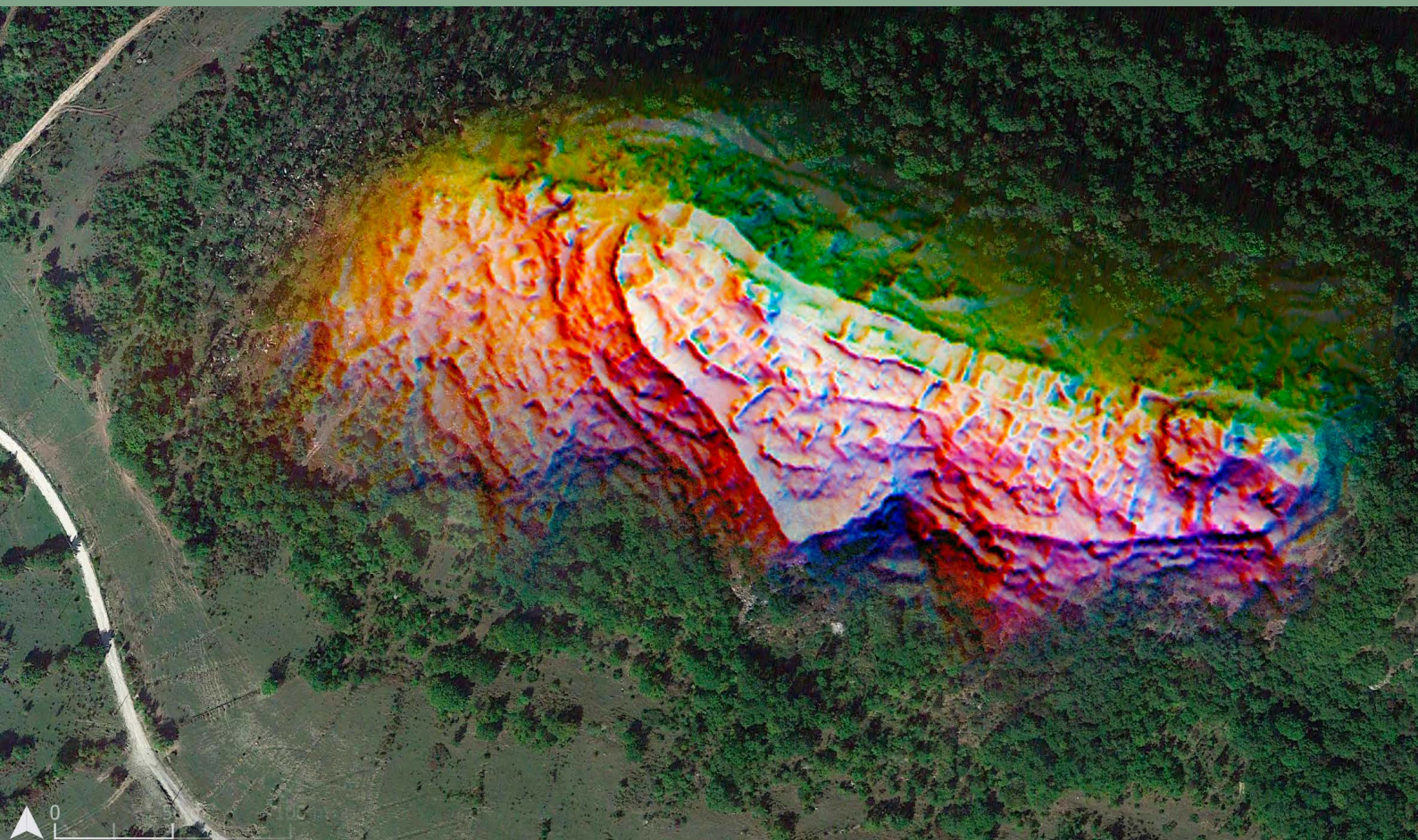


# GUIDELINES FOR THE USE OF AIRBORNE LASER SCANNING (LIDAR) IN ARCHAEOLOGY

Edited by Rebecca Bennett and Dave Cowley





Archaeological surveyors stand beside the sign for Lidar church in Øystre Slidre municipality, Innlandet County, Norway. Image supplied by Innlandet County Council, Norway



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# PREFACE

**T**he statement attributed to Paul Cézanne, “The day is coming when a single carrot, freshly observed, will set off a revolution,” reflects the transformative potential of new perspectives. In a similar vein, Airborne Laser Scanning (ALS) data have profoundly revolutionized the field of archaeology, offering unprecedented insights into ancient landscapes. This innovation has breathed new life into traditional archaeological techniques. A fresh observation of the existing ALS developments and applications has enabled the impressive body of work you are discovering today.

This volume provides a thorough and well-structured explanation of ALS data acquisition, as well as good practices for post-acquisition analysis and archiving. Furthermore, it offers illustrative examples of the diverse outputs generated by ALS data, while addressing the challenges and potential for future advancements. These guidelines are invaluable not only for fostering knowledge integration across the archaeological profession but also for supporting the work of archaeological managers. One of the primary motivations for the European Archaeological Council

(EAC) to commission this project was the recognition that the integration of ALS data into heritage projects significantly impacts decision-making processes in daily archaeological practice, transforming how professionals and various stakeholders perceive and engage with our fragile archaeological heritage.

I extend my gratitude to the extensive network of ALS professionals and researchers from over 30 countries, as well as the Aerial Archaeological Research Group (AARG), for their participation in the online survey that informed the development of these critical guidelines. Their collective efforts have made this crowdsourcing initiative a model for a bottom-up approach within the sector. Special thanks are due to Rebecca Bennett, Dave Cowley, Rachel Opitz, and Chris Gaffney for bringing together the 49 co-authors who contributed to the creation of these essential guidelines.

This “carrot” will undoubtedly spark a new revolution. Enjoy the read!

**Ann Degraeve**

President

European Archaeological Council

## SECTION 1

# Airborne Laser Scanning Technology and Data Acquisition

This section focuses on sensor technology and data acquisition, preparing users to commission airborne laser scanning survey for historic landscape assessment and to assess the suitability of existing archives for a range of purposes.

In this section you will find:

- tips on how to use this guidance document
- an introduction to laser scanning technology
- quick reference diagram illustrating the stages of integration of ALS in heritage projects
- details regarding the required parameters for ALS survey for cultural heritage
- guidance for assessing the suitability of archive ALS data, including a printable checklist
- a case study in the use of ALS for heritage management in coastal environments.

## 1.1 Introduction

Author: **Rebecca Bennett**

Airborne Laser Scanning (sometimes referred to as lidar) has been described as revolutionary for the understanding and management of cultural landscapes. The ability to create highly accurate three dimensional (3D) models and visualise the topographic features that represent past human interaction with the land surface has undoubtedly changed our view of the world and our approach to heritage management.

The use of airborne laser scanning (ALS) for cultural heritage management across Europe has increased greatly in the first two decades of the 21st century as data have become more widely available. While there is a growing expertise in the implementation of ALS derived visualisations for our discipline, it is clear from our survey of practitioners that this specialism is often represented by only a few experts scattered across a country. Specialist practitioners<sup>1</sup> have facilitated knowledge exchange at training and networking via conferences and events such as the TRAIL (Training and Research in the Archaeological Interpretation of Lidar) meetings. However there have been few opportunities to capture the collective understanding of how to make the most of ALS for cultural heritage management that has developed over the last two decades.

The aim of these guidelines, instigated by the European Archaeological Council (EAC), is to bring together for the first time a reference document that combines the experience of colleagues across

Europe. The guidelines have been designed fully collaboratively by an extensive network of cultural heritage professionals. The foundation was an online survey conducted in 2022 to which more than 100 individuals and organisations from across 30 countries responded, detailing the status quo and their needs and aspirations with respect to integrating ALS data into their work. Using the results of this baseline survey to define the requirements of the wider community, 49 co-authors worked together to design the structure and content of the guidelines, in doing so ensuring their relevance and impact. The development of the guidelines was undertaken entirely online in Autumn 2022 and Spring 2023, an approach that has paid dividends in the quality and relevance of the end product by facilitating the input of so many experts from across the continent.

Airborne Laser Scanning is frequently referred to as lidar and this term has come to have a variety of common uses in the heritage sector. Lidar is frequently, and confusingly, used to refer to the sensor technology, the height data captured during ALS survey and the models and images created from these data. In these guidelines we will provide explanations of these aspects to provide a clear understanding of technology, survey outputs and digital products. For clarity we prefer to use the term lidar only when specifically referencing the sensor itself, using airborne laser scanning (ALS) as the more appropriate

<sup>1</sup> The anonymised results of the survey are available here: [doi.org/10.5281/zenodo.14039886](https://doi.org/10.5281/zenodo.14039886)

Part 1 focuses on the sensor technology and data acquisition, preparing users with the tools to commission ALS survey for historic landscape assessment and to assess the suitability of existing archives. Part 2 covers best practice for the post-acquisition stage, how lidar data should be processed and analysed and how to integrate the products of ALS survey (models and visualisations) into work in the field and with communities, as well as the growing role of ALS data in automated archaeological feature detection. Part 3 provides guidance for reporting and archiving ALS data and the many derived products of ALS survey.

It is imperative that these guidelines reflect the potential uses of ALS data and the challenges that professionals across our sector face when integrating lidar data into their work. Thus, part 4 contains sections relating to the many specific applications of ALS data within the heritage sector including 3D visualisation, feature detection, change monitoring, planning and landscape management. Supporting these applications throughout the guidelines are a series of case studies that identify the benefits and challenges of using ALS data to understand the historic landscape in specific environments.

A key audience for these guidelines are cultural heritage managers though it is anticipated that the info-mating in this document will provide an important baseline for knowledge integration across the profession. Throughout the guidelines we have tried to provide a level of detail that meets the needs of the widest range of users of this resource. We have also aimed to provide a representation of good practice that is applicable across different environments, jurisdictions and communities. The primary intention is that anyone can identify the information relevant to their needs in an efficient and accessible way and be signposted to further specific publications and information as required.

We are grateful to the combined efforts of colleagues from across Europe in contributing expertise and text to this document. The guidelines are a truly collaborative effort to present best practice in a sector that has expanded rapidly in the last two decades and continues to see rapid change where it interfaces with technological advancements. Where possible we have highlighted expected future developments, their challenges and potential. While the EAC provides support for cultural heritage practitioners, the

professional and research network of ALS users across Europe is also supported by the Aerial Archaeological Research Group (AARG) who hold annual meetings and encourage discussion and publication of all aspects of remote sensing theory and practice within the sector. Engagement with this professional network is the key factor that will ensure resilience through technological advances and the adaptation of professional standards to ensure best practice.

### **How to use these guidelines**

The structure and content of these guidelines were co-designed by the community with the view to being presented as a digital publication. As such it is intended that the guidelines can be used as a single "how-to" document, read from start to end to enhance knowledge across the topic. However the sections have been structured to group the guidance topics into logical themes that track the life-cycle of a heritage project incorporating airborne laser scanning, starting with acquisition then moving to processing and through to reporting and archiving, each with its own illustrative case study. Guidance for specific heritage applications is given in the final section, and it might be tempting for the time-pressed heritage professional to dive straight into these, however these applications rely heavily on the preceding content and as such users are strongly advised to make use of the cross-references to develop their supporting knowledge.

The document is searchable, with key terms highlighted so they can be easily identified and defined. It has been structured such that useful information can be located and cross referenced swiftly. In addition to extensive examples and citations throughout, contributing authors have also provided a series of printable forms and flow diagrams to support best practice. In this way our hope is to make the depth and breadth of information presented here as accessible and applicable as possible.

## 1.2 What is Airborne Laser Scanning?

Rebecca Bennett and Žiga Kokalj, with contributions from Michael Doneus and Ole Risbøl

### What's in a name?

The term lidar (a contraction of **L**ight **D**etection and **R**anging) can be technically defined as both the technique of using a laser to measure distance and as the sensor unit that emits and records the laser. Lidar sensors have a wide range of uses across many different sectors including manufacturing, autonomous vehicles, surveying, mapping, hydrological modelling, gaming and infrastructure planning.

In the cultural heritage sector, lidar is typically used as a synonym for airborne laser scanning (ALS), where metric data of a landscape is captured from the air by plane, helicopter or unmanned aerial vehicle (UAV). For this reason, the focus of these guidelines is exclusively on airborne lidar as a tool for heritage management, omitting all other forms such as terrestrial or mobile lidar (Grussenmeyer et al., 2018).

Confusingly, the term lidar has a variety of common uses in the heritage sector and can variously also be used to refer to:

- the 3D data produced by the sensor, (more correctly referred to as a **point cloud or ALS data**)
- the 2D models produced from the point cloud (more correctly referred to as **ALS-derived elevation models**)
- the 2D visualisations of those models, most commonly used to identify the microtopographic change that represents past human interaction with the landscape (more precisely referred to as **ALS-derived visualisations**)

These guidelines are designed to help the user clearly understand what is meant in variety of contexts and applications. To reduce confusion henceforth we will therefore use the most applicable and descriptive terms including **airborne laser scanning (ALS)**.

### The role of Airborne Laser Scanning in the Cultural Heritage Sector

The application of airborne laser scanning has led to a revolution in archaeological prospection, giving new insights to landscapes and features and

complementing existing remote sensing and field techniques. Despite still frequently being referred to as a “new” technology, the application of airborne laser scanning (ALS) for archaeological prospection and cultural heritage management has become increasingly routine in many countries over the last two decades. There are many advantages to the use of ALS but key to the uptake of this technology is the ability to collect high resolution, high accuracy metric data for large areas and the ability to classify and filter these data to exclude buildings and vegetation from the resulting models of the landscape.

For cultural heritage applications the ability to accurately model the ground surface especially below woodland canopies distinguishes ALS from other established remote sensing methods such as aerial photography and satellite imagery. An abundance of published case studies demonstrate its value but the key benefits of ALS are neatly explained by the first application of the technique to the Stonehenge World Heritage Site in the UK during the early 2000s (Bewley et al., 2005). The landscape around Stonehenge has been the subject of intensive study, specifically multiple aerial surveys (Crutchley, 2002). The area therefore provided an excellent baseline against which to evaluate the application of ALS as a new technology. The conclusions of the work underlined the principal advantages of ALS data for archaeological landscape research. Specifically, when mapping archaeological topographies ALS-derived models of the landscape:

- facilitate the identification of previously unrecognised features and sites and increase the extent and level of detail of those already known
- reveal previously unknown features in woodland
- allow the identification of very subtle topographic features that are largely imperceptible to observers in the field
- provide location corrections to existing feature records
- allow clarification of topographic relationships between features
- improve the potential for and accuracy of a range of landscape-wide analyses and modelling (e.g. viewshed analysis, least cost paths, change detection)
- facilitate more effective monitoring and management, supporting condition analysis and assessments of risk to a site or feature.



**Figure 1:** Leaf off and leaf on conditions (Images: J.Hageluken)

Within the cultural heritage sector we now have many hundreds of examples of projects that have used ALS data to map, understand and manage cultural landscapes and the features within them. This number continues to grow year on year, benefiting from the increased availability of national lidar archives across much of Europe.

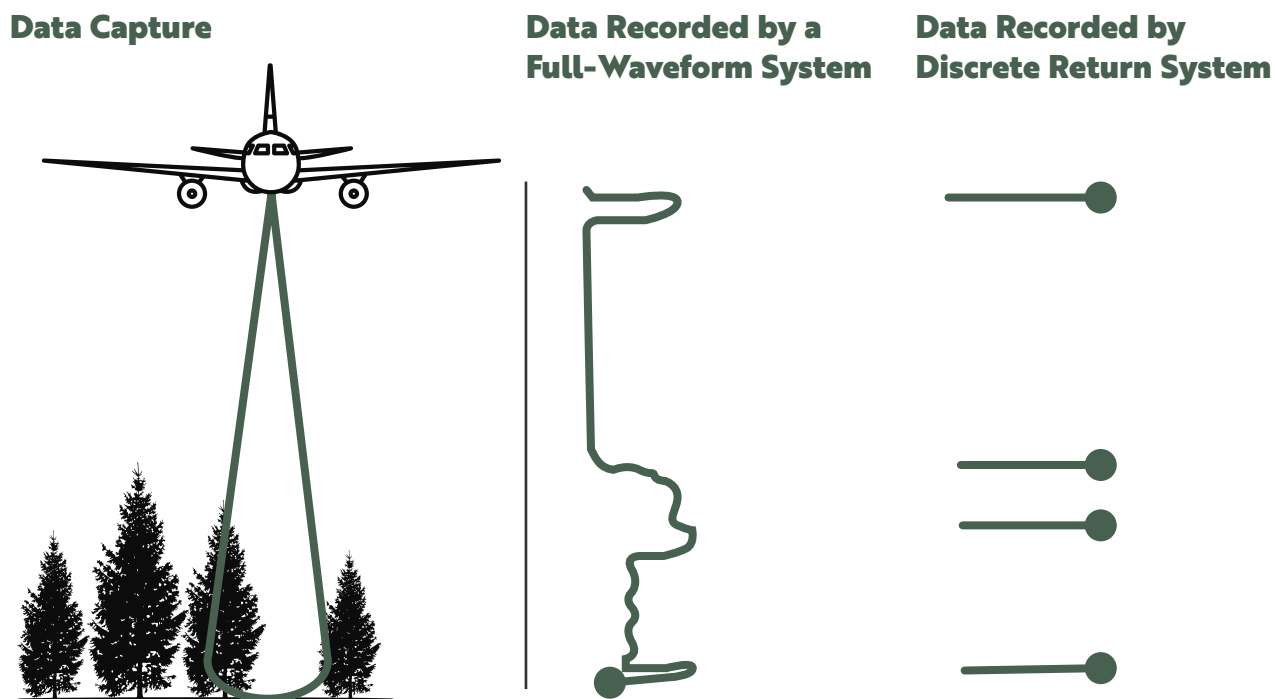
The high uptake of the technology has led to the expectation that ALS data will be routinely incorporated into cultural heritage management. However, as the survey of professionals undertaken in 2022 clearly indicated, expertise is fragmented and more specific guidance is required in order to use and benefit from ALS data while also understanding its limitations. The technical competencies required within a team using ALS data are covered in detail later in the guidelines (section 2.8), but it is undoubtedly helpful for all professionals to have a basic understanding of lidar sensor technology and the four phases of data processing that are required for cultural heritage projects.

### **How does ALS work?**

Airborne laser scanning uses a lidar sensor to measure the distance between the laser scanner mounted on the underside of an airborne platform (fixed-wing aircraft, helicopter or UAV) and objects on the ground below. Lidar sensors are an active remote sensing system that computes this distance using a reflection of a laser light emitted from the sensor. This means that data can be acquired day and night as the lidar sensor is not dependent on ambient light from the sun.

It also means that the laser can only penetrate where light can, so unlike a microwave or x-ray, it cannot pass through solid objects. This means that when colloquially lidar is referred to as “seeing through trees” what is meant is that the laser is able to measure the topography of the ground below the canopy using ALS as **the laser light emitted from a lidar sensor can pass through gaps in the canopy** (with the exception of the densest vegetation, see section 2.1 and Case Study 3). The quality of measurements is of course improved if the survey is undertaken in leaf-off conditions as more light, and therefore more laser pulses, can penetrate the canopy.

To ensure accurate distance measurements the sensor must be deployed alongside a GNSS (Global Navigation Satellite System) receiver that records the absolute position of the scanner, an IMU (Inertial Measurement Unit) that records the orientation of the scanner on the platform, and a base station (GNSS receiver) on precisely known ground location. These complementary systems provide data that is used to process the measurements recorded by the lidar sensor, so that the data is immediately recorded in 3D and geo-referenced to real world locations. The absolute accuracy of the height points derived from ALS survey depend on several factors, the most important of these being the flying height and quality of the accompanying GNSS system. Accuracy of measurements is generally very high, with a vertical accuracy range that is typically  $\pm 5-10\text{cm}$  and a spatial distribution of points between 10 and 1ppm (points per metre) leading to a horizontal accuracy of a few decimetres.



