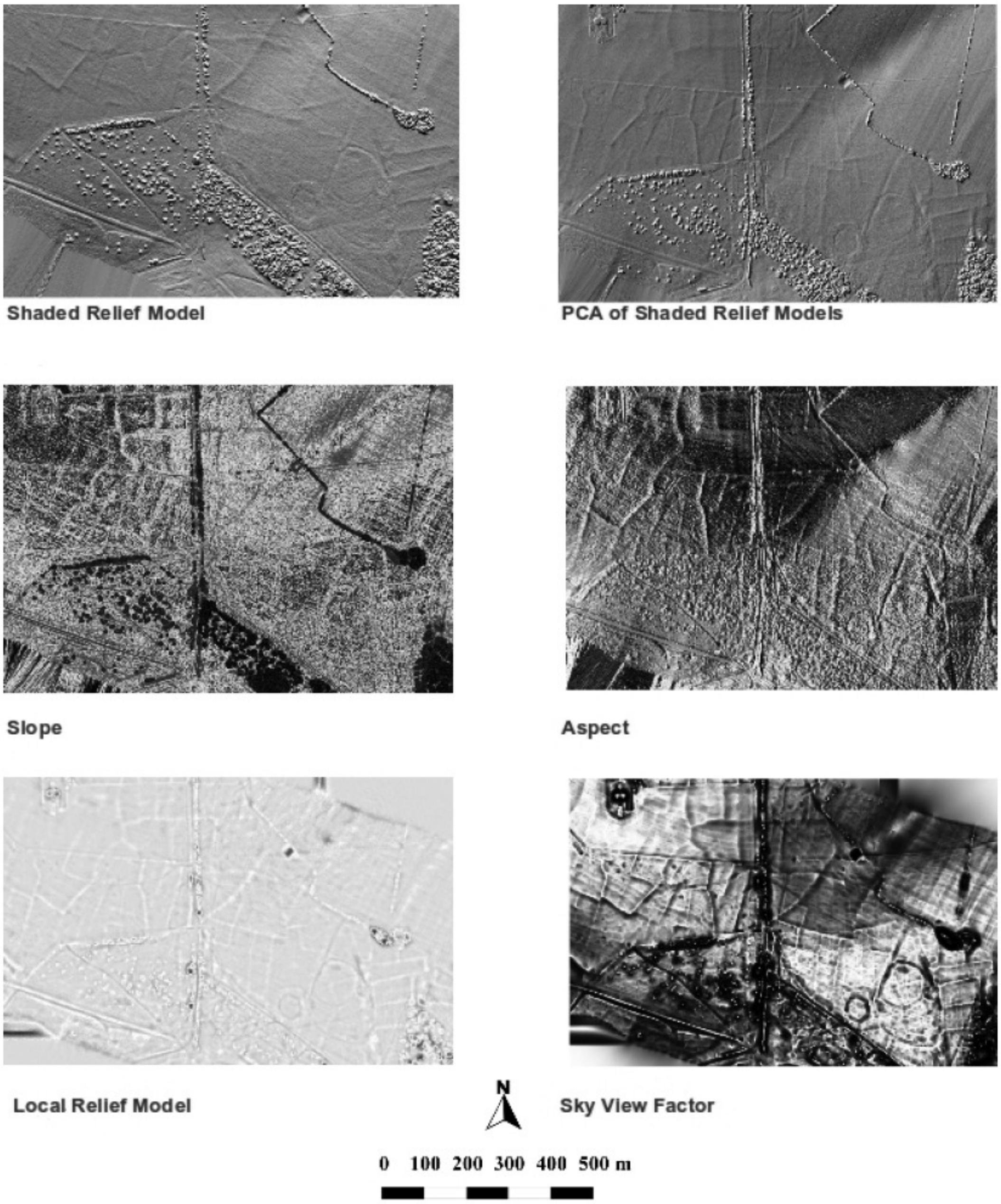


Figure 7. Comparison of visualisation techniques mentioned in this chapter

such as canopy determination (e.g. Donoghue *et al.*, 2007) and landcover classification (e.g. Yoon *et al.*, 2008) and earth science applications such as volcanology e.g. Spinetti *et al.*, 2009) and glaciology (e.g. Lutz *et al.*, 2003), there are an number of problems with its application to archaeological prospection at the present time. The foremost of these is the fact that the intensity measure is affected by many factors in addition to the reflectance properties of the target, including the range distance from the sensor to the target, the power of the laser, angle of reflection, optical properties of the system and attenuation through that atmosphere (see Starek *et al.* 2006) for a fuller discussion). Additionally recent research has shown that standard ALS wavelengths (generally between 800 nm and 1550 nm) are generally less sensitive for archaeological feature detection than shorter NIR wavelengths and due to the lack of calibration of most models of ALS scanner, the intensity bears little correlation to reflectance recorded at the same wavelengths by an airborne spectral sensor (Bennett, 2012).

Sensor technology is improving, with calibrated ALS / hyperspectral systems such as that developed by the Finnish Geodetic Institute (Hakala *et al.*, 2012) soon to be available commercially. Although these have yet to be tested regarding their application for archaeological research, it is anticipated that this new generation of combined sensors will provide higher quality spectral information than the intensity data currently collected. For now at least, the use of ALS intensity data for archaeological prospection is limited in scope by the factors listed above and users may find analysis of complementary data a more profitable use of time.

2.1.5 VISUALISATION TECHNIQUES

Due to their subtle topography, archaeological features can be difficult to determine from the DTM, even when the height component is exaggerated to highlight topographic change. To map these features some form of visualisation technique is required to highlight their presence in the DTM to the viewer. This section covers the most common forms of visualisation applied to archaeological research and explains their uses, and some pitfalls, for archaeological prospection. Figure 7 gives an example of each of the visualisation techniques mentioned below.

Shaded Relief models

The creation of shaded relief models is the most common process used to visualise ALS data for archaeology (Crutchley 2010). This technique takes the elevation model and calculates shade from a given solar direction (or azimuth) and altitude (height above the horizon – see Figure 8), thus highlighting topographic features (Horn, 1981). Shaded relief models provide familiar, photogenic views of the landscape and can be used to mimic ideal raking light conditions favoured by aerial photographic interpretors (Wilson, 2000:46).

Despite their frequent use and familiarity, shaded relief images pose some problems for the interpretation and mapping of archaeological features. Linear features that align with the direction of illumination will not be easily visible in the shaded relief model, requiring multiple angles of illumination to be calculated and inspected (Devereux *et al.*, 2008). To mimic raking light (and so highlight micro-topography) the shaded model must also be calculated with a low solar altitude, typically 8°-15°. This means that shaded relief models work poorly in areas of substantial macro topographic change, with deep shadows obscuring micro-topography regardless of illumination direction (Hesse, 2010).

