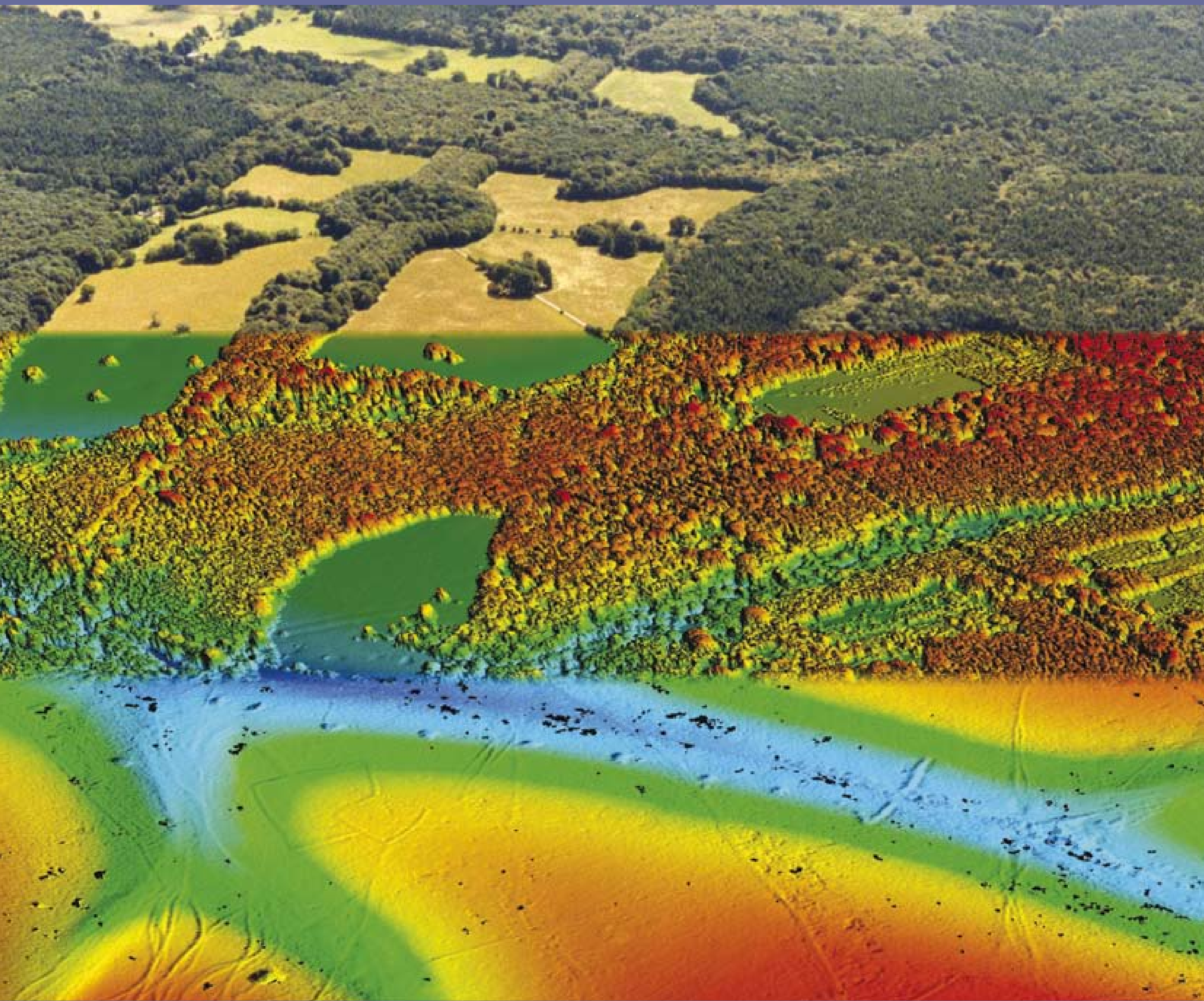
2010

The Light Fantastic

Using airborne lidar in archaeological survey



ENGLISH HERITAGE

Contents

Preface

These guidelines are designed to help those intending to use airborne laser scanning (ALS), also known as lidar, for archaeological survey. The aim is to help archaeologists, researchers and those who manage the historic environment decide first whether using lidar data will actually be beneficial in terms of their research aims and then how it can be used most effectively. The guidelines will be most useful to those who have access to data that have already been commissioned, or are planning to commission it for a specific purpose. They also provide an introduction to the interpretation of the data to separate archaeological and non-archaeological features.

Although the main themes will be introduced, these guidelines are not intended as a definitive explanation of the technique or the complexities of acquisition and processing of the raw data, particularly as this is a still developing technology. This document is intended to be complementary to the Heritage3D guidelines, which cover the wider range of uses of laser scanning for heritage purposes.

Part 1
What is lidar and what does it do?

1 What is lidar? A brief history and introduction to technology

Lidar, like radar, is an acronym and stands for light detection and ranging, which describes the method of determining three-dimensional data points by the application of a laser. It is a Remote Sensing technique, using either ground-based (Terrestrial Laser Scanning (TLS)) or airborne systems (Airborne Laser Scanning (ALS)), and is also referred to as Airborne Laser Swath Mapping (ALSM); in some military contexts it is known as LaDAR (Laser detection and ranging). For the purposes of this guidance note the term lidar will be used.

In its broadest sense lidar refers to a much wider spectrum of techniques than can be addressed in this note, and can be used from static or moving platforms including aircraft and vehicle mounted scanners. It is the application of aerial systems to which these guidelines refer.

As with many technologies that have since been turned to uses within the commercial and domestic sphere, lidar had its origins in the military. Although some of the first uses for laser beams tested by the military utilised high-power beams in attempts to destroy missiles etc, the modern concept of lidar grew from a somewhat less destructive idea. Following on from the concepts behind radar, Airborne Laser (or lidar) Bathymetry (ALB) grew out of efforts in the mid 1960s to use the newly invented laser to find submarines. Tests were carried out in the 1970s and by the 1980s there were operating systems in the US, Canada and Australia. Current models of bathymetric lidar, specifically the US Geological Survey SHOALS system (Scanning Hydrographical Operational Airborne Lidar Survey), can map topography above and below the surface of the water, down to a depth that is roughly equivalent to three times the visible depth. While bathymetric lidar was being developed, the concept was also extended to topographic lidar for measuring surfaces on land.

One of the key reasons behind the delay in implementation lies in the nature of the lidar technique. As is explained in greater detail below, the core constituent of the lidar system only measures relative position by recording the time taken for a single laser pulse to be fired from a sensor array, strike the surface of an object below and be detected as a reflected signal. It is only possible to calculate the actual location on the ground by knowing the exact position of the sensor array at the time that it fires and records the beam. Previously, from the 1960s, Transit (or NAVSAT – Navy Navigation Satellite System), the world's first operational satellite navigation system, had enabled positional accuracy of *c* 200m, but this was insufficient for the purposes of lidar. The launch of the Navstar System, together with improvements in the development of IMUs (Inertial Measurement Unit, which records the pitch, roll and yaw of an aircraft), introduced accuracy of a sufficient level to make lidar a practical reality. Early systems were developed at NASA and commercial models became available in the mid-1990s.

In this country the Environment Agency (EA) began using topographic lidar shortly after it became available with their first surveys carried out south of Coventry in December 1996. Mapping began in earnest in 1998 when they surveyed *c* 3000 km^2 and has continued since that date.

The Environment Agency has used the lidar data for the production of cost-effective terrain maps suitable for assessing flood risk. While their standard 2m resolution data (one data point for each $2m^2$), an example of which is shown in Figure 1, were the norm until recent years and was entirely adequate for measuring large-scale topographic changes for flood modelling etc, it was generally considered that this resolution would not be suitable for the identification of a wide range of archaeological features. This assumption was based on previous experience in examining satellite imagery at a similar resolution. In fact, prior to 2000 it seems that the archaeological community in the UK had not even considered the possibility of using lidar for archaeological survey and indeed very few had even heard of the technique.

Lidar is currently used in a wide range of scientific applications such as the detection of atmospheric constituents. One of the many general descriptions of what you can do with lidar available on the web is given by M7 Technologies, a company that carries out research into laser-based measuring techniques, and shows the breadth of its interpretation; it states that lidar can 'measure distance, speed, rotation, or chemical composition and concentration of a remote target where the target can be a clearly defined object, such as a vehicle, or a diffuse object such as a smoke plume or clouds' (http://www.m7tek.com/terminology.htm). Elsewhere on the web various sources report that there are three basic types of information that can be obtained:

Fig 1 The Roman fort at Newton Kyme, North Yorkshire showing as a slight earthwork (© Environment Agency copyright 2008. All rights reserved).

- range to target (Topographic Lidar, or Laser Altimetry)
- chemical properties of target (Differential Absorption Lidar)
- velocity of target (Doppler Lidar)

Differential absorption will be briefly covered under the heading of Intensity Data, but otherwise these guidelines mainly relate to the use of the topographic data recorded by lidar and specifically those from an airborne platform. It should be noted, however, that the development of mobile ground-based platforms may have potential for the recording of earthworks in pasture such as deserted settlements; for small areas a ground-based survey is likely to be considerably cheaper than an airborne one.

1.1 Airborne lidar

In basic terms airborne lidar consists of an active laser beam being transmitted in pulses from a fixed wing or rotary aircraft and the returning reflection being measured. The precise location of the sensor array is known due to a combination of Global Positioning System (GPS) and the Inertial Measurement Unit (IMU) in the aircraft (Fig 2). Using the principle of measuring distance through the time taken for a pulse of light to reach the target and return it is possible to record the location of points on the ground with a very high degree of accuracy, typically 100–150mm in both plan and height.

The majority of laser sensors operate by sending out a laser beam that scans across the ground surface by means of a mirror

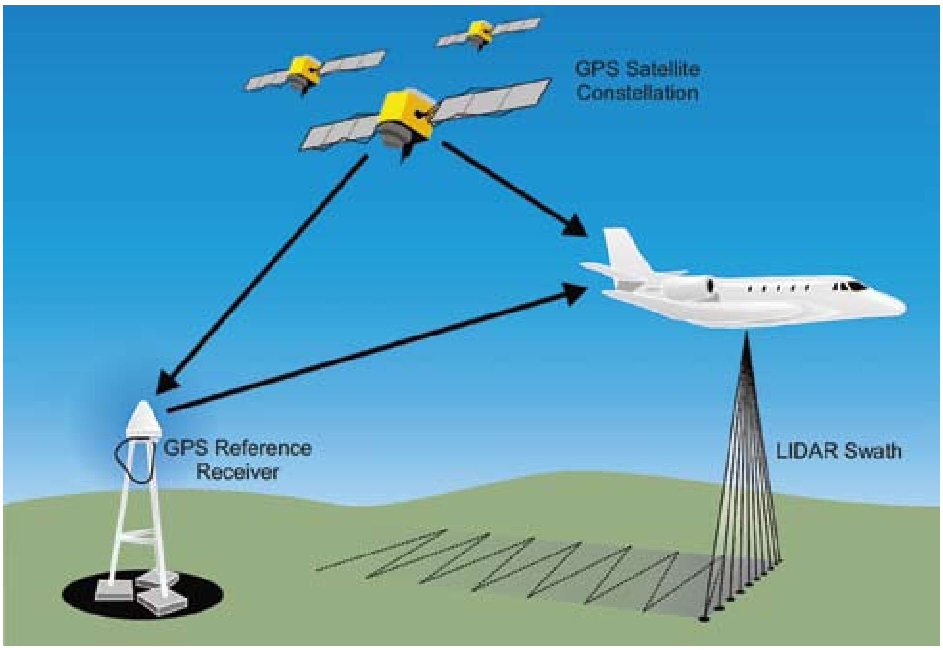


Fig 2 Principals of lidar (after Holden 2002).

(rotating or oscillating depending on the sensor) or alternatively by a fibre optic scanner. Whatever is the means of emitting the beam, the calculations that enable the creation of Digital Terrain Models (DTMs) etc are based on the returning (reflected) pulse to the sensor. In general, most airborne lidar uses eye-safe lasers within wavelengths in the infrared (IR) range; those systems on the current market range from 900nm to 1,550nm. The exception to this is bathymetric lidar, which uses a twin beam system; the green beam penetrates the water and detects the seabed, while the infrared beam detects land and sea surface.

Airborne lidar, therefore, provides the ability to collect very large quantities of high precision three-dimensional measurements in a short time. This facilitates very detailed analysis of a single site, or data capture of entire landscapes. It does not necessarily provide any information about the point being recorded in the way that multi-spectral data can, nor does it give any inherent information about the nature of the feature being recorded (though see below for full waveform lidar). What it records is the three-dimensional location of a point in space (together with some information on the intensity of the reflection).

It should also be noted that unlike some remote sensing tools lidar is an active sensor in that it sends out a beam and as such it is possible to use it at night or in circumstances when passive sensors would not work. It should be noted, however, when planning a survey that flying at night means that the aircrew are less able to see whether there are clouds present that may affect the quality of the survey, until after the data have been processed.

For further details of the principles behind lidar see Holden *et al* 2002, Pfeifer and Briese 2007 or Wehr and Lohr 1999; and for further information on the use of intensity data see Challis *et al* 2006, and Höfle and Pfeifer 2007.

Summary

- For archaeologists the key value of lidar is in providing accurate three-dimensional measurements of a surface.
- Although lidar can be used from stationary or ground based platforms, these guidelines deal only with airborne lidar.

2 What does it provide?

Lidar is seen by some as a tool that will record all aspects of the historic environment, making other techniques redundant; this is especially true when it is described as being able to 'see through trees'. This is a misleading statement, however, and can lead to disappointment if the properties of lidar are not properly understood. The key element of lidar is light, and as such it cannot see through trees or anything else. However, in some appropriate circumstances significant gaps in the canopy can make it possible to record the ground surface under woodland, something that is discussed in further detail below. What lidar will do is provide accurate locational and height data, enabling the creation of a three-dimensional model of the land surface that can be examined to identify historic features that exhibit some form of surface topographic expression, although this does depend on the resolution of the data and on other factors described in detail below. The intensity of the reflection of the laser pulse can also in some circumstances provide useful information.

Like any other tool for archaeological recording lidar has its strengths and its weaknesses and it depends to a large extent on the ability of the user to interpret the data effectively. Lidar will not make other techniques redundant, but will rather provide an additional source of data. Specifically because of the generally relatively low resolution of the data (*see* section 1.4 for exceptions) airborne lidar is best fitted to large area survey such as is categorised as English Heritage Level 2 survey. Details of the different levels of survey defined by English Heritage are given in the guidance document on understanding the archaeology of landscapes (English Heritage 2007) and should be considered before the initiation of any survey.

2.1 Height data

There is a long tradition of archaeologists interpreting historic sites from humps and bumps visible on the ground or from the air. However, the height data recorded by lidar (as shown in Fig 5 *below*) is not a straightforward record of the ground surface. When the laser is fired from the plane it travels towards the ground and if it strikes anything in passing, part of that beam is reflected back to the sensor and forms the first return; the rest of the beam continues towards the ground and may strike other features that produce further returns until it finally strikes the ground, or a surface that allows no further progression. The final reflection that reaches the sensor is known as the last return. In practice, built-up areas and open land act as solid surfaces and the first and last returns are often identical. Woodland, however, functions as a porous surface where the first return generally represents the top of the tree canopy while the last return may be a reflection from the ground surface, but equally may be from the main trunks of the trees or areas of dense canopy or undergrowth (Fig 3).

For many early-generation sensors only a small number of return echoes were collected from each pulse – often just the first and last return, with occasionally an additional one or two in between. The first

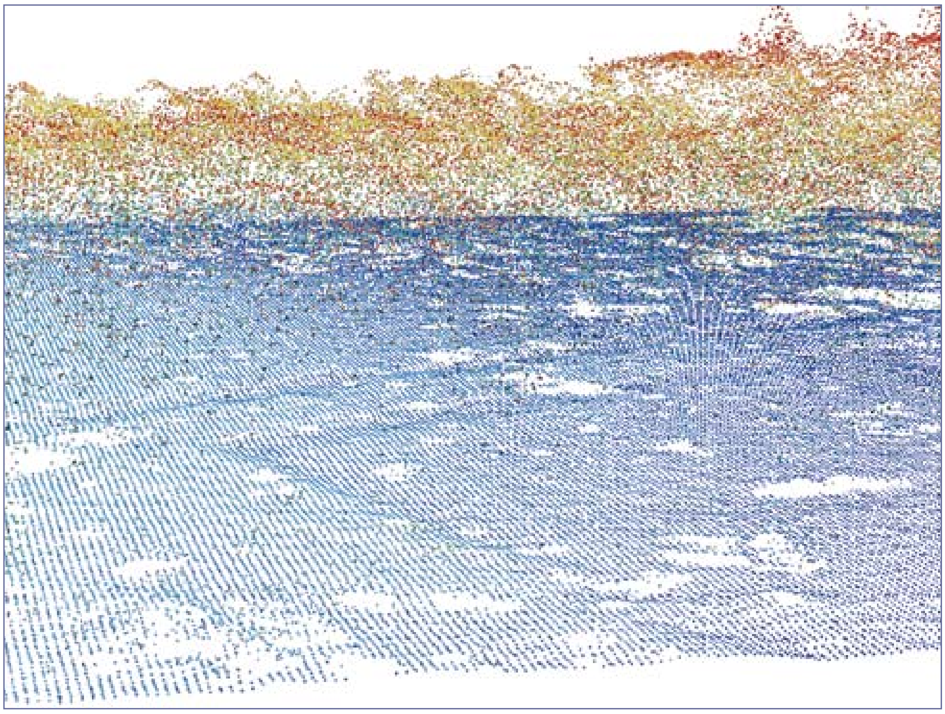


Fig 3 First and last returns: the image shows the scatter of points returned by the laser pulse; the blue points represent the last returns which have penetrated through to the ground while the red and orange represent those that struck the canopy.

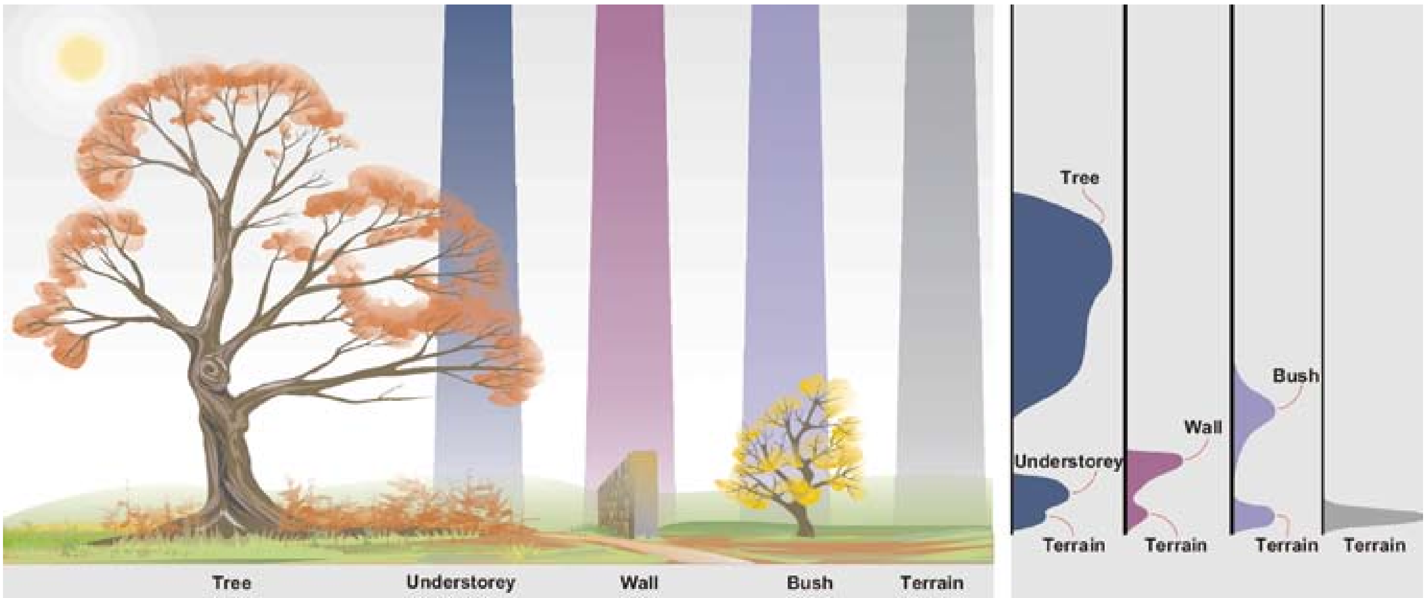


Fig 4 Full waveform lidar (after Doneus) – The image shows how the full waveform of the lidar pulse is recorded over various ground surfaces.

and last returns were considered the most important: the first being equivalent to the Digital Surface Model (DSM) and the last being used as a means to help calculate a Digital Terrain Model (DTM).

Within the last few years the latest development of lidar sensors has expanded and now, instead of just recording between two and four returns, the new full waveform system digitises the entire analogue echo waveform for each emitted laser beam (Fig 4). During post-processing, it is possible, by combining the added detail from the whole pulse of the beam such as the echo width and amplitude, to produce much more accurate models of the ground surface by more accurately eliminating ground cover such as low-level undergrowth, which can give a false reading that appears to be the ground surface (Doneus and Briese 2006; Doneus

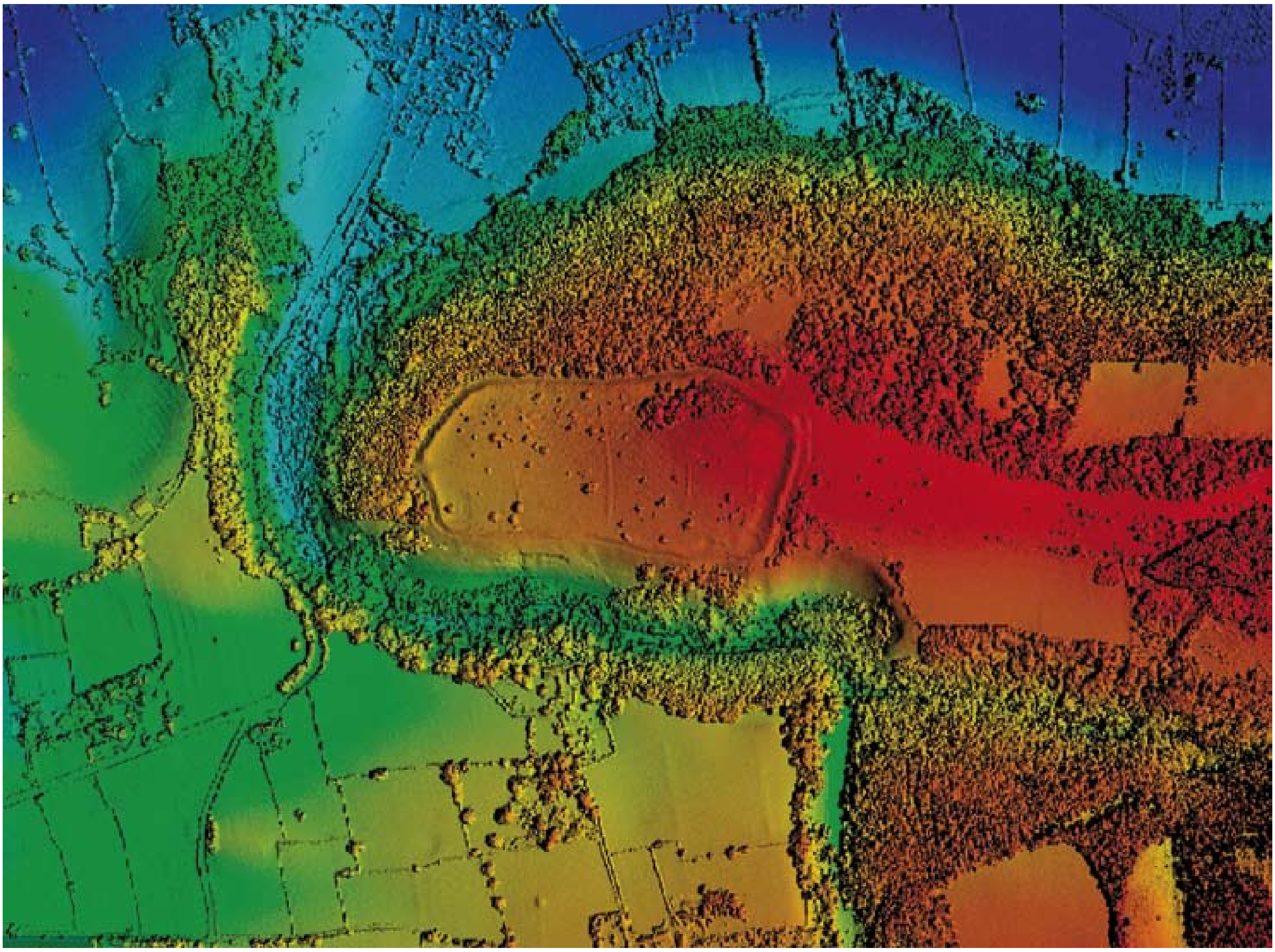


Fig 5 Generic lidar tile showing heights differentiated by colour shading (lidar © Mendip Hills AONB; source, Cambridge University ULM (April 2006)).

et al 2008). Being able to analyse the entire waveform also means that it is possible to obtain data from weaker returns and achieve a more accurate observation by better resolving the return information.

This technology is still partially in the development phase; full waveform scanning is a practical working product in so far as there are full waveform scanners that will provide good results (eg IGI LiteMapper 5600, TopEye Mk II and various sensors from Riegl LMS and TopoSys GmbH), although there is currently only limited availability within the United Kingdom. Furthermore, at the moment, there is very limited consumer software that provides full control over the analysis of full waveform data (eg extracting echoes from the waveform etc) on the market. There is the standard operating software that comes with the scanners, but this tends to be expensive and you need to be experienced to use it. Rather, it is currently necessary to have contacts with those institutions researching the topic. There will, however, certainly be further advances in full waveform analysis within the next few years.

Although using full waveform digitisation produces significantly greater amounts of data at the time of survey, after processing the size of the key dataset, the DTM, is solely dependent on the resolution required. Because of the additional time and cost required in production of the data use of full waveform data may only be appropriate for vegetated areas where the additional data can inform and enhance the vegetation removal processing.

However it is generated, the most useful product of lidar for archaeologists is the three-dimensional model of the ground, the DTM, because of the information it can provide in woodland; in non-wooded areas the DSM is preferable because of the absence of smoothing effects (*see below*). The DTM still requires careful manipulation using specialist software, to facilitate analysis and interpretation of the archaeological features, discussed further below (Fig 5).