**Figure 2:** Representation of Airborne Lidar Data Capture systems: Full Waveform and Discrete Return Data (R.Bennett)

There are two basic principles for calculating the distance between the laser scanner and the object (Vosselman and Maas, 2010). The commonly known one is the **'time-of-flight'** method, where the laser emits a short pulse of light that is then reflected from various surfaces, e.g. a roof, treetop, branches, bushes or/and the ground, and the distance is calculated from the time difference between the emitted pulse and the received return signal. In **phase-shift scanning**, the laser scanner emits a constant beam into multiple phases and compares the phase shifts of the returning laser energy. The second method is (much) faster, but the effective distance is shorter (typically less than 100m) and the data is noisier. The technology and processing algorithms are still developing and continue to be tested for phase-shift lidar. This means that the 'time-of-flight' sensors are the preferred choice for cultural heritage survey applications.

There are two main types of lidar sensor, depending on how the reflected laser light is recorded. To understand the difference we need to think of light as a wave of energy to be captured and transcribed as values to give height points. A discrete return system records discrete points for peaks in the wave based on predefined value thresholds. It may record one or more returns from each laser pulse waveform, discarding the intermediate data. These returns are stored as a point cloud of data points, each describing the x, y and z co-ordinates of the locations from which the laser reflected. Other data such as beam intensity, angle and timestamp

can also be recorded in the point cloud. All landscape models associated with ALS survey are then derived from this point cloud (sections 2.1 and 2.2).

A **full waveform system** records the distribution of the reflected light energy as a graph with samples every few nanoseconds rather than when a threshold is passed, and in doing so retains more detail about the returned laser pulse. In practice, the full waveform data is also often converted into a point cloud using classification thresholds but the full shape of each return can be re-processed at a later stage to provide more insight or extract different data by altering these threshold parameters.

The laser light is usually emitted in the **near-infrared spectrum** (at 1064nm). Multi-channel systems also have a laser that emits green light (at 532nm) and possibly another in the shortwave-infrared region (at 1550nm). Near-infrared light is absorbed by moisture and does not penetrate water, while green light does. In practice this means that both surface water (lakes, ponds, wet snow) and air moisture (rain, fog, cloud) will affect the strength of the returning pulse impacting the quality of the data recorded. The combination of both wavelengths is useful for coastal, intertidal and bathymetric applications where the surface or objects to be measured are under water. The quality of bathymetric ALS is affected by both the clarity and turbidity of the water, rendering it most effective in still, shallow waters with little sediment load.

## Seeing the Ground under the Trees

As mentioned above, a major strength of laser scanned data is the ability to accurately measure and model the ground surface even when it is covered in vegetation. All laser scanning techniques produce 3D point clouds comprising millions or billions of xyz points containing information about the terrain and the objects on it (vegetation, buildings etc). In order to make appropriate products that show the ground surface from these point clouds, the points must be **classified**. The classification process is typically automated and is the process by which each individual point is assigned to different predefined categories using a computer algorithm, according to the standard of the American Society for Photogrammetry and Remote Sensing (ASPRS, 2019).

For archaeology, the points classified as “ground” and “off-ground” are the most critical as these are used to derive digital terrain models (DTM) comprising ‘ground’ points only and digital feature models (DFM) comprising ‘ground’ and ‘building’ points. (Buján et al., 2020; Lozić and Štular, 2021; Pingel et al., 2015). In addition to the 3D coordinates (x, y and z) and the classification (represented as an integer value as shown in the table below), the points also carry additional information that can vary depending on the scanning system used (e.g. radiometric information, echo width, pulse shape deviation). This information can be used for further products such as calibrated reflectance images of the scanner’s specific wavelength (532 nm, 1064 nm, or 1550 nm), commonly referred to as **intensity** (Briese et al., 2014; Sevara et al., 2019).

Class	Definition
0	Created but never classified
1	Unclassified
2	Ground
3	Low Vegetation
4	Medium Vegetation
5	High Vegetation
6	Building
7	Low Point (“low noise”)
8	Reserved
9	Water
10	Rail
11	Road Surface
12	Reserved
13	Wire - Guard
14	Wire – Conductor (Phase)
15	Transmission Tower
16	Wire-structure Connector
17	Bridge Deck
18	High Noise
19	Overhead Structure
20	Ignored Ground
21	Snow
22	Temporal Exclusion
23-255	Reserved and User definable classes

**Table 1:** ASPRS Standard Lidar Point Cloud Classes as listed in the LAS Specification (ASPRS, 2019)

**Technological developments to watch for...**

In traditional lidar sensors the laser pulses are spatially distributed by the movement of the platform and the scanning mechanism (e.g. oscillating or rotating mirrors, fibre-optic bundle) that emits the laser in a particular set of directions. This is known as linear scanning. Lidar scanners based on newer technologies (i.e. flash lidar, single photon lidar, Geiger-mode lidar) capture the reflected light in a matrix and collect data like a pushbroom scanner or a frame scanner. Their biggest advantage is that they collect data about 20 times faster than linear scanners, however the data collected in this way are more noisy. The technology and processing algorithms are still developing and continue to be tested, but it is anticipated that this type of sensor will become more common in close range cultural heritage applications, where the object is less than 200m from the sensor.

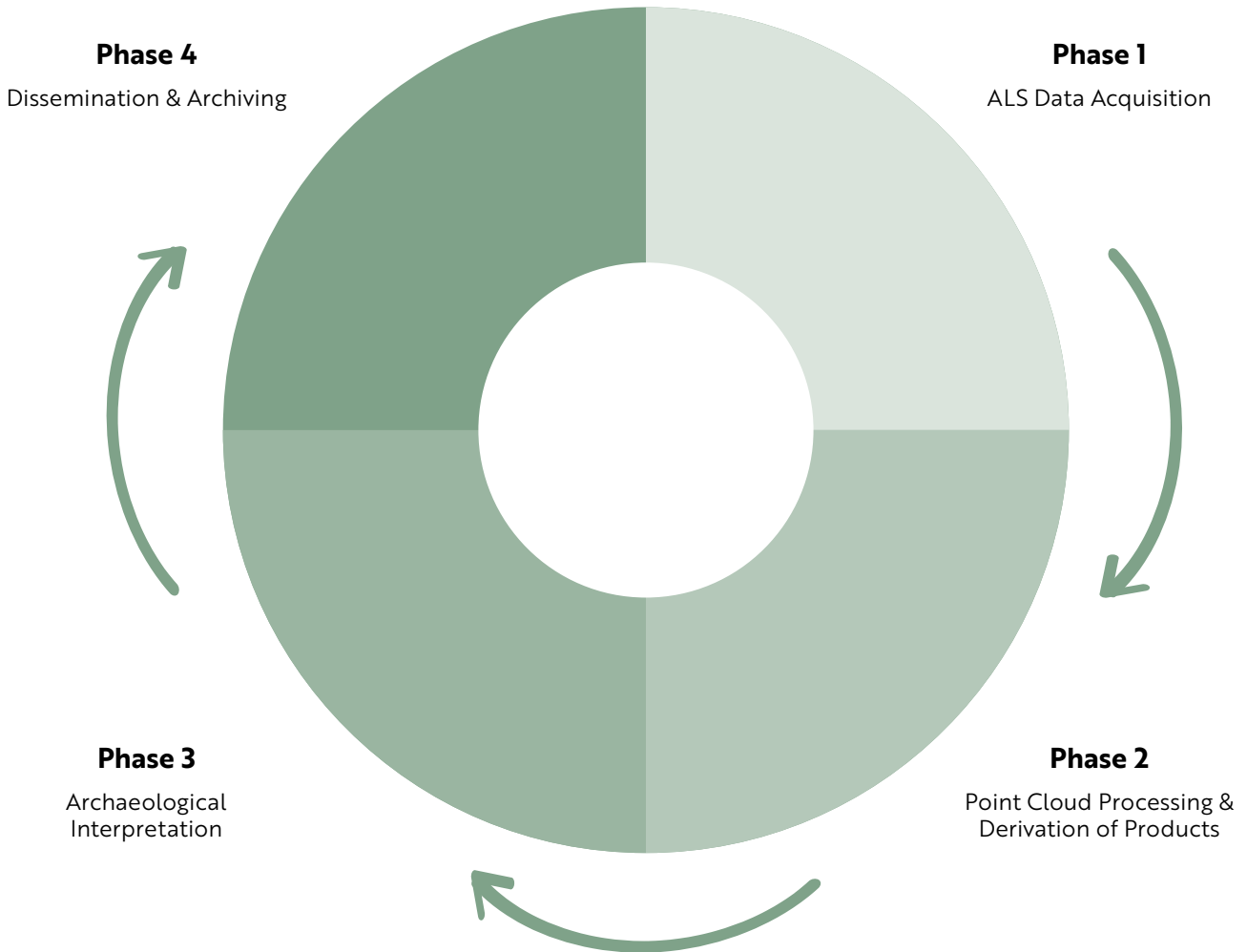
**Key Information Lidar Sensors and Airborne Laser Scanning**

- The term “lidar” is often used inaccurately or loosely in the cultural heritage sector with interchangeable meanings which can lead to confusion
- Airborne Laser Scanning has many benefits for cultural heritage applications specifically the creation of high resolution and high accuracy measurements of the ground surface
- It is helpful for all users to have a basic understanding of the technology underpinning ALS survey
- A typical lidar sensor uses a laser with a near-infra red wavelength that is absorbed by water. Light of green wavelength is needed for bathymetric applications
- Regardless of the type of lidar sensor (pulse or full-waveform) the key product is a point cloud of x, y and z coordinates of the places from which the laser reflected

Phase	Description	Role of the Cultural Heritage / Archaeological Professional	Quick Reference
<b>Phase 1:</b> ALS data acquisition	This phase comprises the collection of ALS data and creation of initial outputs such as the point cloud and tiles.	Archaeologists are usually not directly involved but influence some aspects of the outputs eg tile size, resolution and file format via the survey specification	Commissioning data 1.5
<b>Phase 2:</b> Point cloud processing & Derivation of products	This phase comprises three parts: 1) classification of the point cloud 2) interpolation of elevation models 3) visualisation of models to support the management of cultural heritage and archaeological investigations.	For archive data, steps 1 and 2 may have already been undertaken and archaeologists or cultural heritage managers may not be able to influence outputs. When commissioning new data, (or approaching archived point cloud data with sufficient resource and expertise) steps 1 and 2 should be tailored to the best outputs for cultural heritage. Step 3 should always be undertaken with the input and expertise of cultural heritage professionals	Archive data 1.4 Commissioning data 1.5  Point cloud treatment and interpolation 2.1  Specialist Visualisations 2.2
<b>Phase 3:</b> Archaeological interpretation	Archaeological interpretation, from data integration, interpretative mapping, field assessment to 'deep' interpretation and automated mapping.	Archaeologists or cultural heritage managers should lead this phase with the direct involvement of skilled professionals	Analysis and mapping 2.3 Archaeological Interpretation 2.4
<b>Phase 4:</b> Dissemination & Archiving	Data management, dissemination and archiving.	Archaeologists or cultural heritage managers should be engaged with this phase directly supporting the work of professionals skilled in archiving and dissemination.	Reporting 3.1 Data Management and Archiving 3.3, 3.4 and 3.5 Public Outreach 3.6

**Table 2:** The four phases of ALS integration for archaeological and cultural heritage management

### Phases of Integration of Airborne Laser Scanning for Archaeological and Cultural Heritage Management



**Figure 3:** Phases of Integration of Airborne Laser Scanning for Archaeological and Cultural Heritage Management

# KEY TERMS

Below is a quick reference for key terms used in this section.

A full glossary is available at the end of the guidelines

**Airborne Laser Scanning (ALS)** – an airborne remote sensing technique that measures distance with reflected laser light.

**Lidar (Light Detection and Ranging)** – can be used to refer to both the technique of using a laser to measure distance and the sensor unit that emits and records the laser.

**Laser** – a device that emits light in a very narrow beam.

**Laser pulse** – laser light emitted for a short duration and usually at a specific repetition rate.

**Discrete return lidar system** – records a few, typically four but can be up to eight, returns for each laser pulse emitted.

**Full waveform lidar system** – records a full profile of a return signal by sampling it at fixed time intervals, typically 1 ns (i.e. 15 cm).

**DEM – digital elevation model** – a grid whose values represent any type of elevation.

**DTM – digital terrain model** – a grid whose values represent the elevations of the 'bare ground'.

**DSM – digital surface model** – a grid whose values represent the elevations of the terrain including all anthropogenic and natural objects.

**DFM – digital feature model** – a grid whose values represent the elevations of the bare ground and buildings.

**Point cloud** – a discrete set of data points in space, with values describing their location (x, y, z) and possibly other attributes such as pulse return intensity, return identification, classification, scan angle, etc.

**Intensity** – the strength of the laser pulse returned from any point. Can be visualised as calibrated or uncalibrated images.

**Pulse density** – the number of pulses (first and only returns) per 1 m<sup>2</sup>.

**Point density** – the number of returns per 1 m<sup>2</sup>. Can be given for different categories, e.g. for ground returns, for a single data strip or for a combined dataset.

**Resolution** – The spatial resolution of an ALS-derived digital elevation model refers to the area of land being represented by a single grid cell or pixel. A spatial resolution of 1 metres means one grid cell represents an area of 1m x 1m. The appropriate resolution for a ALS model is calculated using the point density and spacing in the point cloud.

# ALS DATA FORMATS

**ALS data can be stored in multiple ways. Only the most frequently used formats are described below.**

## Full waveform

Full waveform data is mostly stored in a native format of the sensor manufacturer (e.g. Optech, Riegl). The *PulseWaves* format exists as a non-proprietary alternative, but is rarely used.

## Point cloud

LAS file format is the most widely used and regarded as an industry standard for the interchange and archiving of lidar point cloud data. It can hold information on metadata, point data records, dimensions of x, y, z range, projection information, waveform packet information, and user application data. Point data records can include x, y, z values, intensity of pulse return, return identification, classification, scan angle, identifier for the source for this point data, if derived from an earlier dataset, GPS time, three 16-bit colour channels and NIR channel, and wave packets.

LAZ is a lossless compressed LAS file format. This is the recommended format for storing airborne laser scanning data.

COPC (Cloud Optimized Point Cloud) is a variant of LAZ format which is structured with indexes for each part of the dataset. The index structure facilitates more efficient streaming as the parts of the data that are required can be accessed without having to download the entire dataset. It is likely that more data will be provided in cloud optimised formats as the quantity and coverage of ALS data increases.

The E57 file format is intended to be a more general format than LAS. While LAS uses a predefined set of fixed-size record types that are specialised for aerial data collection, the E57 format allows users more flexibility in choosing the information associated with each 3D point as well as the number of bits used to represent the information. It also supports gridded data, embedded images from cameras, built in error detection, and groupings of points into rows, columns, or user-defined groups.

The information in a LAS file can be stored as *ASCII* text, but this requires much more disk space. Point clouds saved as text therefore usually omit information and save just the most important data, such as x, y, z, and classification.

## Gridded data

Gridded (raster) data has values in an evenly spaced matrix of cells (pixels). Examples of raster lidar data are a digital elevation model, intensity, pulse density or derived products such as slope, local dominance and other visualisations. A raster can have multiple bands.

TIFF is a tag-based file format for storing and interchanging raster images. It supports different compression schemes (e.g. LZW), schemes for colour representation and bit depth. A geotiff includes georeference and geocoding information.

As noted for point cloud data above, it is likely that cloud optimised raster formats for example COGS (cloud optimised geotiffs), zarr and rasquet will become increasingly popular due to the advantages they give for streaming data efficiently.

Gridded data is often stored as simple *ASCII* text with three columns, delimited by a single space or some other character. The first two columns are x and y coordinates and the third are raster values.

*Esri grid* or *Arc/info ASCII grid* is also a text file, but it has a six-line header at the beginning expressing the numbers of columns and rows, x and y coordinates, cell size, and the no data value. The raster values for each cell are then listed starting at the upper-left corner and delimited by a single space character.

## 1.3 Justification and archaeological parameters for survey

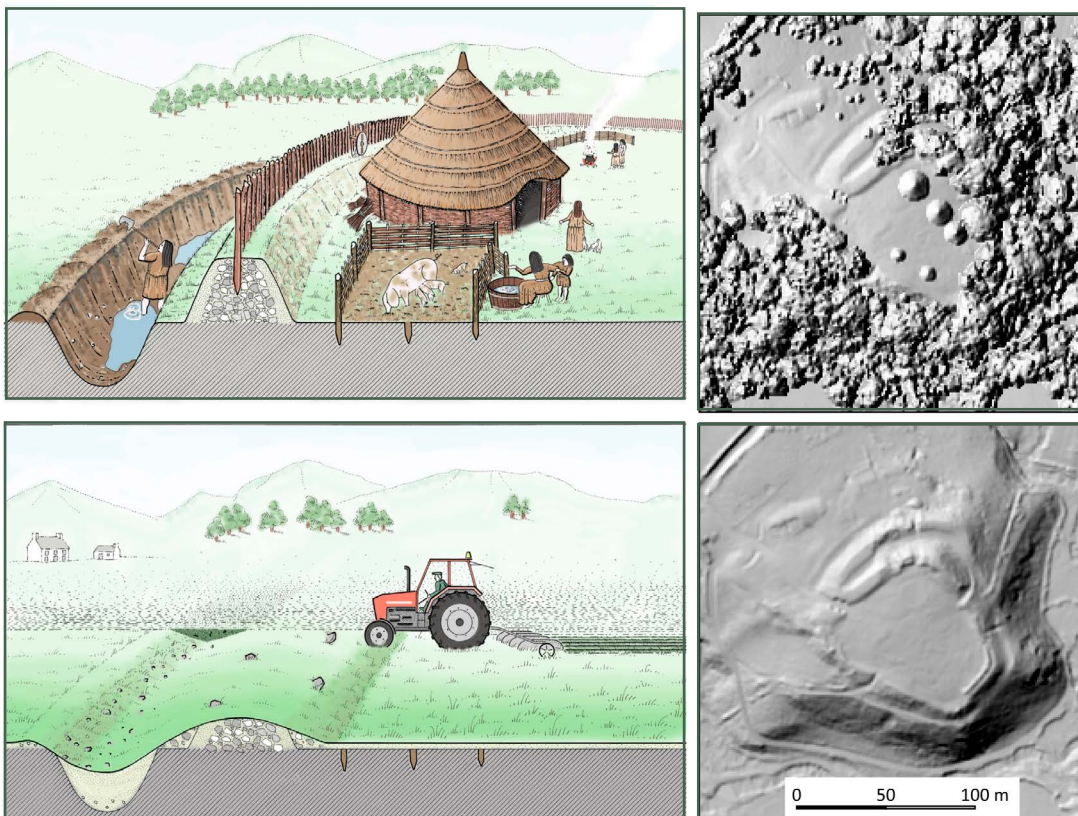
Michael Doneus, Ole Risbøl

### Introduction

Human activities leave traces on the earth's surface and, depending on many factors, these can last for millennia as local changes in the terrain. As these traces are often very subtle, archaeologists have developed methods to reveal them more clearly. Traditionally microtopographic changes were observed and documented through field observation and with the development of aerial photography from shadows cast by oblique light that provide a **proxy indicator** of terrain change. Increasingly, archaeologists use detailed terrain models created using photogrammetry or **topographic laser scanning**, (including ALS) to measure **directly** the changing heights of the surface of the terrain. These 3D models can be enhanced by various visualisation techniques, allowing the user to determine more microtopographic detail from the data. In this way changes in the terrain relating to past human activities can be recorded and analysed.

### 3D models from Photogrammetry

Terrain modelling from recent or historic vertical aerial photographs is also possible (see Bedford, 2017). Depending on the quality and scale of the photographs the horizontal and vertical accuracy of photogrammetric models are comparable to models created from ALS survey (Remondino, 2012). However it is not possible to remove the vegetation from 3D models created from photographs which renders them less suitable for vegetated areas. By using historic aerial photographs, historic elevation models can be created to complement more recent ALS survey, opening up the possibility of tracking terrain changes over the past decades (Risbøl et al., 2015; Sevara et al., 2017)



**Figure 4:** Illustration of site formation processes (© Crown copyright: RCAHMW, Image Archive Number 6179823) presented alongside an example of presentation in airborne laser scanned data of a reconstructed Iron Age village at Castell Henllys, Wales as a hillshaded digital surface model (top) and hillshaded digital terrain model (bottom) (1m resolution ALS data © Natural Resources Wales).