Recent research by the author has also shown that the choice of both the azimuth and angle of light impact feature visibility in a quantifiable way. For example, altering the angle of the light from the "standard" output of 45° to 10° improved feature detection by 6%. Additionally when eight shaded-relief models with identical altitude illumination but varying azimuths were assessed a 12% difference in the number of detectable features was observed between the best and worst performing angles (see case study and Bennett, 2012). These differences result in the requirement to create and assess multiple models from a variety of illumination angles and azimuths; a serious expenditure of time for significant yet diminishing return. One of the proposed solutions to this is by statistical combination of the shaded-relief models through Principal Components Analysis (see below).

A final point to consider when using these models to plot potential archaeological features is locational inaccuracy. As the shaded-relief model is a computation of light and shade the perceived location of features alters as the angle of illumination is changed (Figure 9) as the observer plots not the topographic feature itself but the area of light or shade. This can lead to substantial locational inaccuracies, especially when using low angle light required to highlight micro topography (see case study).

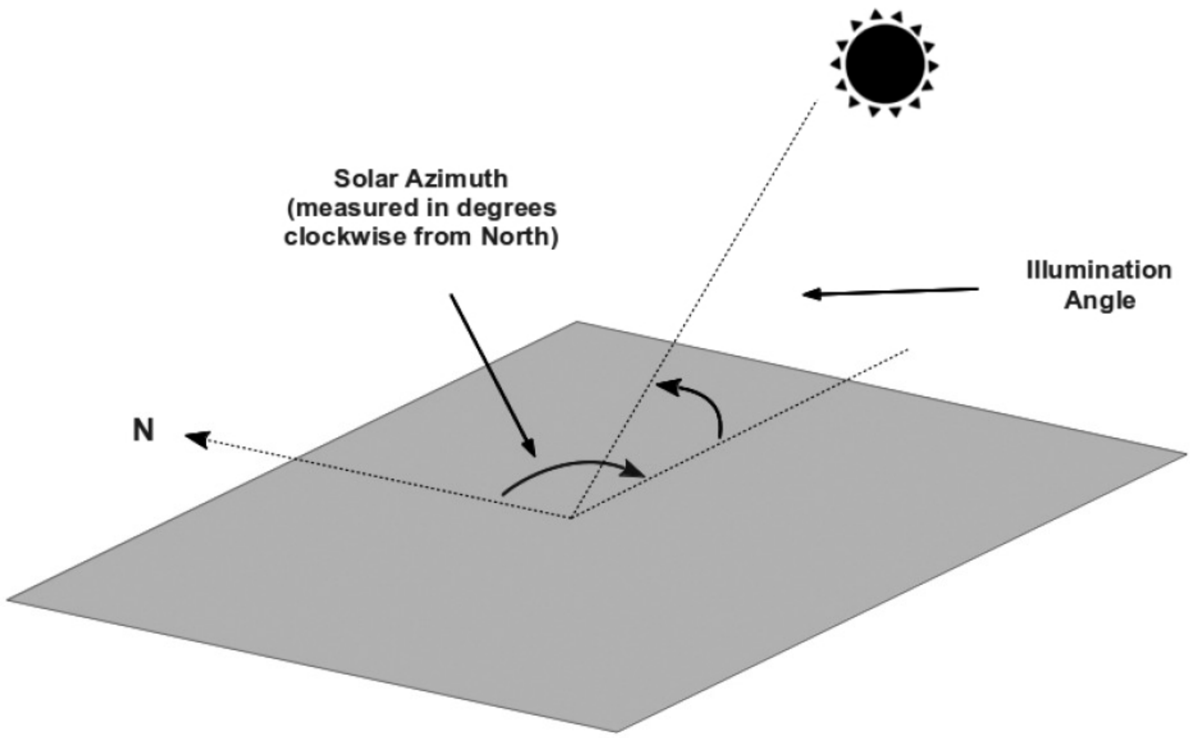
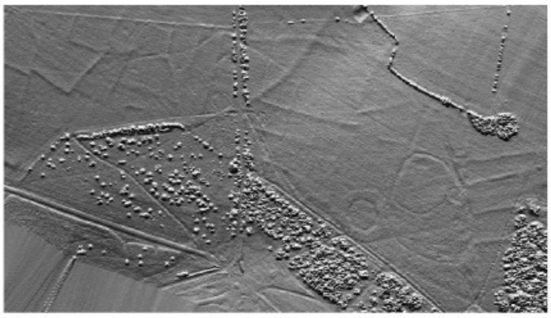
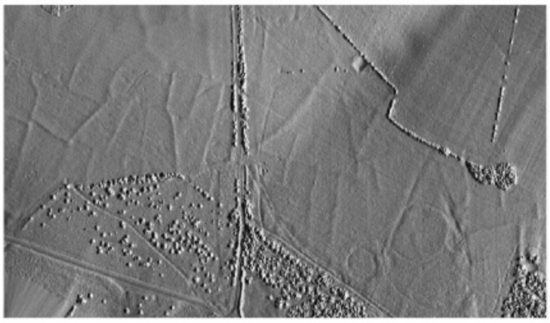