Fig 6 Generic lidar tile showing the intensity of the returned signal (lidar © Forestry Commission; source, Cambridge University ULM (May 2006)).

2.2 Intensity data

While the height data are generally seen as the core product from the lidar survey they are not the only information recorded. As well as the relative x, y and z position of the point on the 'ground' the sensor also records the intensity of the reflected signal. This can be affected by a combination of factors (eg flying height, laser power, atmosphere, direction of laser beam, number of returns), but as long as these constants are known the data can be calibrated such that the results are largely determined by the wavelength of the laser beam and the nature of the surface from which the pulse is reflected; different surfaces provide a different absorption rate and consequently reflect back differing signal strengths, which can be analysed to characterise different surfaces.

As a result of this, after appropriate correction, (Höfle and Pfeifer 2007; Boyd and Hill 2007) the intensity data can be used to analyse the reflectivity of the surface being hit by the laser and thus aid in interpretation. When seen as a simple image file the intensity information translates into a series of tonal differences and provides an image of the return surface similar to that of a true panchromatic orthophoto at the same resolution (Fig 6). One point that needs to be borne in mind is that because the lidar pulse is generally in the near infrared (NIR) rather than in the visible spectrum, the reflectance is not what might be expected by those unused to working with wavelengths outside the visible range (eg those used to dealing with standard aerial photographs). Whereas a flat, solid surface such as stone or concrete will reflect almost all of the light in the visible spectrum, this is not the case with infrared light; instead asphalt for roads has a low return value, while grass or a green crop will have a high return

There may be archaeological potential in using intensity values as a method of assessing the moisture content of exposed soils. A project funded by the Aggregates Levy Sustainability Fund (ALSF) investigated whether this could be used to predict the likelihood of preservation of waterlogged archaeological remains, but results have proved inconclusive (Challis *et al* 2008a). While the results suggested that from a visual standpoint the lidar intensity data proved useful in qualitative analyses of certain areas, the report stated that 'the application of lidar intensity data to predictively model sediment units of high preservation potential can be deemed at present to be untenable'. However, while the usefulness of the intensity data to identify damp ground seems to be uncertain there is definitely useful information in the data in other circumstances.

Chlorophyll in plants reflects near infrared radiation, so changes in the chlorophyll content of a single plant species, perhaps as a result of stress such as drought, can be represented in the intensity data in the same way that they are seen in the visible spectrum as cropmarks. In fact, because chlorophyll reflects *c* 50% of NIR radiation, as opposed to 15% of visible, plant stress (eg grass growing over buried walls) is much easier to discern than in the visible spectrum (Verhoeven and Loenders 2006). This is something that has long been recognised by archaeologists and was first systematically investigated by Hampton in the summer of 1970 when he reported that compared to standard film the NIR film 'showed distinct advantages at the early stages of cereal growth' (Hampton 1974).

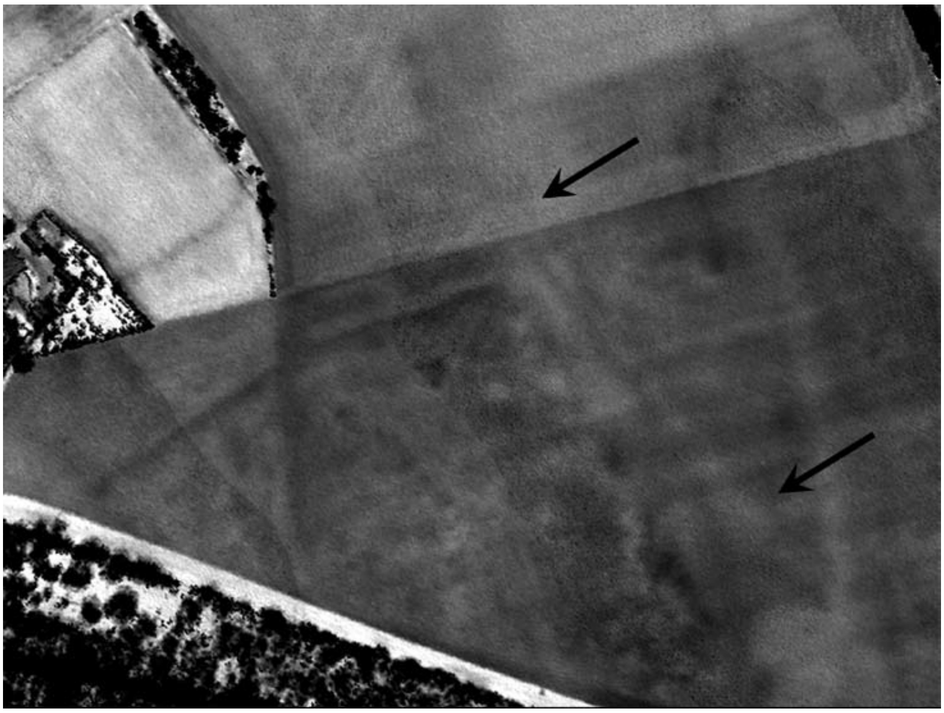


Fig 7 Lidar tile over Savernake forest showing the Roman road appearing as a feature due to the difference of the intensity of the returned signal (lidar © Forestry Commission; source, Cambridge University ULM (May 2006)).

While lidar intensity data have not been tested extensively by English Heritage, one striking example of its potential occurred in Savernake Forest on the course of the Roman road heading to the town of Cunetio. The lidar height data did not reveal the course of the road, but the side ditches showed clearly in the intensity data (Fig 7). Unfortunately, no photography was captured at the time of the lidar flight so it is impossible to say whether these ditches were also showing then as a cropmark in the visible spectrum, but they have done so at other times.

Summary

- The primary product of lidar survey is three-dimensional data; this is only effective for recording features that exhibit some form of surface topographic expression.
- The key element of lidar is light and as such it cannot see through trees or directly identify sub-surface features.
- In wooded areas the last return lidar data may give measurements for the forest floor.
- Full waveform lidar is enabling much more accurate recording of ground surfaces within wooded and otherwise vegetated environments.
- Intensity data can be used to analyse the reflectivity of the surface being hit by the laser and thus aid in interpretation in a similar way as cropmarks on traditional aerial photographs.

3 Data types

During the process of a lidar survey there are a number of stages at which data are generated and can be provided to a client. However, in order to be able to reprocess and manipulate the data to gain the maximum benefit from them, it is important to ensure that the most appropriate type of data is chosen. It is also important to be aware of the stages of processing the data have been put through, as these can result in data artefacts that can be misleading.

The primary data are collected by the scanner simply as a series of points in space based on the calculation of the time taken for the beam to return to the sensor. It is only after these data have been registered (placed in a common coordinate system) that they are readily usable. This procedure is carried out by the data provider. After the data have been registered it is then necessary to align the grids of individual survey swathes to ensure that there are no discrepancies between scans that could lead to interference patterns. Again this procedure is best carried out by the data provider. These processed data can finally be manipulated by the archaeologist within specialist software to emphasise the features of interest. Various different software packages are used to produce these processed data, but these software packages are too varied for discussion here. It is important to note, however, that users should try to gain some understanding of the processing that has been carried out by their data provider in order to understand any issues of data degradation or artefact creation that may have occurred. This is particularly important where filtered bare earth DTMs are provided that may have utilised classification algorithms to extract and remove buildings and any other features (*see* Part III 2.2).

The data can be provided in a variety of forms and as a range of products (eg point clouds, pulse data, images, DTMs, DEMs), the suitability of which depends on their planned use. It should be noted that while there are a number of proprietary formats in which laser scanned data can be provided there is a growing general consensus that the standard format for recording the three-dimensional point data should be the ASPRS LAS format V2 (Graham 2007).

Unfortunately, because the use of lidar within the archaeological world is relatively new, the discussion of formats etc is quite jargon heavy. Many of the terms used will be familiar to those used to working within GIS or certain other remote-sensing techniques, but may be confusing to others who are planning to commission a survey or utilise existing data. While it is not essential to understand all the technicalities of how lidar operates – some of which has been outlined above – it is useful to understand the difference between the different products.

3.1 Raw and gridded data; TINs and raster

The two most obvious differences are between what are often referred to as 'raw' and 'gridded' data. In 'raw' data the individual points are scattered across the survey area exactly as they have been recorded, while in 'gridded' data the survey points have been processed to form a regularly spaced array.

In the most basic of terms, raw data are simply a series of tables that record the x, y, z and intensity data for large numbers of points on the ground (NB 'the ground' refers to the surface struck by the laser pulse and does not necessarily equate to a point at ground level). If point data are viewed as a text file they are simply strings of numbers with columns for x, y, z and intensity data values. Additional sets of columns may be provided to separate first and last (or even intermediate returns). Each row equates to data from a single laser pulse.

The x and y points are calculated to map the actual centre point of the laser footprint (*see* Glossary) transformed to the OS NGR and the z coordinates are the elevations of the points of reflection. In

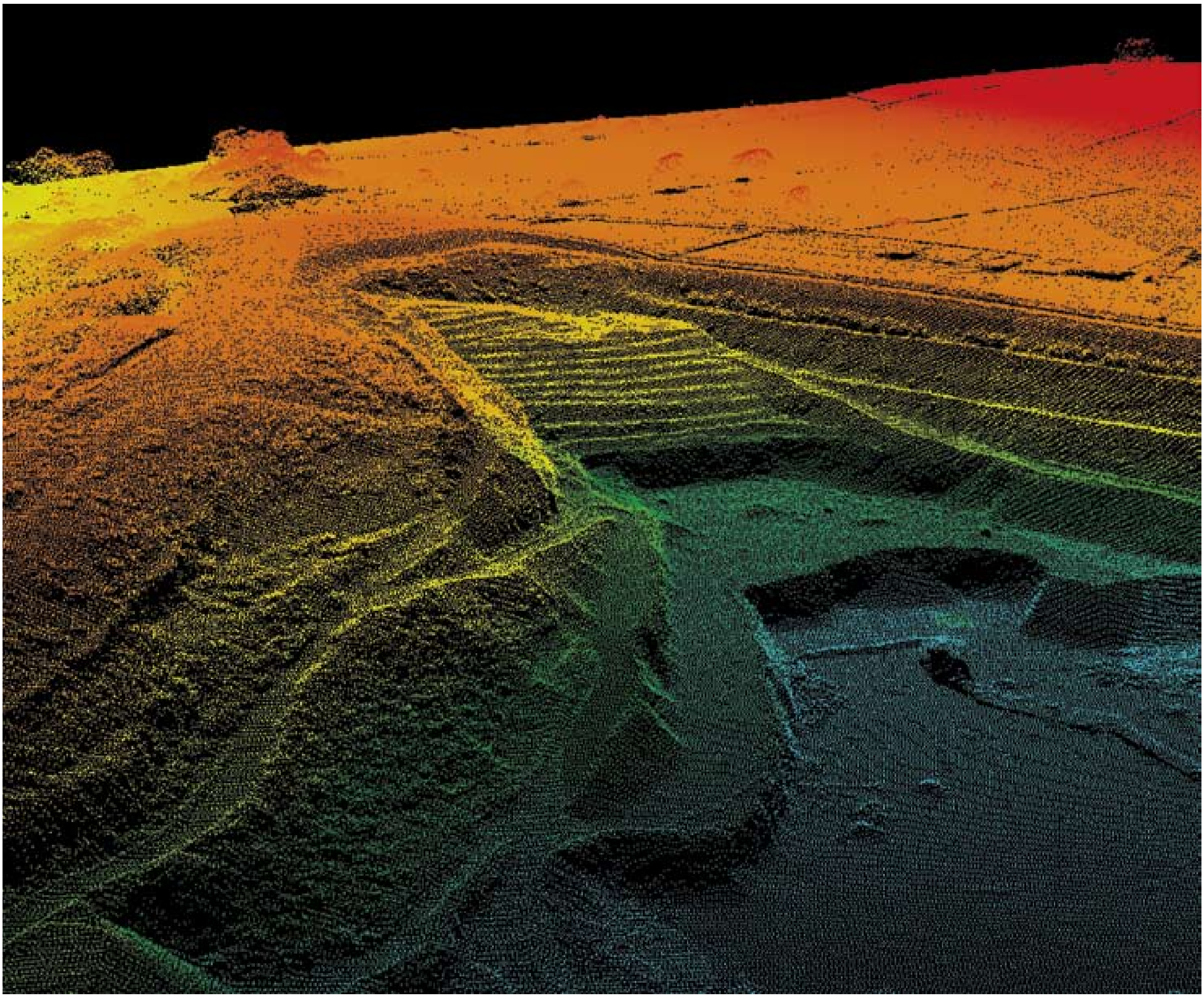


Fig 8 A point cloud showing how the general structure of features can be revealed (lidar © Mendip Hills AONB; source, Cambridge University ULM (April 2006)).

some cases the z coordinates are recorded in centimetres or millimetres rather than in metres, and this can cause problems when plotting in GIS. When imported into a GIS package these x, y and z points produce a point cloud, which is exactly what it sounds like: a cloud of points.

A useful way to imagine the result of a point cloud, suggested by Peter Crow, is to liken it to snow with flakes (lidar points) 'settling' on each surface that they contact; some flakes will be scattered over trees and bushes and fences, and some will also reach the ground. If you mentally remove everything on which the 'snow' has settled, you are left with a cloud of flakes floating in three-dimensional space (Figs 8 and 9). A point cloud is defined by Heritage3D as 'a collection of XYZ coordinates in a common coordinate system that portrays to the viewer an understanding of the spatial distribution of a subject'. The key thing to remember with regard to a point cloud is that these are individual points in

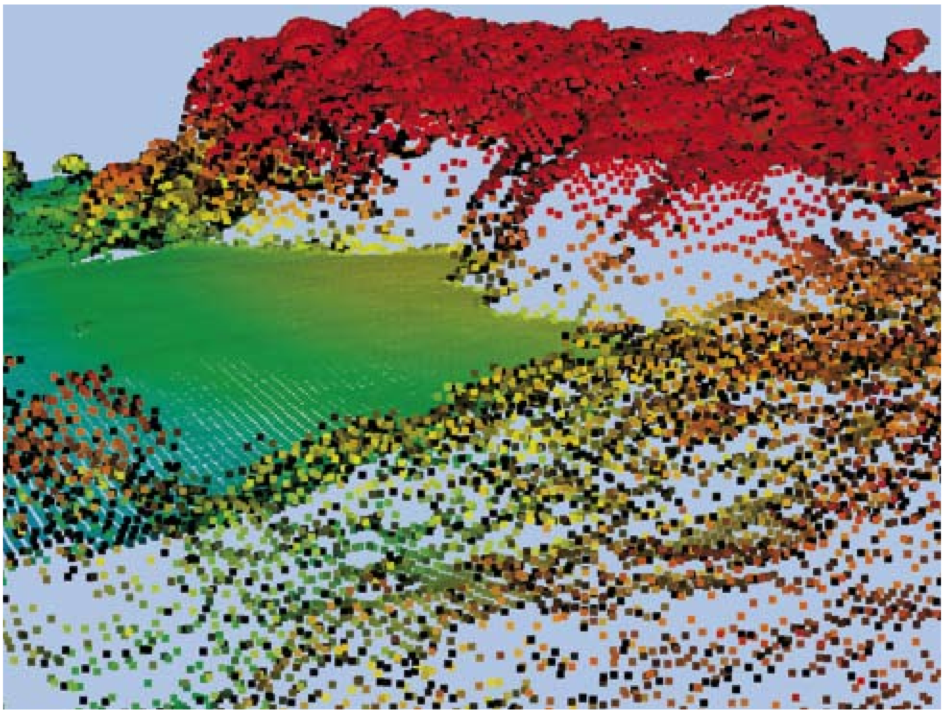
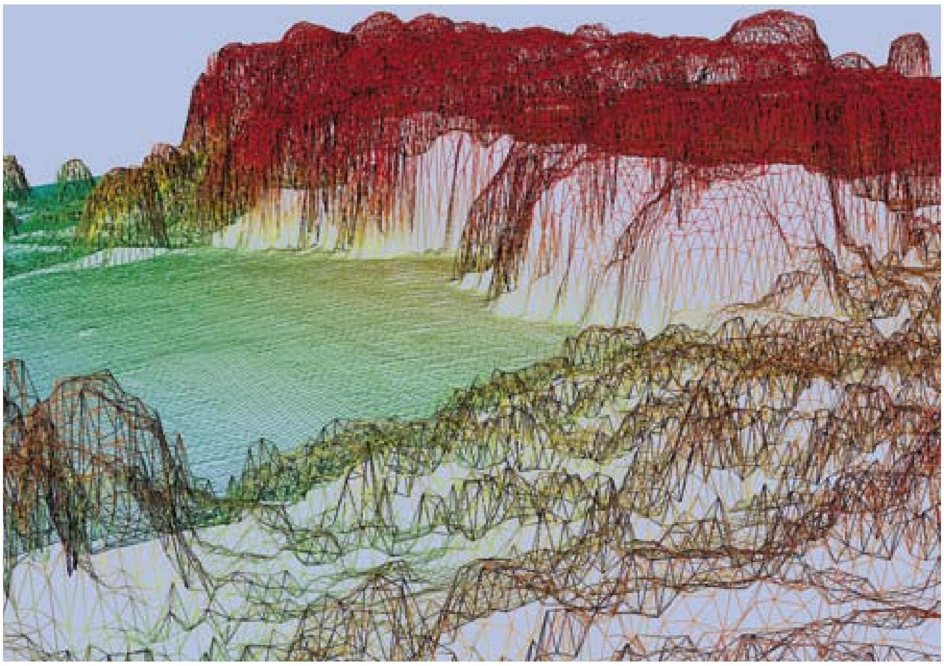
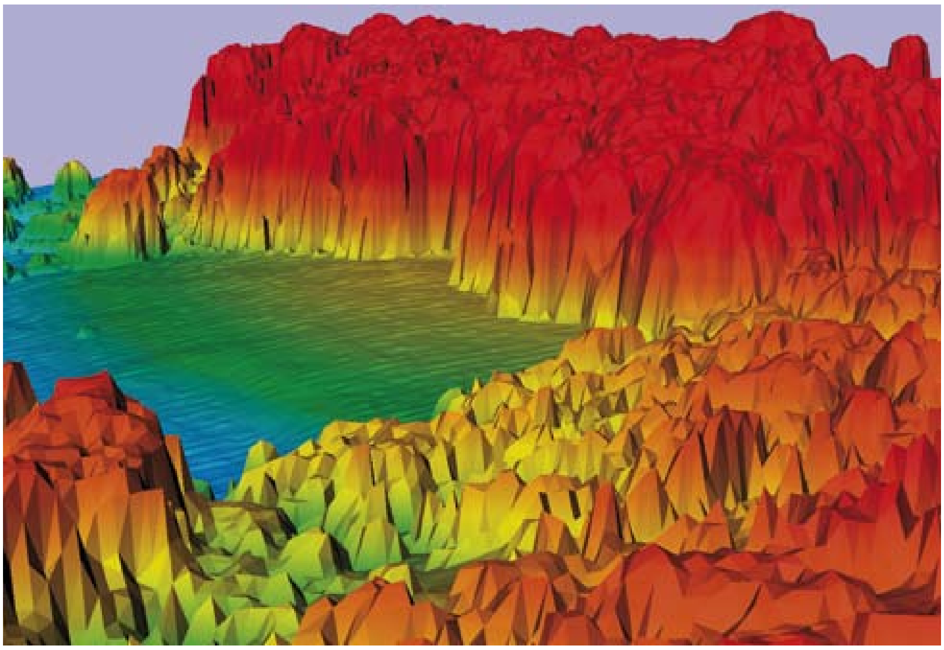
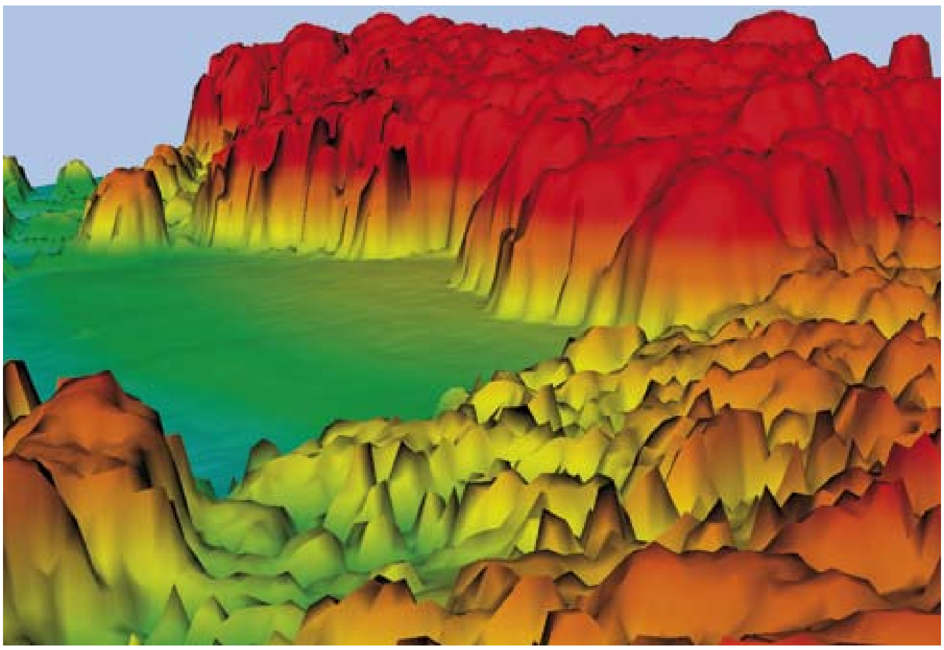


Fig 9 Point cloud showing how features can be viewed using enlarged points (lidar © Mendip Hills AONB; source, Cambridge University ULM (April 2006)).







space that have no physical relationship between them, but because of their density they can still help to define features.

However, in spite of the fact that the density of points makes possible a degree of visualisation, it is not possible to create shading etc, which makes viewing features much easier. By contrast, by creating a surface from the data, they can be visualised more easily, especially as this permits the use of lighting effects and surface analyses such as slope and hill-shade generation.

There are two main forms of surface that can be generated, either creating a TIN (Triangulated Irregular Network) direct from the cloud data or a raster surface indirectly through the creation of gridded data.

A TIN (Triangulated Irregular Network) consists of nodes that store the z values, connected by edges to form continuous, non-overlapping triangular facets (Figs 10 and 11). TINs are essentially vector based and therefore can have a variable area size; the input features used to create them remain in the same position as the nodes. As a result, no extra data are created or lost through interpolation, so a TIN maintains all the accuracy of the input data with a minimum file size, while at the same time enabling modelling of values between the known points. Another advantage is that it is sometimes easier to visualise exactly what a TIN consists of by looking at a wire frame image without any surfaces.

A raster surface is different from a TIN in that it is stored in grid format, ie a grid of defined cell size is effectively draped over the point data and each cell is allocated the z value that falls within it. Because it consists of a regular array this means that the points are 'derived' from the original data, rather than comprising the actual points that were captured in the survey. Any empty cells have values allocated, which are derived through the interpolation of adjacent points. Cells containing multiple points will be given an average value. The smaller the cells, the greater the precision of the grid, or in other words the higher the resolution of the image.

Fig 10 Wireframe model of the same area showing the nodes connected by edges (lidar © Mendip Hills AONB; source, Cambridge University ULM (April 2006)).

Fig 11 TIN surface of the same area showing the effects of rendering (lidar © Mendip Hills AONB; source, Cambridge University ULM (April 2006)).

Fig 12 Raster surface of the same area showing the more natural smoothed surface (lidar © Mendip Hills AONB; source, Cambridge University ULM (April 2006)).

Because values are interpolated into the grid it is impossible to locate individual features more precisely than the size of the grid cells. Care should be taken over the creation of a raster, as creating cells of a larger size than the resolution of the data capture will result in a loss of information.

Equally, while using a cell size smaller than the resolution of the original data capture can produce 'sharper images', the interpolation required will create artificial data in addition to that captured. For example, if a survey is captured at one laser hit per metre, creating a grid with a 0.5m cell size would result in 75% of the final data being calculated rather than measured, and will therefore be less reliable. If two hits per metre were initially captured, then a grid of 0.5m cells would double the number of data points in the raster. It is recommended that interpolation does not exceed this doubling of data.

While it maintains the accuracy of the original data better than a raster the TIN is not generally as easy to manipulate compared to a raster file of comparable size. In most cases the surfaces produced by suppliers will tend to be rasters, as they are simpler to create and fulfil the main requirements of lidar surfaces (Fig 12). Furthermore, many standard GIS packages require a TIN to be converted into a raster before any second-order derivatives can be produced or additional analysis carried out. The question of TINs will therefore not be addressed further here.

There are some key differences between data provided as a point cloud and data provided as a surface. As discussed above, and noted in further detail in Section III 2.2 below, data can be provided either as 'filtered' or 'unfiltered'; while such data can be provided in either point cloud or surface format they are much easier to visualise and understand as a surface. This is irrespective as to whether the data are provided as a gridded raster image or as a TIN. There are pros and cons to both sets of data that are discussed in detail below:

Point Cloud

PROS

- All the subtleties are present in point cloud form; no data have been lost during the gridding process.
- If it is provided as x, y and z data it can be read by most standard GIS software.
- With additional three-dimensional components to GIS or stand-alone software it is possible to manipulate the data extensively.
- There are no additional processing costs.

CONS

- Visualisation and interpretation are more difficult; requirement to mentally filter out distractions and imagine how to join the dots.

Surface

PROS

- It is easily readable in standard GIS software.
- Surfaces are much easier to visualise and make possible hill-shade and other types of raster analysis.
- It facilitates cross-section investigation of elevated landscapes and features.

CONS

- With raster surfaces there is the risk of some loss of original data resolution leading to smoothing away of features or creating a greatly increased dataset from using smaller cell size.
- Misleading data processing artefacts may be created.
- Depending on the format of processed data, there will be limited options for manipulation.
- There are additional processing costs.

3.2 Surfaces DEM, DTM and DSM

Of much greater importance is the issue of the distinction between the types of raster surface available, most specifically among DEMs, DSMs and DTMs.

A Digital Elevation Model (DEM) is a form of raster image in which the value assigned to each cell is a height (elevation) value, rather than a tonal one. This is a generic term that can refer to both DSMs and DTMs. In basic terms a Digital Surface Model (DSM) is precisely that; a model of the surface of the earth (or a section thereof) that includes all the features on it such as vegetation, buildings etc. By contrast a Digital Terrain Model (DTM) is a 'bare-earth' model. There are various techniques to remove surface features.