### Rationale - When should we consider ALS?

When ALS was introduced to archaeology around the year 2000 (Holden, 2001), its advantages were quickly recognised (Bewley et al., 2005; Holden et al., 2002). In particular, the realisation that ALS very well suited to prospection in many types of woodland (Sittler, 2004,) has led to a massive increase in applications. These applications have permanently changed our view of archaeological landscapes, revealing past earthworks, terraces and field systems, interconnected networks of paths and hollow ways, irrigation systems, extraction sites and many other categories (Bernardini et al., 2013; Chase et al., 2010; Evans et al., 2013a).

Once the need to map the surface topography of an area to better understand past human interactions with the landscape has been identified, cultural heritage managers must design a methodological approach that addresses this need. This approach should consider best practice in using remote sensing methods for heritage management, providing an evaluation of alternative approaches and determining whether to use a single technique or a combination of methods. The outcome of this evaluation process will also be driven by factors of cost and time, prevailing environmental conditions and land use, and the specific technical benefits of each remote sensing technique. Decision makers also need to determine whether to use existing datasets or commission project-specific data (see for example decision trees in Czajlik et al., 2019 and Historic England, 2018). Sections 1.4 and 1.5 respectively give detailed guidance on this matter of archive and commissioned data, but in either case the use of ALS must be underpinned by consideration of the applicability to the cultural heritage questions to be addressed.

### Vegetated Environments and Large Landscapes

ALS is currently **the only archaeological prospection method that can be efficiently applied in environments covered by woodland and scrub vegetation**. Methodological comparisons have shown that ALS-derived DTMs can identify very subtle features, including those that have been slighted by ploughing, that would not be detected by trained surveyors in the field (Doneus et al., 2008). Additionally, ALS-based terrain models tend to cover large areas, allowing landscape-based approaches (Mlekuž, 2018).

Another advantage that should not be underestimated is that ALS can document areas that are difficult to reach by land or have limited access. In some cases, ALS may be the only solution due to problems in accessing a landscape for example due to difficult terrain, legal challenges or security issues.

### Shallow Water

Using a green laser (532nm), intertidal and very shallow water zones can be documented (between 0 and 10m depth depending on water clarity). This is currently the only method to measure the topography of extremely shallow underwater bodies with high accuracy over large areas, creating topographic models of both terrestrial and underwater terrain. Coastal areas can therefore be mapped in their entirety using a single method (see Case Study 1: ALS in Coastal Environments). Shipwrecks, sites and submerged landscapes, even from the Pleistocene, have been documented in various applications (Doneus et al., 2013; Hale et al., 2023).

### Value for Money

While ALS has high costs associated with data collection and processing, the benefits have often been demonstrated to outweigh the initial financial outlay, making the technique good value for money. This is especially true in comparison to ground-based topographic survey of equivalent detail which can be hundreds of times the cost of ALS acquisition and processing, (see Corns and Shaw, 2011 table 2 for comparative costs of GPS and ALS survey).

### Multi-Purpose Data

Finally, digital terrain models have a **wide range of applications and are an important basis for all kinds of governmental decisions**. For this reason, many countries have programmes for the nationwide acquisition of ALS data. These general-purpose data are often freely available and are therefore widely used in archaeological projects and heritage management (Banaszek et al., 2018; Bofinger and Hesse, 2011; Johnson et al., 2021; Seitsonen and Ikäheimo, 2021; Wroniecki et al., 2015). In some countries access is provided to the point cloud data, but in others data are only available as pre-processed digital surface and terrain models.

### When is ALS not the solution?

While all of these advantages have led to a high level of acceptance of ALS for cultural heritage projects, there are some significant limitations that need to be considered in a decision-making process. There are circumstances where using ALS will not contribute to the assessment or research being undertaken due to environmental, technological, feature bias or project management factors. Various specific limitations are outlined below but perhaps the most important principle is that **ALS is only useful in areas where the desired archaeological information is preserved as measurable topographic changes.**

### Impact of Past and Present Land Use

Good conditions for the survival of topographic features relating to past land use are usually found in vegetated areas (e.g. woodlands, forests, scrubland), but also in long-term unploughed pastures, heathland and alpine areas. Extremely dense and low canopy cover, such as that found in scrub, heather, densely planted conifers or deciduous trees during the growing season, can have a negative effect on the number of laser measurements that can penetrate the canopy and reflect from the ground. This leads to poorer resolution data and impacts the quality of archaeological information content (see Doneus et al., 2022).

Poor land use conditions for the application of ALS are those where surface topography has been severely impacted by levelling or extractive processes such as ploughing or mining. In these areas, upstanding topographic features of archaeological interest are more likely to have been removed or heavily degraded by these processes. Likewise, areas prone to the deposition of deep alluvial or colluvial deposits, upstanding archaeological features are more likely to have been buried by later sediments. Finally in heavily developed and urban areas, the ability to map open ground between buildings may be negligible, making these landscapes unsuited to prospection using ALS.

### Feature Bias

Critical to evaluating the usefulness of ALS survey is the consideration that an **ALS-derived model does not represent all features of interest equally.** It is biased toward the representation of modern and post-medieval structures which are more likely to be

visible as topographic changes (chronological bias), linear features (morphological bias) and types of sites that originally had a strong topographic representation (type bias). An ALS-derived model may provide a wealth of detail for a large area but the analysis must always bear in mind that the full range of features that represent the cultural heritage of any landscape that will not be fully represented in topographic changes.

### Practical and Project Management Considerations

ALS survey has a high overhead cost (e.g. the deployment of the airborne platform, sensor set up, data processing). As the cost per square metre scanned becomes cheaper as the total area increases, the most appropriate applications are landscape scale > 50km<sup>2</sup>. Drone-based approaches are very time-consuming and are therefore usually only applied in smaller areas rather than across a landscape (Adamopoulos and Rinaudo, 2020; Campana, 2017; Pepe et al., 2022; Risbøl and Gustavsen, 2018). In addition, since it is advisable to extend the area to be documented beyond the boundaries of individual sites in order to obtain contextual information essential for archaeological interpretation, care should be taken when assuming that UAV ALS is a more cost-effective approach for certain applications.

ALS data may also record the “intensity” of reflected returns and images derived from these values may show changes in vegetation or soil properties that relate to buried archaeological features (Briese et al., 2014; Challis et al., 2011a; Coren et al., 2005). Intensity is considered an attribute of ALS survey which is under-researched and a poor comparator to dedicated spectral survey. Weather conditions such as wet snow, fog and high humidity can also have a negative effect on the quality of the laser scanned data (see section 1.4). Finally, snow cover, especially in combination with drifting or differential melting, can distort the topography of the terrain.

From a project management perspective, it is important to understand that many workflow steps are involved, from planning to the final archaeological interpretation (Fernandez-Diaz et al., 2014; Lozić and Štular, 2021). The ALS survey parameters must be adapted to the project objectives and research questions, the type of archaeology and the

environmental conditions. This includes the choice of platform and sensor and specific resolution of the resulting model (among other factors, see section 1.5). Each of these choices may involve compromises that

will affect the quality of the final result and successful implementation of the data relies on developing a team with appropriate skills and competencies (section 2.7).

### Considerations before Commissioning New Data

Due to the high costs involved, there are a number of issues to consider before commissioning new ALS data

<b>Method</b>	<p><b><i>Is ALS a valid tool for answering the desired research question? Are the above-mentioned biases acceptable?</i></b></p> <p>What range of archaeological features are expected? Are they likely to be preserved as upstanding topographic remains of sufficient scale to be captured in the ALS data?</p>
<b>Environment</b>	<p><b><i>Are the environmental conditions appropriate for ALS?</i></b></p> <p>ALS is cost effective in many environments, including Long-term unploughed pastures, heathland and alpine areas and is the only efficient airborne prospection technique for vegetated areas.</p> <p>For some environments (grasslands, open stone landscapes, agricultural areas,) archaeological features may be documented more cost-effectively and comprehensively either by using other techniques such aerial photography, terrestrial laser scanning or photogrammetric techniques or by using these techniques in combination with ALS (Verhoeven et al., 2012, 2013).</p> <p>Environments dominated by scrub, heather, densely planted conifers (or deciduous trees during the growing season) or where there are deep alluvial / colluvial deposits covering historic land surfaces may be unsuitable for ALS especially as a stand-alone prospection technique.</p>
<b>Competencies</b>	<p><b><i>Do you have the appropriate team?</i></b></p> <p>Are the skills of your team commensurate with the ALS processing and analysis the project requires? (section 2.8)</p>
<b>Existing Data</b>	<p><b><i>Finally, it is worth investigating whether ALS survey has already been undertaken in the desired area and whether terrain models are available?</i></b></p> <p>An increasing number of countries have been fully surveyed in recent years and this general-purpose data may be publicly available. It is important to check that the quality of the data is suitable for research. An evaluation of the metadata will be necessary and it may be desirable to reprocess the original point cloud data into models more suitable for cultural heritage purposes (see also section 1.4).</p>

## Case Study 1: ALS in Coastal Environments

Tom Fildes, Toby Driver, Rebecca Bennett

### Introduction

As the zone that interlinks the land and the sea, the coast can comprise a broad range of geographic elements and environments. These environments can incorporate land, the inter tidal zone and the seabed and often contain a rich record of past human landscape interaction alongside many modern activities. Coastal zones are often contain a mix of land uses from rural agricultural land to dense settlement, industry, leisure and transport. These areas contain the archaeology of the coast (the cultural heritage of the terrestrial-marine interface in its many forms) but also at the coast (features that are located at the modern coastline but due to changing sea levels, they represent historic and prehistoric activities that would have been undertaken in a different environment). As the dynamic interface of land as sea, coastal regions are especially vulnerable to environmental change and can be difficult to access physically. Consequently they can be challenging to manage. With this in mind, remote sensing methods, including airborne laser scanning, can prove an effective means of defining and monitoring the highly variable cultural heritage of the coastal zone.

### Application

ALS-derived models can be used to record topographic remains of past human activity both of and at the coast. If the ALS data are captured at low-tide this can include features in the intertidal zone such as fish traps, jetties and wrecks. Commissioned high-resolution ALS survey is particularly suited to the creation of baseline dataset for monitoring weather and climate impacts such as erosion. Dynamic coastal environments are often a priority for ALS data collection for other purposes (such as flood risk management) so there may be a quantity and time-depth to archive ALS data available for these areas that can be an advantage for heritage management (section 4.4).

**It is recommended that data for coastal areas are captured at low tide to maximise the detectability of features in intertidal areas, in the season when vegetation is most dormant and at resolution that results in spatial models of 0.5m resolution or**

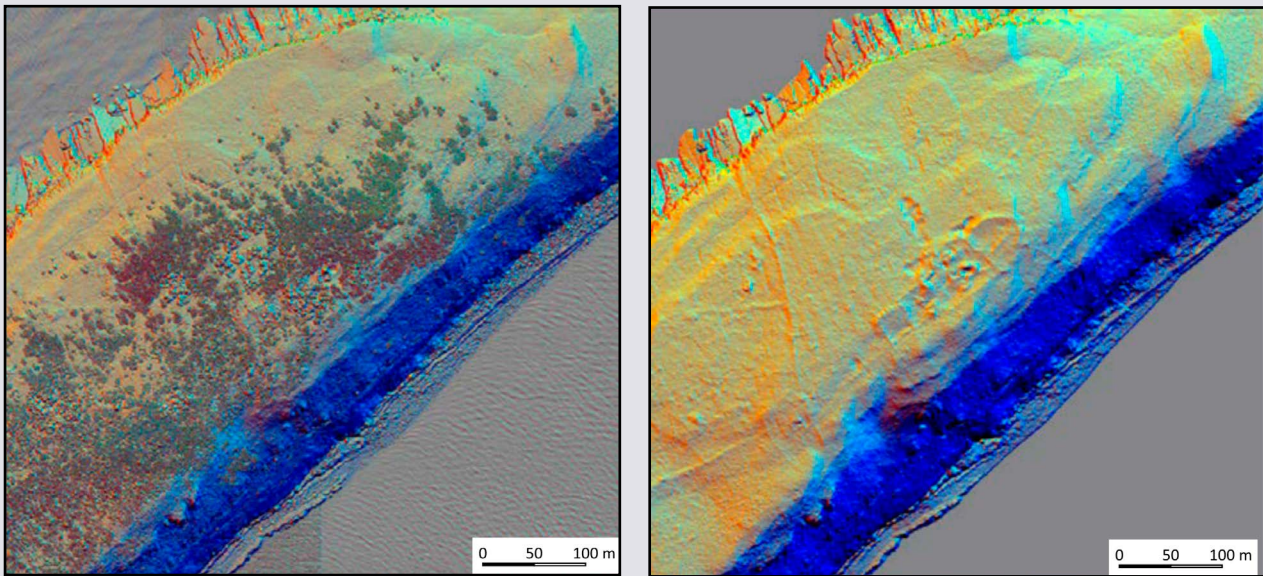
**better.** The CHERISH Climate Change And Coastal Heritage Project has published an extensive toolkit for investigating coastal and marine areas, comparing a wide range of different techniques (Barker and Corns, 2023). With respect to ALS data they have provided analysis of the benefits and challenges along with comparative ratings and examples for the following key questions:

- Environment: Where is the approach applicable?
- Scale/Coverage: What size/extent of site is the technique suitable for?
- Spatial Resolution and Accuracy
- Temporal Repeatability
- Cost
- Training/Experience
- Outputs
- Cultural Heritage Value
- Climate Change Monitoring Value

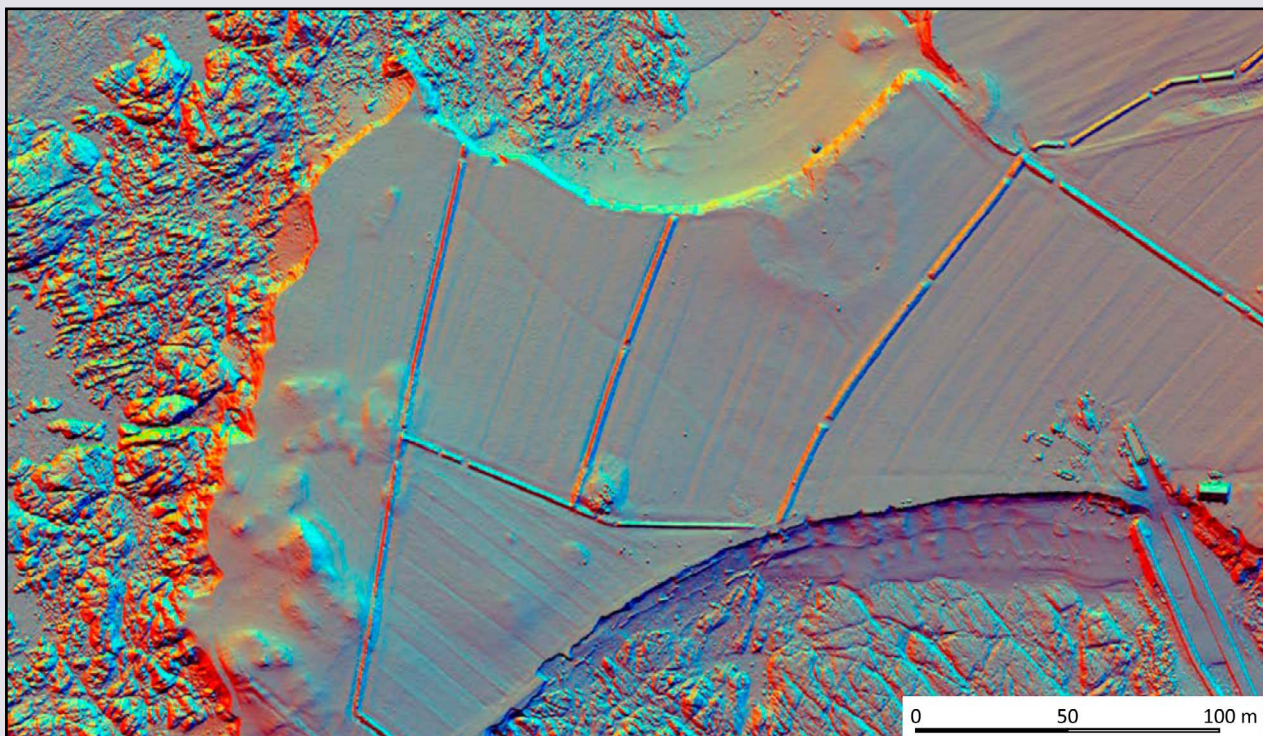
Readers are strongly advised to access this resource in addition to the summary information below.

### Benefits

ALS data can provide various advantages in the strategic management of the intertidal zone and its neighbouring areas. This can be useful both for the large geographic areas that coastlands typically comprise, as well as locations that are more difficult to access, such as small islands, cliffs, and submerged or semi-submerged features in the intertidal zone (e.g. traps or shipwrecks). Research has shown that ALS survey provides large volumes of useful data, generating new insights even for landscapes that were considered to be well-studied (Barker and Corns, 2023). Surveying from the air can be particularly efficient where there are significant challenges for access and investigation over land, for example in areas of high environmental or ecological sensitivity or where the safety of personnel would be compromised to gain access. Barker and Corns (2023) provide a case-study of high resolution ALS survey for islands off the coast of Wales. The ability to remove vegetation from the elevation models allowed the medieval monastic settlement on Puffin Island to be mapped for the first time.



**Figure 5:** A comparison of the Puffin Island ALS digital surface model (DSM) (left) which retains woodland and scrub vegetation and digital terrain model (DTM) (right) revealing the archaeological features (right). Both models have been visualised using multi-directional hillshading (after Barker and Corns, 2023) ALS data © Crown: CHERISH PROJECT 2017. Produced with EU funds through the Ireland Wales Co-operation Programme 2014-2023. All material made freely available through the Open Government Licence.



**Figure 6:** The 0.25m ALS model on the Henllwyn isthmus, Bardsey Island (visualised using multi-directional hillshading). The beach/shingle topography can be identified along with the collapsed concrete sea defences on Henllwyn beach at the bottom right of the image. ALS data © Crown: CHERISH PROJECT 2017. Produced with EU funds through the Ireland Wales Co-operation Programme 2014-2023. All material made freely available through the Open Government Licence.

In challenging environments, ALS data can be employed as a recording tool to mitigate the loss of topographic features, in a similar vein to standard archaeological site recording where features are preserved by record prior to destruction. ALS data can be utilised to both record a baseline of the terrain at a particular time, and as part of long-term programmes repeated acquisition and monitoring (see s 4.3). The latter is increasingly affordable due to the availability of UAV ALS surveys. Barker and Corns (2023) demonstrate that the level of detail provided by the ALS survey proved highly suitable as a baseline against which to monitor change on Bardsey Island. In addition to identifying cultural heritage features of interest, ongoing observations can also identify newly exposed material as a result of shifting deposits in a time-critical way, allowing interventions to be planned to mitigate the effects of the dynamic coastal environment.

For coastal regions, ALS data also have many uses outside of the archaeological remit of this document, e.g. ecology, geography, climatology and can provide excellent opportunities for multi-disciplinary collaboration. This can enable archaeologists to more readily consider factors outside the typical parameters of a defined investigation, as well as potentially providing greater opportunity to commission ALS survey.

As ALS derived models can be a powerful visualisation tool (section 4.7), they can also be used to create as additional content for public and stakeholder engagement and allow different interest groups to visualise the coastline in new ways. Owing to an increase in public access to material such as this, ALS derived models and derived data can prove an especially effective interactive tool, and can provide opportunities for people to better engage with both coastal archaeology, as well as the threats it faces.

### Challenges and Limitations

Whilst ALS survey can support monitoring of a coastal landscape, the specifications of the survey must adhere to certain, repeatable criteria in order to be effective. The quality of the models produced from the ALS data will reflect the conditions under which it is captured and can be affected by many variables in coastal contexts. Water levels, tide times, dense and low vegetation cover typical of some coastal environments and generally more inclement weather (with high

winds impacting the stability of a UAV platform or fog affecting the laser penetration of the atmosphere for example) are all commonly occurring factors that could impact whether the data gathered is fit for purpose. Meeting the requirements for good ALS data capture in coastal areas can be restrictive and impact on project management.