Figure 8. Angle and Illumination of a shaded relief model

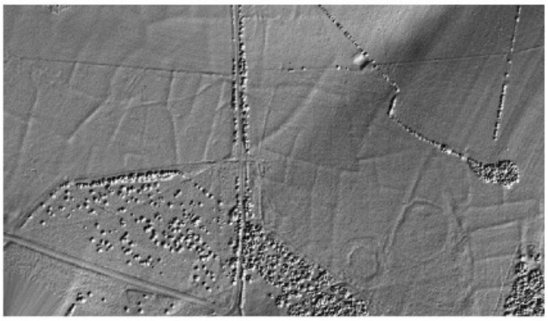


Shaded relief from 0° east of north

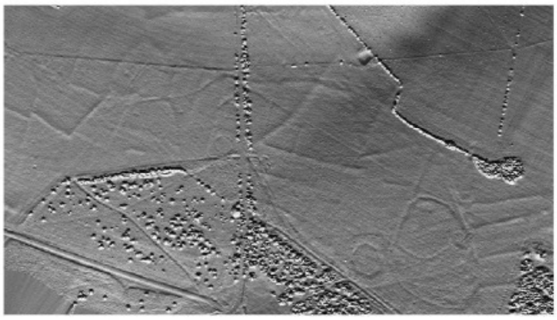
Shaded relief from 45° east of north



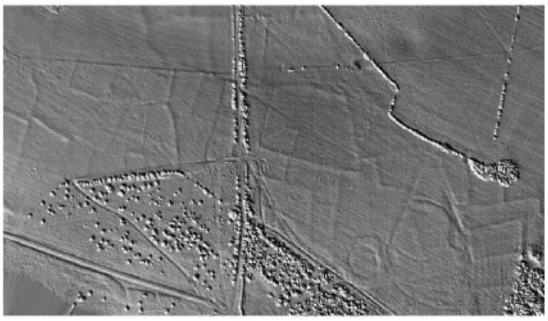
Shaded relief from 90° east of north



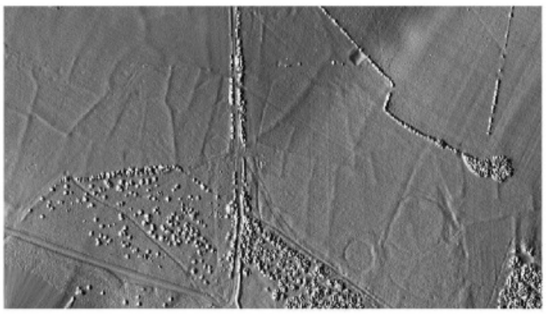
Shaded relief from 135° east of north



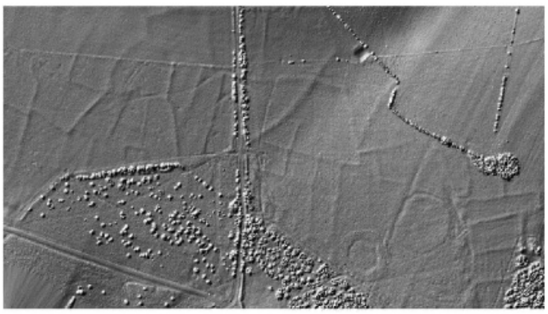
Shaded relief from 180° east of north



Shaded relief from 225° east of north



Shaded relief from 270° east of north



Shaded relief from 315° east of north

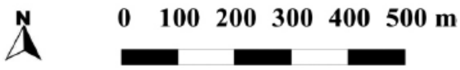


Figure 9. Different angles of illumination highlighting different archaeological features

In all the shaded-relief model provides an aesthetically pleasing view of the landscape for illustrative purposes but, due to the issues outlined above, it should always be combined with at least one other visualisation technique in order to map potential archaeological features.

Principle Components Analysis of Multiple Shaded Relief Images

Principle Components Analysis (PCA) is a multivariate statistical technique used to reduce redundancy in multidimensional or multi-temporal images. It has been skilfully applied by Kvamme to geophysical data (2006) and is used for minimising the number of images to be analysed. PCA has also received some attention in archaeological work (Winterbottom and Dawson, 2005; Challis *et al.*, 2008; Devereux *et al.*, 2008).

While the PCA transformation reduces the dimensionality of the shaded relief technique, the interpreter must still analyse a large number of shaded images to access the information content of the terrain model. Also, to ensure the most representative model of the topography, every possible angle and azimuth should be processed. At the time of writing this approach has never been undertaken; the only published method for using the technique with ALS shaded relief images used 16 angles of illumination at the same azimuth (Devereux *et al.*, 2008). The limit on the number of input images is principally due to the relatively diminished return of new information compared with the increased costs in terms of computation and interpretation time.

Principle component (PC) images represent statistical variance in light levels of the shaded relief models, rather than the topographic data collected by the sensor. While this might seem a pedantic distinction to make, the visibility of archaeological features is highly dependent on angle and azimuth of illumination. The PCA will reduce some of this directional variability but cannot account for the features that were poorly represented in the original shaded relief images. The output of the PCA will therefore be highly influenced by the selection of these factors at the outset and this could prove a limiting factor for subsequent interpretation. Consequently, the choices made in the processing of shaded relief and PC images (see above) may mask features that were present in the original ALS data. Additionally, for profiles drawn across archaeological features in a PC image, the z component of the profile will not be a logical height measurement as in the original DTM but a product of the statistical computation of varying light levels. While related to the topographic features, this light-level scale is unhelpful when trying to quantify or describe the feature as it is entirely dependent on the input parameters chosen for the shaded-relief models.

Although applying PCA to the shaded-relief images does reduce redundancy somewhat as the first PC will typically contain 95-99% of all variation in an image or data stack, it has been shown that significant archaeological information is detectable in subsequent PCs (Bennett *et al.*, 2012). As PCA can compute as many PC images to assess as original input images used, it is still necessary to assess multiple images to derive the full archaeological potential from this technique.

Slope and Aspect

Slope, aspect and curvature maps are commonly used for analysing topographic data in other geographic disciplines. Slope mapping produces a raster that gives slope values for each grid cell, stated in degrees of inclination from the horizontal. Aspect mapping produces a raster that indicates the direction that slopes are facing, represented by the number of degrees north of east.

Although common for geographical applications, there has been limited application of slope, aspect and curvature mapping for the detection of micro-topographic change relating to archaeological features, though low resolution aspect and slope terrain maps are well established in predictive models of site location (Kvamme and Jochim, 1989; Challis *et al.*, 2011). It is anticipated that topographic anomalies relating to archaeological features will be identifiable in these images, in particular the slope and aspect maps may aid pattern recognition for features such as the lynchets of a field system.

Horizon Modelling or Sky View Factor

To overcome some shortfalls of shaded relief models, specifically the issues of illumination angle and multidimensionality of data, the technique of horizon or sky view factor (SVF) has been applied recently by researchers in Slovenia (Kokalj *et al.*, 2011). The calculation is based on the method used to compute shadows for solar irradiation models. The algorithm begins at a low azimuth angle from a single direction and computes at what point the light from that angle 'hits' the terrain. The angle is increased until it reaches the angle where it is higher than any point in the landscape (on that line of sight). This procedure is then replicated for a specified number of angles producing a number of directional files which can then be added together to produce a model that reflects the total amount of light that each pixel is exposed to as the sun angle crosses the hemisphere above it. Consequently, positive features appear brighter and negative features are darker, replicating the visual results of the shaded relief models but without bias caused by the direction of illumination. As with all light-level techniques, the SVF preferentially highlights negative features, does not provide a direct representation of topographic change and additionally has been noted to accentuate data artefacts more than other techniques (Bennett *et al.*, 2012).