Usually, mathematical algorithms are used to classify the nature of the various returned points into those on the ground and those off ground. This classification will aid the removal of all those features that it estimates to be above the natural ground surface by comparing the relative heights of adjacent recorded points. DTMs are used extensively in planning and terrain analysis for removing buildings etc but really come into their own in woodland landscapes.

From an archaeological point of view there is generally little difference between the DSM and DTM in open landscape, and interpretation is often easier from a DSM that has not had buildings and field boundaries removed, as these can help in the interpretation and screening out of features related to modern land use. Furthermore, the processing of the data to create the DTM that allows for the canopy penetration can also smooth out certain features of archaeological interest (Fig 13). However, in woodland the DTM is invaluable. While the last return data from woodland will penetrate through a degree of the canopy as compared to the DSM (Fig 14), as noted above, it will leave a number of tree trunks etc where the lidar pulse could not reach the ground surface and these interfere with visualisation of the ground surface. By processing this data with algorithms to create the bare earth DTM, an unrivalled view of the woodland floor can be created (Fig 15).

3.3 File formats

These elevation models can be provided in a number of formats depending on the requirements of the end user and on the software that is being used to analyse the data, so it is important to be clear as to how the data will be used from the outset.

The simplest way to view the data is as an image, either as hard copy or in a standard image format as used for digital photographs (eg Tiff and jpeg). These are usable to a point, but are somewhat limited and do not take advantage of the full potential of using lidar data. That said, there are situations described below where the use of basic imagery can provide a useful tool for further research and analysis.

There are some issues dealing specifically with image files that relate to the different file formats available, such as the product specific (eg img) versus the generic (eg jpeg). The nature of image files is such that they contain different levels of data often in relation to their file size and the questions of format with regard to viewing are not specific to lidar applications, and so are not dealt with in detail here. For further information see http://ec.europa.eu/ipg/standards/image/standard_image_file_formats_en.htm. One other important factor to bear in mind when planning the use of lidar data and the format in which

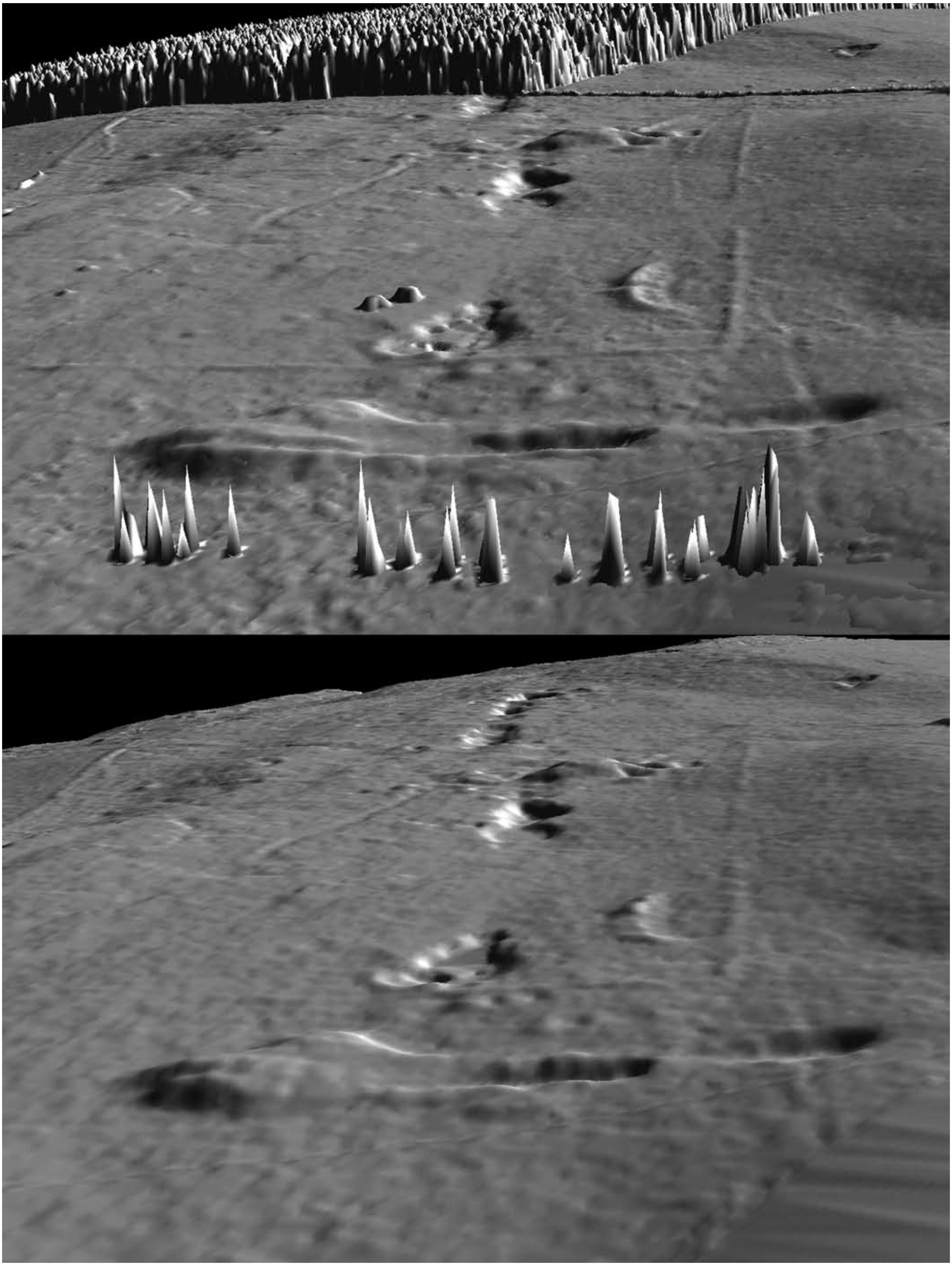
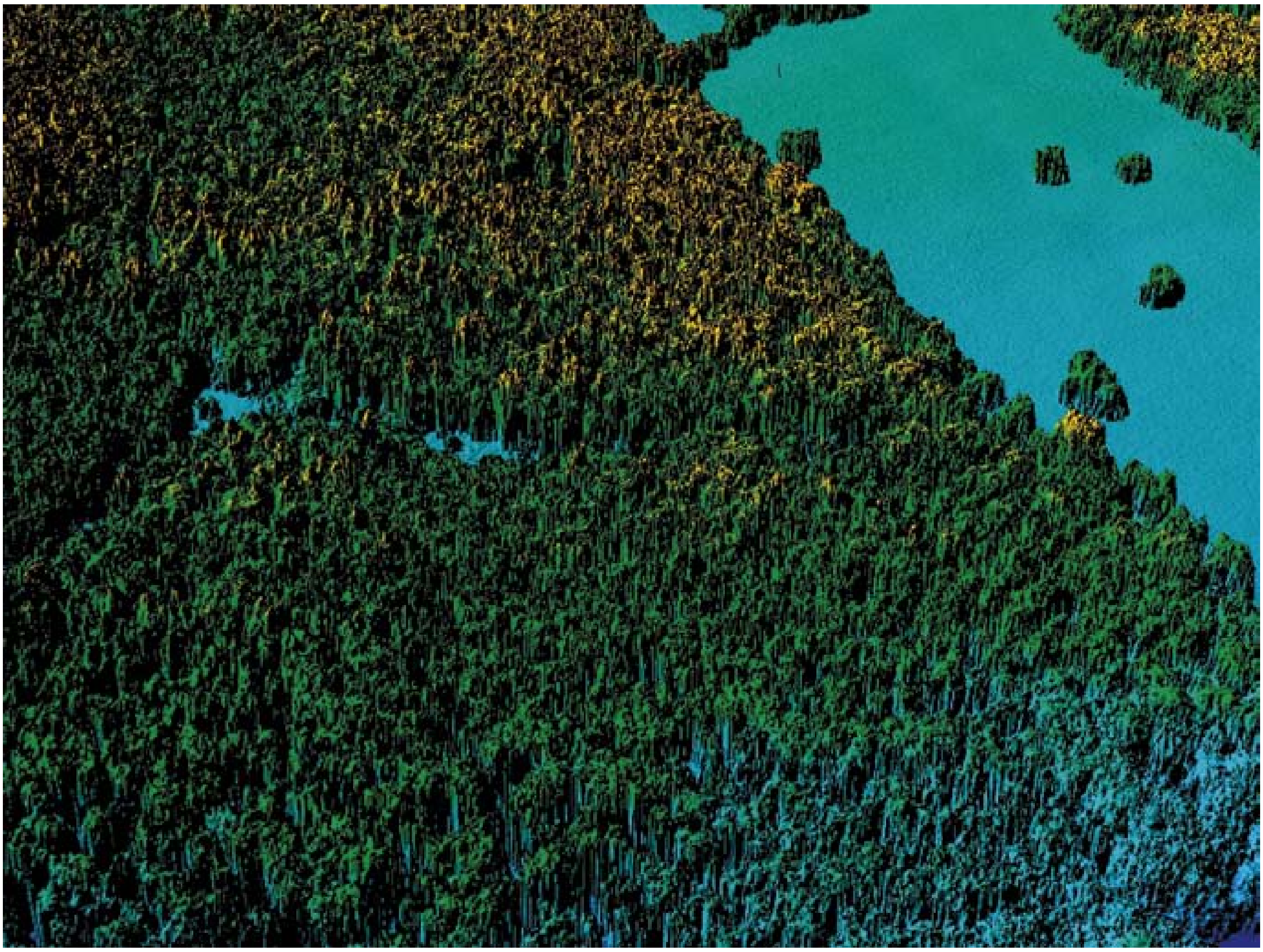
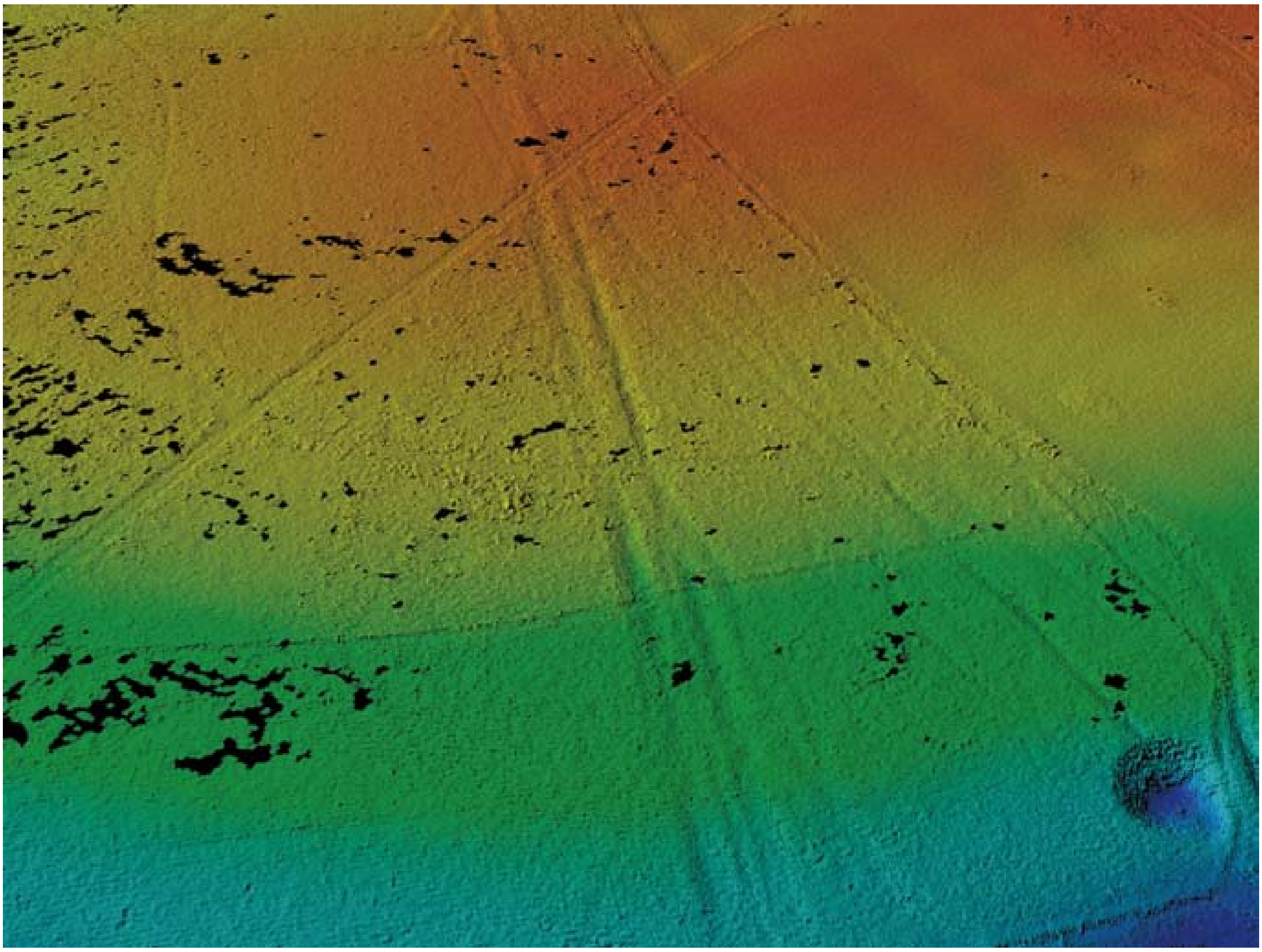


Fig 13 (above) Comparison of lidar DSM and DTM near Alston; note that as well as removing trees there has been a softening of archaeological detail on the DTM particularly for the lead-mining adit in the foreground and the quarry and small dam in the centre of the image. (© English Heritage).

Fig 14 (top opposite) DSM of an area of woodland in Savernake Forest showing the tree canopy (lidar © Forestry Commission; source, Cambridge University ULM (May 2006)).

Fig 15 (bottom opposite) DTM of the same area clearly showing the course of the Roman road (lidar © Forestry Commission; source, Cambridge University ULM (May 2006)).





it will be supplied relates to the size of the files. It is quite possible for a large area covering several tens of kilometres to be provided as a single dataset, but the size of the files may make it impractical to actually work with. The data file for the survey of an area 64km^2 recorded at 0.5m resolution is nearly 1GB in size when provided as an ASCII grid (256 million cells). Even on relatively high-end workstations with high-speed processors and gigabytes of RAM it is impossible to view the file at its collected resolution, which reduces its usefulness considerably. It is preferable to specify that the data be supplied as discrete blocks (eg the 2km × 2km squares as generally supplied by the Environment Agency) whatever the format of the data.

Summary

- The data go through many levels of processing before they reach the end user; these processes can simplify use of the data but can also remove useful information and create misleading data artefacts. Surface data are generally much more user friendly and easier to visualise, but there can be data in the raw point cloud that are lost in the processing.
- DSMs, showing landform, buildings and vegetation, and DTMs, showing a ‘bare-earth’ landform, provide different information and both have a role to play in archaeological interpretation.
- In areas of largely open landscape using the DSM or unprocessed last return data is preferable to using the DTM.

4 Accuracy and Resolution

As noted above, for archaeologists the key data recorded with lidar are height data or more accurately, three-dimensional coordinates on the ground; it is the height values that are emphasised because they make possible the detection of features of archaeological interest, but the x and y coordinates are just as important to accurately locate the features on the ground. However, it should be noted that what is actually recorded by the sensor is only relative data; it is only through the GPS and IMU recording of the position of the sensor that it is possible to obtain absolute coordinates.

There are therefore, two levels of accuracy that may be given for a given sensor and/or a given survey: absolute and relative accuracy. The relative accuracy of the data are typically in the range 100–150mm, but may be better (often 70–80mm), and the absolute accuracy depends on the registration with the datum that is used. In most cases within England this will be the Ordnance Survey (OS) grid. In general, laser-scanned data are registered initially against WGS84 and it should be borne in mind that the transformation to OSGB can create potential distortions depending on the transformation used.

These issues should normally be addressed by the supplier and need not be a cause for concern, but it is worthwhile to remember that there are potential problems in absolute accuracy when combining with other highly accurate data.

It should be noted that in many cases for the archaeologist it is the relative difference that is more important than the absolute, as this difference reveals the presence of features; it is the fact that there is an area of ground that is slightly above or below the surrounding level that reveals the presence of a bank or ditch. At the first level of information and interpretation it is less important whether the feature is at 120.25m OD or 122.25m OD than whether it accurately depicts the presence of a previously unrecorded enclosure, but the difference in absolute accuracy may lead to difficulties in interpretation and registration between adjacent lidar datasets (*see* Fig 22, showing wavy swathe edge) and when additional data are recorded using ground survey techniques with a higher level of accuracy (eg differential GPS).

It is not only the accuracy of the lidar data that needs to be considered, but, as with any remote sensing technique applied to the recording and interpretation of archaeological features, it is also its resolution. However, unlike imagery where it is simply the case that any feature that is smaller than the resolution of the data will not appear, the issue of resolution with regard to lidar is more complex because resolution is a relevant factor at different stages of the process and is consequently affected by different specifications.

The resolution of the gridded data that are used for visualisation is important because it limits the size of the features that can be seen and recorded, much in the same way as for other image-based data, such as satellite or standard aerial photography. Figure 16 shows how this can affect the visualisation of different archaeological features.

More important for the accuracy of visualisations, however, is the original resolution of the data defined by the number of hits within a square metre and the footprint (diameter) of the laser beam when it strikes a surface. As a parameter largely determined by the flying height of the aircraft above the ground, footprints tend to range between 0.25m and 1m. If using only a small footprint, say 0.5m, and an average of one hit per metre, measurements will only be taken from 20% of the ground surface. Because the number of hits per metre is an average, in a survey described as ‘one hit per sq m’ it is quite possible for several squares to have more than one hit and several to have none.

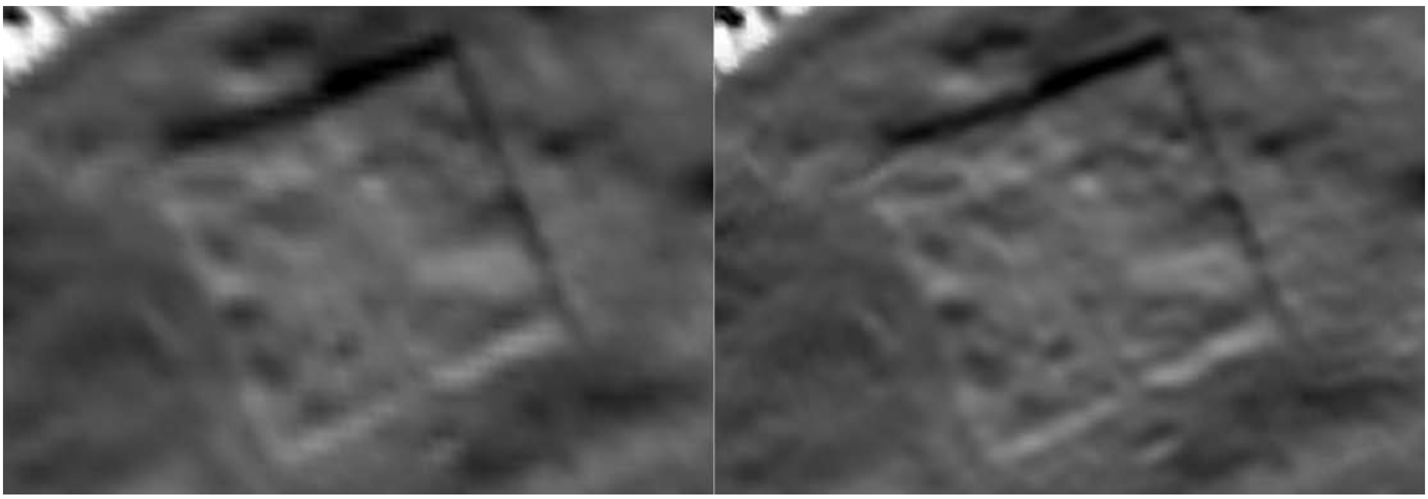


Fig 16 Effect of resolution on feature visibility – A Roman signal station on Hadrian’s Wall seen at 2m ground resolution (left) and 1m (right) (lidar © English Heritage; source Cambridge University Unit for Landscape Modelling (March 2004)).

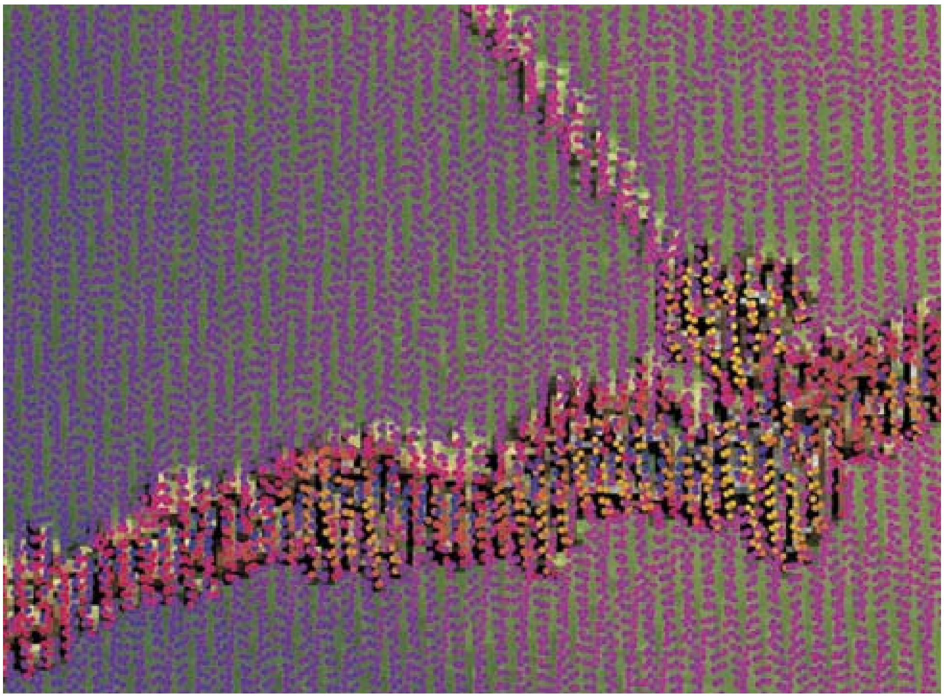


Fig 17 Point density, showing the actual distribution of points over an area (lidar © Mendip Hills AONB; source, Cambridge University ULM (April 2006)).

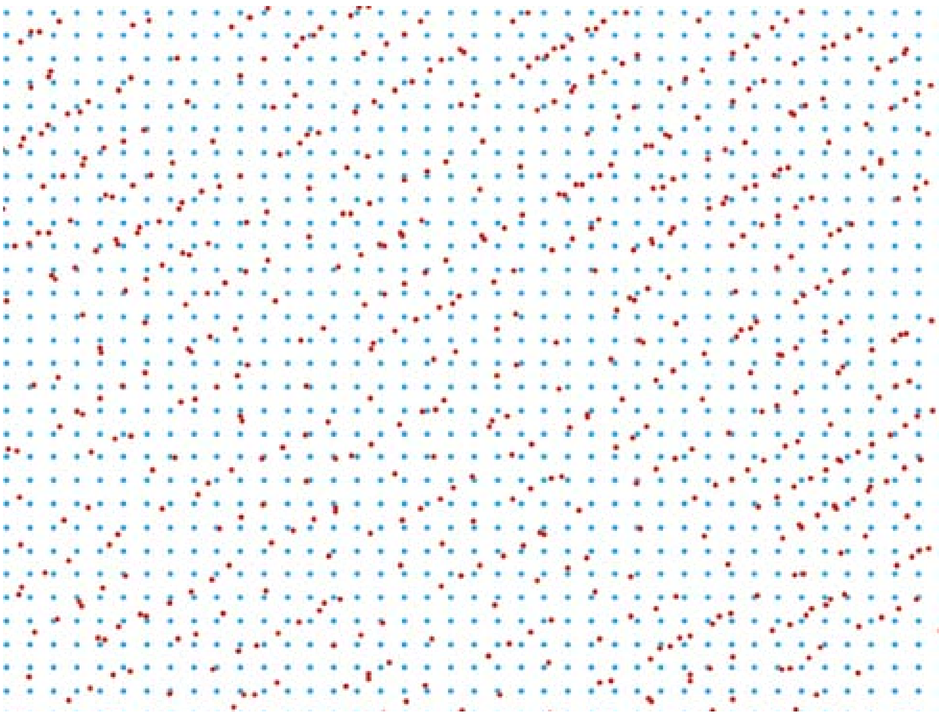


Fig 18 Point density: gridded versus as captured (lidar © Mendip Hills AONB; source, Cambridge University ULM (April 2006)).

Figure 17 shows the actual distribution of points over an area of field, while Figure 18 shows the difference between the actual points as captured (red) and the resulting grid (blue).

A good example of this is shown by the stones at Stonehenge. The lidar imagery captured at one hit per square metre does not appear to show several of the bluestones. Figure 19 shows the outline of the main stones within the henge in pink against the surface model generated from the lidar data captured at one point per metre. There is no clear trace of several of the bluestones in the north-east quadrant.

Figure 20 shows the gridded data against a rectified aerial photograph. The outlines of the stones are coloured according to the number of points that fall within their outline; those in green have no strikes at all. Although the point data used here is gridded rather than the original point cloud it demonstrates the same point: that small features can be missed or equally small features (eg sheep) can affect the apparent height of the ground surface!

A second example of this effect is found on the Welsh coast where lidar data were being used to monitor the erosion of a promontory fort (Fig 21). Here comparison with ground-based GPS survey showed some substantial discrepancies in the position of the cliff edge, which are most easily explained by the assumption that certain pulses were on the extreme edge of a given 2m square and missed the cliff entirely.

Careful planning at the data capture stage can minimise later difficulties with resolution. In wooded landscapes Forest Research and Cambridge University's Unit for Landscape Modelling have been doing the surveys at two hits per metre and gridding to four, ie 0.5m ground resolution. They also have a fairly large footprint to maximize the chance of getting a reflection from the forest floor and transects have a 65% overlap to ensure good coverage.

Note that all the airborne lidar data discussed thus far has related to data collected from fixed-wing aircraft, which due to restrictions on speed and altitude are limited to collecting data in the range of up to eight points per square metre with each pass; it is possible to collect more points by carrying out multiple passes, but this has implications for flight time and consequently for costs. There are also systems on the market that are designed to be mounted on helicopters that can collect much higher densities of data. The Fli-map and ATLAS systems were deployed by DEFRA (Department for Environment, Food and Rural Affairs) for measuring changes in beach levels and recorded between 12–28 points per metre (McCue *et al* 2004), while the Discovery Programme in Ireland surveyed Dún Ailinne prehistoric hillfort in Co. Kildare at 15–30 points per metre and the Hill of Tara at 60 points per metre using Fli-map 400 (Corns *et al* 2008). This higher resolution shows a much greater degree of detail, but comes at the price of generally smaller areas being flown.