To gain useful data about coastal erosion and the loss of or risks to cultural heritage, any monitoring programme will need multi-temporal data acquisition. This poses both financial and practical obstacles for commissioning data, and the criteria above can also rule out the use of archive datasets collected for other purposes as comparative data. This is particularly true where there are no or limited metadata available for the archive ALS data making it harder to assess its quality. In addition, whilst ALS can provide a means of data collection for remote or sensitive locations, relevant military, naval and aviation authorities may also forbid airborne access to coastal areas primarily used for such purposes.

Interpreting ALS-derived models in coastal contexts can be challenging as the coast is often an area of dynamic environmental change, rich with historic and ongoing anthropogenic interactions. It is important to note these processes may complicate or obfuscate reading the archaeological landscape as presented in the ALS data. As with any ALS survey, comparison to complementary data, for example aerial or satellite imagery to improve interpretation and mapping is essential (see sections 2.3 and 2.4). In the context of rapidly changing and heavily utilised coastlines, aerial imagery that is contemporary to the ALS data is an essential resource and should be factored into the project planning and data acquisition.

### Bathymetric ALS for Shallow Marine Environments

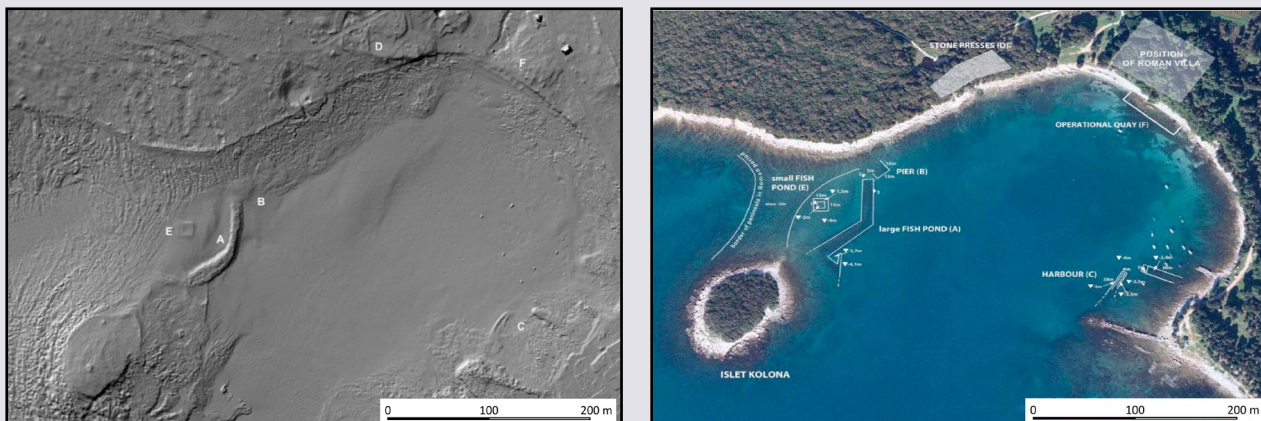
Surveying shallow marine contexts requires a specific approach in order to penetrate the water column and record sub-marine topography of the sea bed. Whilst it is possible to obtain data for the intertidal zone using a conventional lidar sensor at low tide, the infrared wavelength used by the laser (typically 1064 nm or 1550 nm) are absorbed by water so the sensor is not suitable for sub-surface survey. It is possible to survey shallow marine areas using bathymetric lidar sensors which have a laser in the green range of the electromagnetic spectrum (typically 532nm). While a bathymetric ALS works in much the same way as a terrestrial system, the processing is complicated by the passage of the laser through two different media, air and water, and the depth of the water that the laser can penetrate is affected by both sediment load and turbidity (Doneus et al., 2013; Doneus et al., 2015). The uptake of bathymetric ALS survey for cultural heritage has been limited by these factors (Hale et al., 2023) that result in either,

- **low spatial resolution but better penetration of the water column**, e.g. 4-5m spatial resolution and 3 Secchi depths (defined as the maximum depth at which a black and white or all white disk of 30 cm diameter disappears from view by the unaided human eye (Preisendorfer, 1986))

or

- **higher spatial resolution and poor penetration of the water column**, e.g. 1m spatial resolution and 1.5 Secchi depths depending on the sensor configuration (Doneus et al., 2015).

Doneus et al (2015) demonstrated the utility of bathymetric ALS for recording features associated with Roman villa and harbour at the coastal site of Kolone in Croatia and a Neolithic lake dwelling at Keutschach, Austria. These two case studies demonstrated the high variability in depth penetration from 11m at Kolone to just 1.5m at Keutschach. Hale et al (2023) also note that maritime areas with high energy flow and high rates of sedimentation result in poor conditions for bathymetric ALS survey. Both studies conclude that bathymetric ALS is a useful survey technique which can provide time and economic advantages over vessel-based methods to map the sea or lake bed. They also emphasise the value of analysing contemporary aerial imagery and targeted underwater survey by divers to verify results of the airborne survey. However it is clear that successful deployment of bathymetric ALS is highly dependent on the local environmental and maritime conditions, and as such care needs to be taken with respect to developing a survey plan that reflects the nature of the specific coastal and maritime geography and hydrology of the target area.



**Figure 7:** Hillshaded digital surface model over the Roman harbour site of Kolone, Croatia (derived from bathymetric ALS) with archaeological Interpretation based on a combination of the ALS model and underwater survey (Igor Miholjek, M. Doneus et al., 2013)

## 1.4 Assessing Existing Airborne Laser Scanned Data

Rebecca Bennett, Anthony Corns, Anthony Russell, Antonio Jesús Ortiz Villarejo, M. Fabian Meyer-Heß, Steve Davis

One of the main drivers of the use of ALS data for cultural heritage applications has been the increasing availability of data and models. Many countries across Europe have now invested in national ALS survey, in part reflecting the requirements of the [INSPIRE directive](#) (an EU directive to homogenise geographical data<sup>2</sup>) which has driven both acquisition and availability of ALS data. While national datasets are often the first source for existing ALS data, there may be other repositories such as commercial survey companies, local authorities and other heritage and land management organisations.

Using archived ALS data can provide a cost-effective method for assessing the landscape, especially in comparison to the cost of commissioning new ALS survey. Depending on the quality of the archive, it can also provide time-efficiencies as the data can be available for immediate download via web interface. This means that processing and analysis of data can commence immediately, unlike when commissioning data when the process of collecting new data is impacted by seasonal schedule and contractor availability leading to delay.

For each project the archived data needs to be assessed as to its suitability. The stages below are designed to help steer users through the questions they need to address in order to ensure best practice in using existing datasets.

### Project Aims

It is important that the user can assess the potential of existing data with respect to both the archaeological aims of the project and their capacity to understand, process and analyse the data. The first necessary step is to **define the use of ALS data within your project**. Establishing clear aims for your project and assessing how ALS derived models will help to meet these aims is a vital early step (refer to section 1.3 to broaden your understanding of the justification and parameters for using ALS data).

Before approaching a data repository you should know the proposed coverage (project area) required and also the dominant land use in that area and how this may affect the presentation of topographic features relating to past human activity. For example if the study area has woodland is it coniferous or deciduous? Both will impact on the ALS data in different ways in different seasons. If land use has recently changed does this pre or post-date the acquisition of the ALS data for that area? Comparing land use using freely available imagery sources such as Google Earth will help to determine the impacts on the proposed work.

### Locating the Data

Locating data within the repositories can be challenging. While publicly accessible datasets have been lauded as excellent examples of derived benefit exceeding the cost of public provision (National Infrastructure Commission, UK, 2017) “open data” status does not necessarily mean the data are easily accessible. Users should keep in mind that there may be administrative (e.g. requiring an account to be set up before data can be accessed) or technical barriers (e.g. size and speed of download, format of the data) to be overcome in addition to potential monetary barriers. Many countries have portals from which national datasets can be downloaded and some of these have also integrated data from third party providers or projects. For example [Ireland’s Open Topographic Data Viewer](#) provides publicly accessible data from multiple sources. Access to data collected for other purposes, for example commercial surveys, infrastructure projects or even previous landscape or cultural heritage projects is often more complex. To locate it may require extensive research and speculative enquiries via a network of contacts. There may also be licencing, redistribution and re-use restrictions depending on the ownership of the data. Thus if data were supplied with a licence that restricts redistribution to the public it would not be suitable to support the landscape fieldwork of a community project under those terms. Many of the problems of access to existing data could be resolved by better archiving practice including the application of FAIR principles (see sections 3.3, 3.4 and 3.5).

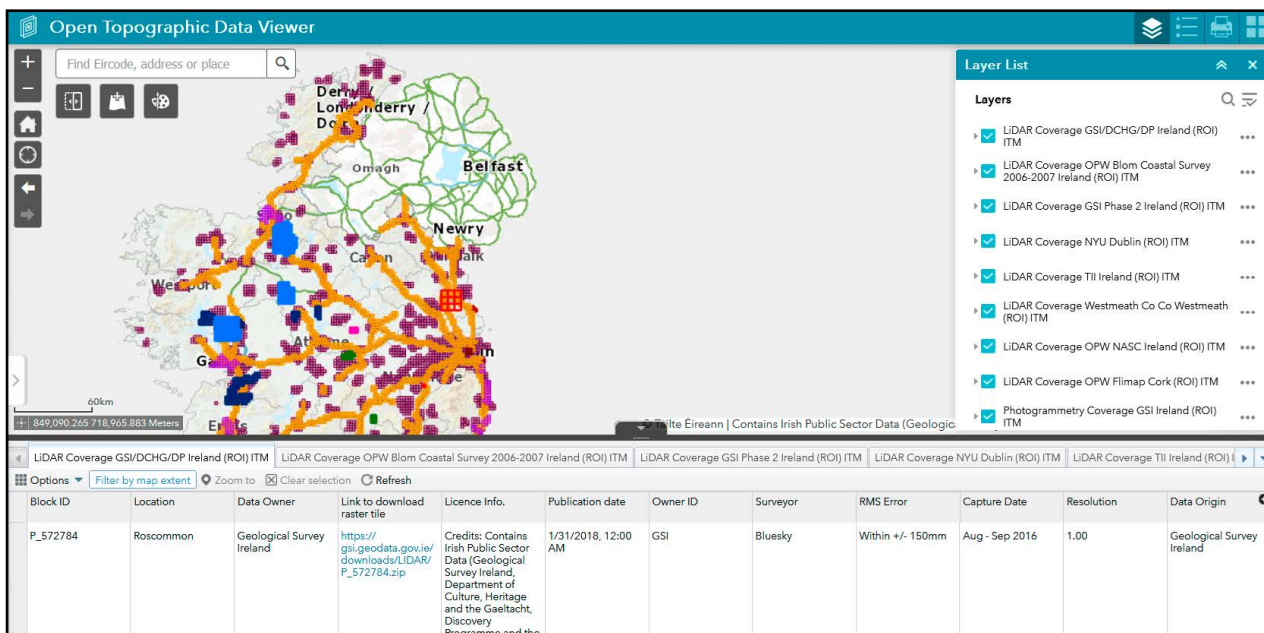
<sup>2</sup> <https://inspire.ec.europa.eu/data-specifications/2892>

<sup>3</sup> <https://dceur.maps.arcgis.com/apps/webappviewer/index.html?id=b7c4b0e763964070ad69bf8c1572c9f5>

## Determining Suitability

Once data have been located, the user needs to be able to assess the data's suitability for the proposed application. ALS data can be captured for many purposes and not all are compatible with cultural heritage requirements. For example ALS data collected for infrastructure planning can be very high resolution (25cm or less), but it is often captured in the leaf-on season (to help identify vegetation impacts along the route) and for a narrow transect, negating some of the landscape scale benefits of ALS survey. Doneus et al. (2022a) provide insight on the impacts of leaf-on ALS datasets on feature morphology as well as visibility, negatively impacting the quality of interpretation.

Many national datasets are captured with a nominal resolution of 1m across the unfiltered data which is less useful for cultural heritage purposes and can result in very low point density and therefore low resolution terrain models in vegetated areas. Data with a nominal resolution of 0.5m or better are generally best suited to cultural heritage applications. Users considering lower resolution (1m +) ALS data for cultural heritage projects need to be aware of the impact of the resolution on the outcomes of their analysis of the data (see section 2.1).



**Figure 8:** The Open Topographic Data Viewer built and hosted by [Geological Survey Ireland](https://tinyurl.com/OTDV-ireland)  
<https://tinyurl.com/OTDV-ireland>

**Point Density:** 1-2 points per metre

**DEM resolution:** ~ 2m

**Description:** basic surface model, flood modelling

**Point Density:** 2-5 points per metre

**DEM resolution:** ~ 1m

**Description:** multipurpose DSM models, noticeably lower resolution where vegetation is removed to create the DTM

**Point Density:** 5-10 points per metre

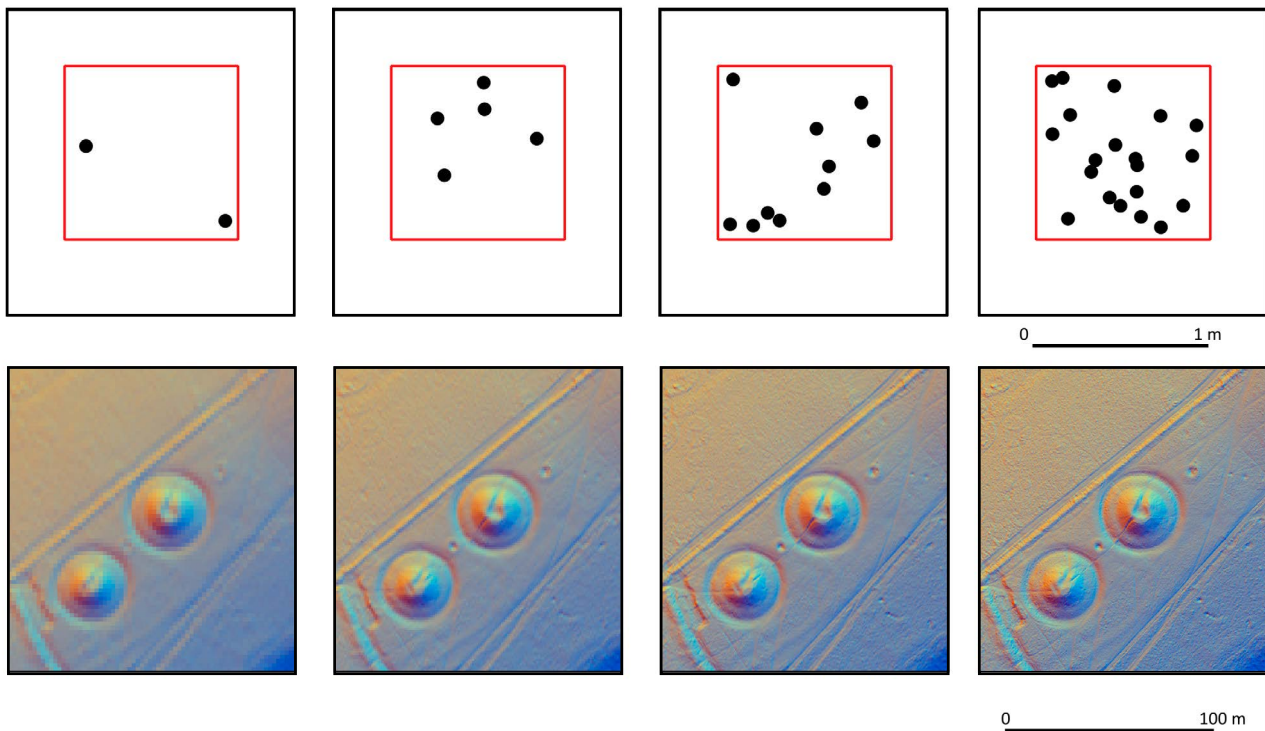
**DEM resolution:** ~ 0.5m

**Description:** detailed DSM model, multipurpose DTM models where vegetation removed

**Point Density:** 10+ points per metre

**DEM resolution:** ~ 0.25m

**Description:** detailed DSM and DTM models



**Figure 9:** Example point densities from ALS data and their impact on elevation model resolution (ALS data © South Downs National Park Authority)

### A note on spacing and density

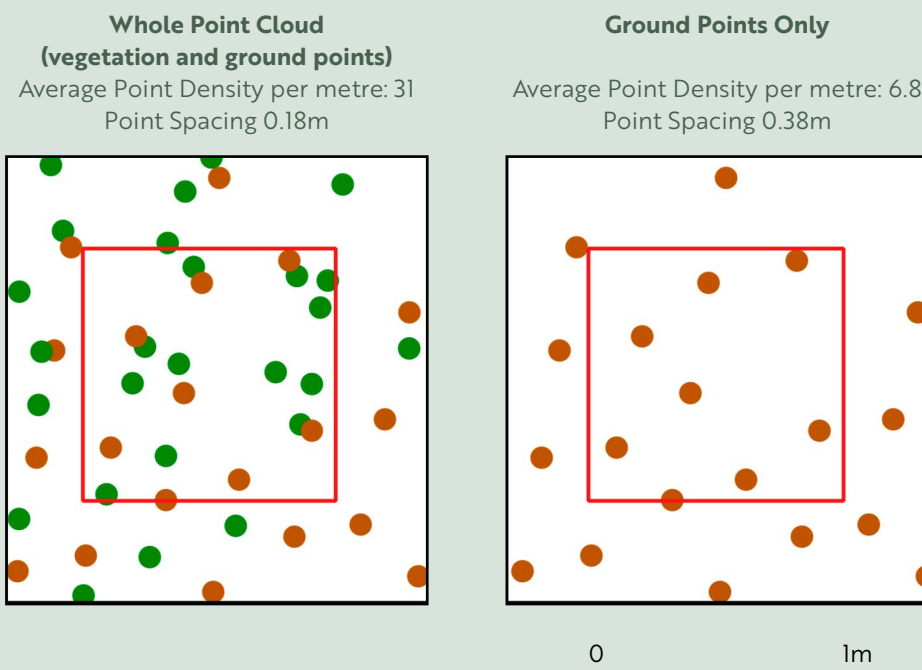
When density and spacing metadata are provided for a point cloud dataset these are often averages for the whole survey area and all classifications in the point cloud. Considering the impact of vegetation cover and the predominant use of the filtered ground points, a more useful measure for cultural heritage purposes is the average density and spacing of points classified as "ground". Vegetated areas result in a reduction of average points per metre and increase in the spacing between points when only "ground" points are considered.

A further example of how important it is to consider the intended purpose of the ALS data, particularly for older datasets, is the impact of the classification algorithms and parameters chosen to remove vegetation and structures on the terrain model. Heavy filtering of these points for hydrological modelling, for example, can remove the subtle topographic features typical of the traces of past human activity, rendering the terrain model less suitable for cultural heritage

applications. In this circumstance, if the point cloud were also available the user would have the option to re-classify the data with a more suitable algorithm. However this level of re-processing has implications in terms of time, software and skills required by the project team.

Data may be archived and made available in different formats. The most common products are ALS-derived models of the landscape (typically a surface model including all features and a terrain model with vegetation and buildings removed, typically in ASCII or geotiff format) but some repositories also provide point clouds of the classified ALS data (LAS or LAZ). Readers are referred to section 1.2 for an explanation of ALS data types and formats.

Ideally for any archived dataset the user should be able to access the **metadata and paradata** which will detail the purpose, parameters, attributes and quality of the ALS data (see section 3.5). Specifically the user will need the following details to make informed use of any ALS data.



**Figure 10:** Illustration showing how density and spacing are affected by the removal of non-ground points. Density and spacing are given as an average of the whole point cloud and illustrated by a 1m<sup>2</sup> sample in a vegetated area. © Rebecca Bennett

## Metadata and Paradata

Essential:

- **Coverage:** does the data available cover your area of interest and can you determine this before procurement.
- **Date of acquisition:** including at a minimum year and month to assess impacts of seasonality and time lapsed since capture. The time of year at which the data was collected, as well as the land use, will also impact the resolution and utility of archive data. Surveys conducted during autumn and winter months will have less vegetation, either canopy or crop, and are therefore more likely to consistently penetrate to ground level.
- **Point density of data / resolution of models:** the density of the point cloud is the average number of terrain classified points per metre. Typically, the higher the point density, the better the resolution, or clarity, of the resulting models. Data with a nominal resolution of 0.5m or better are generally better suited to cultural heritage applications.
- **Type of data available:** point cloud, ALS-derived surface and terrain models.
- **Format of the data:** point cloud in LAZ /LAS / txt, ALS-derived models in gridded raster format, e.g. geotiff, ASCII (see section 1.2 for further details).
- **Data Ownership:** including reuse and licencing restrictions.