Local Relief Modelling (LRM)

While shaded models provide useful images, there has been much recent emphasis on developing better methods for extracting the micro-topography that represents archaeological or modern features from the landscape that surrounds them while retaining the height information as recorded by the sensor. One of these methods, Local Relief Modelling or LRM devised by Hesse (2010) for analysing mountainous and forested terrain in Germany, has received particular attention. The technique reduces the effect of the macro-topography while retaining the integrity of the micro-topography, including archaeology-cal features by subtracting a low pass filtered model from the original DTM and extracting features outlined by the 0m contour. The advantage of this technique over the others mentioned is that it allows the creation of a model that is not only unaffected by shadow but which retains its topographic integrity allowing measurements to be calculated from it in a way that is not possible using shaded relief models, PCA or Horizon View mapping. However the extent of distortion of the micro-topographic feature extracted has yet to be quantified as the development of the model took place without any ground control data.

Although developed for mountain environments, the technique has also be applied to gently undulating landscapes to highlight archaeological features (see case-study). Due to the isolation of the microtopography the LRM model could also have the potential to be used as a base topographic layer for digital combination with other data.

Selecting a visualisation technique

Unfortunately for users of ALS data, there is no "perfect" visualisation technique for identifying archaeological topography. However, thanks to the development of techniques such as the LRM and SVF described above, archaeologists now have access to both generic and specific tools to visualise ALS data. Understanding how and when to apply these techniques is not an easy task and until recently there was little published comparative data meaning that users could not assess the appropriateness of any technique for their research environment. To this end readers are advised to consult the case study presented with this chapter, which focuses on the comparison of ALS visualisation techniques for a site on the Salisbury Plain, Wiltshire, UK (see Bennett *et al.*, 2012 for a further publication relating to this).

While only one environment, grassland, is assessed by this work undertaken on the Salisbury Plain, it provides the only quantitative information published to date regarding the varying visibility of individual archaeological features in shaded-relief, slope, PCA, LRM and SVF visualisation. The case study and published paper give details of how various techniques affect position, scale and accuracy of the archaeological features represented along with a discussion of the nature of "false positives" or artefact features whose presence was enhanced by certain visualisation techniques.

Two other recent publications have also addressed this issue. Challis *et al.*'s (2011) paper presents the results of visual analysis from four different locations, covering a range of six processing techniques – colour shading, slope, hill-shading (shaded-relief), PCA (of shaded-relief models), terrain filtering (LRM) and Solar Insolation (SVF). Although the fact that the latter techniques are not referred to by the most recently published names may confuse some readers, the publication provides very useful information regarding processing software and a workflow to guide users through visualisation selection in high and low relief landscapes.

Štular *et al.*, (2012) present the results of similar analysis of a range of techniques for an area of known sites in a wooded, mountainous environment. These include colour-ramped DTMs, slope, LRM (termed here as trend removal) SVF and a number of variants of solar-illumination They also incorporate a survey of 12 users with a range of experience in ALS data interpretation and propose a method of quantifying efficiency of the techniques by means of assessing contrast between cells of the image using the median of five different standard deviations. Noise is also calculated using the standard deviations of the standard deviations although there is little further explanation of how this enabled the authors to quantify contrast and noise.

These comparisons all conclude that there is no silver bullet, but the papers agree on the following points:

- Although visually pleasing and the most commonly used visualisation technique shaded-relief modelling is a poor method for identifying and accurately mapping archaeological features
- Multi-method analysis is recommended, with LRM and SVF and slope shown to be valuable techniques
- Users should try to familiarise themselves with the potential pitfalls of any technique prior to its application
- The most effective and appropriate selection comes from the trial of a number of visualisation techniques for a given environment.

Consulting the existing comparative papers by Challis *et al.*, (2011); Bennett *et al.*, (2012) and Štular *et al.*, (2012) is a good place to start, but visualisation techniques will need to be tailored to the landscape surveyed and type of feature to be detected. It is recommended that a pilot study is undertaken using a number of sample areas of <1 km^2 across the survey, to visually assess a number of the listed visualisation techniques and their suitability for feature detection in that environment (Štular *et al.*, 2012). Bear in mind also that the most complete results in terms of feature mapping have been demonstrated by the use of multiple visualisation techniques, Hesse (2010) recommends using both LRM and shaded-relief models for mountainous terrain, while Bennett *et al.*, (2012) report that a combination of LRM and SVM provided the most comprehensive visualisation for feature detection in a grassland environment when compared with a range of other techniques. Another advantage of this approach is that artefacts and interference patterns in the data are often easier to identity as anomalies when comparing two visualisations.

2.1.6 SOFTWARE CONSIDERATIONS

There are a number of viewing and processing tools available to users of ALS data, by far the most powerful and accessible of which at the time of writing is the open-source LASTools suite developed by Martin Isenberg (http://lastools.org). LASTools can be used as a stand-alone series of processing modules or be integrated as a toolbox in ArcGIS and QGIS. The value of ALS data lies in its geographic and morphological accuracy, therefore it is most appropriate to use these data as a GIS layer, to enable overlay with other forms of data. A range of GIS software, both proprietary and open-source, is available to do this, all of which should be capable of producing shaded-relief imagery from a DTM. However for the more specialised visualisations like SVF and LRM, the processing becomes more complex. In some cases users must apply external tools, for example an IDL module for the creation of SVF models (http://iaps.zrc-sazu.si/en/svf#v), or be comfortable creating a workflow for multi-stage models such as LRM across multiple software (Hesse 2010) or as a script process in GRASS (see the Appendix A of Bennett 2012 for details of the GRASS workflow). Although work is in progress on a stand-alone application to assist with creating multiple advanced visualisation techniques, currently a good knowledge of raster data processing is essential and this inhibits the wider application of advanced ALS visualisations.

2.1.7 CONCLUSIONS

Through the course of this chapter a number of key factors to consider when using ALS data for historic environment assessment have already been raised. Users must be aware of issues such as mode of capture, resolution and pre-processing of the ALS data, all of which should be made clear by the provision of adequate metadata by the data supplier. Attention should be given to the original purpose of the data, usually hydrological or environmental monitoring, and any filtering that has been undertaken and how this might affect the representation of archaeological features. This is not to say that archive data collected for other purposes is not useful to archaeologists, (the ever-increasing number of studies testify this is clearly not the case) rather that users of the data should familiarise themselves with the technical details and make clear the processing applied to a dataset.