Summary

- From an archaeological point of view relative accuracy is often more important than absolute accuracy.
- The relative accuracy of the data is typically in the millimetre range (100–150mm), but can be higher.
- The absolute accuracy of the recorded data is heavily dependant on the accuracy of the GPS.
- The resolution of the gridded data is important because it limits the size of the features that can be seen and recorded; 2m resolution data are

Fig 19 Stonehenge bluestones: comparison of the lidar data with the known stone positions shows several are missing (lidar © Environment Agency (December 2001)).

Fig 20 Stonehenge bluestones: gridded lidar data versus the actual position of the stones (lidar © Environment Agency (December 2001); aerial photograph © English Heritage. NMR NMR24182/003 (01-MAR-2006)).

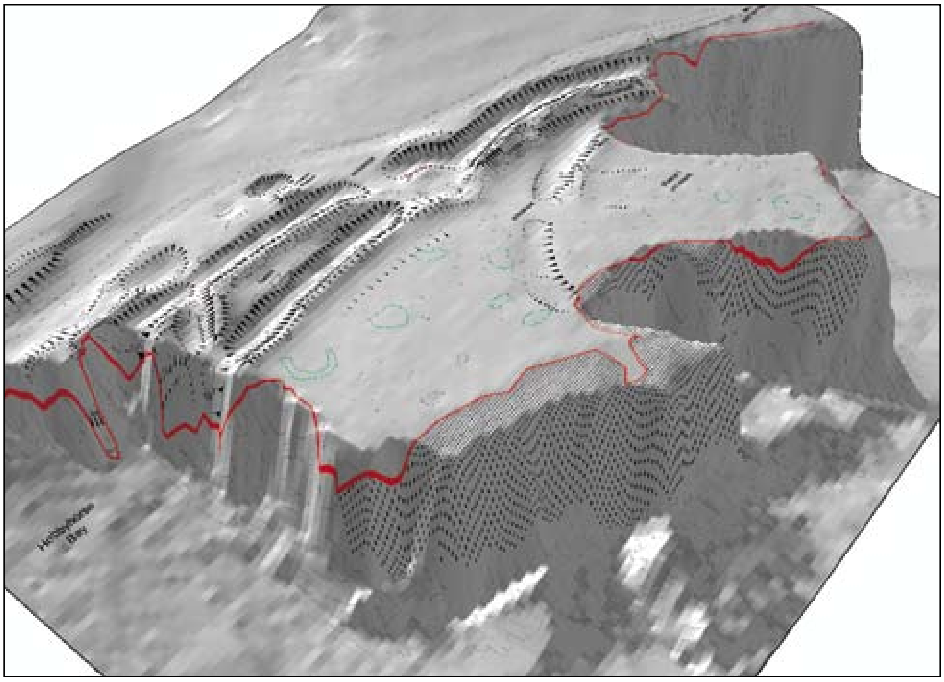


Fig 21 Linney Head promontory fort, Pembrokeshire showing the discrepancy between the lidar modelled data and the ground based GPS survey. (NPRN 94226, © Environment Agency copyright, D0055624. All rights reserved. View generated by RCAHMW).

generally inadequate for recording many archaeological features; 1m resolution is the basic minimum, but where greater detail is required higher resolution data are preferable.

- Survey in woodland requires higher resolution data (typically two hits per metre gridded to 0.5m ground resolution) to achieve sufficient canopy penetration.
- Original point density is as important as final resolution, as insufficiently densely spaced points can risk missing features altogether.
- Low-level survey can record points up to a density of 60 points per metre, but for large area survey one or two points per metre (gridded to 1m resolution) is adequate to record most features of interest.

Part II How to decide if you need it: practicalities and limitations

1 Project planning

(*see* decision tree on page 39)

1.1 MoRPHE

The potential for lidar data to contribute to a project should be identified as early as possible. Under Management of Research Projects in the Historic Environment (MoRPHE) guidelines (Lee 2006), its use should be assessed as part of the project design document. Advice may be required as to whether the site or landscape in question is appropriate for the use of lidar survey and whether it will yield useful results. In England this advice can be sought in the first instance from the English Heritage Aerial Survey and Investigation (AerSI) team or from the relevant English Heritage Regional Science Advisor. More technical advice may also be obtained from the Aerial Survey and Investigation Team, and the Archaeological Survey and Investigation team could advise on the likely cost benefits of alternative terrestrial survey techniques and archaeological interpretation, especially if the survey area is quite small or if the level of detail required is higher than will be readily achievable using lidar data. If your survey area covers a largely wooded area, then technical advice may also be obtained from Forest Research, some of whose staff have a particular expertise in this area.

1.2 Survey considerations and options

As with any project, one key element before any work is undertaken is to be clear about the objectives, requirements and end-use of any lidar data. While lidar as a technique has been around for some time its use is still relatively new for archaeologists and while it is particularly useful in certain situations and can produce spectacular results (Bewley *et al* 2005 and Devereux *et al* 2005) it is less useful in other situations and always needs careful interpretation (Crutchley 2006).

A key point to remember is that lidar primarily records height information, therefore the features being surveyed must have a three-dimensional surface aspect. As noted above, the intensity data from the lidar return are able to record certain aspects of the reflective nature of the surface recorded, which may provide information on factors such as angle, roughness, dampness and colour absorbency, but only in exceptional cases will this information directly reveal archaeological features.

The bottom line, however, is that lidar does not penetrate the ground. If the archaeological features of interest are not represented on the ground surface then lidar will not be able to record anything except the general topography of the survey area. Of course, having an accurate record of the general topography of an area and the surrounding landscape can be a useful resource in itself, but if this is all that is required then lidar may not be the most appropriate, or cost-effective, method with which to collect these data.

Basic topographic height data at scales suitable for general topographic relief are available from alternative sources. Depending on the resolution required there are commercial datasets available, such as those from the Ordnance Survey (http://www.ordnancesurvey.co.uk/oswebsite/) or from NextMap (http://www.xyzmaps.com/NextmapTerrainData.htm), or even freely available from the web (eg US Geological Service http://seamless.usgs.gov/ or NASA https://wist.echo.nasa.gov).

Once it is clear that there are likely to be features that can usefully be recorded by lidar, the next stage is to be clear about the end use of the data. Is the lidar data required as the primary source, an interrogatable dataset that can be analysed by different staff to provide an interpretation of archaeological features, or is it seen as a background layer for other datasets available elsewhere? This decision will determine the form in which the data will be provided, which will in turn dictate the requirements for software and hardware.

The precise nature of these options is discussed in more detail below.

If the aim is simply to use the surface model derived from the lidar data as a background layer, the hardware and software requirements are probably quite low, but the processing of the data to an appropriate format for GIS etc (*see below*) will need to be budgeted for. If, however, the intention is to analyse the data in-house and carry out any type of interpretation, then the appropriate hardware and software must be available to deal with the large datasets. While it is possible to view the processed data that are provided by most suppliers in standard GIS packages such as MapInfo or ArcGIS, without specialist extension modules this is not a very user-friendly option (*see below*).

This is not just a question of hardware and software, but also of technical expertise; familiarity with the process of generating and manipulating digital models is necessary. Similarly, the interpretation of archaeological features from these models is best done by someone experienced in the interpretation of aerial data, especially if the intention is to look at other sources at the same time, something that is recommended for reasons given below.

If there is the further requirement to actually map archaeological data (or indeed any other type of feature) from the lidar data, then this presents a different set of problems. Until recently there were no simple tools for mapping directly from processed lidar data, ie derived surface models that can be manipulated to control height exaggeration and lighting position (*see* Interpretation) and English Heritage had to develop their own flowlines and working practices. However, given that software and hardware capabilities are changing all the time it is wise to consult someone already actively working with such processed data.

Summary

- Advice on whether lidar can be useful for a given landscape can be obtained from the English Heritage Aerial Survey and Investigation team or from the relevant English Heritage Regional Science Advisor.
- More technical advice on the use of lidar data may also be obtained from the Aerial Survey and Investigation Team.
- The English Heritage Archaeological Survey and Investigation team can advise on the likely cost benefits of alternative terrestrial survey techniques.
- If the survey area covers a largely wooded area, then technical advice can be obtained from Forest Research, some of whose staff have a particular expertise in this area.
- Basic topographic height data at scales suitable for general topographic relief are available from alternative sources, for example the Ordnance Survey or NASA.
- It is important to be clear as to whether the lidar data are required as the primary source or whether it is seen as a background layer for other datasets available elsewhere.
- To make best use of lidar for archaeological survey the project team should include someone with suitable experience in using aerial data.

2 Where can you use it?

One of the major factors affecting the usefulness of lidar is the current land-use of the area of interest, as this can have a major impact on the survival and consequent visibility of features.

2.1 Grassland

Many archaeological earthworks are found in areas of open grassland and lidar can be a useful tool in such landscapes. Although archaeological aerial reconnaissance and field survey have often targeted such areas in the past to great effect, and continue to do so, the manipulability of lidar data can prove a valuable additional tool. This is particularly the case for improved pasture, one of the more difficult types of landscape for survey by other means because the ploughing has eradicated most traces of any former earthworks, but the presence of grass as opposed to an arable crop restricts the possibility of cropmarks to periods of extreme drought. However, if there are any traces of earthworks surviving, even in a smoothed and eroded state, then lidar is an excellent tool for recording them. This is true for all forms of grassland ranging from upland grass and stone landscapes such as the Yorkshire Dales, to coastal saltmarsh.

2.2 Moorland

Moorland is another landscape type where ground survey is often difficult and dependent on the season. Typical moorland vegetation such as bracken and heather can make the surveying of features on the ground difficult and limit the window of recording to certain times of the year. The timing of any lidar survey flight is likely to be of particular importance. Although it is possible that the use of last-pulse data will enhance the visibility of features under heather and gorse during autumn and winter it is likely that at other times they will prove too dense for the beam to penetrate.

It has been suggested that there may be issues with regard to the use of lidar on open-stone landscapes or on features created from stones, for example cairns, rock waste mounds. So far English Heritage staff have limited experience in such landscapes, but a project currently underway in the North Pennines may help clarify matters.

2.3 Arable

Landscapes currently under arable cultivation are generally the most responsive when it comes to conventional aerial photography and survey. Given the right conditions they will produce

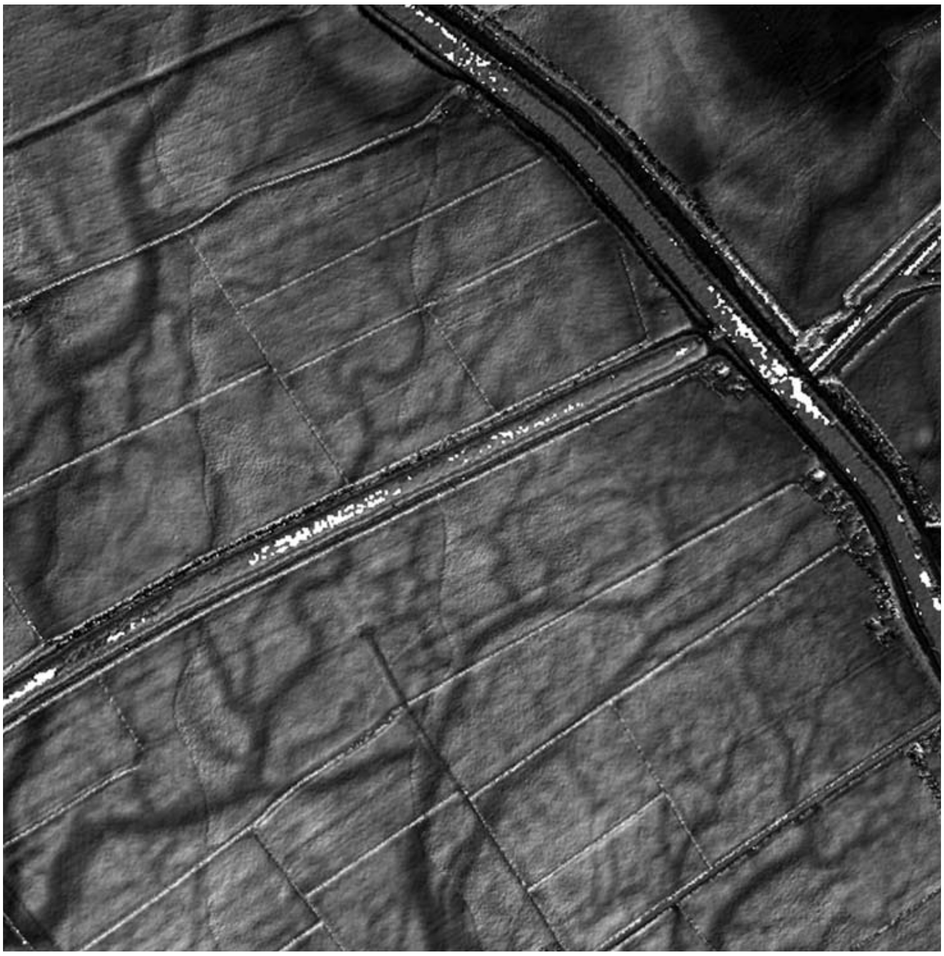


Fig 22 Lidar showing palaeochannels in the Witham Valley. Note also the two wavy lines running down the image; these are processing artefacts resulting from the overlapping of adjacent data swathes. (lidar courtesy of Lincolnshire County Council; source, Environment Agency (March 2001)).

evidence of former activities in the form of cropmarks and soilmarks. By contrast, they are probably the worst for analytical field survey because any earthworks have been consistently eroded by the plough, until there are very few surface traces left. Lidar can still recover some information from such landscapes because even where former banks and other features have been heavily eroded and are only visible as broadly spread features raised about 100mm above the surrounding ground level they still have a surface expression.

The capacity for lidar to look at large areas and pick out patterns, together with the ability to manipulate the data to enhance slight features, means that it is possible to record features that would be almost impossible to locate on the ground in a ploughed field. However, while lidar may be successful in showing extensive features such as field systems it is likely to be less successful for discrete features such as barrows or enclosures.

The majority of cropmark sites are unlikely to have any other significant surface expression of the buried features and so lidar height data will not be able to identify them. Although, as noted above, there may be some potential for lidar intensity data to reveal cropmarks, and there is a chance that if the cropmark itself has sufficient height difference this might register in the lidar first return data.

An understanding of surface geology is important, as in many arable areas, particularly those where there has been significant deposition such as flood plains, the results will be less successful, something that is equally true for traditional aerial photography. On the plus side, the majority of low-lying arable areas will already have some lidar data through the Environment Agency's policy of recording river valleys, so these data might be available more cheaply than having to commission a new survey.

The archaeological value of lidar in revealing geomorphological features (Fig 22) should not be underestimated, particularly in the main river valleys and in the fenlands, where much of the Environment Agency survey work has been targeted (Challis 2006 and Jones *et al* 2007).

2.4 Woodland

The key area of land use where lidar comes into its own and has substantial advantages over other forms of survey is woodland. The efficacy of the technique is demonstrated in the case study on Savernake and in the separate section on woodland below Part V.

3 To map or not to map?

As noted above, one of the key questions with regard to the use of lidar data is whether it is planned to actually map from the data, or just to use it as a background. For specific site surveys a case can be made for using lidar derived imagery as the basis of a field survey. This enhances and improves planning of site details in the field based on of a combination of field survey and image interpretation. Alternatively the lidar derived imagery can provide a useful topographical background against which survey can be carried out. This is particularly the case in areas of ancient rivers where lidar provides an excellent source for palaeoenvironmental data that can in turn aid in the interpretation of sites based on their location (*see* Part IV 2, Witham Valley case study).

It should also be borne in mind that the data from the lidar survey can be useful apart from simply interpreting readily visible archaeological features. For example, because of the high level of detail provided by the data, it can be used to compare the relationship of the man-made rampart slopes to the steepness of the underlying topography in upland areas. It can be used to assess the local topography and how this might have affected movement or supply, such as confirming the practicality of a given route for an aqueduct. It should, however, be noted (*see* Part II 1.2) that there are other sources of data available that provide basic topographic data at a range of resolutions. These can be derived from other sensors, such as radar (see NextMap) or by using photogrammetry from conventional aerial photographs (eg as part of the Cawthorn Camps survey, Stone 2004).

However, in most cases the extensive dataset provided by lidar is probably best treated as one of the sources for a desktop survey, maximising the value of the initial cost of the product and making it possible to target more expensive fieldwork more carefully. Interpreting the lidar data into a mapped form ensures that the data are fully examined and that the archaeological results are properly documented. The quality of interpretation and metrical accuracy possible from lidar, used in conjunction with air photos and other sources, provides a high degree of confidence in the results. Field survey can then be used to examine those areas where there is a lower degree of confidence, for example stratigraphic relationships between features, areas with poor visibility in available datasets or confused by surface features such as dense undergrowth or piles of forest residue, or areas where the complexity of remains and management issues can only be addressed through direct observation.

The results from the Savernake Forest survey (*see* Savernake case study) suggest that for continuously wooded areas, using lidar is likely to be the best single remote sensing method and therefore a combination of lidar and field checking may be an appropriate methodology. However, if there are areas of open ground within the area of survey (or there have been in the last 50 years), then it is likely that checking the available air photo sources will be of significant benefit. Generally this is best done in parallel with the lidar analysis, but for some projects a staged approach may be more appropriate.

In areas of mixed woodland and arable the air photo sources will be essential to ensure the best possible understanding of the archaeology. A survey comparing existing HER information and a selection of aerial photographs with lidar data was carried out by Birmingham University and concluded that both sources are required for a complete picture of the archaeological remains of any given area (Challis *et al* 2008b).

Summary

- In many cases the extensive dataset provided by lidar is best treated as one of the sources for a desktop survey to produce an interpretative map of the features identified.
- The quality of interpretation and metrical accuracy possible from lidar (used in conjunction with air photos and other sources) provides a high degree of confidence in the results and makes it possible to target fieldwork carefully.

4 Data acquisition

One of the first steps when planning to acquire lidar data is to assess whether the data for your area of interest already exist. As noted above, the Environment Agency has been carrying out lidar surveys around the coasts and river valleys for about ten years and these data are available to purchase from them either as hill-shaded jpeg images or as the actual gridded data. A catalogue of their holdings – updated regularly – is held by the Environment Agency and available for download from their website (http://www.geomatics-group.co.uk/GeoCMS/Order.aspx).

Other commercial companies have also been carrying out lidar surveys for several years throughout the country, as have research companies such as the Unit for Landscape Modelling at Cambridge http://www.uflm.cam.ac.uk/ and the Natural Environment Research Council (NERC) http://www.nerc.ac.uk/.

Unfortunately, because the majority of these projects were carried out on behalf of paying clients the data are not readily available and indeed there is no central record of where the surveys cover. However, there are exceptions and organisations such as the Forestry Commission are in the process of collating a central record of the lidar data that they hold. The general lack of coordination is an issue that is being considered by Heritage3D and the Remote Sensing and Photogrammetric Society (RSPSoc). There are some international sites on the web that claim to have records of general lidar cover such as http://www.lidardata.com. These are currently very much restricted to the United States, but it is possible that a commercial company may fill this gap in the UK in the not too distant future.

If no data exist for your area of interest, or if the data that do exist are of insufficient quality for any reason (it may be of insufficient resolution or simply too old etc), then it will be necessary to commission a new survey. It is worth bearing in mind, that a large number of lidar surveys are carried out each year for non-archaeological purposes, for example for infrastructure planning. For many large infrastructure projects such as roads or pipelines that are covered by PPG16 (or its successor) it is quite possible that a lidar survey may be commissioned by the developer to establish the nature of the topography of the area and for other reasons. Surveys may even be commissioned by local authorities or other bodies that have links with archaeological organisations, as lidar can have a significant role to play when first appraisals of large landscape developments are undertaken, say for EIA (Environmental Impact Assessment) planning stages.

The level of detail required for such surveys would most probably be sufficient for archaeological needs (especially for open landscapes), but it is worthwhile trying to influence any project you are aware of so that it provides the most useful data. This can be particularly important in either wooded or moorland areas where a survey carried out in the height of summer when all vegetation is at its densest will be less useful than one targeted for winter or spring when vegetation is less prevalent. Equally, if a heritage-based lidar survey is being considered, there may be other potential users of the data in other disciplines or organisations and it may be possible to collaborate on a project.

A lot of the elements with regard to commissioning any type of laser scanning survey were addressed by the Heritage3D project, and the guidance document resulting from it includes a section on the commissioning of an airborne lidar survey, finding a contractor and ensuring that the survey is carried out to the correct standards ('Developing professional guidance: laser scanning in archaeology and architecture', English Heritage 2007 http://www.heritage3d.org/).

What is not currently specified in that guidance is what those standards and specifications should be when lidar survey is to be used for examining archaeological sites and landscapes. As noted, one of the key factors is the resolution of the data defined by the point density on the ground. The point density is defined by Heritage3D as the average distance between the x, y and z coordinates in a point cloud, and for lidar this refers to the number of hits on a surface within a one-metre square for the raw data. While it is fairly evident that a higher ground resolution is likely to be able to record more features, the cost of obtaining and using these larger datasets also needs to be borne in mind.

Some of the variables that determine the resolution of the data are defined by the aircraft, such as altitude and ground speed; others by the lidar system, including laser frequency (pulses per second), scan frequency and scan angle. The actual laser frequency of the system is generally fixed, but it has been increasing over time and is likely to get faster. Early lidar systems had a frequency of only 10–15KHz, whereas today there are systems capable of up to 250KHz (ie 250,000 points recorded every second).

With a fixed scan frequency, in order to increase the point spacing it is necessary to reduce the altitude of the aircraft, which is often impossible because of aviation regulations; to fly with larger overlaps, which increases flying time and hence costs; or to reduce the scan angle. Reducing the scan angle reduces the swath and increases the number of passes that need to be flown, again increasing the cost. At an altitude of 1000m a 15° scan angle produces a swath of 536m; a scan angle of 7° produces a swath of only 246m. The Unit for Landscape Modelling (ULM) at Cambridge University provides a useful calculator on their web site (http://www.uflm.cam.ac.uk/lidar.htm) to assist in planning surveys

The shape and size of the survey area can also influence the costs of data acquisition per unit area. For example, a large, rectangular survey area is often the most cost effective, having the minimum number of turns at the end of each aircraft run (ie minimal flight time). Equally, given that there are also fixed costs associated with getting an aircraft airborne and to a survey location, small or irregularly shaped areas will be less cost effective to capture.

For surveys of wooded landscapes, a smaller scan angle (or lower flying height) is preferable, as it will have better, near-vertical penetration of woodland, with fewer occurrences of the laser pulses being blocked by the trees. Additionally, a more complete view of the forest floor can be obtained by ensuring a greater degree of overlap on adjacent flight paths.

The continuing improvement in the speed of new sensors is likely to reduce some of these issues, as the increased frequency will enable the collection of more points while maintaining speed and scan angle.

At present, however, it is necessary to take current conditions into account and balancing cost against product. English Heritage staff's experience suggests that while 0.5m resolution is ideal for small areas, surveying at this resolution for anything greater than about 20 square kilometres becomes very expensive. Furthermore, several surveys have been carried out using 1m resolution, which has proved perfectly adequate at recording the majority of features (eg barrows, enclosures and mining pits) that we would expect to be able to see on aerial photographs in open areas, and even data at 2m resolution can provide some archaeological information. It must be noted that a greater point density of at least two hits per metre is recommended when dealing with woodland (*see below*) and there will of course always be variations based on the density of vegetation; but it is nonetheless useful to provide some outline guidance.

The other key element to be defined when commissioning a survey is the actual form in which the data will be provided, covered in greater detail above. Examples are known of situations where data were acquired from a contractor, but in a format that the archaeologists could not use!

It is worth noting that with most lidar units there is room for at least one other sensor to be flown; most common is a digital or analogue camera, but other options are CASI, or other multi-spectral or hyperspectral sensors.

Summary

- Step one – assess whether the data for your area of interest already exist – see Environment Agency catalogue etc.
- A large number of lidar surveys are carried out each year for non-archaeological purposes, such as for infrastructure planning.
- Lidar can have a significant role to play when first appraisals of large landscape developments are being undertaken, say for Environmental Impact Assessment (EIA) planning stages.
- A lot of the elements with regard to com-missioning a laser scanning survey were addressed by the Heritage3D project.
- The Unit for Landscape Modelling (ULM) at Cambridge University provides a useful calculator on their web site to assist in planning surveys by estimating the total flight time required.
- Large, rectangular survey areas are the most cost effective, having the minimum number of turns at the end of each aircraft run; small or irregularly shaped areas are less cost effective.
- Ensure that you know the actual form in which the data will be provided; it is no good obtaining data from a contractor if it is in a format that the end user cannot use.

5 Dissemination, archiving and copyright

It is essential that all issues relating to dissemination, archiving and copyright are considered at the outset of a project. This will ensure clarity in what data and imagery it is possible to publish or make available to others for future research.

5.1 Dissemination

Lidar data files and the generated imagery are generally quite large files; the gridded ASCII text files for 2km × 2km tiles at 1m resolution are in the region of 150Mb, and the original ungridded data *c* 250Mb. As such they are not easily supplied to third parties or colleagues. They can also prove taxing to process for lower specification PCs.

It must also be remembered that the actual lidar data are often copyright to a third party and so cannot be distributed; however, while the actual data are usually strictly controlled, this is not always the case with the imagery generated from them.

Another key point to remember is that in terms of useful data from a given survey, the key product is the interpreted layers and attached records. In most cases, however, it would be good practice to support this with at least a layer of uninterpreted information, for example a hill-shaded image etc (where available).

5.2 Archiving

Heritage3D raised many questions about appropriate formats for long-term storage of data. As this is an area that is constantly developing, advice should be sought at the outset of a project from ADS (see Bewley *et al* 1998; or http://ads.ahds.ac.uk/project/bigdata/). If the copyright of the data is held by a third party then the question of what derived products – such as hill-shaded images – can be archived should also be addressed at an early stage.

5.3 Copyright

Several questions have been raised about the nature of copyright with regard to lidar data. The most important of these is to what extent does the 'added value' of creating hill-shades etc create copyright in the hands of the author of those images? Unfortunately this issue is still not entirely clear.

When commissioning work, however, or when getting data off the shelf, it is important to try to be clear from the outset where copyright lies and how the data can be disseminated. Copyright of any images generally resides with whoever created them, unless a different specific arrangement was made. But even in this situation the data source is usually acknowledged as a courtesy.