Highly Desirable:

- **Purpose of the survey:** the specification of the survey should be designed for its primary purpose and this may impact on the ways the data can be reused. It can determine factors including the point density, point spacing, time of year at which the data was acquired, the method of collection, the level to which the data has been processed and the formats in which it is available. Knowing the purpose for which the data was collected can provide an insight into the quality of the data and whether it is likely to be suitable for your purposes.

- **Method of data collection:** including details of the survey platform (fixed-wing aircraft, helicopter, UAV) and the strategy for collecting ground control points. For all methods but especially UAVs, it is essential that ground control points have been used to ensure metric accuracy of the resulting models.
- **Processing undertaken:** it is important to determine to what extent the ALS data has been processed into consumable, products such as geotiffs. Which software / parameters have been used to process the data. Is any additional processing required to create the product needed? For example, if only a point cloud is available, terrain models will need to be processed from the point cloud data for assessment.
- **Data Statistics:** e.g. average point spacing which describes the space between each measurement derived from the survey.

Desirable:

- **Size and coverage of the downloads:** some data are grouped into packets for download based on size or geographical area.
- **Sensor used and sensor parameters:** e.g. swath width and overlap (see section 1.5).

Readers may find it helpful to use the printable check sheet to support their assessment of archival data (Figure 11).

The wealth of existing ALS data is a huge benefit for cultural heritage management and research. Despite differing in resolution and purpose from commissioned data (see 1.5), existing datasets are useful especially if assessed correctly and integrated appropriately to meet the aims of the project.

EAC Guidelines for the use of ALS in Cultural Heritage Management

## ARCHIVE LIDAR DATA ASSESSMENT CHECKSHEET

### PROJECT INFORMATION

<b>PROJECT NAME:</b>
<b>ASSESSOR:</b>
<b>DATE OF ASSESSMENT:</b>

### ESSENTIAL INFORMATION

<b>DATA SOURCE:</b>			
<b>COVERAGE:</b> Does the data available cover your area of interest?			
complete	<input type="checkbox"/>	partial	<input type="checkbox"/>
<b>Notes:</b>			
<b>DATE OF ACQUISITION:</b>			
<b>RESOLUTION:</b>			
<small>Stated resolution of the ALS data and / or models</small>			
2m	<input type="checkbox"/>	1m	<input type="checkbox"/>
0.5m	<input type="checkbox"/>	0.25m	<input type="checkbox"/>
0.2m	<input type="checkbox"/>	other	<input type="text"/>
<b>AVERAGE POINT DENSITY &amp; SPACING</b>		<b>Density:</b>	<b>Spacing:</b>
		ppm	metres
<b>DATA AVAILABLE:</b>	<input type="checkbox"/> Point cloud	<input type="checkbox"/> Surface / Terrain models	<input type="checkbox"/> Visualisations
<b>FORMAT(S):</b> <small>Circle available formats</small>	LAS / LAZ / TXT	GEOTIFF / ASCII / OTHER	GEOTIFF / ASCII / JPEG / PNG / OTHER
<b>DOWNLOAD SIZE:</b> <small>For each format</small>	GB/MB	GB/MB	GB/MB
<b>ADDITIONAL PROCESSING REQUIRED? YES / NO</b>			
<b>DATA OWNER:</b> <small>Add contact details if required for access</small>			
<b>REUSE TERMS:</b> <small>Detail any restrictions on data use/ reuse here</small>			

### DESIRABLE INFORMATION

<b>PURPOSE OF THE SURVEY:</b>	<input type="checkbox"/> Cultural Heritage	<input type="checkbox"/> Environment / Landuse	<input type="checkbox"/> Forestry
	<input type="checkbox"/> Cartography	<input type="checkbox"/> Transport / Engineering	<input type="checkbox"/> Other / Unknown
<b>SURVEY METHOD:</b>	<input type="checkbox"/> UAV	<input type="checkbox"/> FIXED WING AIRCRAFT	<input type="checkbox"/> HELICOPTER
<b>GROUND CONTROL POINTS USED? YES / NO</b>	<b>METADATA AVAILABLE? YES / NO</b>		
<b>SENSOR AND SENSOR PARAMETERS:</b>			
<b>LANDUSE:</b>			

Figure 11: Archive ALS Data Assessment Checksheet

## 1.5 Commissioning new survey

Elise Fovet, James Eogan, Magdalena Rybska, Paul O’Keeffe, Rebecca Bennett, Anthony Corns, Anthony Russell

### Preparing to Commission Airborne Laser Scanning Survey

Before commissioning ALS data collection a number of issues need to be considered. Foremost of these is whether commissioning new data is the best way to address the objectives of the project. Keeping in mind that collaborative projects will often have non-archaeological objectives to meet through ALS survey (e.g. engineering design), there may be existing datasets that could be reanalysed or even reprocessed to create an appropriate elevation model and these should always be investigated (see section 1.4).

When considering the management of ALS data acquisition and processing, data commissioners need to be sure that there are there sufficient qualified, competent and experienced suppliers to carry out the survey and create the required products (see section 2.1). Timescales and funding deadlines also have an impact on survey project management, so data commissioners should ensure that there is sufficient time or enough flexibility to obtain the data in optimum conditions (e.g. leaf-off, no snow cover etc.) and assess the implications to the project if the data cannot be acquired as planned.

Data commissioners should consider possible collaborators in setting up an ALS acquisition project. Many common applications such as engineering and construction, where ALS data may be deployed to inspect power lines, civil infrastructure or to monitor work progress, will not necessarily involve specifications for data capture that fit well with cultural heritage requirements. Applications relating to forestry, ecology and land management are often more compatible, requiring a coverage of data that allows for landscape scale biomass calculations or quality that allows for measurement of morphometric parameters such as the structure or height of individual trees (see Case Study 3). They may also require the collection complementary datasets such as aerial imagery which can significantly enhance interpretation (see section 2.4). However they may also require data to be gathered in leaf-on conditions which are not conducive to archaeological survey. While compromise in any collaboration is

expected, data commissioners in the cultural heritage sector must be confident that any acquisition meets their project requirements appropriately.

### Understanding Airborne Survey Platforms and the Survey Process

Choosing the right platform for data collection is vitally important when planning an acquisition. Traditionally ALS data have been collected using fixed wing aircraft or helicopters and the advantage of these systems is that they enable efficient data collection over large areas and have a payload that supports the multiple instruments, the ALS sensor, GPS, IMU, computer system etc. required for high quality survey (see section 1.2 for further details). As sensor technology has become smaller and lighter, UAVs are becoming an increasingly reliable alternative platform for smaller survey areas, especially when budgets are limited. UAVs also have the advantage of rapid deployment when weather conditions are suitable for data capture. It is anticipated that the UAV based survey technology will become increasingly popular due to its low cost, rapid deployment and data collection, high repeatability and high data quality.

Many factors help determine which type of aircraft and sensor are required for each survey, including the specific aims of the project, precision and accuracy requirements, the size of the survey area and the terrain. An important factor to keep in mind is flying time and coverage, as this will have a direct impact on the cost and efficiency of data acquisition. Very rough or mountainous topography, as well as certain types of upstanding remains, cannot be precisely scanned in all dimensions with fixed-wing aircraft as their flight height and sighting parameters do not adequately capture data for vertical or near-vertical surfaces (steep slopes) and overhanging areas. Oblique scanning to capture vertical faces and overhangs requires the use of aircraft such as helicopters or multi-rotor UAVs (provided that the on-board ALS sensor has a sufficiently wide scan angle). Additionally, while lidar as an active sensor can be operated day or night, complementary collection of aerial photographs or spectral imagery requires specific light conditions. For this reason, it is important to recognise that the platform and sensor combination might impact on the data being collected, survey timescales and associated costs.

Regardless of the platform, flight planning is also crucial to achieve high quality data. This includes consideration of the altitude of the flight, speed, and side and forward scan overlap. High overlap increases the data accuracy and reduces mismatches and data voids. The flight paths should include cross-flight lines (perpendicular to the main direction of survey) to allow better calibration. To ensure complete coverage and high image quality results at the edge of the area of interest it is recommended that the flightpaths extend beyond the area boundary to allow the capture of data in a "buffer" zone.

For good data collection the lidar sensor and other supporting systems (IMU and GPS) must be properly calibrated. This will avoid navigation and stabilisation problems that could impact the quality of the data and this factor is particularly important when commissioning survey by drone. Survey companies should be able to provide calibration certificates for their sensor systems and experienced survey companies will be able to explain the benefits and limitations of their proposed platform and sensor combination and tailor their survey approach to the project specification.

### Defining Requirements

Before inviting survey companies to tender for the work, the data commissioner needs to accurately identify the **area to be surveyed**, the **level of detail** appropriate, and what **deliverables** are expected. These elements should be clearly laid out in the survey specification. Survey companies will be used to responding to detailed technical specifications **but may not be particularly familiar with cultural heritage applications**. Clearly communicating the expectations of the project to the survey company will reduce the chance of disappointing survey outcomes.

A **written specification** is required setting out the aims, the extent of the proposed survey, the minimum survey accuracy, and the mandatory deliverables (digital data and reports). The specifications must be as clear as possible in order to guide the survey company in presenting its offer and to enable the client to assess the offers fairly in a competitive environment. A mutually agreed specification is also a tool that will ensure good communication during the project execution, limiting misunderstandings between the data commissioner and survey company and other project partners or stakeholders.

The **area of survey** should be considered primarily with respect to the archaeological objectives of the project but should also consider the practicalities of survey planning. It is much more efficient and therefore economical, to survey a continuous regular shaped area (square or rectangle) than to have smaller, disparate or irregular shaped areas for data capture. Data commissioners should also plan for an effective buffer zone around the key area of interest to guard against potential edge effects or omissions from the survey. Some projects approach the commissioning process with an "essential" and larger "desirable" boundary to test cost efficiencies in the approaches of the different survey companies to a larger but contiguous area.

The **precision and accuracy needed** depend on the objectives being pursued e.g. archaeological prospecting over a large area vs. three dimensional (3D) model of a particular site. For these two cases the required geometric quality of the ALS survey to develop a ground or surface model of sufficient accuracy to undertake a detailed archaeological assessment will not be the same. The level of classification of ALS data is also an important aspect to consider, especially if the survey project is carried out within the framework of an interdisciplinary and/or inter-institutional consortium. A large number of classes, for example to distinguish vegetation from other above-ground objects such as buildings and vehicles, may greatly increase the cost of the processing with little benefit for cultural heritage applications.

**Point density and spacing** should be explicitly stated. It is important to state the expected minimum "ground" classified point density as this will vary from the overall average density of the point cloud (see section 1.4) especially in vegetated areas (see Figure 9 and Figure 10). The expected averages can be stated in the text or tabulated e.g.

"We expect the lidar data to be collected with an average pulse density of 12-16ppm and spacing of  $\leq 0.35m$  and the resulting terrain models should have a resolution of  $0.25m$ ."

	Average Minimum Pulse Density	Average Minimum Pulse Spacing
<b>Whole point cloud</b>	$\geq 8$ pls/m <sup>2</sup>	$\leq 0.35m$
<b>Ground classified</b>	$\geq 5$ pls/m <sup>2</sup>	$\leq 0.5m$

**Expected ALS survey precision and accuracy** can also be stated in the survey specification. This may be particularly helpful to determine the approach to ground control for both traditional platforms and UAV. For example

- Non-vegetated vertical and horizontal accuracy at 95-percent confidence level  $\leq 9.8\text{cm}$
- Vegetated vertical and horizontal accuracy at 95-percent confidence level  $\leq 14.7\text{cm}$

For the gridded models the specification should state expected pixel size, e.g 1m, 0.5m 0.25m. **Typical survey outputs (deliverables)** required are:

1. A classified point cloud
2. A gridded, GIS ready Digital Surface Model (DSM)
3. A gridded, GIS ready Digital Terrain Model (DTM, terrain only)
4. A gridded, GIS ready Digital Feature Model or (DFM, terrain and building points)
5. Survey reports including paradata and metadata

The DFM is specifically useful where the nature of the upstanding cultural heritage includes ruins, buildings or structures. Table 3 gives examples of the detail that could be specified for each of these deliverables.

**Data ownership and sharing terms** should be explicitly outlined in the brief. The commissioning organisation should reserve the right to share the unprocessed and processed survey data, elevation models and survey reports with third parties for non-commercial purposes and to publish data and derived visualisations.

If the project requires full-waveform ALS data this should be specified along with file formats. Full-waveform data can be significantly more complicated to utilise than pulse data and so extra care should be taken to make sure that the specification matches the formats required.

Finally as discussed elsewhere, there may be benefits to additional data capture during the survey such as orthophotographs or spectral data. The specification should include the technical expectations for these datasets, but also make explicit which data takes precedence in the event of a compromise needing to be drawn.

## Communication is Key

Remember that the cost, timeline, and specific details of the survey will vary according to factors such as the size and complexity of the area, the required level of detail, and the specific deliverables you need. It is important to have clear specification and a commitment to ongoing communication with the survey company to ensure they understand the project's requirements and can deliver the desired results.

Deliverable		Example of Suggested Requirements
i	Classified point cloud	A classified cloud in .las or .laz format. The data shall be supplied in the specified coordinate reference system and be fully compliant with the American Society for Photogrammetry and Remote Sensing (ASPRS) LAS Specification, Version 1.4 – R14 (March 2019).
i-iv	Elevation Models (DSM, DTM, DFM)	A Digital Surface Model (DSM) (maximum cell size 0.5m) in industry standard, GIS compatible, floating point raster format. The Digital Surface Model shall be supplied in geo-referenced tiles, each covering an area of 1 sq. km and shall edge match seamlessly without gaps or overlaps. The data shall be supplied in the specified coordinate reference system.
v	Survey reports	Report should demonstrate how the results achieved meet the minimum requirements of the specification. describe <ul style="list-style-type: none"> <li>• the methods, techniques and equipment used in the survey</li> <li>• the software parameters and methods used in the data validation and processing, including how data voids, if any, were treated</li> <li>• any issues encountered.</li> <li>• The report shall demonstrate that the results achieved meet the minimum requirements of the service requirements.</li> </ul>
vi	Paradata and metadata	Metadata and paradata should be delivered with the survey reports and should include: <ul style="list-style-type: none"> <li>• An .xml file for each deliverable including classified point data, bare-earth DEMs, breaklines, digital surface models, intensity images, height above ground surface and others. These should be in compliance with the "Content Standard for Digital Geospatial Metadata" (CSDGM) (FGDC, 1998) (see ch3.5) and include details of the <b>processing software and variables used</b></li> <li>• A georeferenced, digital spatial (GIS compatible) representation of the detailed extents of each deliverable dataset, including each ALS swath collected.</li> <li>• A "mask layer" in geotiff format showing all pixels within the DEMs that did not contain a point to aid with further interpretation.</li> </ul>

**Table 3:** Suggested Requirements for Data Deliverables

## Commissioning and Conducting the Survey

Following careful definition of requirements you are ready to commission a survey. Depending on organisational / national procurement rules for high value contracts, these may be subject to formal processes beyond the scope of this guide, but the following steps outline the typical process for commissioning a survey.

Commissioning:

1. **Research Service Providers:** Look for professional surveying companies and use the professional network of cultural heritage professionals within your region to gather recommendations. Consider the experience, expertise, equipment and the types of projects the companies have worked on in the past.
2. **Request Proposals:** Contact the selected service providers and request proposals for your survey. Provide them with details about your project, including the area to be surveyed, the desired deliverables, and any specific requirements you may have.
3. **Evaluate Proposals:** Review the proposals received from different service providers. Consider factors such as cost, timeline, experience, technical capabilities, and the quality of deliverables offered. It is often beneficial to ask for sample data from previous projects and follow up references. Seeking the support of a cultural heritage professional experienced in commissioning ALS data may be valuable at this stage to help to assess the proposals.
4. **Select a Provider:** Based on your evaluation, select the service provider that best meets your requirements and aligns with your project goals. Cost will always be an important factor but be sure to balance quality and experience.

Once the provider has been commissioned the project should progress through the following stages to completion.

1. **Project Planning and Execution:** Work closely with the chosen service provider to plan the survey project. This includes defining flight plans, coordinating logistics, and establishing data processing and delivery schedules.
2. **Data Collection and Processing:** The service provider will carry out the survey according to the agreed-upon plan. They will collect the data using their airborne lidar system and process it to generate the desired deliverables. It is good practice to build in a quality assessment stage for the cultural heritage project team to make sure that the data will meet the project requirements (see below).
3. **Data Delivery and Analysis:** Once the data is processed, the service provider will deliver the final results, such as point cloud data, digital elevation models, or other requested outputs. You can then analyse the data or use it for your intended purposes.

## Questions to ask when evaluating a proposal

When evaluating proposals, you may wish to use the following questions to guide your assessment.

### Quality of the proposed flight(s) and acquisition(s):

- How will the required density of ground points be obtained (taking into account the context: acquisition in forests, on steep slopes, on alluvial plains or in an urban context)?
- How will the flight strips be aligned? What percentage overlap is proposed?
- What equipment will be used? Have the sensors been calibrated recently?
- How many flights are planned?
- What is the maximum distance between the aircraft and the GPS base station(s)?

### ALS data processing quality:

- Which processing and software will be used to process the raw data?
- What methods will be used to classify the points?
- How will the relative and absolute accuracy of the points be calculated?

### Quality of digital model production:

- Which software, techniques and interpolation models will be used to produce the DEMs?
- How will large data voids be dealt with?

### Quality of the mission plan and practical ability to conduct the survey:

- Does the data provider already have authorisation to fly over the area? If so, when can they carry out the flight and does this conflict for priority with other planned acquisitions?
- What is the proposed timetable (verification/validation stages and milestones)? Are the person(s) dedicated to the operation namely designated (surname, first name, CV to be attached)?
- What experience does the contractor have of similar operations? Preference may be given to service providers offering complementary or innovative solutions to ensure the quality of the assignment, providing the risks of such solutions can be adequately assessed.

## Quality Assessment and Validation by the Project Team

The survey company is expected to implement quality control measures to ensure that they meet the requirements of the project and to report on the global statistics of the data collected (see Kraszewski et al., 2020; Luethy and Ingensand, 2004 for an overview of expected quality control steps).

In addition to these measures, it is good practice for the project team to also undertake **quality assessment during the processing phase of acquisition**. The team should be supplied with sample data deliverables (e.g. LAZ, DSM, DTM, DFM) for a number of pre-selected, small but representative areas within the survey coverage. These areas should be chosen to represent a range of terrain, land uses and archaeological remains and need be no more than 1km<sup>2</sup> in extent. The sample data should be processed into specialist visualisations and subject to rapid visual assessment (see section 2.2), including comparison to aerial imagery and a field visit if possible. It should be possible to feed the results of the evaluation back to the survey company and the classification and processing of the data altered if necessary before the final data delivery.

### Quality Assessment and Validation by the Project Team (continued)

When the survey data are delivered it is strongly advised to undertake **an independent validation of the data** and other survey outputs to ensure that they comply with the minimum requirements and are presented in the required formats. It is important that data validation happens as soon as possible after data delivery and ideally before any final payment is made to the survey company so that any problems can be raised and rectified in a timely fashion.

It is recommended that:

- All files are checked for missing data and the consistency of the information on the point clouds (LAS or LAZ) is confirmed, in particular the class, return number, GPS time and scan angle. Is the data supplied in the correct range? An incorrect return number can render the data unusable for certain applications. GPS time and scan angle are useful information to check that the required flight line overlaps have been made and that the data on the edges of the flight strips are accurate (for UAV lidar especially). This can be done using free tools such as [LASinfo](#).
- Point densities and spacing are calculated for the ground classified point in each point cloud file as well as across the whole dataset. This helps to highlight errors and inconsistencies that may be masked by global statistics.
- The altimetric and planimetric accuracy is confirmed by using ground control points on open and flat terrain.
- All gridded data tiles (DSM, DTM, DFM) are visually checked as being in the correct geographic coordinate system and providing the expected geospatial coverage. This can be done by importing and viewing the data in a GIS and via tools such as [gdalinfo](#).
- The gridded data are checked for gaps where there are pixels without ground points. A “mask layer” can be produced (or requested from the data provider) showing all pixels that did not contain a point to aid with further interpretation.
- The project team undertake further data processing into specialist visualisations as soon as possible on delivery of the data. Some data errors can be highlighted by processing carried out either on the point clouds (e.g. using ambient occlusion in point cloud software to identify errors) or on the terrain models (e.g. skyview factor or curvature calculation)
- The visualised ALS data is checked for artefacts. These are regions of anomalous elevations or oscillations and ripples within the DEM data due to systematic errors, environmental conditions, or incomplete post-processing. They can also include “steps” in the model which present as an abrupt change in elevation, typically seen between adjacent flight lines.