Together with the case study and articles referenced, this chapter provides a starting point from which to begin to understand the visualisation techniques that are most appropriate for your research. However it is also important to remember that ALS data captures only part of what is archaeologically significant within a landscape. Features such as vegetation marks or soil change that are detectable using aerial photographs or in digital spectral data will not be represented in ALS data unless they also show a distinct topographic change from their surroundings. Consequently, ALS data is most effective when used as part of a multi-sensor approach that also incorporates aerial imagery. Bennett *et al.*, (2011, 2013) provide details and discussion of the key role that ALS data can play when incorporated into this type of landscape study.

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7.4 AIRBORNE LASER SCANNING FOR ARCHAEOLOGICAL PROSPECTION – A CASE STUDY IN THE USE OF ARCHIVE ALS DATA FROM THE SALISBURY PLAIN WILTSHIRE, UK

Rebecca BENNETT, Kate WELHAM, Andrew FORD and Ross A. HILL

7.4.1 INTRODUCTION

This case study uses the work of a doctoral research project at Bournemouth University from 2009-2011 looking at the use of airborne remote-sensing (ARS) techniques for analysis of the historic landscape of a chalk grassland environment. As will be shown the ALS data made a significant contribution not only to the number of features identified but also to understanding the contribution of various airborne sensors. The project is somewhat a-typical in that it focussed on the technical aspects of the application of ALS data rather than purely site prospection but in this case study readers will see clear links to some of the issues discussed in Chapter 2.

7.4.2 BACKGROUND

The Salisbury Plain Wiltshire, England comprises 39,000 hectares of the rolling chalk outcrops of the Plain and is owned and managed by the Ministry of Defence as the largest training area in the UK (Figures 1 and 2). The archaeological landscapes of this area are remarkable both for their location between the World Heritage status prehistoric landscapes of Stonehenge and Avebury and for the outstanding preservation of their archaeological features. Purchased by the War Office following the agricultural depression of the late 19th century, the Plain is the last area of chalk grassland that remains predominantly unaffected by agricultural intensification. The Plain is also remarkable for the quality of previous and ongoing archaeological investigations, which have characterised the nature of the archaeology through aerial, ground based metric and geophysical survey, providing an excellent baseline record. The area is generally well understood with a number of previous archaeological investigations, including full mapping of the aerial photograph archive by the National Mapping Programme (NMP) and the trial application of airborne remote sensing for environmental conservation (Crutchley 2002; Barnes 2003). Barnes' initial work looking at the application of digital spectral (in the form of CASI) and ALS data established that many known archaeological features could be seen in the airborne data that was collected primarily for vegetation condition mapping (2003:86). The NMP transcription of features from the aerial photographic archive provided the baseline for comparison of ALS data via the GIS layers held by Wiltshire HER.

The aims of the project as applied to the processing of the ALS data was to compare a range of visualisation techniques with regard to their application to archaeological sites in grassland environments. This aim reflected the fact that a number of visualisation techniques had been proposed in the archaeological literature but as yet there was no quantitative comparison to enable informed choices about the

7.4.3 DATA AND METHOD

The ALS dataset used for this project was collected by the Environment Agency of England and Wales (EA) in November 2005 for hydrological purposes using the Optech ALTM 2033 sensor. These data covered and area of 4 km^2 south of the village of Everleigh and were of 1m resolution.

The ALS data were supplied in the form of eight space-delimited, last return, ascii files containing x, y, z and intensity values, and were gridded to a 1m resolution Digital Elevation Model (DEM) using the last return of the laser pulse. No metadata were available for ALS survey, so original point density is unknown. The data were not filtered to remove vegetation as the Everleigh study site comprised open fields with little scrub.

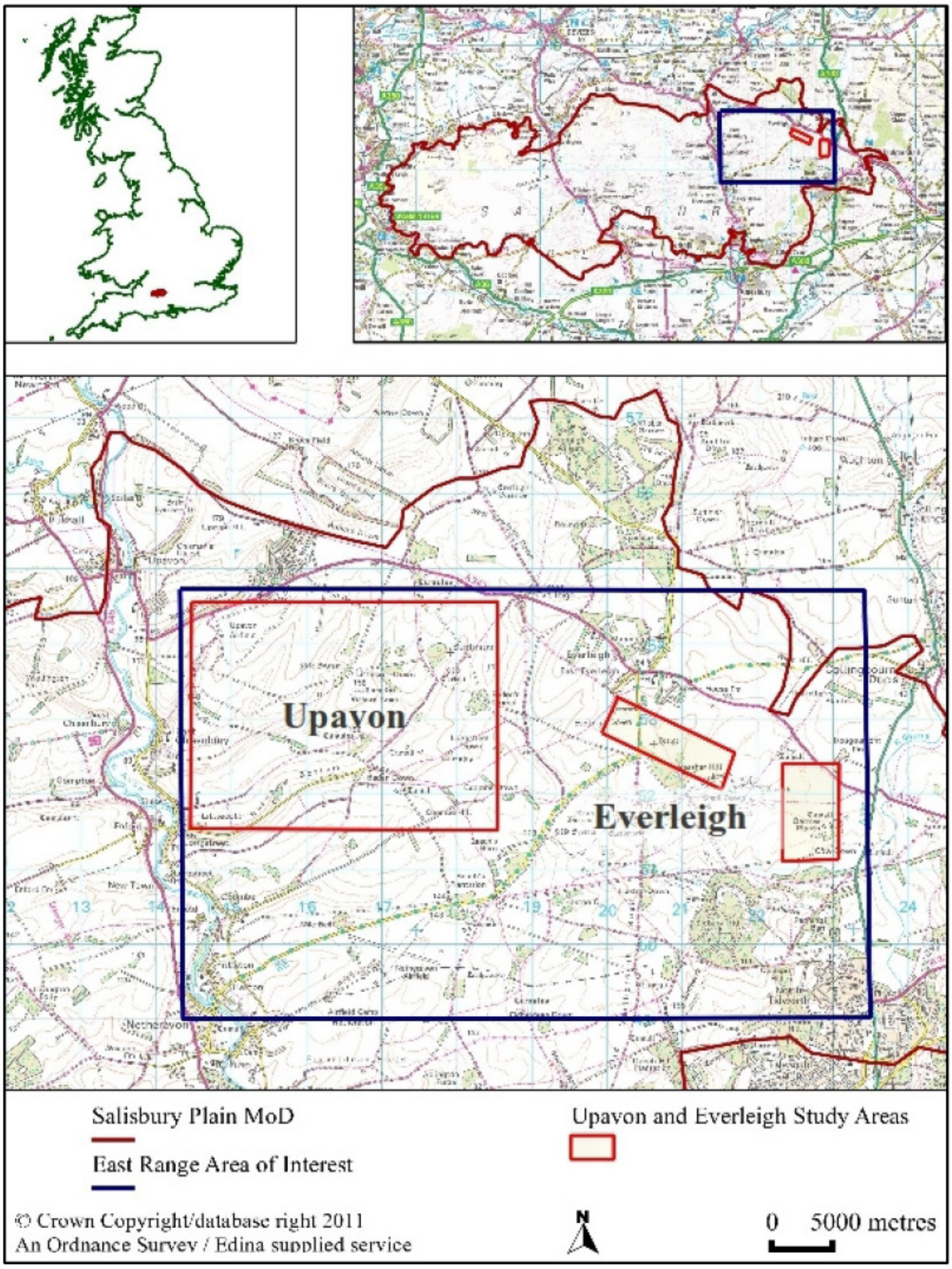

Figure 1. Location of the Salisbury Plain study areas

Figure 2. A view west across the East Range of the Plain in the vicinity of the study areas