There are inevitable copyright restrictions on lidar data and costs of purchasing existing data can vary according to the size of the area in question, the resolution and its age. However, for most archaeological purposes, the use of older data may not be an issue. Equally, if the primary archaeological requirement is to examine features from hill-shaded images, it is often possible to acquire these at significantly lower costs than the fully manipulable elevation data; and copyright on any images may also be more relaxed.

Summary

- It is essential that all issues relating to dissemination, archiving and copyright are considered at the outset of a project to ensure clarity in what data and imagery it is possible to publish, make available to others.
- Lidar data files and the generated imagery are generally quite large files and as such they are not easily supplied to third parties.

Part III – How do you use it?

There is no single answer to the question of how to use lidar data. Much will be determined by the nature of the survey and by the technical equipment, or lack thereof, available to those doing it. For some surveyors it may be appropriate to rely solely on a hard copy of a hill-shaded image provided by others; for others such an image may be viewed using a portable GPS device. Elsewhere, where the hardware and software are available, on-screen desktop analysis is preferable, as this makes it possible to view and manipulate the data to maximise its interpretational value. In all cases the surveyors need to understand how to interpret the visual evidence and be aware of likely pitfalls.

1 Visualisation

Probably the key aspect that determines the usefulness of lidar data and how they are used in relation to archaeology is the question of how the data are viewed. If the user does not have the facilities to view and manipulate the original data in a specialist package, it is still possible to use two-dimensional snapshots of the data as standard jpeg or Tiff files. As noted above, these are somewhat limited compared to being able to view and manipulate the data, but they can still be useful. It should specifically be noted that what may at first appear to be a relatively unpromising image in greyscale, or even in colour (Fig 23), can reveal a considerable amount of 'hidden' information after some basic enhancement techniques – such as equalisation, available in standard image processing packages – have been applied (Fig 24).

Assuming that there is access to software and hardware to view the data and that hill-shaded images alone have not been specifically requested, the standard product from a lidar survey is likely to be an ASCII grid. This can be read in a standard GIS (Fig 25), but is not very user friendly; it requires specialist three-dimensional viewing modules (*see* Glossary for a definition of three-dimensional in this context) or separate programs to really enable interpretation.

There are a number of three-dimensional viewing programs on the market, ranging from freeware available over the web (such as Landserf http://www.soi.city.ac.uk/~jwo/landserf/) to specialist corporate viewing and modelling software (such as Applied Imagery's Quick Terrain Modeler http://www.appliedimagery.com/, Terrascan http://www.3dlasermapping.com/uk/airborne/software/terrascan.htm or the three-dimensional Analyst module

Fig 23 Standard jpeg lidar image from the Environment Agency (© Environment Agency copyright 2008. All rights reserved).

Fig 24 The same image after equalisation; note the number of additional features visible, particularly the short stretches of bank in the pale green fields in the centre left of the image. (© Environment Agency copyright 2008. All rights reserved).

in ArcGIS). It is not practical to give a complete listing of all available software as this is constantly changing, but a quick search on the internet will list those available.

(Note: The mention of any specific hardware or software used by English Heritage does not necessarily imply endorsement of this product over any other, but simply reflects the current limited use by staff within English Heritage.)

Without the use of some form of viewing software, either to view interactively or to create hill-shaded models (Fig 26) etc, the point cloud data, DEMs or DTMs are not particularly useful. With the software it is possible to view and manipulate the data and generate your own images, highlighting specific features (and even view them truly three-dimensionally).

Ideally the three-dimensional data should be viewed stereoscopically, taking advantage of the brain's natural ability to interpret three-dimensional objects aided by the opportunity to stretch and light the surfaces differently. This can be done using specialist viewing packages and photogrammetric packages using a variety of special glasses (anaglyph, polarized, flicker) – although it is to be noted that special screens are now becoming available that do not require these glasses. However, for most users this is another level of expense that is not feasible, and the viewing of flat two-dimensional images on paper or on-screen – or better, as interactive three-dimensional images on screen – is the easiest way to view the data; although described here as 'three dimensional' these are actually 'two-and-a-half-dimensional' – a two-dimensional representation of three-dimensional data (*see* Glossary). If the interpreter can be provided with a flexible tool for viewing, manipulating and mapping from the gridded data in real time then many of the limitations of two-dimensional data can be addressed.

Such software can be used to visualise different lidar-derived datasets in a number of ways (*see* Data Formats [above] and Algorithms [below]). The most obviously user-friendly product, because it is relatively easy to interpret, is the hill-shaded image. One of the key benefits of the surfaces derived from lidar data is the fact that like all DEMs it is possible to manipulate them with various software packages to produce images lit from any conceivable position, even from positions impossible in nature. Coupled with the ability to increase the vertical exaggeration of features it is possible to visualise features that have only a very slight surface indication on the ground.

Nevertheless the very possibility of viewing features from a multitude of angles and lit from a variety of positions can cause complications. Those used to viewing aerial photographs are used to the fact that when features on the ground run parallel to the direction of the light source they do not create a shadow and are therefore virtually impossible to view. This situation is one that also occurs with lidar-derived imagery, as is demonstrated in Figures 27 and 28, which show two blocks of medieval ridge and furrow cultivation.

The obvious way around this problem is to produce multiple images lit from different directions. However, if you are dealing with hard copy paper images and looking at a large area, this practice soon becomes impractical. Some success has been achieved in creating composite images using the transparency tools within image editing or GIS packages (*see* Figs 51, 55 and 56), but a more effective process is now seen in the use of principal component analysis (PCA) a statistical method to examine multiple hill-shaded images and compile a composite image that shows the main features from each image (*see* Fig 54) (Devereux et al 2008). There are two issues with this procedure, however: first, while there are a number of off-the-shelf packages that will create PCAs, they do not necessarily produce the best results, which can really be obtained only by those with a degree of experience of working with the process; secondly, whereas a single hill-shaded image is relatively easy to interpret for anyone used to viewing aerial photographs, PCA images with their multiple colours and sometimes conflicting shadow and

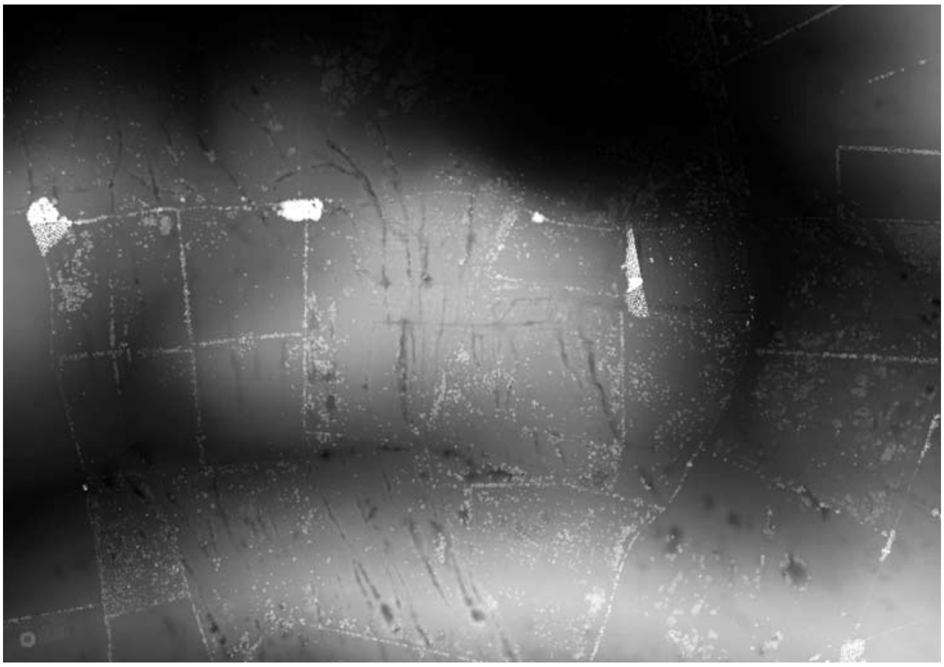


Fig 25 Standard greyscale raster image in Arc (lidar © Mendip Hills AONB; source, Cambridge University ULM (April 2006)).

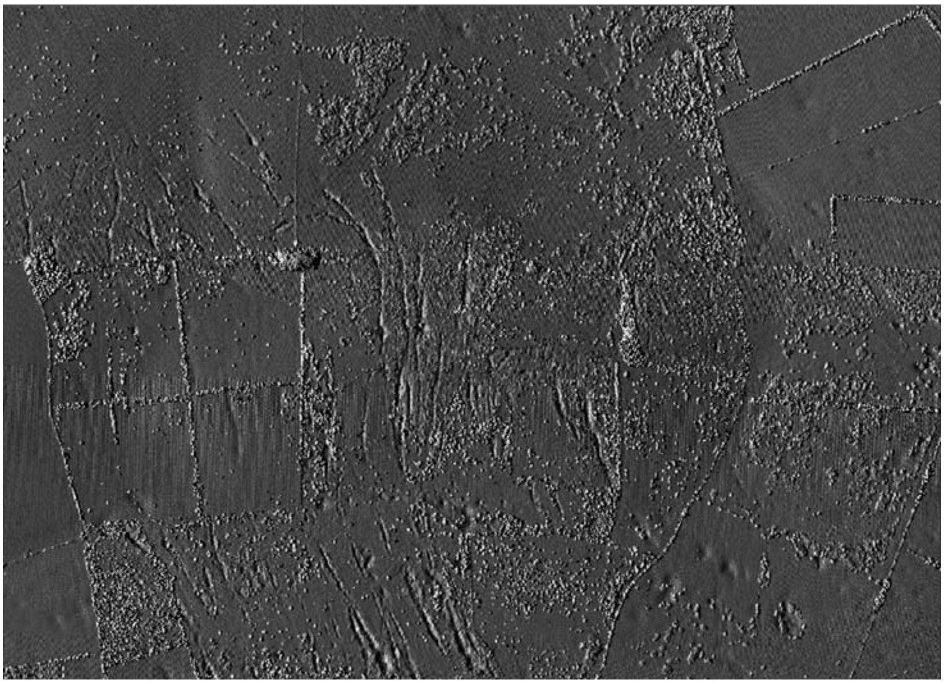


Fig 26 Hillshaded image in Arc (lidar © Mendip Hills AONB; source, Cambridge University ULM (April 2006)).

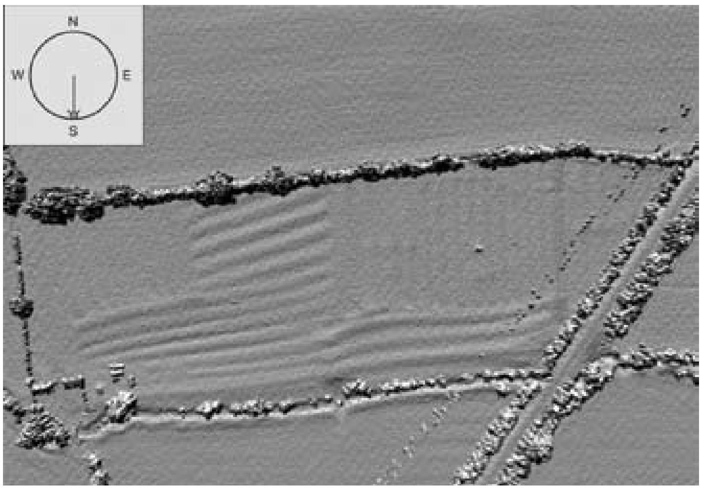


Fig 27 Ridge and furrow near Alchester illuminated N–S (lidar © Cambridge University ULM (Dec 2005)).

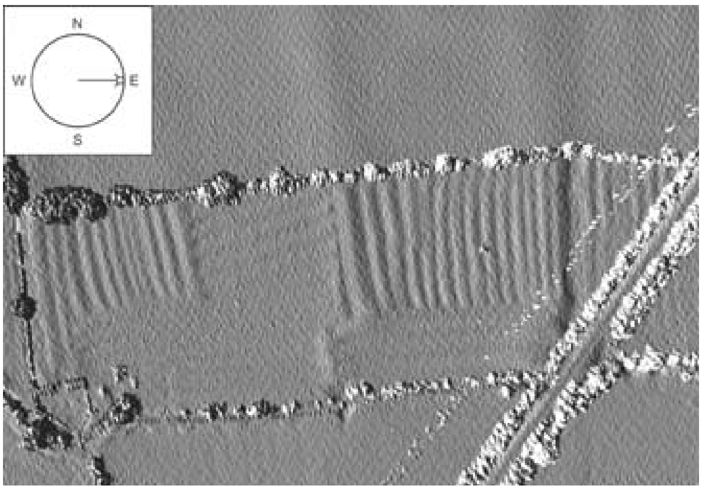


Fig 28 Ridge and furrow near Alchester illuminated E–W (lidar © Cambridge University ULM (Dec 2005)).

highlight patterns can be more misleading, particularly when it comes to interpreting whether a feature is positive or negative. This is very important when it comes to interpreting the function of a feature, as there is a major difference between a mound and a hollow. However, altering the colours of PCA images or draping a semi-transparent standard hill-shaded image over the top can help to compensate for this potential for misinterpretation.

There have also been attempts to improve hill-shaded models in other disciplines by combining models lit from different directions and then giving weight to the different slopes. While these may have some benefit for other disciplines, because the features of interest to archaeologists tend to be occur irrespective of the direction of slope this methodology seems less valuable in archaeological applications. It also requires a greater degree of knowledge of sampling and weighting techniques common to GIS than most archaeologists have (Loisios *et al* 2007).

In his assessment of the use of hill-shaded images in the field for the rapid recording of features in woodland, Hoyle 2008 states that they 'enable the extent and location of recognised features to be simply recorded with reference to the visible features, generally by direct tracing, and no further surveying is necessary.' He adds that 'this not only improves the accuracy of the recording but also significantly speeds up the time needed to locate, survey and record identified features, and its cost benefit cannot be overstated. The hill-shaded images also present an accurate and up to date map view of the ground surface, which is often more comprehensive than the mapping available from the Ordnance Survey, particularly of areas of woodland.'

While hill-shaded images and PCA images are the principal easily interpreted forms there is also some promise from slope models (Doneus and Briese 2006). However, as with PCA imagery these models are not as simple to interpret, as the natural reaction is to see them as hill-shades, which can again lead to interpretational mistakes regarding positive and negative features. This is clearly an area with promise, as it is the slope of a feature, or rather the change in slope from what appears to be the underlying topography, that alerts one to the presence of man-made features, but further work is required to demonstrate the full potential of the technique.

Summary

- The way lidar data are used will be determined by the nature of the survey and by the technical equipment available to those doing it.
- The standard digital product from a lidar survey is likely to be an ASCII grid; this can be read in a standard GIS, but requires specialist three-dimensional viewing modules to really enable interpretation.
- There are a number of three-dimensional viewing programs on the market ranging from freeware available over the web to specialist corporate viewing and modelling software.
- Ideally the three-dimensional data should be viewed stereoscopically, taking advantage of the brain's natural ability to interpret three-dimensional objects.
- For most users the viewing of flat two-dimensional images in paper or on-screen – or better, as interactive three-dimensional images on screen – is the easiest way to view the data; although described here as 'three dimensional' these are actually 'two-and-a-half-dimensional' – a two-dimensional representation of three-dimensional data
- The most obviously user-friendly product is the hill-shaded image that can be produced as lit from any conceivable position, even from positions impossible in nature.
- PCA makes it possible to create a single composite image that shows the main features from each different lighting angle.
- While hill-shaded images are the principal easily interpreted forms there is also some promise from slope models.

2 Interpretation

2.1 Archaeological

Like an aerial photograph a lidar-derived image often appears misleadingly simple to interpret; however, to ensure the best results from a survey the interpretation must be done by someone with the necessary skills and experience. This becomes even more important if there is an intention to do any more than mark 'dots on maps' and if the work is not going to be followed up with total ground survey. There will usually be a significant cost benefit in detailed evaluation of the imagery prior to any field survey work.

Lidar data and imagery viewed as hill-shaded images appear similar to vertical photographs of earthworks lit by low sunlight, so the analysis of lidar for the identification and characterisation of archaeological sites requires similar skills as those applied to air photo interpretation, for example the ability to recognise slight earthwork banks or ditches based on their appearance with reference to shadows and highlights, while filtering out features due to modern agricultural practices, geology and data processing artefacts. However, the lack of any colour or of tonal variations due to the type of vegetation and other surface cover can either aid interpretation or make it more difficult, depending on the particular feature involved.

As noted above, the basic data recorded by lidar is height data, and as such there are no colour data to aid interpretation. To those unused to interpreting such data, the wear pattern around an animal feeding station may look like a small barrow or a sewage works, defined by low banks, will appear little different to a small enclosure (Figs 29 and 30). Without the use of other sources it is very easy to make erroneous judgements, even for those used to dealing with aerial photographs. During an early project using lidar data, failure to examine all available sources at the outset almost led to a major misidentification of a site (Crutchley 2006).

Experience in interpreting aerial imagery will help to ensure that the sorts of features caused by either geological activity or by recent farming practices can be filtered out, and ensure that the effects of different lighting angles are used to best effect to reveal subtle features. For predominantly non-wooded landscapes, the possibility of commissioning a mapping survey using sources other than just lidar – for example a full aerial photographic survey using both historic and modern photographs – should be considered, as often the interpretation process is made much easier by comparing different sources.

Aerial photography in England will normally only be able to photograph earthworks lit by the sun from the west, south or east, and requires the photographer to be there at the right time to make the record. The great advantage of lidar data is that they make it possible to view archaeological earthworks with the light coming from any direction or elevation. This gives much greater confidence in interpretation and can often reveal previously unseen features. Because the user will normally be mapping from a two-dimensional image, it is essential to remember in which direction the light is falling to enable the difference between cut and raised features to be correctly identified. (If the data are being viewed stereoscopically this is less of a problem). Most people find it easiest to interpret an image when the light

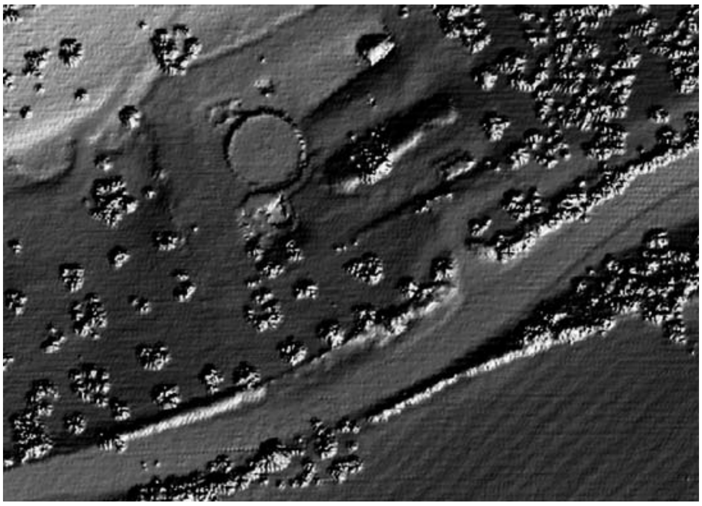


Fig 29 Feature misinterpretation: lidar derived image (lidar © Forestry Commission; source, Cambridge University ULM (March 2004)).

Fig 30 Feature misinterpretation: aerial photograph showing the true nature of the feature (© Cambridge University ULM. zknpp0001 02-FEB-2005).

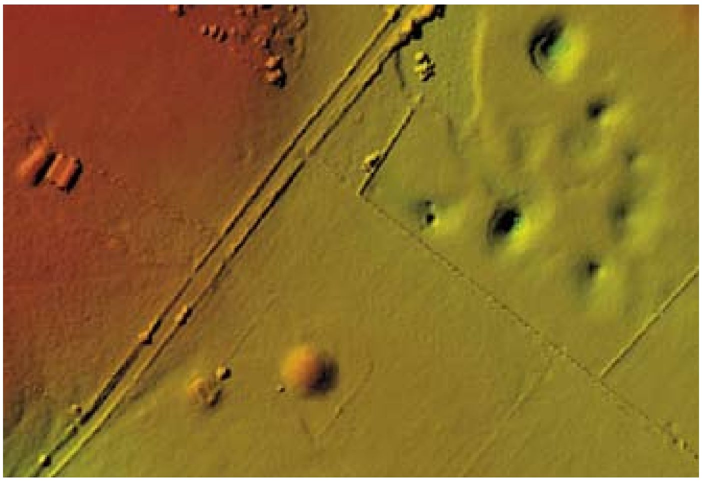


Fig 31 Feature misinterpretation: lidar derived image (lidar © Mendip Hills AONB; source, Cambridge University ULM (April 2006)).

Fig 32 Feature misinterpretation: aerial photograph showing the true nature of the feature (photo PGA_ST5050_2006-04-30_part. Licensed to English Heritage for PGA, through Next Perspectives™; OS background map © Crown Copyright. All rights reserved. English Heritage 100019088. 2009).

falls from the top of the image as viewed and the tradition in hill-shading for maps is with an imaginary sun in the north-west.

Figure 31 shows some of the difficulties of interpretation from a single hill-shaded image. In the top right corner of the image are number of features with highlights to the south-west (north is to the top of the image) and shadows to the north-east. By contrast, in the bottom centre is a feature with highlights to the north-east and shadows to the south-west. Without reference to other information, or knowledge of the direction of lighting it is not immediately apparent which are negative and which are positive features. Once the correct three-dimensional aspect of the features has been acquired, the feature in the bottom centre gives every appearance of being a burial mound, being of a similar size and shape to other known barrows in the vicinity. However, the evidence from aerial photographs and mapping (Fig 32) reveals that this is in fact the site of a covered reservoir.

Viewing packages usually provide hill-shading of the surface model (DSM or DTM) – that is, they show the amount of light that would be reflected from a surface lit from a single light source, sometimes combined with a certain amount of ambient light. This means that objects may have shaded sides but do not cast shadows. The interpretation is therefore slightly different to that of aerial photography, in which cast shadows can obscure features. Where shadow effects are used it is important to remember that the edge of the shadow of a feature is not necessarily (or even usually) the edge of the feature itself.

DEMs can be coloured within most viewing packages to show changes in height. In some software, fine control makes it possible to represent a small change in height through a wide range in colours. This can be used to display the topographic differences of a site on a two-dimensional display. Draping a semi-transparent hill-shaded image over the top will help to clarify features and this will often be the most useful way to view the data. Some software packages can also be used to create cross-section analysis of DEMs, and hence, of archaeological sites or features.

2.2 Filtering

In some areas of environmental remote sensing, algorithms can be used to identify the 'signature' of particular features, but this has not been successfully proven for archaeological features. Rather in archaeology, algorithms are used to 'clean' the lidar data to aid visual interpretation. In arable, pasture and moorland situations the first or last return data on its own is generally suitable for the recovery of archaeological remains (indeed in open land the first and last returns may be identical). Lidar comes into its own in wooded landscapes where the use of algorithms to filter out vegetation makes it possible to record features beneath the woodland canopy. It is possible in certain circumstances to use just the last return data, rather than any filtered data, but this is very dependent on the nature of the vegetation and on the time of flight. As explained above, the last return data are the result of the final return of the laser beam from either the ground surface or from a feature so dense that it does not allow any of the beam to penetrate; this may be a rock, a fallen tree trunk or in certain cases a holly bush or other area of dense undergrowth.

Last return data were used with great success by English Heritage at Welshbury hillfort in the Forest of Dean (http://www.heritage3d.org/casestudies/2008/jan/1/case-study-15-forest-dean/). Here the last pulse data revealed the bulk of the hillfort remains, though leaving in place off-ground 'features' such as tree trunks etc. The fact that tree trunks are retained in last return data was actually used to assess veteran trees in Savernake Forest where they were seen as larger 'stumps' than the norm. The downside to using the last return data in wooded areas is that if a DEM is created from it, the upstanding tree trunks are displayed as spikes in the model. When this is illuminated from a low elevation to create a hill-shaded image, the spikes show strongly, distracting the viewer from the more subtle archaeological features.

However, while this information can be useful in open areas or in certain types of woodland, it is preferable that for a fuller and more accurate interpretation that as many off-terrain points as possible are removed from any dataset. The analysis of full waveform data (*see above*) enables the identification and removal of even more off-terrain points than standard lidar, but in practice there are always likely to be some remaining. These are normally readily identifiable as being of non-archaeological origin. Because it has always been important to be able to create accurate DTMs for a number of non-archaeological applications – such as calculating topologies etc – there have been algorithms for creating 'bare earth' DTMs for almost as long as there has been access to lidar data. However, the early filtered terrain models were not concerned with the sort of small-scale variations that archaeologists are usually interested in, but were more interested in the broad lie of the land. As a result they ran the risk of filtering out – as noise to be removed – those objects that the archaeologist sees as a feature to be interpreted. Equally, and possibly more worryingly, the resulting surface from using these early algorithms could also contain processing artefacts that can be confused with archaeological features; certain processes in particular created regular gridded patterns that bear striking similarity to 'celtic fields'.

These guidelines are not the appropriate place to discuss these issues in detail, but those wanting further details should see Sithole and Vosselman 2004. Over time more sophisticated filtering/classification methods have been devised that create an accurate ground surface while maintaining the subtle features in which archaeologists are interested.

One point that should be emphasised is that during the creation of a DTM, where last return points are located 'off-ground', options are available on how these are dealt with. For example, they can be used in the creation of a terrain model and the surface forced over them (creating something resembling a TIN). However, this can create false features. Alternatively, they can be ignored and gaps left in the model where they occur either left empty or filled using average data from the surrounding model. Where dense vegetation occurs, there may be significant areas where last returns do not reach the ground, so rather than smoothing these areas over, there is value in leaving them blank to emphasise the fact that the technique was ineffective in those areas and that further work on site may be necessary.

2.3 Artefacts and issues

One area that needs more analysis is that covering the various artefacts created in lidar data. As noted above lidar data primarily record height data, and as such will not differentiate between archaeological features created by human interaction with the landscape centuries or millennia ago and the remains of modern agricultural or other practices. However, as well as the features of modern origin that need to be recognised and ignored, there may also be some elements in the data, and in derived images, that are not related to any features on the ground, but are artefacts of the original data collection and subsequent processing. While some of these are quite obviously artificial, others may have an appearance similar to archaeological features, so it is important that these are recognised and not misinterpreted.

One key way of recognising artefacts is borrowed from aerial photographic interpretation: this is to look at how a suspect feature or pattern relates to those features about which you have greater confidence, for example roads and hedges.

For example, any feature that visibly crosses a modern road or hedge, is not of archaeological origin but is on the 'surface' of the image – therefore, in the case of lidar, a data artefact. Clearly when they are available, examination of other sources such as aerial photographs, preferably taken at the same time as the lidar data were captured, will help to clarify areas of uncertainty.