If the project team does not have the technical expertise to undertake quality assessment and validation it is advisable to factor the time of a specialist to assist with this work.

## SECTION 2

### Data Processing and Interpretation

This section focuses on best practice for the post-acquisition stage of projects, how ALS data should be processed and analysed and how to integrate the products of ALS survey (models and visualisations) into work in the field and with communities, as well as the growing role of ALS in automated archaeological feature detection.

In this section you will find:

- information about best practice in ALS data processing and visualisation
- guidance on the process of archaeological interpretation from ALS derived visualisations
- an example schema for vectorisation of features and presentation of ALS-derived digital datasets to a wider audience
- an introduction to the key topics of automated detection and citizen science
- guidance on the integration of ALS with archaeological fieldwork including a summary table of considerations for integrating ALS data with other complementary fieldwork methods along with an example schema for collection field observations.
- advice about the skill and expertise of staff, and a competencies matrix to support the development of professionals working with ALS data in the heritage sector.

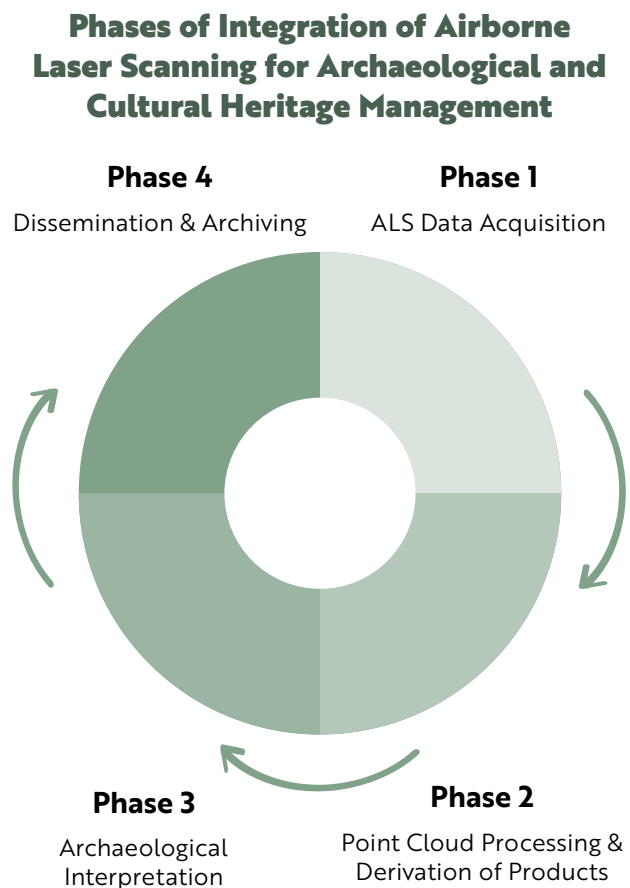
### 2.1 ALS Data Processing

Michael Doneus, Žiga Kokalj

The processing and integration of airborne laser scanning data for archaeological and cultural heritage management purposes can be divided into four general phases, each consisting of a number of individual steps (as detailed in section 1.2, Table 2). This section focuses on the first two steps of **Phase 2: Point cloud processing and derivation of products**. Specifically, it covers classification of the point cloud and interpolation of elevation models of the landscape of interest. Creation of specific visualisations to highlight micro-topography is detailed in section 2.2.

When working with existing ALS datasets, these steps will likely have already been undertaken and archaeologists or cultural heritage managers may not be able to influence outputs. It is therefore important to understand the impact of the choices made during these processing steps on the data products available.

When commissioning new data or approaching archived point cloud data with sufficient resource and expertise, the steps of classification and interpolation of the data should be tailored to cultural heritage requirements.



**Figure 12:** Phase 2: Point Cloud Processing and Derivation of Products

## Step 1: Classification of the Point Cloud

The integration of data from the laser scanner, IMU and GPS (via the processes of **registration** and **strip adjustment**) results in a highly accurate, georeferenced point cloud of the scanned area. This cloud contains millions or even billions of x,y and z points that represent the surfaces of the terrain, the vegetation and all objects (such as buildings, cars, rocks, powerlines but also people and larger animals).

These points can be classified into categories based on their relative geometry. The American Society for Photogrammetry and Remote Sensing (ASPRS) defines the range of classes for ALS data in the las 1.4 specification (ASPRS, 2019). Depending on the application, different classes of points are of interest and so different **digital elevation models (DEM)** are derived from the point cloud by selecting certain classes of points for interpolation. In general, a distinction is made between **digital surface models (DSM)**, which represent the surface of the terrain and all natural and man-made objects projecting from that surface, and **digital terrain models (DTM)**, which are a representation of the 'bare earth' terrain.

For the detection and mapping of archaeological remains, the point classes of interest are primarily ground (where features such as roads and earthworks will be recorded) and **buildings** (where upstanding features such as walls, standing stones, ruins will be recorded). If points assigned to both these classes are interpolated into a DEM, the term **digital feature model (DFM)** is used (Lozić and Štular, 2021; Pingel et al., 2015). Other classifications can also be of use. For example, the density of low vegetation points can be analysed to provide information about the accessibility of potential archaeological features detected in the data in advance of on-site visits (Doneus et al., 2022b).

No matter which point categories are used to interpolate an elevation model, the process involves three steps:

1. the classification (or semantic labelling) of the point cloud
2. the selection (filtering) of points assigned to certain categories
3. an optional manual enhancement of the filtered point cloud (to correct errors in the classification generated by the algorithm)

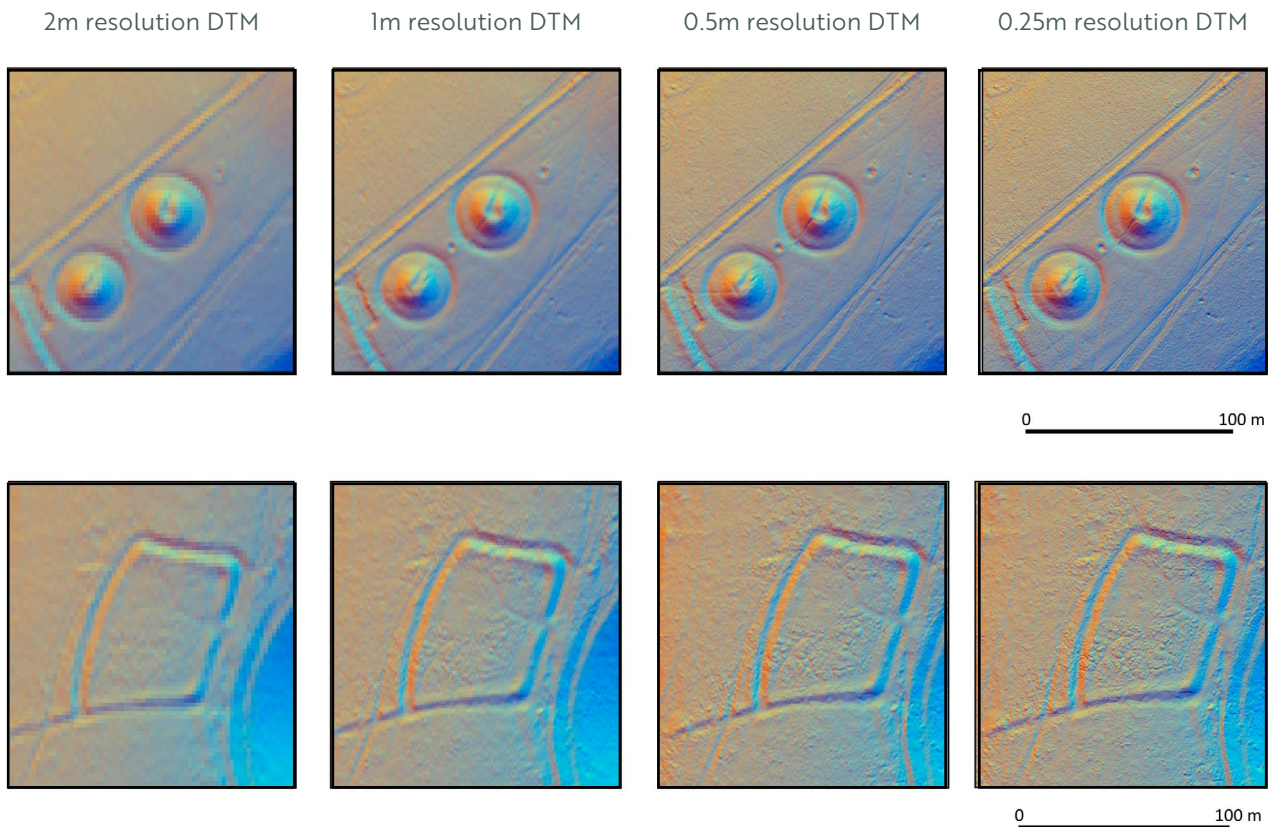
To better understand the impact of this process on the resulting outputs (DSM / DTM / DFM), it is important to remember that the outputs are **models**, i.e. a simplified representation of the selected type of surface. Since there is no 'definitive' surface of a terrain, the same area can be correctly represented by a variety of models. The differences between the models are primarily due to how individual points are classified. Consequently, it is best practice to ensure that the parameters of the classification algorithm underpinning the model are tailored to cultural heritage purposes (Doneus et al., 2020).

The classification of a point cloud is generally a two-step process, firstly identifying the ground and non-ground points, and then assigning different point classes of interest depending on the application. There are many software solutions to determine ground and not-ground points and assign subsequent classes to point cloud data (recent list of publications in (Štular and Lozić, 2020)). Each offers a range of parameters to adapt the classification to specific requirements and situations to improve the quality of the resulting model but the process is entirely automatic once these parameters have been set.

Numerous tests have shown that there is no optimal software solution or parameter combination suitable for all scenarios (Korzeniowska et al., 2014; Štular and Lozić, 2020). Rather, it requires a skilled person to derive the most suitable DTM or DFM from the available data,

Class	Definition	DTM	DSM	DFM
0	Created but never classified			
1	Unclassified			
2	Ground	X	X	X
3	Low Vegetation		X	
4	Medium Vegetation		X	
5	High Vegetation		X	
6	Building		X	X

**Table 4:** Table adapted from the LAS Specification (ASPRS, 2019), highlighting which point classes are used to create different elevation models



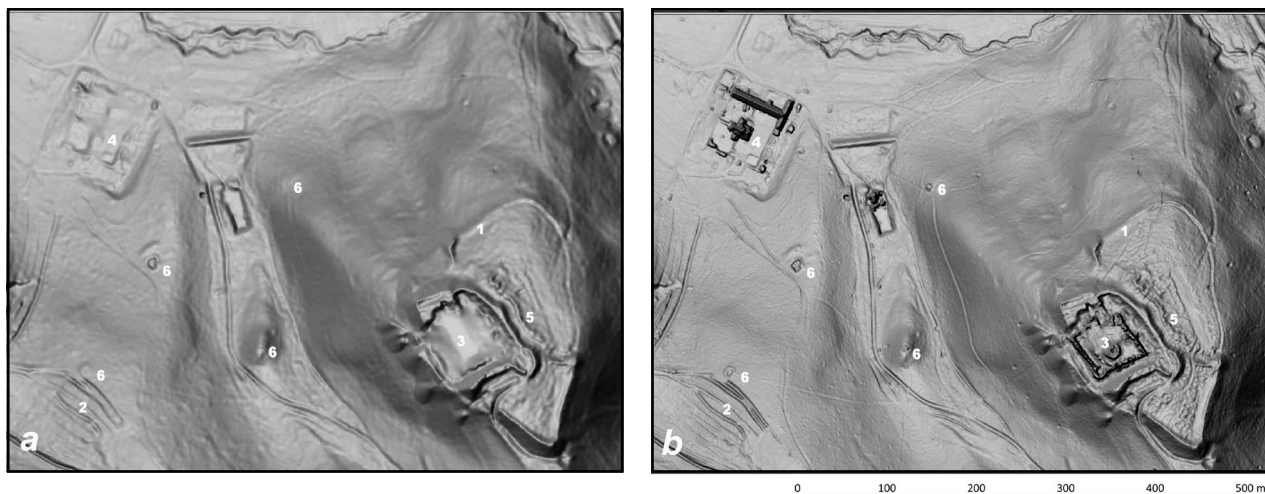
**Figure 13:** Figure showing improvements in feature clarity with increased resolution using barrow and enclosures from the South Downs National Park, UK as examples visualised using multidirectional hillshade (ALS data © South Downs National Park Authority)

depending on the question, and the environmental context of the survey (e.g. topography, vegetation). Ideally, a person with experience in landscape analysis for cultural heritage is involved in this process to help optimise the results.

General purpose DTMs, such as those made available through national ALS portals, may contain limited archaeological information because the classification of the point cloud has not been optimised for cultural heritage applications. This is not to say that these models are not useful, but detailed archaeological mapping may be compromised to missing structures and a terrain model that has been harshly filtered removing microtopography and upstanding remains. Even commissioned data can fail to match the expectations of heritage management and archaeological users if the point cloud has been classified by archaeologically inexperienced data providers using standard routines and not subject to quality assessment by the project team (see section 1.5).

A further complication to achieving fit-for-purpose classifications and elevation models is the presence of a

variety of **terrain** (e.g alternating flat and steep terrain with or without abrupt changes), **vegetation** (open areas, dense shrub, deciduous, coniferous or mixed woodland with or without dense undergrowth) and **surface texture** (smooth or rough, characterised by few or many stony outcrops of different sizes and densities). Different filter settings are needed to adequately model these different types of landscape. Therefore typical models produced using only one filter are a compromise which may more or less appropriate depending on the degree of local variations in topography, vegetation and surface texture. There have been some implementations of adaptive classification to address this difficulty. Adaptive classifications are based on spatial segmentation, where individual segments represent spatial areas with similar topographic, land cover and/or point cloud characteristics (Doneus et al., 2022b). This segmentation approach, where varying parameters are used to match different characteristic areas within the landscape, significantly improves the quality of the resulting model. It is expected to become more widespread as improved data processing capability and machine learning are integrated into the classification process (Mazzacca et al., 2022).



**Figure 14:** St. Anna in der Wüste. Comparison of a general purpose DTM (a) and a DTM derived from ALS data scanned and filtered for archaeological purposes (b). 1: rampart of a prehistoric hillfort; 2: hollow ways; 3: building structures of the ruined castle of Scharfeneck; 4: monastery; 5: pit-structures surrounding the castle; 6: small buildings (after Doneus and Briese, 2011)

### Manual editing and enhancement

Automatic classification algorithms deliver a certain level of output that may need to be benefit from manual inspection and classification as part of point cloud processing to maximise fitness for the intended purpose. This involves reclassifying points that have been misclassified but whose correct classification is very important for a particular application. An example in archaeology is high free-standing walls, which are usually classified as vegetation by automatic algorithms. The process requires familiarity with the particular landscape and knowledge of basic mapping principles, conventions and best practices. Manual classification therefore depends largely on the experience of the operator and is carried out on a point cloud that has already been automatically classified. It is a time-consuming process, so it is usually only done for targeted (site-scale) areas where it helps to identify archaeological features. Manual classification should be supported by fieldwork (see section 2.7) and reference to supporting information such as aerial photographs, to ensure that data artefacts do not produce misleading models. The workflows for all editing and enhancement should be recorded in the metadata (see section 3.5).

### Tips for Manual Classification

The decision as to which areas should be examined in more detail and which points should be reclassified depends on the general roughness of the terrain and the type and structure of the vegetation of the study area. Special attention should be paid to uneven terrain or broken slopes, dense forest areas with very few ground returns, and areas with low and dense vegetation, which is often ignored by ground filters. To help with identification and reclassification of errant points, the point cloud can be coloured by intensity, classification, elevation (relative or absolute) and draped with single or multiple rasters. They can be checked for anomalies and artefacts against background imagery such as orthophotos, elevation models, thematic or topographic maps, and displayed as profile cross-sections or in three dimensions.

## Step 2: DEM interpolation

DEM interpolation (also referred to as gridding or rasterisation) in the process of converting point cloud data into a raster format by assigning a height value from the points to each pixel in an image. The **pixel** size, expressed in metres, is determined by the user by calculating the **density** and **spacing** of the recorded ALS points. The resulting raster model is a continuous surface that can be used to assess the landscape and forms the starting point for advanced visualisations. Typical rasters created by this process are DSM, DTM or DFM (depending on the classification of points included), but rasters can also be used to display intensity or statistical parameters such as point density.

Interpolation has not received as much attention as other processing steps in cultural heritage applications (Štular et al., 2023), in part because much archive ALS data is provided in raster formats produced using processes over which the end user has no control. However, as more point clouds are made accessible there are greater opportunities to tailor the creation of the raster models to a particular purpose.

If there is no point in a particular pixel, the interpolation algorithm derives the elevation value from the surrounding area. Consequently, the choice of interpolation algorithm is more important when scanning density is low and/or there are large data gaps. The most common techniques include triangulation with linear interpolation, inverse distance weighting (IDW), nearest neighbour and natural neighbour. Kriging can also be used, but mostly for research applications as it is very time consuming. The appearance of the interpolated surface varies, but the main differences are in the overall smoothness and preservation (clarity) of the breaks or changes in topography. The same technique can be implemented differently in various software packages and therefore there is no consensus yet on which ones work best although a comparison of six techniques identified inverse distance weighting (IDW) as performing best for precision, cost and availability (Štular et al., 2023). In terms of future developments in this process, combining the results of several interpolation algorithms based on terrain type, scanning density and pixel size may provide optimal solutions (Štular et al., 2021).

The artefacts produced by some interpolation algorithms may be considered unattractive and inappropriate for display. However the use of such algorithms is still recommended especially when the goal is visual interpretation. The artefacts are recognisable and thus help to avoid misinterpretations of smooth continuous but erroneous surfaces based on insufficient data.

### Why interpolate?

If all the topographic data is present in the point cloud, why do we need to create elevation models? The answer is that our human eye-brain system is evolved to understand and recognise patterns in surfaces, and we are ill-equipped to deal with clouds of points. Therefore, we can best interpret the data when it is interpolated into models with continuous surfaces. A second factor is the need for integration with other datasets in a GIS. While the integration of 3D data and point cloud formats into GIS is improving rapidly, traditionally they have only been able to handle 2D representations, requiring the conversion from point cloud to surface model, and that requirement is likely to remain for visual interpretation by human beings.

This section has introduced the two processing steps required to create elevation models from ALS survey, namely **classification and gridding**. The results that best meet the needs of cultural heritage management will derive from using data where complete control can be exercised over the whole process. However, this is often not possible or may be only partially achievable and in these cases reviewing the metadata with the processing requirements in mind will help to determine if the dataset is good enough for the purpose of your research.

## Case Study 2: ALS for Agricultural Environments

Łukasz Banaszek, Antonio Jesús Ortíz Villarejo

### Introduction

Agricultural practice has always impacted the survival of older features in the landscape, and the rate of these impacts has increased greatly with modern intensification and industrialisation of agriculture (Vogt and Kretschmer, 2019). The likelihood of archaeological earthworks or remains of upstanding historical structures surviving in agricultural land is quite low, though the extent of their vulnerability varies depending on the farming practices and cultivation techniques employed (Stevenson, 1975; Trow et al., 2010). Repeated ploughing and field improvements, and in some cases deliberate levelling of features, will have degraded or removed their surface expression. However, slight relief features can survive even in heavily cultivated fields. Finally, discrete earthworks may survive for instance in small areas of woodland that form part of the mosaic of land use in agricultural production zones. Such pockets of land have been important elements of agricultural landscapes, closely linked to traditional agricultural management practices, such as post-medieval field systems and enclosures, that historically modified existing features or actively created new traces (Poschlod and Braun-Reichert, 2017). As a result, to understand the complexity of agricultural landscapes requires a range of perspectives. This section discusses the application of ALS for documenting sites in agricultural areas, with the caveat that the majority of archaeological features found in agricultural landscapes will not be best represented by a topographic survey due to the impact of modern farming practices.