The topographic data were interpolated using a simple inverse distance weighted (IDW) nearest-neighbours method, most suitable for near continuous point data, producing a raster with 1m resolution. While this technique is not as accurate as some others (Mitasova *et al.* 2005), it provides a quick, mathematically simple and robust method for processing the large dataset. It is also the most commonly used method of interpolation, available in identical form across many software platforms, including ArcGIS and ENVI, and as such provides a baseline for comparison of visualisation methods. The rasterized ALS data were then processed in GRASS 6.4 (GRASS Development Team, 2010) to create six common visualisations as outlined in the Table

Table 1. Details of ALS visualisation models used for the Everleigh data

Technique	Acronym	Brief Description	Source
Shaded Relief Model	None used	Shaded relief modelling takes the elevation model and calculates shade from a given azimuth and altitude, thus highlighting topographic features.	(Horn 1981)
Slope	None used	Slope mapping produces a raster that gives slope values for each pixel, stated in degrees of inclination from the horizontal.	(Jones 1998)
Aspect	None used	Aspect mapping produces a raster that indicates the direction that slopes are facing, represented by the number of degrees north of east.	(Skidmore 1989)
Principal Component Analysis of Shaded Relief Models	PCA	PCA is a multivariate statistical technique used to reduce redundancy in multiple images. The product is a series of images representing statistical variance in the light levels of the original shaded relief images.	(Devereux *et al.* 2008)
Local Relief Modelling	LRM	LRM was developed for mountainous regions and produces a model where the affect of the macro-topography is reduced while retaining the integrity of the micro-topography.	(Hesse 2010)
Horizon Modelling	None used	Horizon Modelling is a visualisation technique based on diffuse light. The product is a representation of the total amount of light that each pixel is exposed to as the sun angle crosses the hemisphere above it. It synonymous with the Sky View Factor (Kokalj *et al.* 2011).	(Kokalj *et al.* 2011)

1. Illustrations of these visualisations are given in Figure 7 of the main chapter and so are not repeated here.

PCA of Shaded Relief Images

The PCA of the eight shaded relief images created was created using the i.pca module in GRASS. Features were mapped from each PC viewed as a grayscale raster to allow comparison of detectability between the components. The PC images were not digitally combined into a colour composite. The spatial records from all the PC images where features were detectable were also combined to create a single dataset for comparison with other techniques.

Horizon or Sky View Mapping

Horizon or sky view models reflect the total amount of light that each pixel is exposed to as the sun angle crosses the hemisphere above it; consequently positive features appear brighter and negative features are darker. The models were created using the r.horizon module.

For the Salisbury Plain study a number of horizon view models were created, with varying step sizes of 7 m, 10 and 30 m. The step size is a parameter of the algorithm that reflects the size of the smallest feature that could be mapped; 7 m and 10 m models reflect the expected size of the smallest archaeological feature that could be recognised in the landscape (and also the kernal size used for the local relief models, see below), while the 30 m model was selected for comparability with published examples. The model was calculated using intervals of 45° as with the shaded relief models.

Local Relief Modelling

The workflow implemented to create the LRM is detailed in Table 2. The size of the kernal is chosen to reflect the expected size of the microtopography that is to be removed, in this instance kernal sizes of 7 m, 9 m and 30 m were trialled. The processing steps of the LRM are detailed in Table 2. Although the Hesse's paper states that a number of software packages were combined to undertake the workflow, for the Everleigh project all the stages were computed using GRASS 6.4 using a custom script written for the task.

Feature Transcription

The raster visualisation detailed above were opened in QGIS 1.7 (Quantum GIS Development Team, 2010) and archaeological features were transcribed to a shapefile. Features were recorded to NMP standards however for this study, lynchet features comprising field systems were considered as single entities rather than recording a single feature for each system. In addition to the 2D display of the raster image, the features were cross-sectioned using the profile plugin allowing a description of their form as well as their plan and significantly aiding feature type interpretations (Figure 3).

The visibility of features in the visualisations was compared both in terms of binary visibility (whether a feature was detectable or not in the visualisation) and average percentage feature length (APFL) (how much of the feature was detectable, recorded as a percentage of the maximum known length of feature visible in any ARS including the NMP mapping and multispectral data).

Table 2. Workflow for the creation of a Local Relief Model, after Hesse 2010

Stage	Description	Project Specific Information & GRASS Tools Used *(in italics)*
1	create Digital Elevation Model (DEM) from the ALS point cloud	Base DEM interpolated using IDW, nominal resolution of 1 m *v.surf.idw*
2	Apply a low pass filter (LPF)	A 7 x 7 m low pass filter was applied to the DEM (matrix as per Neteler *et al.* 2008:308) *r.neighbors*
3	Subtract LPF from original DEM	This creates a difference map which highlights local relief variations however it is biased towards small features *r.mapcalc*
4	Extract the zero metre contour from the model created in Stage 3	To delineate positive and negative changes in local elevation *r.contour*
5	Extract elevations from the original DEM along the contour lines created in Stage 4 and interpolate a new DEM	DEM interpolated using IDW. This model will be purged of small-scale features *v.to.pointsv.what.rastv.surf.bspline*
6	Subtract the purged DEM created in Stage 5 from the original DEM	This results in an enhanced local relief model which is less biased towards small scale features *r.mapcalc*