There is not room in this publication to discuss all the potential problems, but two of the most frequently encountered and potentially misleading classes of such artefacts can be highlighted: where the interference patterns between overlapping swathes give rise to wavy lines (Fig 22) and where the interference patterns have the appearance of ridge and furrow cultivation (Fig 33);

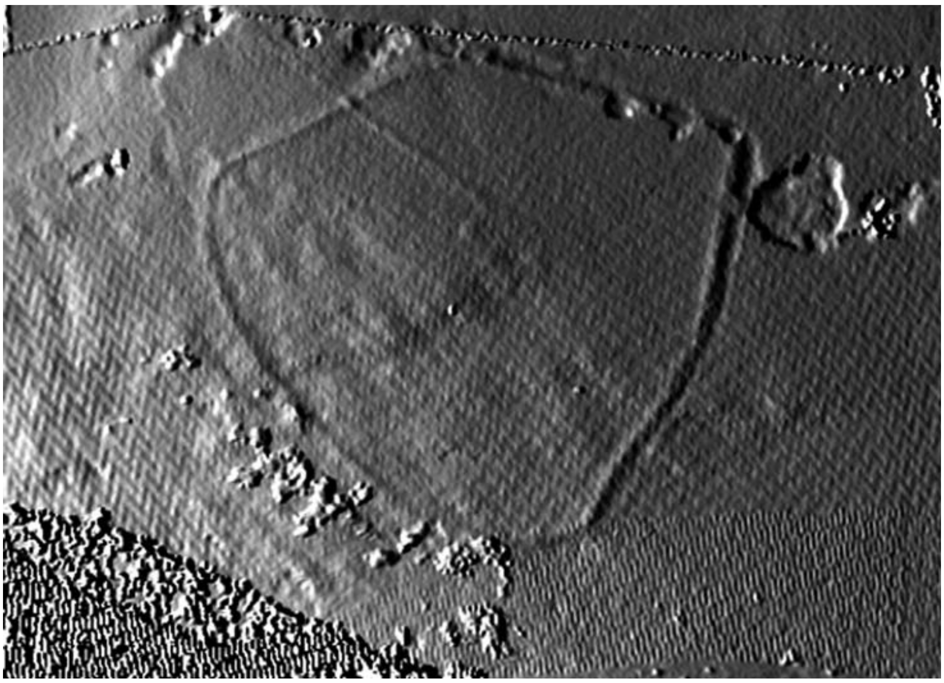


Fig 33 Lidar artefacts: Wave patterns (lidar © Mendip Hills AONB; source, Cambridge University ULM (April 2006)).

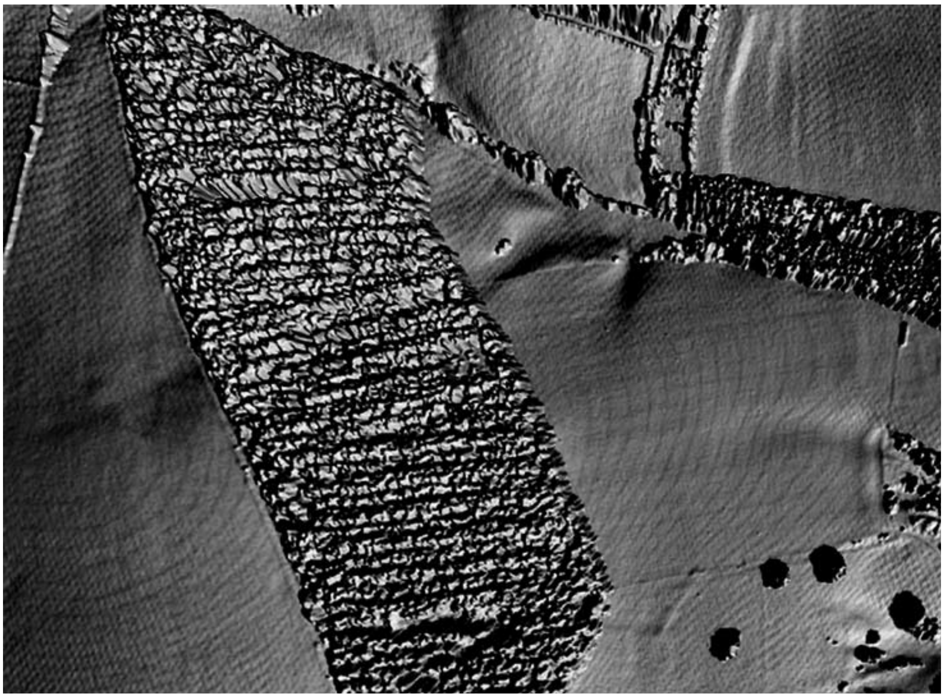


Fig 34 Lidar artefacts: False lynchets (lidar © Mendip Hills AONB; source, Cambridge University ULM (April 2006)).

and where rounding errors in the processing create slight steps in the data that have the appearance of possible lynchets (Fig 34).

Summary

- Like an aerial photograph, a lidar-derived image appears misleadingly simple to interpret; to ensure the best results from a survey the interpretation should be done by someone with the necessary skills and experience.
- There will be a significant cost benefit in detailed evaluation of the imagery before any field survey work.
- For predominantly non-wooded landscapes, the possibility of commissioning a full aerial photographic survey using both historic and modern photographs should be considered, as the interpretation process is made much easier by comparing different sources.
- Lidar has particular advantages in wooded landscapes where the use of algorithms to filter out vegetation makes it possible to record features beneath the woodland canopy.
- In certain circumstances unfiltered last return data can reveal a significant amount of detail beneath the canopy, but for the best results you really need a processed bare-earth DTM.
- As with all data sources there are artefacts created during the original data collection and subsequent processing; while some of these are quite obviously artificial, others may have an appearance similar to archaeological features and it is important that these are recognised and not misinterpreted.

3 Mapping

Mapping is an essential part of archaeological survey using lidar; in order to adequately record the results of interpretation of lidar data it is almost always necessary to map the features identified; in fact experience shows that the actual mapping process concentrates the mind and often clarifies the interpretation. Depending on the level of survey and the detail required, the same mapping conventions as those used in aerial and ground based archaeological surveys can be used. Normally, mapping will be done in a digital environment, but where interpretation is done in the field using paper copies of lidar imagery then the use of manual methods on transparent overlays may be appropriate.

Where mapping is to be carried out in a digital environment, however, there is a small problem. The nature of lidar and laser-scanned data in general means that the majority of lidar packages are designed for viewing; they will enable data to be seen in three dimensions, creating surface models that can be rotated, flown through etc. A second set of programs are available, especially within the commercial zone, that are designed to extract data automatically from point clouds, such as for planning the presence of pipes in a refinery etc. Such programs have their uses, but the best packages for viewing the data are not necessarily the best for mapping and recording purposes.

To interpret features effectively, viewing software with full three-dimensional functionality and controllable lighting etc is essential, but for the mapping of the features compromises may need to be made. Until recently the best method was to use the viewing software to produce a hill-shaded raster image that could be used as a flat base image within the mapping software. This can be an effective method, especially when used alongside a viewing package that allows real-time manipulation of the source data to aid interpretation. New developments enable real-time manipulation within some mapping packages, and it is hoped that further developments will facilitate wider use of this technique.

The three-dimensional data can also be used in modern photogrammetric packages, viewed in stereo and mapped in three dimensions. The use of such software is still a specialised area, but may be worth considering for particularly important sites. It is also worth remembering that modern digital photogrammetry can produce high-resolution datasets from traditional or modern digital photographs that are similar to those produced by lidar; such datasets can be used and manipulated in the same way as lidar data and imagery.

It is important to remember that mapping a feature or features visible on the lidar derived imagery is only part of the recording process; it is crucial that in addition to the graphical depiction of any given feature there is a database record as well. If the mapping is carried out within a GIS environment it is possible to attach relevant data – such as suggested date and interpretation – along with additional sources, comments etc. If it is not possible to work in a GIS package then these data need to be recorded in a separate database and some form of linkage made between the two datasets.

Summary

- Mapping is an essential part of archaeological survey using lidar; in order to adequately record the results of interpretation of lidar data it is almost always necessary to map the features identified.
- It is important to remember that mapping a feature or features visible on the lidar-derived imagery is only part of the recording process; it is crucial that in addition to the graphical depiction of any given feature there is a database record as well.

4 Field use: hard copy versus digital; raster versus vector

Lidar is still a relatively new tool in the archaeologist's toolkit and relatively few projects have combined its use with field survey. English Heritage survey staff have compared the results of lidar analysis with field survey in projects in the Mendip Hills, in mature, deciduous woodland in Savernake Forest, and are beginning to do so more systematically through the 'Miner – Farmer Landscapes of the North Pennines Area of Outstanding Natural Beauty'. This early work is confirming the accuracy and increased efficiency of recording that the lidar data provide.

Much of the work using lidar for archaeological investigation in the field has so far been centred on its use in woodland, led by the Forestry Commission. It has been seen as a technique particularly suited to survey in an environment in which it has previously proved very difficult to work.

One of the key factors relating to survey in woodland before the advent of lidar was the issue of speed. Because of the nature of woodland, in which features may be obscured by the presence of trees and even more by undergrowth, previous projects have mostly employed 'walkthrough' surveys in which transects of varied width were used (see 'Section D: field-based surveys' in Rotherham *et al* (eds) 2007; and concluding remarks from the Woodland Archaeology seminar organised in June 2003 by Gloucestershire County Council http://www.gloucestershire.gov.uk/index.cfm?articleid=7261). In order to maximise a survey, particularly given the short timeframe during which vegetation was at a sufficiently low level so as not to impede study, one option was to use large numbers of trained volunteers. Taking this methodology forward to check features on the ground against the lidar-derived imagery, the emphasis had been on using hard copy printouts. There are many advantages to using such plots in the field, especially the lack of the need for any complex hardware or software. A sheet of A3 paper with a hill-shaded or PCA-composite image can provide suitable reference material to which notes can be added as observations are made. Indeed this is arguably the most effective technique even in open country.

Fig 35 Using lidar data on the GeoXt in the field.

It should be noted that even where fieldwork is intended there is benefit to carrying out a more detailed desktop survey utilising lidar and other sources (eg standard aerial photographs), and taking this information into the field instead of, or together with, the simple lidar-derived imagery. Similarly, the results of field survey can feed back into further analysis of the original datasets on a PC.

So far only a small amount of research has been carried out by English Heritage staff using lidar data in the field but further projects are planned that will include more direct use of the lidar data, both as hard copy or loaded into mapping grade GPS devices (Fig 35). There appears to be great potential for more rapid surveys in a number of different environments.

Summary

- Lidar is still a relatively new tool in the archaeologist's toolkit and relatively few projects have combined its use with field survey.
- Field checking of lidar data has confirmed the accuracy of desk-based interpretation and mapping.
- It is possible to produce hill-shaded imagery and take this out into the field; a sheet of A3 paper with a hill-shaded or PCA composite image can provide suitable reference material to which notes can be added as observations are made.
- Even where fieldwork is intended there is benefit to carrying out a more detailed desktop survey utilising lidar and other data sources, such as standard aerial photographs, and taking this information into the field instead of, or together with, the simple lidar-derived imagery.

Part IV Case studies

1 Stonehenge

The Stonehenge project was the first archaeological project in England to make use of lidar data, albeit in a test environment. The project was carried out to test the usefulness of lidar and the Stonehenge area was chosen partly because it had been such an intensively investigated landscape in the past. It was felt that if lidar was able to add information in this landscape then it was likely to be able to do so anywhere. Unlike later projects, the lidar data were not examined simultaneously with the standard aerial photographs, but rather examined separately some time after completion of the air photo surveys. For further details of the project and methodology see Bewley *et al* 2005.

Even though there were a number of methodological issues that meant that the lidar data were not examined in the most effective manner, a number of new observations were made. One of the more interesting was not a new discovery, but rather the confirmation of the physical state of some features. Just south of the Winterbourne Stoke crossroads, immediately east of the A360, there is a field system of probable later prehistoric or Roman date recorded from 1940s vertical photographs taken by the RAF and the USAAF. In the 1940s the features of the field system were well preserved earthworks, but they have been ploughed consistently since the mid-1950s and were believed to be largely destroyed, and only visible as soilmarks (Fig 36). The record of a field visit in 1970 states: 'There are no definite traces of this field system on the ground'. There may well be no easily discernable traces of the system on the ground, but there is no doubt from the lidar data (Fig 37) that evidence of the field system is still identifiable and definable on the present ground surface as slight banks outlining individual fields.

Elsewhere, in fields to the north-east of the Winterbourne Stoke Barrow group, a previously known field system was recorded from aerial photographs as consisting largely of elongated fields unlike the generally square 'celtic' fields in the area. The lidar data revealed the cross banks dividing the fields into their expected shape.

2 Witham Valley

The Witham Valley project was the first in which English Heritage staff had access to lidar data to manipulate. Whereas in the Stonehenge project they could only work with a series of flat two-dimensional images with hill-shading, for the Witham project they had the gridded data to manipulate. Unfortunately the actual data available were not as high resolution as that for the Stonehenge survey: only data at 2m resolution (one data point for each 2m x 2m cell) from the Environment Agency, as ASCII gridded files. For further details of the project and methodology *see* Crutchley 2006.

Two of the key findings from the survey were the confirmation that 2m resolution was not necessarily high enough for the identification of a wide range of archaeological features, and that those mapping the archaeological features really required direct access to the manipulable data, although accurate hill-shaded imagery created specifically for archaeological purposes would be a good second best.

As was noted in section III 1, and

Fig 36 Aerial photo of field systems south of the Winterbourne Stoke crossroads (© English Heritage. NMR NMR21140/14 17-APR-2001).

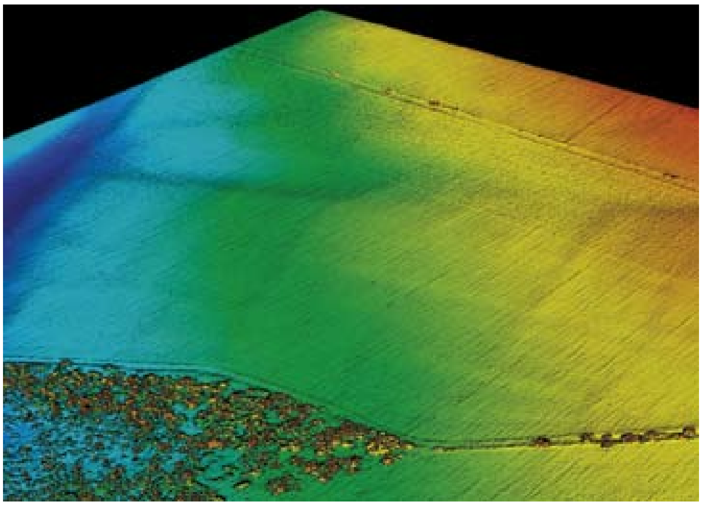


Fig 37 Lidar imagery of field systems south of the Winterbourne Stoke crossroads (lidar © Environment Agency 2001).

Fig 38 Unshaded lidar imagery for area around Washingborough showing a possible barrow cemetery (centre) and the course of the Carr Dyke (left centre) (lidar courtesy of Lincolnshire County Council; source, Environment Agency (March 2001)).

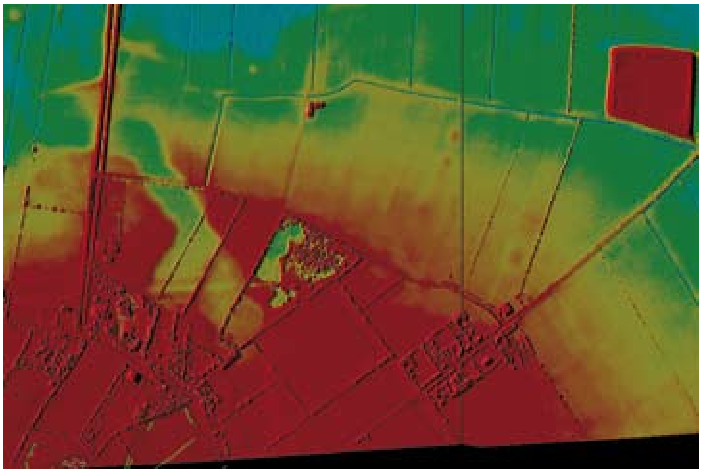


Fig 39 Colour contour and hill-shaded lidar imagery for area around Washingborough showing the possible barrow cemetery (centre) and the course of the Carr Dyke (left centre) (lidar courtesy of Lincolnshire County Council; source, Environment Agency (March 2001)).

especially in Figures 25 and 26, there is a great deal of difference between the information that can be extracted from raw lidar imagery and from hill-shaded imagery. Use of lidar data with greyscales or colours depicting height, and without hill-shading, can only reveal the most substantial of archaeological features; it does, however, provide a very good topographic background to the mapping that has its own archaeological value.

Figure 38 shows the area north-east of Washingborough, where the National Mapping Programme (NMP) project recorded the remains of a possible Bronze Age barrow cemetery. Examination of the unshaded imagery was able to add little in the way of confirmation of the site but did reveal the old water channels clearly. Analysing the data with full three-dimensional capability (Fig 39) reveals the clear outline of a number of the barrows previously recorded only as soilmarks, as well as delineating the course of the Carr Dyke running from just below the middle of the left hand edge of the image.

3 Forest of Dean

The Forest of Dean was the first time that English Heritage staff had access to the actual raw/ungridded lidar data and had the necessary software to manipulate it to extract the maximum data possible. This was also an opportunity to look specifically at the potential for mapping in a woodland environment (*see above*).

The project did not examine the whole of the Forest, but rather a small section around the Iron Age hillfort at Welshbury. The area was surveyed at a high resolution – up to four points per metre – and the data provided as ungridded text files recording x, y and z coordinates, and intensity data for both first and last returns. For further details of the project and methodology see Devereux *et al* 2005.

Since the survey flight, considerable further work has been carried out in the surrounding Forest and the benefits of the processed data have been shown to be enormous. Following on from both the NMP survey and Stage 1 of the Forest of Dean Archaeological Survey (Desk Based Assessment), the SMR for the Forest of Dean survey area contained disproportionate numbers of records for the post-medieval and modern periods and, with the exception of the remains of late post-medieval industrial features, the results were heavily biased in favour of the identification of features outside of areas of woodland. It was as a result of this bias that the investigation of those wooded areas was identified as a priority for further research. Although few of the features identified through the lidar survey can currently be dated with any certainty, many may date to earlier periods previously under-represented in the area.

Hoyle 2008 reported that preliminary analysis identified 2,165 possible features, of which 1,687 were thought to be archaeologically significant. The vast majority of these had not been previously recorded, and even where they were known sites, significant supplementary detail was often added.

Of these 1,687 possible archaeological sites, 46% were called significant or very significant. They included 42 enclosures,

Fig 40 DSM of the landscape west of Speech House, Forest of Dean showing little but the trees and part of the road (lidar © Forestry Commission; source, Cambridge University Unit for Landscape Modelling (March 2004)).

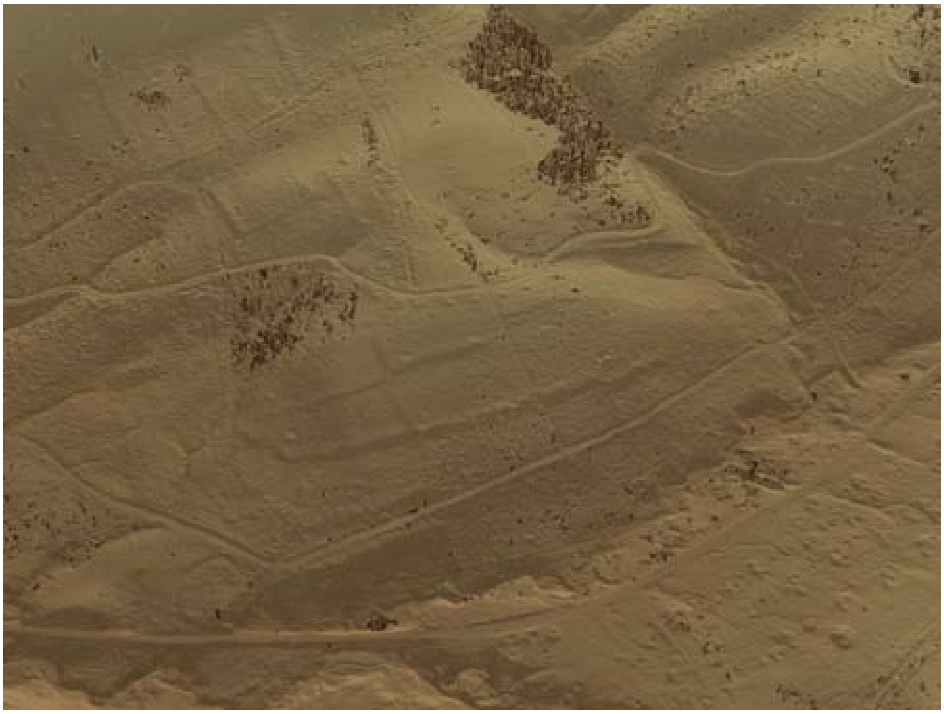


Fig 41 DTM of the landscape west of Speech House, Forest of Dean revealing evidence for large scale past human activity (lidar © Forestry Commission; source, Cambridge University Unit for Landscape Modelling (March 2004)).

some of which were interpreted as early Roman military features or prehistoric settlements; others are considered more likely to be related to former field systems.

As well as these individual enclosures, 165 areas of regular linear systems, mostly thought to be field systems, were identified; 42% of these, by area, were recorded in woodland and covered an area of more than 6km^2. While they are largely undated, many are thought to be related to 13th- or 14th-century assarting, while others were almost certainly prehistoric, based on their location and appearance. 'These features … are broadly similar in form and give the impression of a large-scale system of landscape organisation predating the patterns of woodland distribution, and [are] similar to prehistoric field systems identified in other areas of the British Isles' (Hoyle 2008).'

Elsewhere, early industrial activity is well represented by evidence of mining in the form of small-scale surface extractive pits and spoil tips, but the largest increase in feature types is the recording of charcoal burning platforms. These were previously known as a site type within the forest and had been recorded in small numbers – 88 individual examples within 25 sites. The bulk of these, however, had been recorded in fields that were now outside the woodland, as the recognition of such ephemeral features within woodland had proven difficult. The new survey increased the number of platforms to 942 (in 111 sites) a percentage increase of 1070% (444%), which supports the suggestion that they may be the most common archaeological feature within the woodland of the Forest (Hoyle 2005, section 2.1.1). Figures 40 and 41 show the presence of a number of previously unknown features such as extensive field systems, together with possible enclosures, charcoal burning platforms and traces of more recent mining activity.

4 Mendip

The Mendip Area of Outstanding Natural Beauty AONB project was the first project where the lidar data were used as an integrated resource along with the standard aerial photographs, as opposed to being used separately after the initial interpretation had been carried out using APs.

The landscape is mainly pasture, but with some areas of arable cultivation and open moorland, plus small patches of woodland, much of it coniferous plantation. This being the case, the lidar data provided by the ULM were simple, unprocessed data, as there was not felt to be the need for the use of canopy removal algorithms.

The data were processed to provide two outputs: one a series of georeferenced, greyscale, hill-shaded images where height exaggeration and controlled lighting were used to highlight archaeological remains to the best degree possible; and secondly a QT file created in the Quick Terrain Modeller format described above, which enabled the data to be viewed interactively in three dimensions. The greyscale images were initially provided with a constant illumination, but it was realised that changes in the topography, especially the presence of steep scarps and incised valleys, meant that it was more useful to have individual tiles lit in the optimum manner, whatever that might be. The provision of the interactive QT files meant that the features could be viewed with illumination from all possible angles and new hill-shaded imagery created if required. The methodology of the project and the key findings are recorded in Truscoe 2008.

There were two key highlights. The first was further data on the route of the Roman road in the vicinity of the Roman town

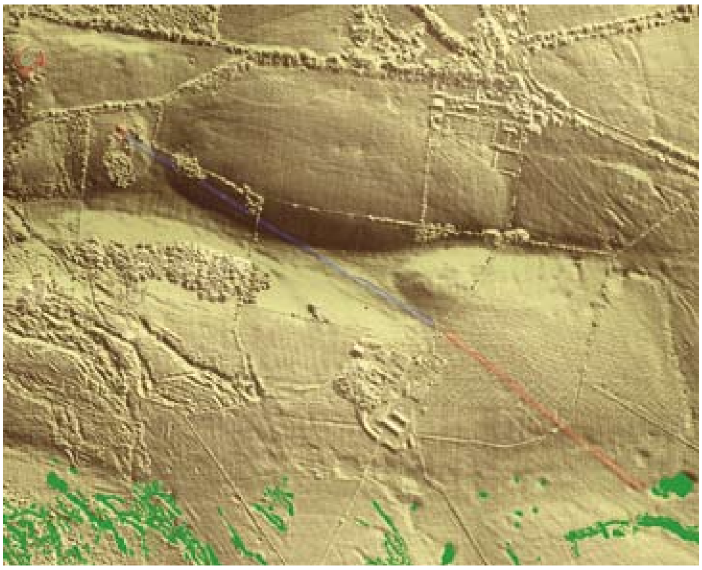


Fig 42 Roman Road east of Charterhouse pre-lidar (lidar © Mendip Hills AONB; source, Cambridge University ULM (April 2006)).

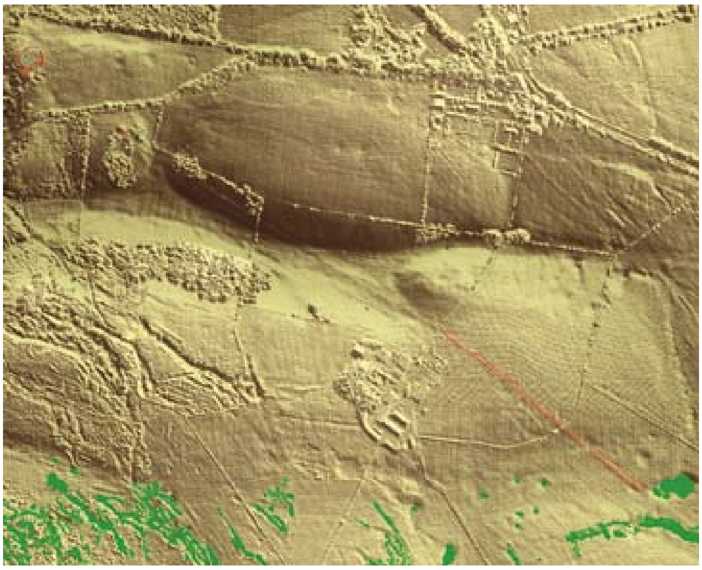


Fig 43 Roman Road east of Charterhouse post-lidar (lidar © Mendip Hills AONB; source, Cambridge University ULM (April 2006)).