### Agricultural Land

Agricultural land is usually defined as an area used for agricultural purposes, including cultivation of crops and rearing of livestock, to produce food, fibre, bio-fuels, and other goods. Definitions differ depending on the context and methodology but often build on the land-use categories or are purpose-driven, e.g. food production (European Commission et al., 2022). Regulations and documents establishing the common agricultural policy (CAP) of the European Union (EU Parliament and Council Regulation 1307/2013) define the agricultural area as “any area taken up by arable land, permanent

grassland and permanent pasture, or permanent crops”. The regulation further outlines three key areas:

- arable land: land cultivated for crop production or lying fallow, including set-aside areas under commitments for rural development
- permanent crops: non-rotational crops, other than permanent grassland, that are established for 5 years or more, including short rotation coppice and nurseries
- permanent grassland and permanent pasture: land not included in the crop rotation and used to grow grasses or other herbaceous forage (natural or sown) for 5 years or longer, possibly including grazed trees and/or shrubs that produce animal feed.

This case study focuses on the use of ALS data in arable land and areas currently covered by permanent crops, (henceforth jointly called agricultural land) rather than managed grassland and pasture, recognising that many of the landuse types will have changed over the preceding centuries, for example in the transformation of former arable land to pasture and woodland.

Results of Land Use/Cover Area frame Survey demonstrate that agriculture, in this case as defined by CAP regulations, was the largest land use type by size in the EU in 2018, accounting for 39.1% of the total area with cropland alone representing the second largest land cover type by size and enclosing 24.2% of the total area (European Commission, 2021). On top of that, extensive agricultural lands in Ukraine, Russia, and other non-EU member states make such land type a predominant feature in this part of the world. At the same time, agricultural landscapes differ greatly across European countries (e.g. Meeus et al., 1990) due to many reasons such as geology, geomorphology, soils, climate, local traditions, crop type, and land ownership pattern and history. Such lands range from vineyards and olive groves in the Mediterranean hills to tulip plantations covering the Dutch polders, to vast open crop fields of Eastern Europe, and to soft fruits grown in polytunnels in the British Isles.

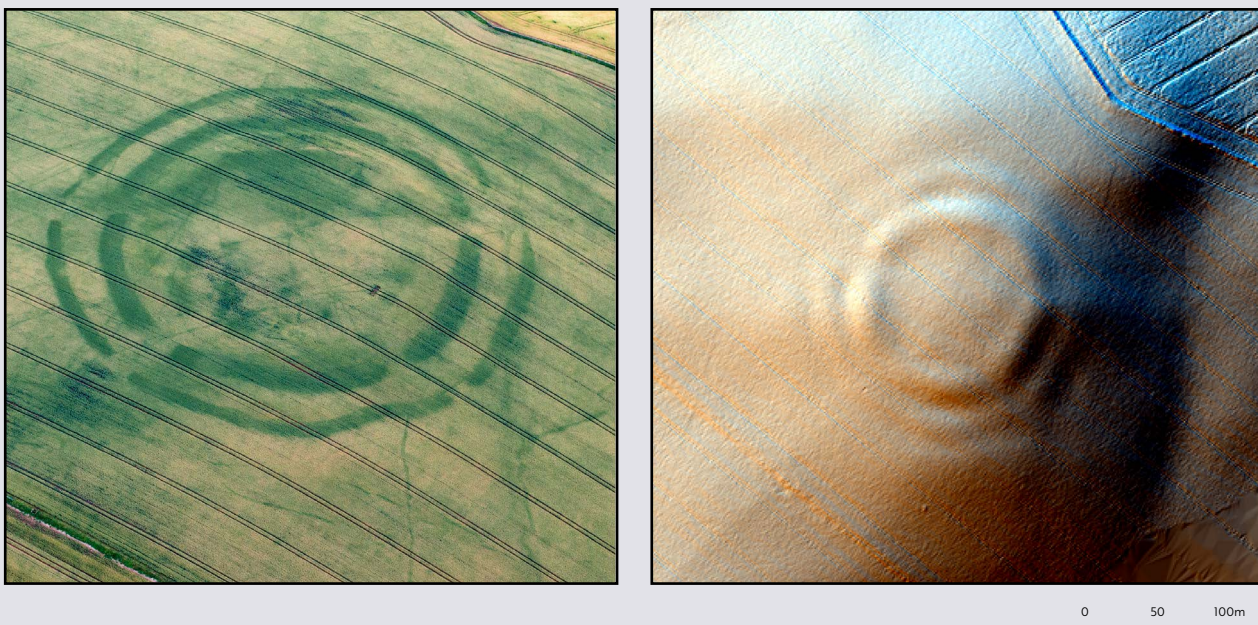
### ALS applications for recording earthworks in agricultural land

Airborne laser scanning has been frequently used to detect and analyse archaeological earthworks and

upstanding monuments in a variety of environments including agricultural land (Dorison et al., 2022; Inomata et al., 2017; Lozić, 2021; Stereńczak et al., 2020). As a rule of thumb, surveys aiming to detect and document such features in non-productive pockets of arable land and in areas with less intensive ploughing, such as orchards and olive groves, can follow procedures applicable to topographic surveys of other environments, including afforested landscapes. Indeed, data collection in leaf-off conditions also mitigates the negative impact of low vegetation on the visibility of archaeological features in ALS derived models (Doneus et al., 2022a).

Contrary to popular belief, denuded sites occasionally survive within cropped fields despite the prevalent practice of intensive ploughing (Banaszek, 2019; Gojda, 2017; Poirier et al., 2013). As a result, ALS holds significant value in the assessment and investigation of agricultural landscapes. In fact, some known sites, initially identified and documented through aerial reconnaissance, exhibit subtle surface expressions that contribute to an enhanced comprehension of cropmark archaeology and improves our understanding of how vegetation indices develop over time and in a variety of weather and climate conditions (Figure 15).

Surveys aiming to document earthworks in cropped fields should time data collection in bare earth or low vegetation conditions to ensure that the surface of the crop is not modelled as terrain. While this risk can be mitigated through the analysis of full waveform data, such data is more challenging to process and is usually only available through specially commissioned ALS surveys (see section 2.1). Full waveform data is rarely available for the archive ALS datasets which are most widely used by archaeologists in Europe. A key issue is that the relief of earthworks surviving in heavily cultivated fields is invariably faint, as upstanding features are reduced in height, smoothed out in form and material from the feature is spread beyond the original feature boundary by ploughing. This means that archaeological features are less well defined than similar remains in landscapes where the ground surface has been less heavily modified. As a result, the identification of ploughed-over earthworks may require different visualisation parameters, such as vertical exaggeration factor, and minimum and maximum radius, from surveys investigating less denuded features (see section 2.2). When studying the ALS-derived models for mixed landscapes it may be necessary to segment the models so that different parameters can be used to create visualisations tailored to the current / recent landuse.



**Figure 15:** The Chesters, Spott, Scotland (Canmore ID: 57792). While the large circular bivalate fort has been recorded on multiple occasions through cropmarking, the faint earthworks, surviving in the heavily cultivated arable landscape, are visible in the ALS data collected on 21 June 2016 (three-directional hillshade). Aerial image: © Crown Copyright: HES, ALS data: Crown copyright Scottish Government, SEPA and Fugro (2020)

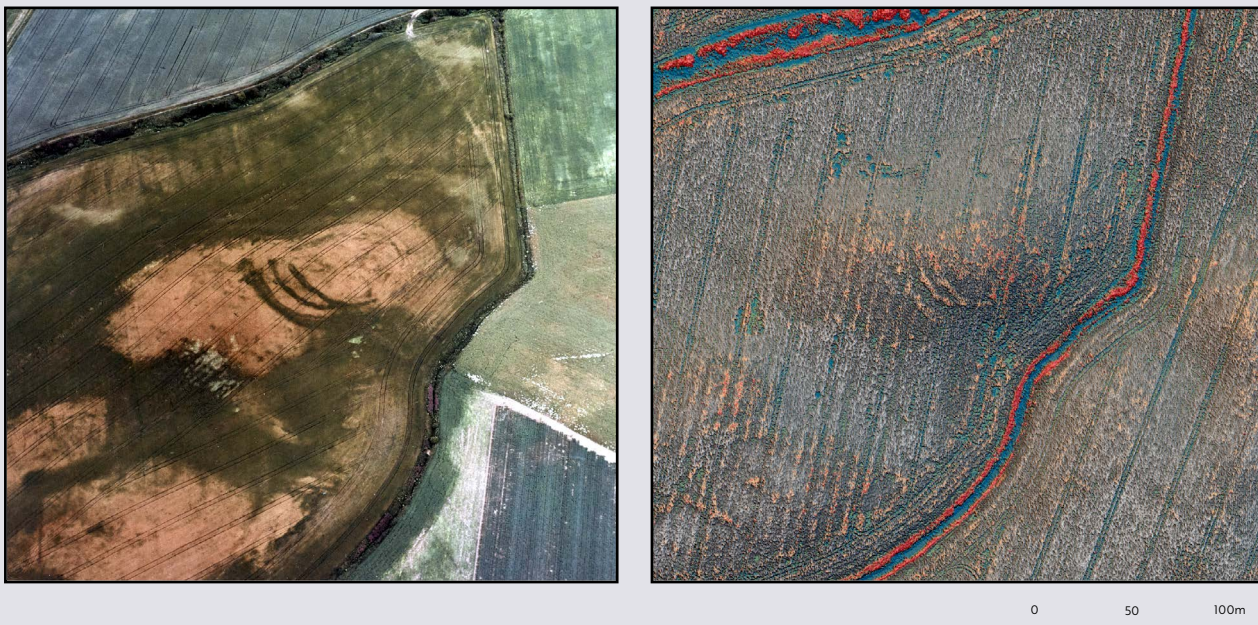
## ALS applications for recording levelled sites

The exploration of ground where levelled sites have no surface expression will likely depend on proxies for buried features such as cropmarks recorded on traditional aerial photographs and multi- and hyperspectral imagery (Agapiou et al., 2012; Czajlik et al., 2021; Evans and Jones, 1977; Gojda and Hejcman, 2012). Indeed, radiometric information gathered as part of the ALS survey may provide proxies for variation in biomass, which indicate how a crop is responding to subsurface variation in soil structure. In addition, ALS data can provide evidence of height variation in crops indicative of subsurface remains (Figure 15).

Radiometric information, often referred to using the umbrella term of intensity, is collected by the scanning system along with geometric and other types of data, (see section 1.2). This information has been proposed to identify various proxies for levelled archaeological sites and analysis of the physical properties and environmental context of landscapes, and early studies were encouraging if not fully fulfilled (Challis, 2006; Challis et al., 2011a; Coren et al., 2005). The routine calibration of radiometric information enhances the results significantly (Challis and Howard, 2013), with

absolute radiometric calibration of full waveform dataset demonstrating major improvement (Briese et al., 2012). The latter requires additional processing steps as well as building on external datasets and in-field measurements, and thus can only be applied for new ALS surveys that have simultaneous acquisition of reference data. In this context, relative radiometric calibration (Sevara et al., 2019) offers wider applications while still delivering improved results and so can be applied in both new data acquisitions and off-the-shelf data. The approach provides the best outputs if the trajectory file generated during the sortie is available (Sevara et al., 2019). Studies building on the relative radiometric calibration of historic ALS data covering large areas, (and thus often collected over multiple sorties) must ensure the scanner wavelength, acquisition times and dates are checked, and in some cases, calibration should be performed separately for each epoch (Sevara et al., 2019).

While the calibrated radiometric data can provide an additional layer of information about the physical properties of the observed features and enhances the visibility of archaeological and paleoenvironmental proxies for levelled sites in ALS derivatives, the date of data acquisition plays a key role in recording such proxies. While cropmark development depends on



**Figure 16:** Nether Drums, Scotland (Canmore ID: 29864). The remains of a small fortification occupying a low hillock show as cropmarks and have been recorded as a difference in crop height in the ALS data collected on 29 July 2020 (simplified relief model superimposed over three-directional hillshade and the visualisation for archaeological topography). Aerial image: © Crown Copyright: HES, ALS data: Crown copyright Scottish Government, SEPA and Fugro (2021)

many factors (Agapiou et al., 2013, 2012), there is a key correlation with crop growth stages. Therefore, it must be stressed that a dedicated survey, undertaken in lowland Austria in late May (Briese et al., 2014) at a time when cropmarks are likely to occur, returned the best results for detecting archaeological proxies in radiometric data amongst the literature referred to in this section. **This does not fit well with the leaf-off conditions that are desirable for most cultural heritage applications of ALS data.** In summary it is possible to detect some archaeological features in ALS intensity data but these detections are rare and inconsistent when compared to the presence of features in topographic data.

The timing of ALS data acquisition is also considered a key factor in surveys investigating multitemporal ALS data for the detection of archaeological vegetation proxies (Stott et al., 2015). The research investigated and compared datasets collected in early spring, i.e. with bare soils or with fields covered with very immature vegetation, and at the peak of vegetation. In this case, the radiometric data was not very informative, however, no calibration method was applied and the analysis built on the peak width, maximum amplitude, and the sum of amplitude extracted from full waveform data (Stott et al., 2015). Instead, the study revealed that differences in canopy height and Leaf Area Index can indicate the presence of levelled archaeological features. Indeed, the use of multitemporal data overcomes the issues associated with the limited dynamic range that characterizes areas covered with low vegetation and thus affects single-date ALS data (Gueguen et al., 2010). As a result, statistical analyses of multitemporal canopy height models indicate the contrast between vegetation overgrowing buried archaeological features and the non-archaeological background. The quality of the results and the absolute values resulting from such analyses differ between case studies and are strongly correlated with local conditions, date of survey, and type of investigated archaeological features, and level of soil disturbance. The issues of absolute and relative accuracy when comparing multispectral ALS surveys should also be considered carefully as many of the observed canopy differences may fall within the margin of error between different ALS-derived models (see section 4.4).

## Conclusions

While most of the available general-purpose ALS datasets in Europe have been collected in leaf-off conditions, the successful use of radiometric information and the analysis of crop canopy height and Leaf Area Index to identify levelled archaeological features in arable land has been limited. Such studies build primarily on bespoke surveys taking advantage of more favourable conditions for the development of cropmarks. As a result, no large area studies set up to record cropmark sites through ALS data have demonstrated whether such methodology translates on to a larger scale. The limited number of studies investigating levelled features through vegetation proxies indicates that the idea of commissioning costly ALS surveys to record such sites in areas successfully covered by traditional aerial reconnaissance is not appealing. However, in areas where a well-established observer-based aerial reconnaissance is producing dwindling returns (Cowley, 2019), ALS might provide additional layer of high-resolution infra-red data collected on a large scale. In fact, limited leaf-on ALS data, collected primarily for non-archaeological purposes, has been released by some countries including Scotland and future studies will likely indicate whether information about levelled archaeological sites can be extracted also from generic surveys on a large scale. Calibrated radiometric information resulting from ALS surveys could improve our understanding of cropmarks and complement local hyperspectral and multispectral surveys (Moriarty et al., 2019).

While ALS has been successfully applied to study remains of agricultural landscapes and historic land use (Affek et al., 2022; Georges-Leroy et al., 2013; Lozić, 2021; McCoy et al., 2011) the recording of archaeological features within the intensively smoothed agricultural land through the interpretation of ALS data is challenging. However the method should be included in a multi-sensor approach to study archaeological landscapes (e.g. Bennett et al., 2013) as it can lead to the discovery of archaeological features, both levelled and surviving earthworks, and provides contextual information for the interpretation of datasets deriving from the application of different archaeological prospection methods.

## 2.2 Visualising ALS Data

Žiga Kokalj, Rebecca Bennett

The potential archaeological information that may be extracted from ALS derived models is highly dependent on the methods used to visualise the elevation models. Understanding the process of visualising ALS models is key to successful implementation and will be explored here, followed by a simple guide for creating visualisations and derivatives for publication.

The skill to process and present quantitative data appropriately is particularly important because many processing methods and visualisation techniques are available as free tools or tool collections. These include a stand-alone version of Relief Visualisation Toolbox (Kokalj et al., 2019) and versions for ArcGIS Pro, QGIS, or a Python library (Kokalj et al., 2022) with QGIS, SAGA GIS, GRASS, and ArcGIS also providing access to at least some visualisation techniques. Testing is useful because different software solutions can give divergent results despite using the same method and small differences in implementation can have a huge impact on the representation of features. There is a danger also that the resulting large number of quite distinct visualisations are likely to confuse or overwhelm the inexperienced user (Kokalj and Somrak, 2019).

### Understanding Visualisations

As visual interpretation is based on observed contrast, this is very often enhanced within a GIS environment via histogram manipulation and scale exaggeration, or artificially introduced as part of the creation of the visualisation. This often has an impact on the scale and shape of the captured features and their representation in visualisations can be misleading (e.g. the bottom of slopes not accurately defined). The informational value of various visualisations varies significantly with respect to the characteristics of structures observed, including size, shape, orientation, concavity or convexity, degree of prominence and edge type.

It is therefore imperative to know how different visualisation techniques work and how best to use them depending on the characteristics of the data, the general morphology of the terrain, and the scale and state of preservation of the features

in question. If a particular technique is chosen for manual interpretation (rather than feature detection) or automatic feature recognition, it is especially important to know what the different visualisation parameters do and how to manipulate them.

It is important to recognise that there is no single perfect visualisation technique, and that fitness for purpose will vary between applications. Thus visualisation methods are often highly complementary and choices can be complex and depend on factors such as the requirement for relative or absolute comparisons.

Nevertheless, a number of techniques, for example local relief model, multiple direction hillshading, openness, and sky-view factor have become widely accepted as core visualisations for use in cultural heritage applications (Table 5). We refer readers to the excellent Airborne Laser Scanning Raster Data Visualization: A Guide to Good Practice for detailed technical information (Ž. Kokalj and Hesse, 2017). Kokalj and Hesse (2017), also give guidance for selection of techniques, their characteristics and optimal calculation settings by feature and terrain type. To briefly summarise, for flat terrain, the rule of thumb is to use a larger filter size and to disregard the inner pixels from the calculation or to use trend removal techniques, such as local relief model or openness.

### **“The computers will do it all” - why take care to visualise ALS data appropriately**

The potential to find traces of past activity using computational approaches such as deep learning is increasingly accepted by the archaeological community (see sections 2.5 and 4.5). The importance of understanding visualisation techniques and assessing their characteristics is important even in light of developments in more automated approaches. The benefits to processing the best possible visualisation for visual inspection can be summarised as follows:

- Deep learning requires a database of a large number of known and verified archaeological sites as learning samples. In the first instance these still have to come from visual interpretation and field observation;
- Large-scale results of deep learning have to be verified and the most straightforward ‘first check’ is visual inspection.
- ALS visualisations may be used for many other purposes alongside automated detection within the same project or landscape. For example during field observations (section 2.7), for public engagement and outreach (section 3.6) or for 3D visualisation (section 4.7). In each of these cases it is important to understand which visualisations are fit for purpose.

### **Progressing from One Visualisation to Many**

Over the years since ALS data were first used for archaeological prospection, there have been many suggested visualisation techniques published and applied, with no single technique proving outstanding to the extent that it could be claimed to be the definitive visualisation for archaeological purposes.

However in practice the number of visualisations that can be used simultaneously is limited and also experience shows diminishing returns will apply to the interrogation of large numbers of visualisations

(especially where similar processes and parameters have been used to create them). This requires careful selection of a limited number of appropriate visualisations for the study at hand, prioritising those that show the majority of features and disregarding those where the return of additional information is limited (unless there are specific questions to be answered).

This section briefly describes the development of a range of visualisations that have proved suitable for identifying micro-topography in the landscape and best practice in their combination as blended images. It also makes explicit the need for detailed metadata to accompany the visualisations to enable replicability.