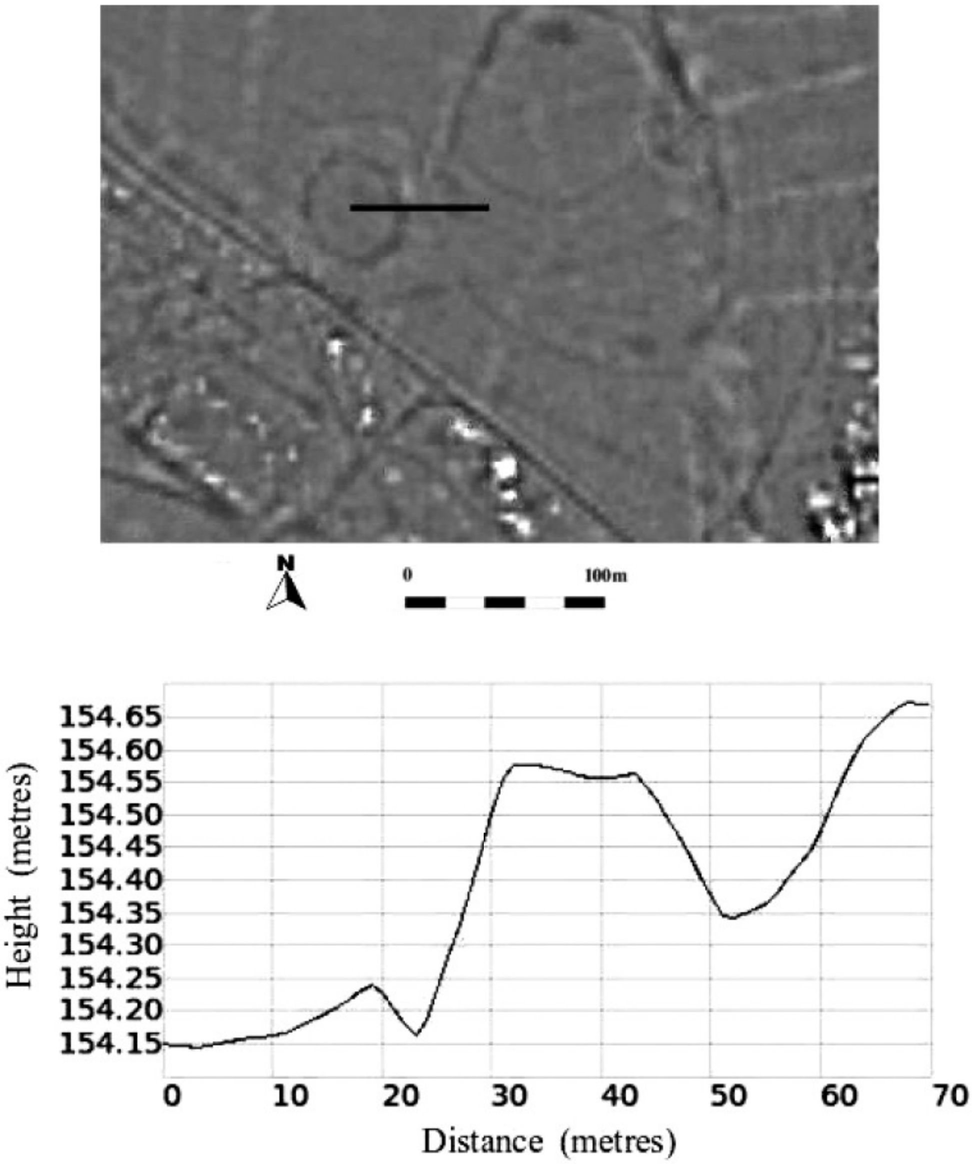

Figure 3. Profile of ground surface across a henge monument in the study area. Location illustrated (top) and plotted (bottom)

7.4.4 RESULTS

The quantitative comparison of feature visibility across a number of visualisations gave insight into the application of each visualisation and their comparative usefulness. For example, by mapping features from each shaded-relief model individually it was observed that changing the altitude of the sun in the model from 45˚ to 10˚, 6% more features were detectable. In comparison altering the direction (angle east of North) from which the model was illuminated caused a 12% difference in the number of features mapped between the best and worst performing angles. Such comparisons help to clarify the relative importance of angle vs. azimuth. A summary of the key results is presented below; a fuller discussion can be found in Bennett *et al.* (2012).

Feature Visibility

Combining the results of all the visualization methods, a total of 122 topographical features were mapped from the ALS models, in comparison with 89 features that were known from the NMP data. This increased the number of known features by 37%. In total 76% of the features mapped in the NMP were also recorded in the ALS data. The general complementarity of different modelling techniques is shown by the fact that no single technique recorded more than 77% of the total number of features identified (Figure 4). When two of the best performing techniques were combined however this rose to 93%. T he PCA, LRM and SVF models outperformed the slope and aspect models in terms of number of features recorded. The length of featured that was detectable (APFL) was almost identical across the visualisations (Figure 4).

One of the important outcomes of this project came from the analysis of profiles used to aid feature identification. As illustrated by Figure 5 the representation of elevation varied dramatically between visualisations which changes in both the scale and position of archaeological features (Figure 5). Of particular note were the inconsistent horizontal shifts of up to 5 m in the position of positive and negative features (banks and ditches) in each of the PCA images when compared with the original DEM. This shift is caused by directional bias introduced to the representation of the features via shade or brightness when using a moving light source and makes accurate location mapping from this type of visualisation impossible.