Fig 44 Ground survey of Christon medieval settlement. © English Heritage

Fig 45 Survey of Christon using lidar-derived imagery. © English Heritage.NMR.

at Charterhouse. An active local Mendip archaeological group (Charterhouse Environs Research Team – CHERT), had carried out extensive area survey, including earthwork and geophysical survey. A key area of interest was the course of the Roman road around Charterhouse, east towards Old Sarum and west towards Uphill. To the south and east, the line of the road was recorded as an earthwork near the Priddy Circles and again just to the south of Ubley Warren Farm. Beyond that point, as it headed towards Charterhouse, the road was simply recorded as 'course of', on the assumption that it was heading towards the town by the most direct route.

CHERT members had examined the area between Ubley Warren Farm and the town using several survey techniques without success. Examination of the lidar data for the area, with a small degree of height exaggeration and controlled illumination, revealed the course of the road as a low bank for over 0.75km north of the farm towards the Roman town (Figs 42 and 43). Examination of the data to the west of the town also revealed probable traces of the road as it heads towards Uphill near Tynings Farm.

The second highlight was working with the EH Archaeological Survey and Investigation team to examine the results of lidar on the ground. The settlement and associated field system at Christon, in the north-west of the survey area, was chosen. Although the area had been flown over as part of the lidar survey and the processed data were provided to the field team for evaluation, it was not an area that had been mapped as part of the NMP project at the time of the field investigation. It was therefore not possible to carry out a direct comparison with the mapping and interpretation based on the lidar data carried out by Aerial Survey and Investigation staff. Precisely this sort of systematic, measurable comparison is currently being undertaken as part of the 'Miner–Farmer Landscapes of the North Pennines Area of Outstanding Natural Beauty' project.

In the Mendips, the lidar data were provided to the field team in the form of hill-shaded images imported onto their Geo-Xt hand-held GPS running FastMap CE (*see* Fig 35). The results of the assessment suggested that while there were some areas where the lidar data did not reveal as much information as a ground survey there were other areas where the lidar data extended what could be seen on the ground. In particular there were two cases where the lidar image indicated the continuation of several broad earthworks beyond where they appeared to fade out on the ground; even when the location was recorded from the lidar data there was nothing recognisable in the field.

After completion of the NMP mapping for the area (Fig 44) the results from the field survey (Fig 45) were compared with those from the lidar interpreted imagery and it was noted that while there was more detail recorded in the ground survey (which was hardly surprising given the larger scale of the latter; *see below*) the bulk of the features relating to the settlement had also been recorded from the lidar data. That said, some qualitative information, such as stratigraphic relationships, can be more easily understood from field observation rather than from lidar data alone.

5 Savernake

The Savernake Forest project finally provided the opportunity to use real lidar data in a fully interactive three-dimensional (or rather two-and-a-half-dimensional, as described above) environment where mapping could take place directly onto the data. The newly available modules in AutoDesk Map made it possible to insert raster surfaces into the AutoDesk environment that enabled mapping directly against these surfaces, and straightforward comparison with aerial photographs.

The survey was commissioned by the Forestry Commission so as to provide information for their management plan and was flown by ULM Cambridge. The data were provided as gridded tiles recording first return, last return and filtered DTM showing the bare ground surface with the maximum vegetation removed (*see above* for restrictions). Because this was the first large-scale project to be able to take full advantage of the capabilities of lidar, and because approximately half of the project area was under woodland, one aim of the project was to assess the relative value of using lidar and conventional aerial photography in a woodland environment.

When the lidar datasets were examined a large number of features that had not previously been recorded by either the NMR or by the local Historic Environment Record (HER) were noted, and it was assumed that these were only visible because of the capability of lidar to penetrate the woodland canopy. In fact, systematic examination of the archive photography, the normal procedure for NMP projects, also revealed a significant number of these features. Comparing data sources for the whole project area showed that of 350 monuments recorded 166 (47%) were best seen on lidar, 131 (37%) were best seen on air photos and 53 (15%) were equally visible on both sources. For further details of this aspect of the survey see Crutchley 2008.

The second element of the Savernake project was an assessment of the precision possible with lidar data, both in terms of metrical accuracy and of its usefulness for detailed archaeological interpretation. To this end one of the enclosure complexes newly revealed by lidar was chosen for large-scale detailed survey. As well as the interpretative plot produced from the lidar derived imagery, the lidar imagery itself was also examined during the course of the survey

Fig 46 Enclosures at Church Walk as seen on lidar derived imagery (lidar © Forestry Commission; source, Cambridge University ULM (May 2006)).

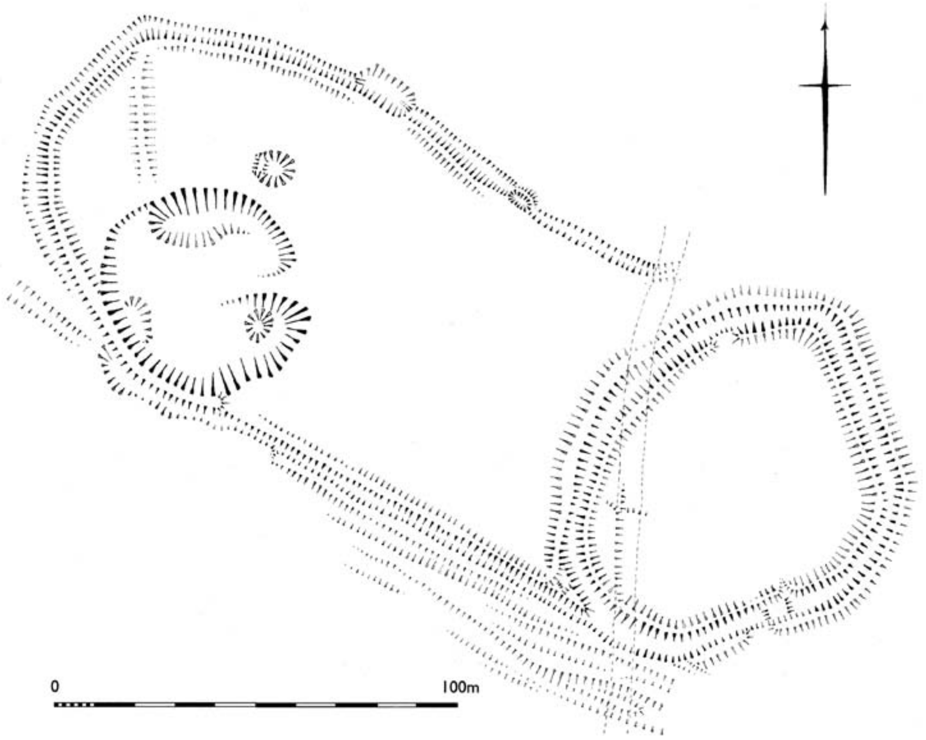


Fig 47 Enclosures at Church Walk as recorded by detailed field survey. © English Heritage.

to analyse other features that might cause confusion during interpretation and to assess the nature of anomalies on the ground.

The conclusion of the survey was that comparison of the lidar image (Fig 46) and plot with the ground survey plan (Fig 47) revealed almost exact agreement over the location, size and shape of the archaeological features; given the 'soft' nature of the earthwork detail involved, the representations could be regarded as 'identical' in terms of accuracy. The ground survey showed a small degree of extra detail that was not visible in the raw lidar data, but the conclusion was that the lidar based survey showed less detail primarily because it was carried out at a much smaller scale than the ground survey (1:2500 and 1:1000, respectively).

The quality of the lidar-derived image was such that, even when enlarged to 1:1000, it presented a readable and useable representation of the ground surface. It was suggested that it was conceivable that a suitably experienced archaeologist could, with data of this quality, create an accurate large-scale interpretative plan of a site directly from the lidar-derived image, without the need to undertake a control survey. However, the archaeologist would have to be aware of several limitations in the dataset, especially: false features caused by vegetation response and related factors; lack of definition or absence of very slight features (especially, on the evidence of this study, positive ones); and discrepancies between mapped OS detail and lidar positioning of the same detail, exacerbated by any enlargement of the OS base.

In this study only one relatively minor feature was surveyed in this way. An interesting test would be to try this experiment by surveying a suitable site with high quality lidar data entirely by this method, and then check it against electronic ground survey.

Part V Lidar for woodland survey

by Peter Crow, Forest Research

While aerial survey of most types of landscape has dramatically increased our understanding of the historic landscape, woodland has always been a hindrance to this process, preventing a clear view of any archaeological evidence hidden beneath (Fig 48). The history of many UK woodlands is often, therefore, poorly understood and as such they have been referred to as one of the UK's last untapped archaeological resources. Survey in woodland also presents its own unique set of problems for ground-based techniques, even before the advent of lidar, and is one of the most difficult landscapes in which to work (Bowden 1999 and Oswald *et al* 2008). The arrival of lidar with the capability to strip away the bulk of the vegetation and reveal the features underneath has proved to be of great benefit (Fig 49), but it is not without problems.

One of the key difficulties is the fact that lidar is indiscriminate in what it records. It has been noted that it is important, where possible, to have an alternative source of data to aid with the interpretation of features. This is especially true in woodland, particularly in managed forestry, because there are several practices that create features that can easily be mistaken for archaeological remains. Unfortunately, the nature of woodland means that for much of it the alternative source of aerial photography is not available or shows nothing beyond the top of the canopy. It is therefore doubly important to understand the types of features that might be seen in woodland, and also the effects that different planting and management regimes might have on the results of a survey.

There are also limitations to what the technology can show and to the types of woodland in which it is best employed.

1 Survey suitability

To gain the most from any lidar survey commissioned for historic environment analysis, surveys are flown at a higher resolution than that required for open ground, and during the winter months when laser penetration to the forest floor has the greatest likelihood. Many existing lidar data may not be suitable for analysis, as they may have been collected during the summer and are often of a lower resolution than the optimum required for archaeological analysis of woodland. Equally, if considering a new survey, it must be emphasised that not all wooded areas are suited to this technique.

Because the survey is dependant upon laser penetration of the forest canopy and understorey vegetation, significant areas of dense, young woodland regeneration or unthinned conifer plantation will greatly restrict the potential of the survey and may prevent it from being a viable option (*also see below* current lidar limitations).

The technology facilitates survey of large areas of forest and woodland dominated landscapes. The best results are obtained from mature broadleaf canopy with little understorey vegetation, for example a beech woodland with bluebells, where the winter survey would ensure that the vast majority of the laser energy would reach the forest floor uninhibited. Under these optimum conditions, the surveys can reveal some very subtle changes in ground surface and reveal many subtle archaeological features. The method is most effective at revealing linear features and even faint earthworks, many of which may be difficult to see on the woodland floor. Examples include earthworks of enclosures (Fig 50), field systems, other boundary banks, lynchets, route-ways and drainage channels. When used over

Fig 48 A typical aerial photograph of a large archaeological feature in woodland (© Peter Crow. Forest Research; source, Cambridge University ULM (May 2006)).

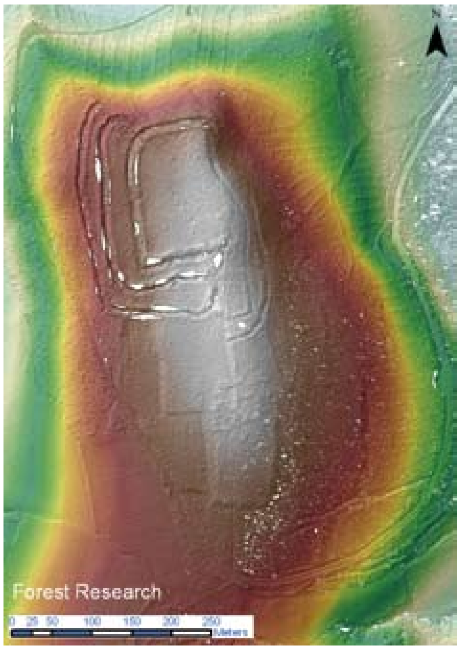


Fig 49 A lidar-modelled ground surface of the same area (© Peter Crow. Forest Research; source, Cambridge University ULM (May 2006)).

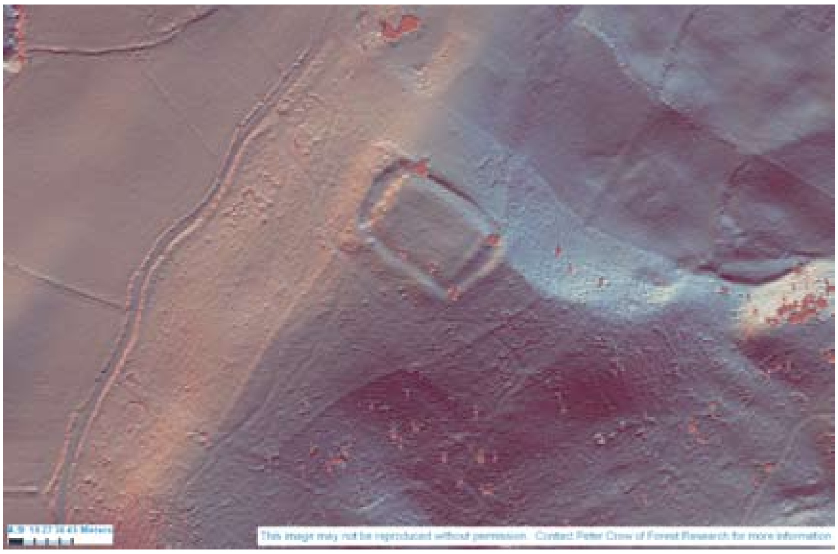


Fig 50 An example of a hilltop enclosure in woodland visible on lidar (© Peter Crow. Forest Research; source, Cambridge University ULM (May 2006)).

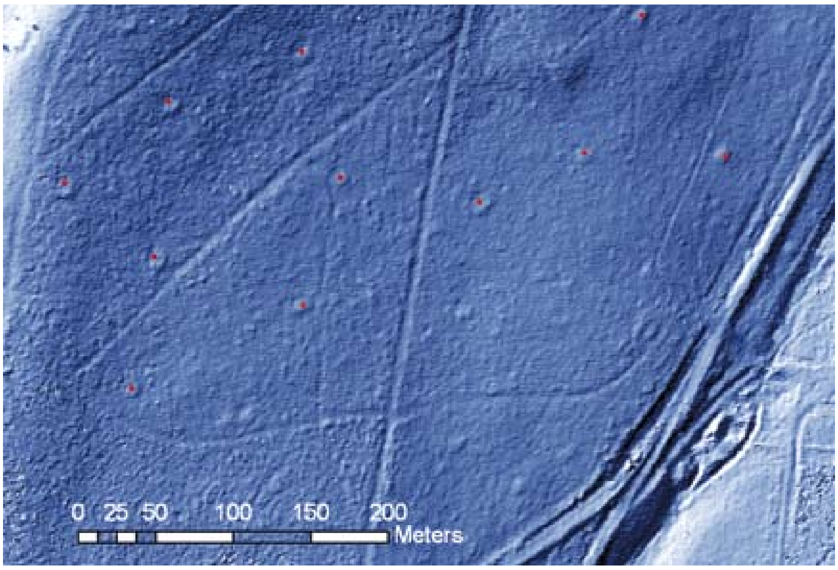


Fig 51 Examples of circular charcoal platforms in woodland visible on lidar (© Peter Crow. Forest Research; source, Cambridge University ULM (May 2006)).

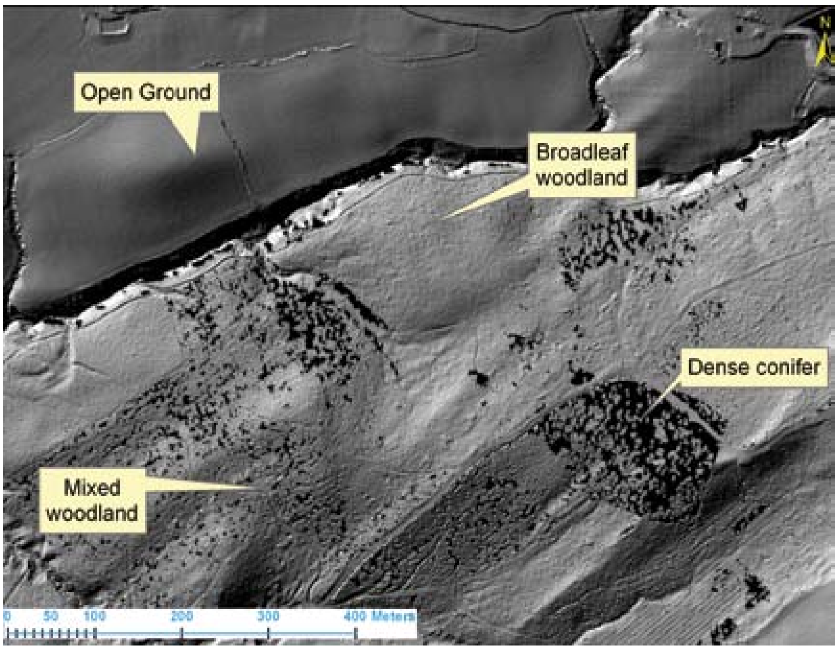


Fig 52 Examples of the effects that different types of vegetation have on the lidar survey as shown in the DTM (© Peter Crow. Forest Research; source, Cambridge University ULM (May 2006)).

optimum vegetation types, smaller, more discrete features such as charcoal platforms have been mapped (Fig 51).

However, as noted above, lidar will not show every historic environment feature and will not work in all woodland types. While the technology will work through mature, thinned conifer – and has revealed linear earthworks, quarries and pits under such conditions – younger, dense conifer plantations will greatly reduce the quantity of energy able to penetrate to the forest floor (Fig 52). However, even where canopy penetration is perceived to be good, dense layers of understorey vegetation such as bramble, bracken, gorse or holly can still inhibit the laser from reaching the true ground surface (Crow *et al* 2007). Indeed gaps in the lidar-derived DTMs caused by understorey holly have been used to map its distribution.

Knowledge of the vegetation types through which the survey is expected to work is therefore essential in considering potential areas for lidar survey, targeting efficient use of resources and providing confidence in the resulting data interpretation.

While lidar has shown such discrete features as charcoal platforms, these tend to be several metres in diameter. However, there is no guarantee that all platforms of this size will be resolved, and circular features of less than 5m diameter may be missed. Part of the problem with the identification of small features is that while the lidar may have detected them, they may only be displayed by a few pixels in the resulting image and distinguishing them from any noise or patches of vegetation can be difficult.

2 Identifying features in woodland

As noted above, hill-shaded images will show not only archaeological features but will also display roads, paths, buildings and, specifically pertinent to woodland survey, forest residue, timber stacks and a host of other modern objects (Fig 53). Additionally, changes in ground vegetation can create patterns that look like features of archaeological potential (Fig 54). Distinguishing between the genuine and artificial historic environment is therefore an important and necessary process, although it is likely to be a long-term project for survey areas of significant size.

The ability to place hill-shaded images into GIS means that other layers can be overlain. Placing aerial photographs, modern and historic maps over hill-shaded images has been discussed, but other forest management data may also identify many features and may provide an indirect explanation for others. This process should help to eliminate many objects and draw attention to those remaining.

Where objects seen in hill-shaded images are not identified from other sources of information, the only reliable method of identification is by on-site examination. While this may not mean that the archaeological feature or its date can be immediately identified, it will at least confirm that it is an earthwork or similar structure of interest, rather than a fence or pile of forest residue (Fig 55).

It is likely to be impossible to 'ground-truth' the whole area in a short time span and to do so would remove the value of commissioning a lidar survey in the first place. However, longer-term projects may be necessary, and would require identification of priority areas or features for any site investigation. Professional archaeologists may undertake this task in conjunction with woodland managers or it may be possible to work with local volunteers. Indeed, there is significant value in engaging with local groups or communities to conduct some of this ground-truthing. Additionally, forest staff routinely working within the survey area may be in the position to examine features.

3 Lidar and managing the Historic Environment in woodland

Important historic environment features located within a forest need to be identified to enable active management and to prevent accidental damage. It is likely that a new lidar survey will have shown a variety of features perceived to be of historic environment potential and interest. Unless these features are known from other records or site visits, it may be difficult to determine their relative importance. Nonetheless, even in areas where no site visit has occurred before the commencement of operations, the hill-shaded images can still be used to raise awareness of potential features and thus help forestry operations to avoid possibly sensitive areas.

Equally, some surveys to date have mapped landscapes of many small, but deep pits and quarries (Fig 56). Here the lidar data also provide a potential map of some on-site hazards and can be used in conjunction with on-site assessments to help reduce the risks of injury. This is relevant not only to those carrying out forest management, but also to anyone involved in follow-up ground survey of recorded features.

Lidar-derived data, models and indeed any mapped features from them offer a powerful tool for the forest design planner.

Fig 53 Example of 'false earthworks': the bracken fallen over a wire fence can create an artificial bank (© Peter Crow. Forest Research).

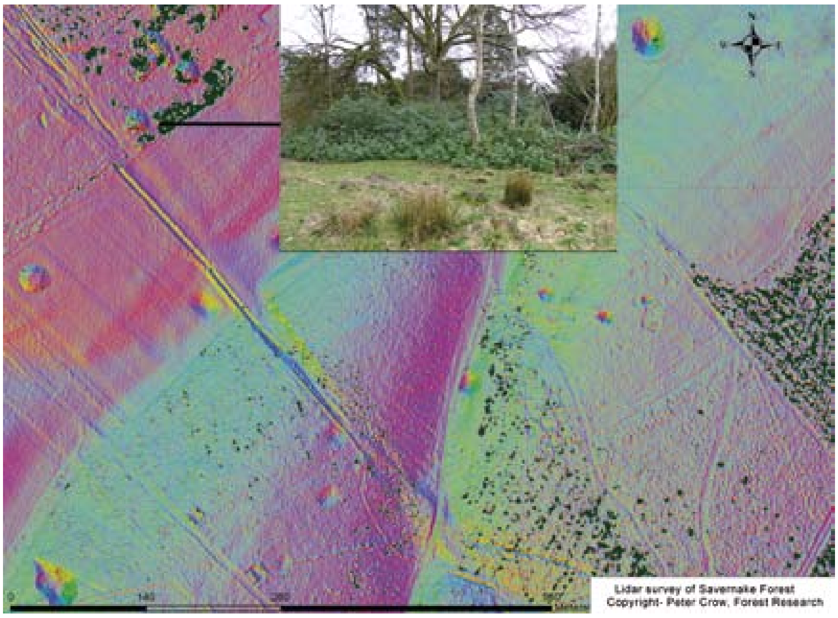


Fig 54 Example of 'false earthworks': this apparent mound is caused by a dense growth of rhododendron (© Peter Crow. Forest Research).

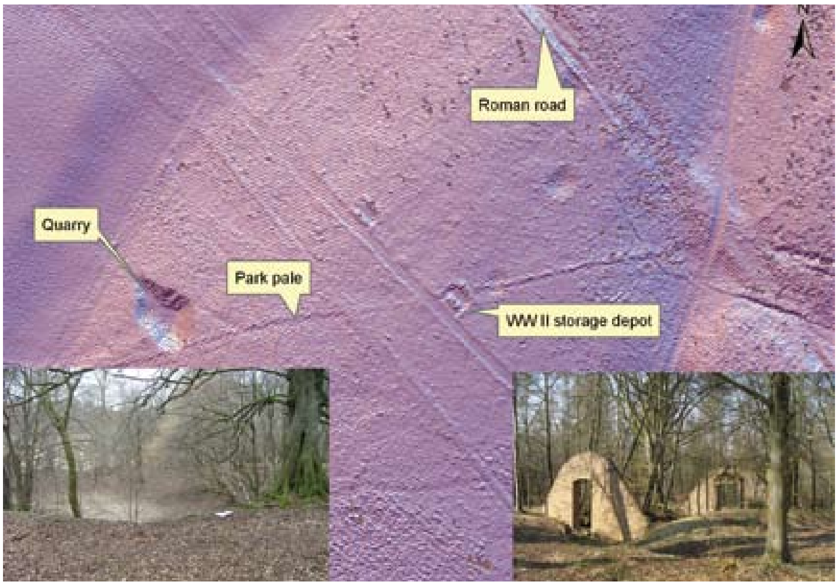


Fig 55 Simple photographic evidence taken during routine site work can be very informative for feature identification and management (© Peter Crow. Forest Research; lidar source, Cambridge University ULM (May 2006)).

Because the survey produces three-dimensional surface models of a forest, which can be manipulated within mapping software, forest views can be examined and planned from all angles (Fig 57). This has the benefit of being able to view archaeological features as they may once have looked in an earlier landscape, and makes it possible for planners to consider possible visual connections associating historic environment features within the landscape, or to change the setting of individual features. Recreational access routes to and around historic environment features can be sensitively planned to increase their value and profile within the woodland, thereby enhancing its cultural value. Indeed this is equally true for other non-wooded environments, such as the restoration of quarries, where reinstatement schemes that seek to create new wildlife and wetland habitats incorporate new footpaths and routes for the public. These can also take in historic environment features that may lie just outside (or be truncated by) a quarry. It is then possible to have display boards that link the newly created environment with the original/historic environment.

Lidar data and modelled outputs have potential uses in many areas. For example, the differences between the DSM and DTM can be used to produce a map of vegetation height. The models of the forest canopy can be used to map individual trees, although this works best on well-thinned or mature woodland where there are differences in tree height or shape due to a change in species or establishment date. These models can be useful in identifying and mapping the health, structure and distributions of ancient woodland or veteran trees within younger plantations (Fig 58). Hedgerows and small areas of woodland can also be mapped to show ecological corridors. When a survey is carried out over mature broadleaf woodland with little understorey, there should be little to prevent the laser from reaching the forest floor. Under such conditions the large boles of any ancient trees present (standing or fallen) can block the laser, and thus be mapped.

With further developments in lidar technology, it may soon be possible to map dead wood, understorey and eventually, full forest structure, with potential applications in biomass calculations and carbon storage.

Lidar is a very powerful tool and when applied to appropriate wooded landscapes has the potential to map both known and previously unrecorded historic environment features. These may provide information about a woodland's history and, in turn, guide its future management. Nonetheless, lidar is not an instant solution to discovering every aspect of a woodland's heritage and is best employed in combination with other sources of information. Because it is most economical to apply the technique at the landscape scale, costs of commissioning surveys will inevitably be considerable. However, such surveys should be looked upon as a long-term investment, for the data, models and images can be useful for planning, management and public engagement.

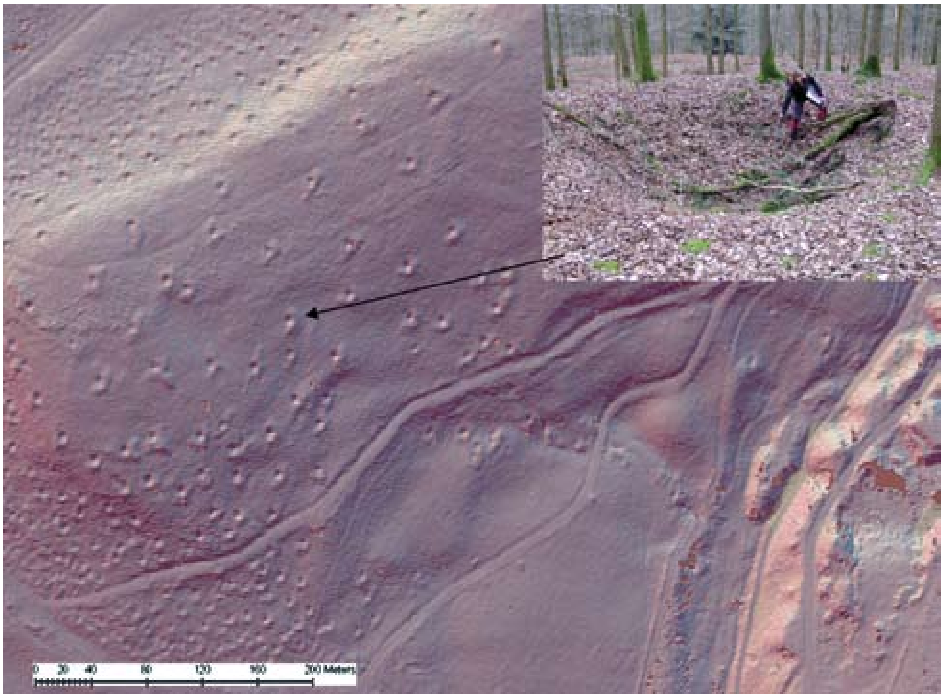


Fig 56 Lidar-derived models can also be useful in mapping difficult terrain (© Peter Crow. Forest Research; lidar source, Cambridge University ULM (May 2006)).

Fig 57 A three-dimensional model with an aerial photograph draped over it can be a very useful planner's tool (© Peter Crow. Forest Research; source, Cambridge University ULM (May 2006)).

Summary

- Lidar provides an unequalled means of recording within wooded areas.
- Significant areas of dense, young woodland regeneration or unthinned conifer plantation will greatly restrict the potential of the survey and may prevent it from being a viable option.
- The best results are obtained from mature broadleaf canopy with little understorey vegetation.
- The method is most effective at revealing linear features and even very subtle earthworks can be shown, such as field

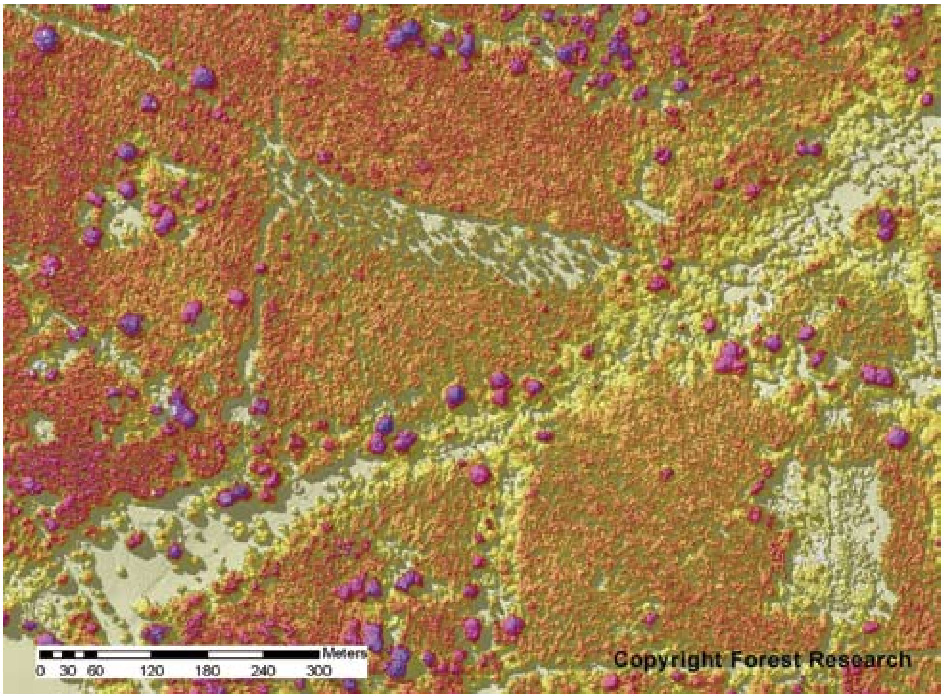


Fig 58 Shows where veteran trees have received a 'halo-thin' (localised management to remove competition from surrounding trees) (© Peter Crow. Forest Research; source, Cambridge University ULM (May 2006)).

systems, lynchets, other boundary banks and trackways.

- Hillshaded images will not only show archaeological features but also roads, paths, buildings, forest residue, timber stacks and a host of other modern objects.
- Changes in ground vegetation can create patterns that look like features of archaeological potential.
- Hill-shaded images can be used to raise awareness of potential features and enable forestry operations to avoid possibly sensitive areas.
- Lidar data can also provide a potential map of on-site hazards and can be used in conjunction with on-site assessments to help reduce the risks of injury.
- Lidar data can be used to help planners design recreational access routes to and around historic environment features to increase their value and profile within the woodland and thereby enhance its cultural value.

Conclusion and summary

Although lidar is a relatively well-established technique it has only been used for archaeological research since the turn of the 21st century. Because it primarily measures three-dimensional data it is only really effective for recording features that exhibit some form of surface topographic expression.

The exception to this generality is intensity data that can be used to analyse the reflectivity of the surface being hit by the laser and thus in certain circumstances may aid interpretation in a similar way to cropmarks on traditional aerial photographs. The accuracy and resolution of the lidar data are heavily dependant on the method of capture and the levels of processing before it reaches the end user. Standard airborne lidar is generally said to be absolutely accurate to within 100–150mm, with a relative accuracy even higher; it should be remembered that from an archaeological point of view, relative accuracy is often more important than absolute accuracy because it is the relative position of features that makes it possible to record them and to understand their relationships with other features.

When planning any sort of archaeological survey for which it is thought that lidar may be useful, advice should be sought in the first instance from the English Heritage AerSI team or from the relevant English Heritage Regional Science Advisor. More technical advice may also be obtained from the Aerial Survey and Investigation team, and the Archaeological Survey and Investigation team can advise on the likely cost benefits of alternative terrestrial survey techniques. If the survey area consists largely of woodland, the Forest Research Team at the Forestry Commission can provide technical advice.

It is essential that all issues relating to dissemination, archiving and copyright are considered at the outset of a project to ensure clarity regarding which data and imagery it is possible to publish and make available to others. Lidar data files and generated imagery are generally quite large and as such they are not easily supplied to third parties.

It is important to be clear as to whether the lidar data are required as the primary source or whether they are seen as a background layer for other datasets available elsewhere. If what is required is basic height data at scales suitable for general topographic relief, these are also available from alternative sources, for example the Ordnance Survey or NASA. If more detailed data are required it is necessary to assess whether such data for your area of interest already exists. The Environment Agency have flown large areas of the country as part of their work monitoring flood risk, etc and a large number of lidar surveys are carried out by other companies each year for non-archaeological purposes, such as infrastructure planning etc.

One of the key factors that affect the viability of lidar is the land use of the area to be surveyed. Because lidar primarily records three-dimensional data, and therefore requires a topographic surface expression to the features to be surveyed, the better the earthwork survival, the better the results. While lidar will work in most landscapes it provides an unequalled means of recording archaeological earthworks within wooded areas. The best results are obtained from mature broadleaf canopy with little understorey vegetation, whereas significant areas of dense, young woodland regeneration or unthinned conifer plantation will greatly restrict the potential of the survey and may prevent it from being a viable option. To achieve sufficient canopy penetration, survey in woodland requires a higher point density in the original data than in an open landscape. The development of full waveform lidar is enabling much more accurate recoding of ground surfaces within wooded and other heavily vegetated environments.

If new data are required then it is advisable to look to Heritage3D, for many of the elements with regard to commissioning a laser scanning survey were addressed by that project. When considering the project area, large, rectangular or linear survey areas are the most cost effective, having the minimum number of turns at the end of each aircraft run; small or irregularly shaped areas are the least cost effective. The Unit for Landscape Modelling (ULM) at Cambridge University provide a useful calculator on their web site to assist in planning surveys by estimating the total flight time required.

Make sure that you know the actual form of data that will be provided; it is no good if the data provided by a contractor, is in a format that the end user cannot use.

The methodology of projects that will benefit from lidar data will vary in detail, but in many cases the extensive dataset provided by lidar is best treated first as one of the sources for a desktop survey. The quality of interpretation and metrical accuracy possible from lidar (used in conjunction with air photos and other sources) gives a high degree of confidence in the results and makes it possible to target fieldwork carefully.

Like an aerial photograph, a lidar-derived image appears misleadingly simple to interpret; to ensure the best results from a survey the interpretation must be done by someone with the necessary skills and experience. For predominantly non-wooded landscapes, the commissioning of a full aerial survey using both historic and modern photographs should be considered, as the interpretation process is made much easier by comparing different sources.

Lidar data can be used in many formats; the standard digital product from a lidar survey is likely to be an ASCII grid, which can be used in standard GIS with add-on modules or specialist three-dimensional viewing programs. Ideally the three-dimensional data should be viewed stereoscopically, taking advantage of the brain's natural ability to interpret three-dimensional objects, but if the user does not have the facilities to view and manipulate the original data in a specialist package, it is still possible to use two-dimensional snapshots of the data as standard jpeg or Tiff files. The most obviously user-friendly product is the hill-shaded image that can be produced as lit from any conceivable position. Other visualisations, such as Principal Component Analysis and slope models, can also be of use.

Mapping is an essential part of archaeological survey using lidar; in order to adequately record the results it is almost always necessary to map the features identified and accompany this with a database record. It is worthwhile noting that even where fieldwork is intended it can be beneficial to carry out a more detailed desktop survey using lidar data and other sources, such as standard aerial photographs, and taking this information into the field instead of, or together with, the simple lidar derived imagery.

In summary lidar can be an extremely useful tool when used in the appropriate circumstances, and particularly when it is used alongside other data sources. It is not a magic bullet that will make possible the recovery of all the types of features currently recorded by other means, and in certain cases the results will be largely uninformative. However, when used in an appropriate environment the results from lidar can be spectacular.

Decision Tree

Preliminaries

Do you need data for detailed archaeological survey and not just for general topography?
- YES: Lidar might be appropriate
- NO: Consider other options as well – OS or similar data; US shuttle DSM; IFSAR or LandMap for UK

Is there likely to be a surface indication of the features you are hoping to record?
- YES: Lidar might be appropriate
- NO: Consider an alternative form of survey, for eg. traditional air photos, geophysics

Does your area of interest contain a large proportion of wooded land?
- YES: Contact Forest Research for specialist advice
- NO

Is the woodland largely deciduous or mixed?
- YES: Lidar is particularly good for survey in deciduous woodland
- NO: Lidar penetration of coniferous woodland, especially dense plantations is very limited and a survey is unlikely to produce the results you require. Consider an alternative form of survey

Is the lidar required as the primary source, an interrogable dataset, or is it seen as a background layer for other datasets available elsewhere?
- YES: You require lidar data
- NO: You probably need lidar derived imagery

Is your area of interest covered by a previous lidar survey? (N.B. It's not always easy to find out except for Environment Agency surveys)
- YES: Go to Section 1
- NO: You will need to commission a new survey – go to Section 2

1. Acquiring off the shelf data

Was the survey carried out to an acceptable specification? Eg. if for woodland, was it carried out in leaf-off conditions; is it at sufficiently high resolution? (see Section 3)
- YES
- NO: You will need to commission a new survey – go to Section 2

Are the data available in a suitable format; eg. is it pre-gridded and filtered for DTM if required; are intensity data available?
- YES: Go to Section 2
- NO

Can the data be processed/ reverse processed to provide it in a suitable format?
- YES: Go to Section 3
- NO: You will need to commission a new survey – go to Section 2

2. Commissioning new data

Are you commissioning data for a relatively large area (>50km2)?
- YES
- NO: A survey may not be cost effective; try to find additional areas in the vicinity where another survey can be carried out at the same time. If necessary, go ahead, but be aware of high costs relative to the area covered

Have you looked at the Heritage3D guidance on three-dimensional laser scanning?
- YES
- NO: Look at Heritage 3D guidance

Do you know what specification is required for your data?
- YES: Contact a number of suppliers to obtain tenders etc. discuss your requirements clearly as they may be able to advise on certain issues. Once you have the data go to Section 3
- NO: Seek advice from someone already using such software or experts at English Heritage

3. Using the data

Do you have the appropriate hardware/software to manipulate and analyse the data?
- YES: Contact supplier and request data in required format
- NO: Contact supplier and request data derived imagery

Do you intend to interpret and make records of archaeological features from the lidar data/ lidar derived imagery?
- YES
- NO: You have the data, so use them as you intended

Do you have expertise in image interpretation?
- YES
- NO: Consider contacting someone with the appropriate skill or approach them for advice and/or training

Do you intend to map archaeological features from the lidar data/lidar derived imagery?
- YES
- NO: Go ahead, but remember to utilise all other readily available sources as well as the lidar data to get a fully rounded picture of the landscape you are investigating and to minimise the risk of misinterpreting features seen on the lidar data

Do you have the appropriate hardware/software to map from the data? N.B. This is currently quite limited
- YES: Go ahead, but remember to utilise all other readily available sources as well as the lidar data to get a fully rounded picture of the landscape you are investigating and to minimise the risk of misinterpreting features seen on the lidar data
- NO: Seek advice from someone already using such software or experts at English Heritage

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Glossary

algorithm A step-by-step problem-solving procedure, especially an established, recursive computational procedure for solving a problem in a finite number of steps.

ALS (Airborne Laser Scanning) Lidar is actually a generic term for all forms of laser measuring, whether ground based or aerial, and so ALS can sometimes be a better acronym.

cell One value in a raster that corresponds to a specific point or area, often referred to as a pixel. A raster cell value may be the elevation above sea level at one position in a survey site or the intensity of red radiation for a pixel in a video image.

DEM (Digital Elevation Model) A **grid** of **cells** or of **pixels** with a height value assigned to each square. This type of **grid** is often called a **raster**. It is differentiated from a standard raster image in that the value assigned to each cell is a height value rather than a tonal one. This is the broad term that encompasses both the **DSM** and **DTM**.

DSM (Digital Surface Model) This is a digital elevation model of the land surface. It records the highest points including buildings and the woodland canopy. In **lidar** terms this is generated by the first return of the laser pulse.

DTM (Digital Terrain Model) This is a digital elevation model of the bare earth – ie the ground beneath any vegetation with other structures such as buildings removed. In **lidar** terms this is generated by filtering the last return of the laser pulse using an **algorithm** to calculate where features exist above the natural ground surface and removing them.

equalisation An image processing technique that redistributes the brightness values of the pixels in an image, so that they more evenly represent the entire range of brightness levels. Equalisation remaps pixel values in the composite image so that the brightest value represents white, the darkest value represents black, and intermediate values are evenly distributed throughout the greyscale.

first pulse/return The first echo of the laser pulse. The laser pulse is sent out from the sensor towards the ground. When any part of the footprint hits a reflective object part of it is returned to the sensor. The first object struck provides the first pulse or first return. In open ground there is often only a single return, but any form of vegetation will produce multiple returns.

footprint The footprint of the laser beam is the area covered by the diverging beam when it strikes a surface.

full waveform The more recent form of laser recording that instead of just recording between two and four returns digitises the entire analogue echo waveform for each emitted laser beam. During post-processing the full waveform can be modelled, for example as a series of Gaussian distribution functions, each representing an interaction between individual objects and the laser.

geoid A mathematical model of the level surface closest to the mean sea level over the oceans. The surface is continued under the land and acts as a fundamental reference surface for height measurement.

GIS (Geographical Information System) A Geographical Information System is an information system for capturing, storing, analyzing, managing and presenting data that are spatially referenced.

GPS (Global Positioning System) A satellite-based positioning receiver and navigation system that pinpoints the geographic location of the user to differing degrees of accuracy, depending on the equipment.

grid A geographic representation of the world as an array of equally sized square cells arranged in rows and columns; each grid cell is referenced by its x and y locations.

HER (Historic Environment Record) Historic Environment Records are the mainly local-authority-based services used for planning, but they also operate a public service and play a role in education. These records were previously known as Sites and Monuments Records or **SMR**s: the name has changed to reflect the wider scope of the data they now contain.

hill-shade The hypothetical illumination of a surface. A hill-shade raster can be calculated for a given surface or hill-shading can be applied on the fly. A hill-shaded image is a computer-generated image used to show subtle changes in the topography of DEMs by the use of shadow in the same way that subtle earthworks can be highlighted by low-angled winter sunlight. An artificial sun position is defined and used to illuminate the DEM.

IFSAR (Interferometric Synthetic Aperture Radar) By combining the principals of Synthetic Aperture Radar (SAR) with Interferometry, Interferometric Synthetic Aperture Radar (IFSAR) is capable of producing both a radar image of the ground surface and calculating elevation changes to enable production of a digital surface model (DSM). IFSAR data are available in the form of a 5m spatial resolution DSM with a vertical accuracy of between 0.5m and 1.0m, and a 1.25m spatial resolution radar image. The low spatial resolution of the IFSAR data means that although it is able to distinguish broad geomorphological zones, such as the river terraces and floodplains, it is of limited value for archaeological purposes.

IMU (Inertial Measurement Unit) An IMU works by sensing its own rate and direction of motion using a combination of accelerometers and gyroscopes, which then enable a guidance computer to track its position using a process known as dead reckoning.

interferometry The use of interference phenomena between a reference wave and an experimental wave or between two waves to determine wavelengths and wave velocities, measure very small distances and thicknesses, and calculate indices of refraction. Radar interferometry relies on picking up the returned radar signal using antennas at two different locations. Each antenna collects data independently, although the information they receive is almost identical, with little separation (parallax) between the two radar images. The phase difference between the signals received by each of the two antennas is used as a basis for the calculation of changes in elevation.

intensity The strength of the signal returned to the sensor. As well as the time taken to return to the sensor that helps calculate the physical location of the point on the ground, the sensor also records the strength of the returning signal. This gives some indication of the reflectance of the surface struck by the beam; rough surfaces generally return weaker signals as part of the beam is dispersed and reflected away from the sensor.

interpolation The process of inserting, estimating or finding a value intermediate to the values of two or more known points in space. In the case of lidar data this generally relates to the estimation of an elevation value at an unsampled point based on the known elevation values of surrounding points.

last pulse or **last return** This is the last echo of the laser pulse. The laser pulse is sent out from the sensor towards the ground; the last return is the final echo returned to the sensor. In the majority of cases in open land this will represent the ground surface, but it can also represent extremely dense vegetation that no part of the beam can penetrate. It can also represent any solid surface above ground level, such as a building.

lidar (Light Detection and Ranging) Variously written as lidar, Lidar and LIDAR. Also known as **ALS**.

nodes The point at which areas (lines, chains, strings) in a polygon network are joined. Nodes carry information about the topology of the polygons.

orthophoto An orthophoto or orthophotograph is an aerial photograph that has been geometrically corrected (‘orthorectified’) such that the scale is uniform: the photo has the same lack of distortion as a map.

panchromatic a greyscale representation of all the visible wavelengths.

PCA (Principal Component Analysis) A multivariate statistical technique to structure complex datasets. In the course of investigating lidar data, it can be used to examine many hill-shaded images and compile a composite image showing more than 95% of the variations seen within them all.

photogrammetry Photogrammetry is the process of obtaining reliable information about physical objects and the environment through processes of recording, measuring and interpreting photographic images. Specifically, photogrammetric packages make it possible to map and interpret visible data in three dimensions.

pixel *see* cell

point cloud The raw data format from the lidar survey, comprising millions of x, y and z coordinates in the form of text. Some software packages make it possible to view this data as three-dimensional points.

raster A grid of data used within GIS software. For elevation models, the cells hold height data; for hill-shaded images, the cells hold tonal values.

SAR (Synthetic Aperture Radar) A radar system in which a series of microwave pulses are emitted continuously at a frequency constant enough to be coherent for a fixed period; all echoes returned during this period can then be processed as if a single antenna as long as the flight path had been used.

SMR (Sites and Monuments Record) The former name for **HER**s; still in use in some parts of the country.

TIN (Triangular Irregular Network) A data structure that represents a continuous surface through a series of irregularly spaced points with values that describe the surface at that point (eg their elevation). From these points a network of linked triangles of varying sizes forms the surface. This is a key difference to a **raster** surface, for which the grid is regular.

three-dimensional visualisation In the context of these guidelines three-dimensional refers to the ability to visualise the height element of the data in a meaningful way. This means that it is possible to create images where the elevation data can be coded and even exaggerated so as to produce imagery with shadows and highlights, in either oblique or plan view. This is sometimes referred to as 2½-dimensional to differentiate it from true three-dimensional viewing (stereoscopic viewing), which requires even more specialised equipment, such as monitors or polarising glasses.

vegetation removal A computer-based process to filter out data from the point cloud derived from vegetation, making it possible to create a DTM

WGS84 ‘WGS’ stands for the World Geodetic System and the ‘84’ comes from the fact that the latest revision dates from 1984. This is a standard for use in cartography, geodesy and navigation, and comprises a standard coordinate frame for the earth, a standard spheroidal reference surface for raw altitude data and a geoid that defines the nominal sea level.

Appendix
Sources of advice on using lidar

English Heritage
Within English Heritage the first point of contact for general archaeological science enquiries, including those relating to using lidar data, should be the English Heritage regional science advisors, who can provide independent, non-commercial advice. Such advisors are based either in universities or in the English Heritage regional offices. Please contact regional advisors currently based in universities at their university address.

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Institute of Archaeology
UCL Room 204
31–34 Gordon Square
London WC1H 0PY
telephone: 020 7679 1539
fax: 020 7383 2572
D.Demoulins@ucl.ac.uk

Specific advice on the use of lidar data for archaeological research can be sought from Simon Crutchley in the English Heritage Aerial Survey and Investigation team.

Simon Crutchley
English Heritage
Kemble Drive
Swindon SN2 2GZ
telephone: 01973 414704
simon.crutchley@english-heritage.org.uk

Forestry Commission
For advice on the use of lidar data for archaeological research in woodland contact:

Peter Crow
Forest Research
Alice Holt Lodge
Wrecclesham
Farnham
Surrey
GU10 4LH

Written by Simon Crutchley with a special contribution on using lidar in woodland by Peter Crow, Forest Research, Forestry Commission. These guidelines should be cited in bibliographies and references as follows: Crutchley, S and Crow P 2009 The Light Fantastic: Using airborne laser scanning in archaeological survey. Swindon: English Heritage.

These guidelines are available via the English Heritage Free Publications list at www.english-heritage.org.uk/publications

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Pete Horne, Mark Bowden and Trevor Pearson
www.forestresearch.gov.uk/lidar

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The Aerial Survey and Investigation team of English Heritage provides a greater understanding of England's historic environment through aerial reconnaissance, combined with interpretation, mapping and analysis of information contained on aerial photographs and related sources. We work closely with many of English Heritage's specialist teams, particularly with the Archaeological Survey and Investigation teams.

We also work with many partners outside English Heritage, from national organisations to local amateur groups, and provide regular work placements for university students and professionals wishing to learn more about the work of the team. All our work helps to expand and update the database of information available to everyone through English Heritage's public archive, the National Monuments Record and its web enabled access Pastscape, and you can obtain copies of any of our photographs, reports and publications from there.

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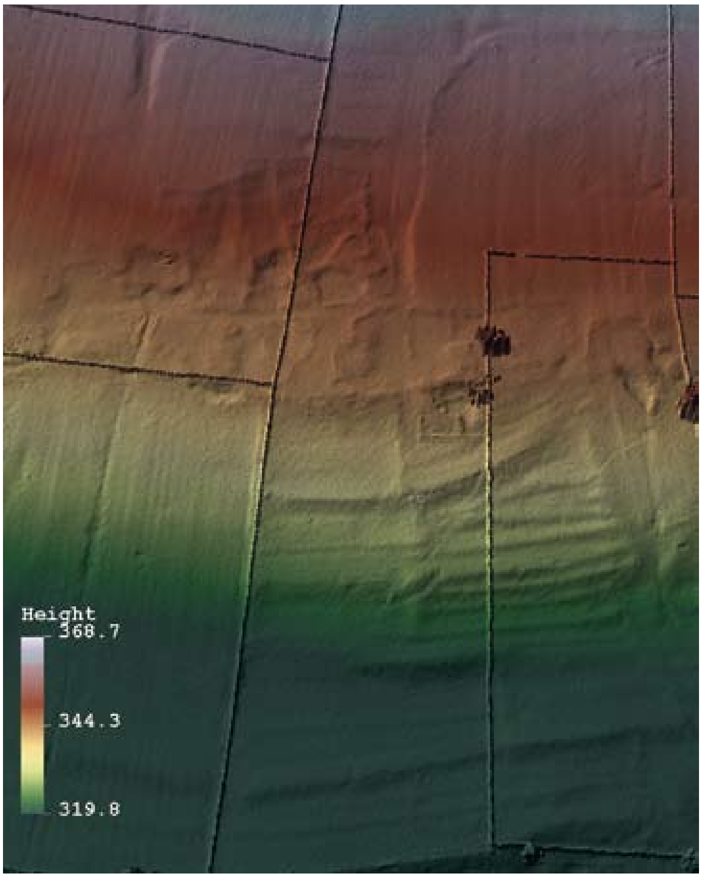

Front cover: *Savernake Forest near Marlborough, Wiltshire. Three views of the forest with a traditional aerial photograph, first return lidar data DSM showing the tree canopy and processed DTM revealing the archaeology hidden beneath the trees (NMR 21339/19 (10-AUG-2001) © English Heritage; lidar image © Forestry Commission, from Cambridge University ULM (May 2006)).*

Back cover: *Previously unrecorded settlement of probable Late Iron Age/Romano-British date with associated boundaries, hollow ways and lynchets near Alston, Cumbria revealed by lidar (© English Heritage, from Infoterra (May 2009)).*

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