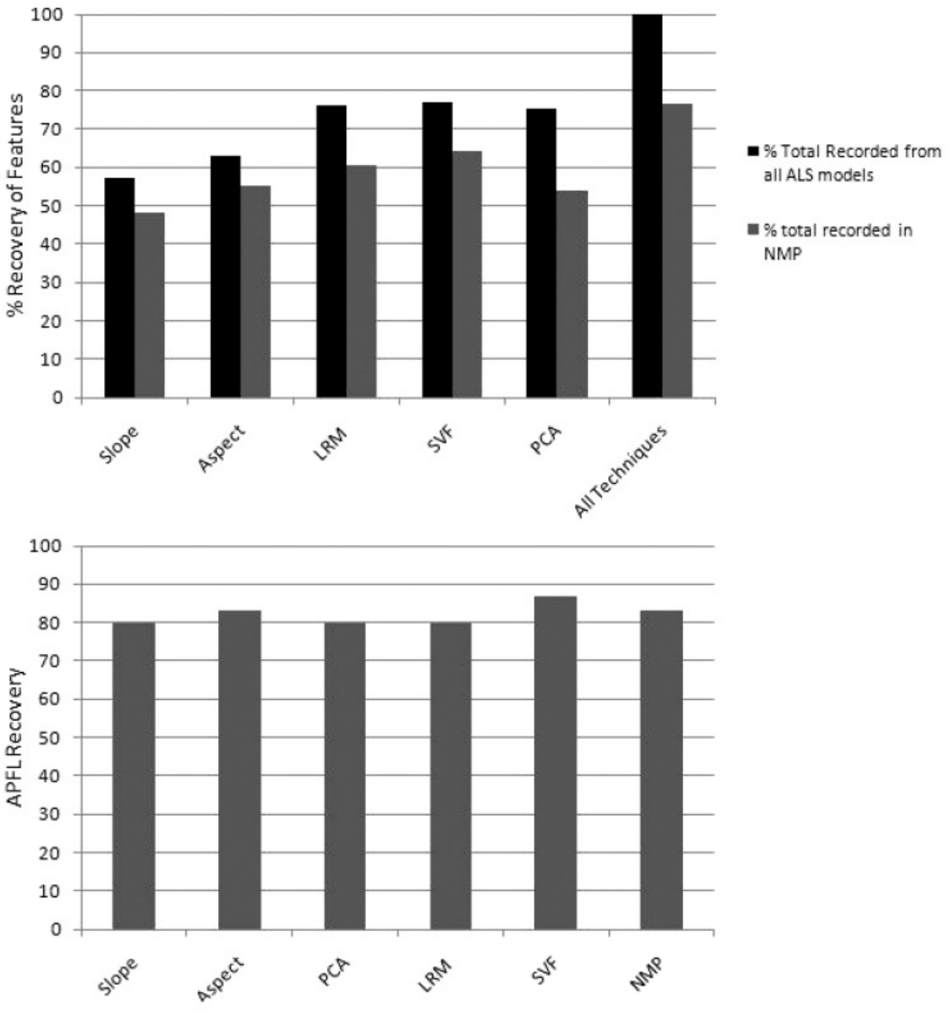

Figure 4. Charts illustrating % feature recovery by visualisation technique (top) and Average Percentage Feature Length detectable by visualisation technique (bottom Positional Accuracy and Scale (bottom)

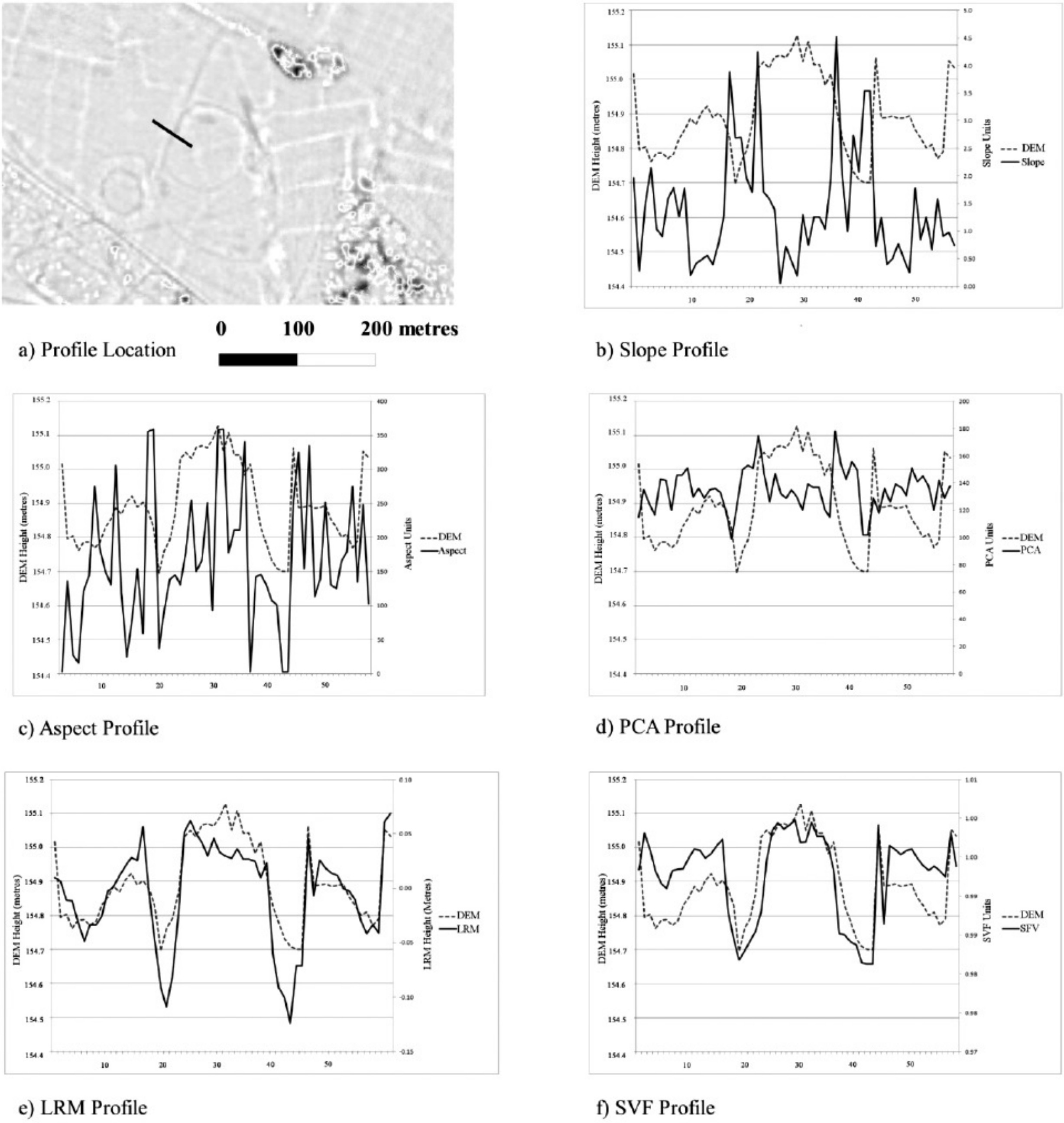

Figure 5. Illustration of the impact of the visualisation techniques on feature location and scale compared with the DTM

The scale represented in visualisations can also be an issue as in all except the LRM, the visualisations represent the factors such as light and aspect that are related to elevation change but do not directly represent it in the original units. While useful indicators of topographic change, with no logical scale these can be difficult to interpret archaeologically.

7.4.5 CONCLUSIONS

Comparing ALS visualisations in this way outlined above contributed significantly to the understanding of how to apply previously published techniques to the Salisbury Plain Landscape. The work illustrated some of the pitfalls of various techniques, bearing in mind the aim of most archaeological survey is to quantify, locate and interpret the topographic features represented in the visualisations. In conclusion it was determined that wherever possible more than one visualisation technique should be used, and that visualisations that allow intelligible profiles to be drawn across features (LRM) are preferred for aiding feature interpretation.

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