The techniques shown in Table 5 (local relief model, multiple direction shaded relief, openness, and sky-view factor) have become widely accepted as core visualisations to use for cultural heritage assessments (Kokalj and Hesse, 2017). Appropriate use of any visualisation technique requires an understanding of the processes and parameters used to produce the visualisation from the ALS data.

It has long been recognised that every visualisation has inherent weaknesses that limit its use for archaeological mapping and interpretation (Bennett et al., 2012). For example:

- a single direction shaded relief model only highlights linear features that are perpendicular to the light source.
- Trend removal techniques such as local relief modelling may affect the profile and presentation of particular feature types (e.g. platforms).
- Sky-view modelling under-represents features with positive topography such as mounds.

Standard practice across the cultural heritage sector has evolved and today it is considered good practice to use multiple visualisations, which should be created using different techniques, not just variations on the parameters of a single technique.

### **Combining Visualisations to a Single Image**

Despite understanding that we should use multiple different visualisations to maximise our ability to identify archaeological features in ALS data, there are still advantages to having a single visualisation when undertaking mapping and interpretation (Kokalj and

Somrak, 2019). Combined visualisations have been developed which can provide the advantages of different visualisation techniques, including better representation of features in a larger range of terrain types, while also conserving computing resources, resulting in faster display and reduced disk space requirements. There is a risk that using a combined image might miss potentially important features in the landscape. This risk should be balanced with the risk of limiting project size or slowing its completion due to the time and resource required to use multiple visualisations when working in a larger survey area.

Kokalj and Hesse (2017) provide guidelines on the choice of different 'basic' visualisations, their parameters and application, and Kokalj and Somrak (2019) give detail on blend modes and how they affect the combined layers. Computing visualisations and blending them is straightforward with Relief Visualisation Toolbox (RVT), which is available either as a standalone image processing software (Kokalj et al., 2019), or the `rvt_py` Python library, QGIS RVT plugin, or ArcGIS Pro RVT raster functions (Kokalj et al., 2022).

Though the choices of visualisations are still largely based on intuitive personal preferences, the application of these combined visualisations for detection and interpretation of a variety of topographic forms has been demonstrated in scientific papers. Other combinations are possible and it is easy to create them with the `rvt_py` Python library or, if someone is not familiar with coding, by combining QGIS RVT plugin processing functions in the Model Builder or ArcGIS Pro RVT raster functions in the Function editor. However, care should be taken to ensure that the basis on which resulting visualisations represent topography is understood.

### Combined visualisation for archaeological topography (Combined VAT)

The combined visualisation for archaeological topography (Combined VAT) is an example of a blended visualisation. It is created by blending two combinations of four distinct visualisations: shaded relief, slope, positive openness (Yokoyama et al., 2002) and sky-view factor (SVF) (Zakšek et al., 2011), computed with settings for normal and flat terrain (Kokalj and Somrak, 2019).

It can be used to enhance the visibility of features of a variety of sizes, heights, orientations, and forms. Features can be convex or concave and occur on terrain that ranges from extremely flat to very steep. Besides this, the foremost merits of VAT are that:

- The results are comparable across diverse geographical areas;
- It does not introduce artificial artefacts;
- The location of edges and therefore the visual extent and shape of recorded features are not altered;
- It shows small topographic features in the same way irrespective of their orientation or shape, allowing their height and extent to be judged accurately;

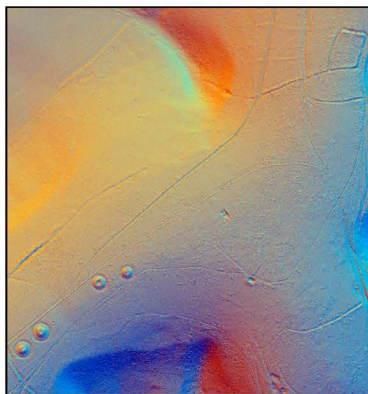
Shaded relief models using three different azimuth directions can be used as a base layer. Colours add information and may appeal to some, but are usually less suitable as a background layer for mapping.

Table 6 gives the details of two alternatives to Combined VAT, enhanced multiscale topographic position (eMSTP) (Guyot et al., 2021) and modified prismatic openness (Verbovšek et al., 2019). While the use of blended visualisations is relatively new, Combined VAT is emerging as a preferred choice for both interpretation and illustration.

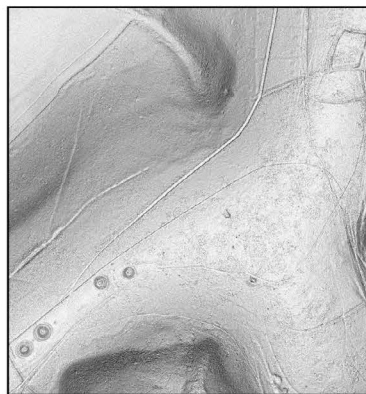
### Multiple scale or multiple visualisations?

Techniques that compute at various scales and either combine the result in a single band or three band image may seem like a solution to the need for multiple visualisations. However, they are less intuitive to read despite enhancing a diverse range of features in the landscape. Techniques of this type include multiscale integral invariants (Mara et al., 2010), multiscale topographic position (Lindsay et al., 2015), multiscale relief model (Orengo and Petrie, 2018), and self-adaptive local relief enhancer (Toumazet et al., 2021). These techniques are more suitable for detection/recognition rather than interpretation and are therefore less favourable than techniques that blend different types of visualisation (such as combined VAT).

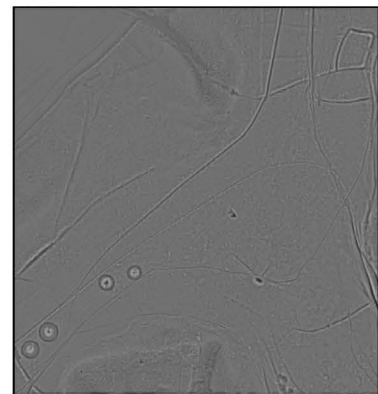
Visualisation Technique	Mandatory Parameters	Optional Parameters	Commonly used to identify Archaeological Topographical Features such as:
hillshade / shaded relief	illumination azimuth	illumination elevation, histogram stretch	burial mounds
slope	histogram stretch		terraces, hollow ways, ridge and furrow
trend removal, local relief model	low pass filter radius	histogram stretch / colour code, type of low pass filter	pits, field boundaries, burial mounds, ridge and furrow
openness	positive/negative, greyscale / inverted greyscale, search radius	number of search directions, histogram stretch	pits, hollow ways, ridge and furrow
sky-view factor	search radius	number of search directions, histogram stretch	pits, field boundaries, terraces, hollow ways, ridge and furrow
local dominance	search radius	observer height, histogram stretch	pits, field boundaries, burial mounds, hollow ways, ridge and furrow



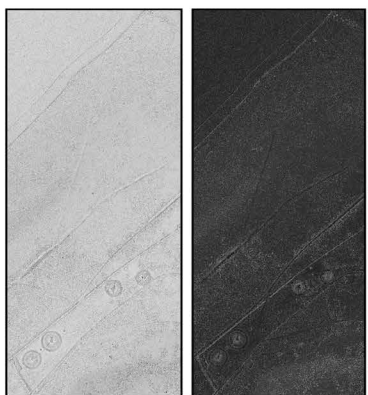
**Multi-directional Hillshade**  
 Angle: 35°  
 Azimuths R=315° G =22.5° B=90°



**Slope**  
 Units: degrees



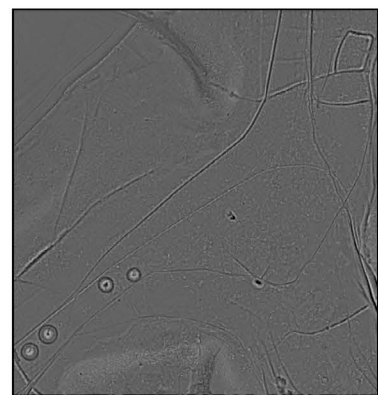
**Simple Local relief model**  
 Radius: 10m



**Openness Positive and Negative**  
 Radius: 10m  
 Directions: 16



**Sky View Factor**  
 Radius: 10m  
 Directions: 16



**Local Dominance**  
 Radius: min=10m, max=20m

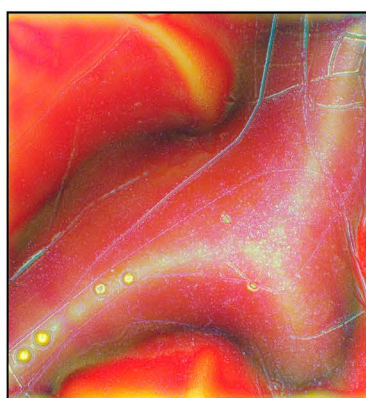
0 250 500 m

**Table 5:** The most common visualisations derived from ALS data (modified from Kokalj and Hesse (2017, p. 35-39) and images to illustrate each one.

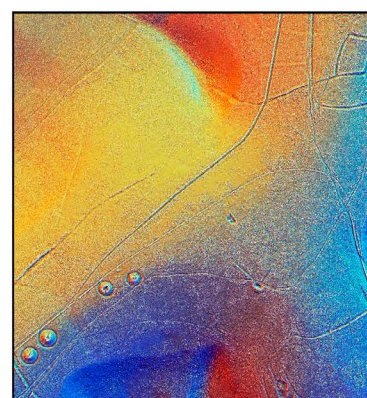
Blended Visualisations	Contributing Visualisations	Settings for General Terrain	Blend (order, opacity, type)
Combined visualisation for archaeological topography (Combined VAT)	sky-view factor positive openness slope shaded relief	5 m radius in 16 directions 5 m radius in 16 directions inverted greyscale colour bar 35° Sun angle, 315° azimuth	3, 25%, multiply 2, 50%, overlay 1, 50%, luminosity 0, base layer
Enhanced multiscale topographic position (eMSTP)	simple local relief model positive openness negative openness slope multiscale topographic position	10 m radius 5 m radius in 16 directions 5 m radius in 16 directions orange-red toned number of  DEVI calculation: 30; micro scale (Blue): 3 to 21 px; meso scale (Green): 23 to 203 px ; macro scale (Red): 223 to 2023 px	2, 25%, screen 1, 70%, softlight  0, base layer
Modified prismatic openness	positive openness negative openness 3 directions shaded relief	10 m radius 5 m radius in 16 directions 5 m radius in 16 directions	2, overlay, 50% 1, overlay, 50% 0, base layer



**Combined Visualisation for Archaeological Topography**



**Enhanced Multiscale Topographic Position (eMSTP)**



**Modified Prismatic Openness**

0 250 500 m

**Table 6:** The most common blended visualisations derived from ALS data (modified from Kokalj and Hesse 2017, p. 35-39).

## Key Information for Visualisation of ALS Data

- Shaded relief modelling, the most commonly used technique for visualising topographic data in the geographic sciences, is particularly poor at representing micro-topographic change relating to past human activity in the landscape.
- A range of visualisations have been tried and found suitable for identification and recording archaeological features (microtopography), but no single visualisation provides the perfect solution.
- The benefits of digitally combining different visualisations into a single image for analysis are typically considered to outweigh the disadvantages. The combinations suggested here can all be considered suitable, and are easy to create using the Relief Visualisation Toolbox (Kokalj et al., 2022). The analyst is still strongly encouraged to familiarise themselves with an understanding of the contributing visualisations.
- Full documentation of the visualisation parameters used is necessary to ensure that the interpretations can be robustly evaluated and re-assessed in the future if necessary.
- Users should remain aware of the risk that the interpreter does not understand the relationships between topographic features on the ground and how these are expressed in different ways in the visualisations. This risk can be mitigated by ensuring that interpreters have knowledge of the study area gained from field visits and that they have compared visualisations with their own field observations for selected remains.

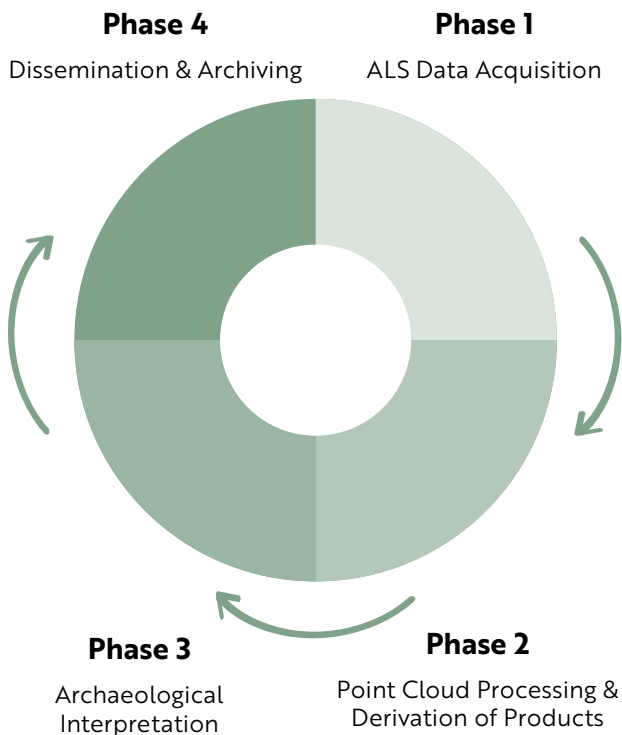
## 2.3 Visual Analysis and Mapping (Vectorisation)

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### Project Management and Approach to Analysis

Once models and visualisations have been created from ALS data, visual analysis can begin. This begins Phase 3 of the process of ALS integration into cultural heritage projects (outlined in Figure 17 below) as it forms the first step of the interpretation process (section 2.4).

### Phases of Integration of Airborne Laser Scanning for Archaeological and Cultural Heritage Management



**Figure 17:** Phase 3 Archaeological Interpretation

Visual analysis is a multi-stage process. The first step is an assessment of the available datasets and mapping (or vectorisation to give the process its geospatial term) of features or areas of interest. The aim of this process is to create digital spatial extents that can be attached to cultural heritage records and is a building

block for producing interpretative maps that reflect the archaeology of the area. While archaeological interpretation is an innate part of the assessment and mapping process, there are specific aspects to the analysis and vectorisation stage that warrant separate and prior consideration for any project using ALS-data. Therefore, this section will focus on the assessment of datasets, technical preparation for mapping, and the process of vectorisation, while section 2.4 discusses the archaeological interpretation and structure of cultural heritage records.

It is essential to begin the digitisation process with an assessment how best to analyse the ALS and other datasets to extract relevant content. The cultural heritage sector has a long history of carrying out archaeological analysis using aerial imagery (Barber, 2011) and this has developed professionally with nationally relevant guidelines available (Evans, 2019). Most of these techniques, especially those relating to the interpretation of extant earthworks, are applicable to ALS-derived data and as section 2.8 illustrates there are many cross-over skills from aerial image interpretation that project managers should look for in their teams.

### Software and Hardware

The analysis of ALS-derived data depends on the software and hardware available to a user. Although some products such as geotiffs can be accessed with simple image viewers, ALS-derived data should be managed within a GIS to allow for comparison to complementary datasets, manipulation of the imagery and the digitisation and management of records. Although users may only have access to ALS-derived visualisations which have been created by others (see sections 1.4 and 2.1), these should be supplied as georeferenced files. When using ALS-derived data in a GIS it will be possible to interrogate them with tools to extract additional information, for example extracting cross-sectional profiles for features of interest. While viewing ALS-derived visualisations is possible without a GIS, the **use of GIS software adds significantly to the analysis and interpretation and should be considered best practice**, to do otherwise is a significant compromise on the process and value of the results.

Hardware is also a significant consideration when using ALS-derived data. The storage of ALS-derived data and visualisations from projects with a large geospatial extent can run to many hundreds of GB of data. Organisations will need to be able to store these data in such a way that they are accessible and usable, and provide adequate desktop processing power to run the GIS software and perform any additional analysis required.

### Sampling

It is not always possible, or necessary for the project's aims, to examine entire geographical areas at the same level of detail. With the increasing availability of data via national ALS programmes and repeat surveying increases the need to consider strategies to sample the landscape at different scales (e.g. Orton, 2000). It becomes important to manage human and storage resources, and to carefully consider how vectorisation addresses the research questions of the project. In this situation it may be best to develop a sampling strategy whereby you can examine a specified percentage of the entire area, for example, and extrapolate results more widely (Cowley et al., 2020).

Such an approach to sampling can be applied at national scales to inform heritage management in which potentially representative small areas are surveyed to illustrate patterns of archaeological remains that are common to larger areas (e.g. Banaszek et al., 2018). Equally, it is sensible to consider how very generalised mapping of archaeological remains (e.g. as polygons defining extents) and more detailed vectorisation of individual features contribute to project aims in a multi-scale approach to understanding landscapes (e.g. Cowley et al., 2020). 'Scale' becomes a key consideration here, a factor that is often forgotten when working in GIS software where zooming in and out is simple, and conceptions of fixed scales, as are routine with paper maps, are easily forgotten. Nevertheless, scale remains important as it informs the level of detail that is vectorised, and relates to the extent to which detail may be visible in source data (see Cowley and Stichelbaut, 2012, 230 for a discussion of this issue with reference to aerial photographs).

Large areas can often be most effectively analysed in teams with several members, dividing the work between them. However, this can lead to issues

of consistency (Cowley, 2016). The best way to get around this is to have regular cross checking between team members and, if possible, external quality assessment (see section 2.8 for more a more detailed discussion of quality assurance). While this collaborative way of working may take time for some team members to adjust to, interpersonal variability in interpretation and vectorisation can be significant (Banaszek et al., 2018) and may have a direct impact on the reliability of outputs.

### Terminology: The meaning of Scale

There is a common misuse of the phrases "small scale" and "large scale" in the cultural heritage sector to refer to the extent of investigations e.g. "small scale" for small local areas of investigation and "large scale" for landscape-wide studies respectively.

However, from a geographic and geospatial data perspective, this common use is incorrect as when referring to maps large and small scale have the opposite meaning e.g.

Large scale maps show a smaller amount of area with a greater amount of detail. Thus, a map with a large-scale would have a small ratio of map units to real world units e.g. 1:100

Small scale maps show a larger geographic area with few details on them.

For example a map with a small-scale would have a large ratio of map units to real world units e.g. 1:1,000,000

To avoid confusion we will use the terms localised and landscape to refer to the geographical extent of an intervention or area of interest rather than small and large.

## Getting the right datasets

The initial step of analysis of ALS-derived data is the collation of the relevant datasets in a GIS environment. Alongside ALS-derived models and visualisations, these data will also comprise a range of other resources at a variety of scales. Complementary data such as aerial photographs, historic mapping and satellite imagery are key to good analysis of ALS-derived data and therefore resource needs to be allocated at the analysis stage to identify and integrate them into the project. Depending on the location and purpose of the project, different input data are available and it is good practice to give full consideration to incorporating data that will improve analysis.

## Elevation Data

Coarse elevation data such as those from the Shuttle Radar Topography Mission (SRTM) cover large areas, are free of charge and are easy to use but are of low spatial resolution (c.30m). These can be complemented by higher-resolution data including elevation models derived from measurements or photogrammetry (for example Ordnance Survey 5m Digital Terrain and Contour Model) and of course ALS derived models. Higher resolution data make detailed analysis of the landscape possible, but they may be expensive to purchase and may require greater technical skill and computational resources.

The scope of the project and level of technical competence of the team are key considerations when choosing suitable visualisations for the elevation data. Common and intuitive visualisations such as colour coding by elevation, allow users to understand the macro relief (large changes in topography across a landscape). They are suitable for regional projects or very flat landscapes, e.g. floodplain analysis, and also provide landscape context to sites and their surroundings. However, micro relief, the small topographic changes that represent traces of past human interaction with the landscape, will not generally be visible in such data. As detailed in section 2.1, the visibility of micro-relief needs to be extracted or emphasised, which can be done by creating specialist visualisations (see sections 2.2 and 3.2). Best practice is therefore to consider the unique terrain and the expected archaeological features of each investigation area and to combine data and visualisations appropriately. If automated detection is to be included,

it should be kept in mind that computers benefit from high (visual or numerical) contrasts (section 2.5).

## Complementary Data

Complementary datasets provide important additional information allowing the analyst to cross-check interpretations, to develop an understanding of the contemporary landscape as well as the archaeological features present and thus reduce the number of erroneous identifications. These sources can also be used to gather a range of additional information about an area under analysis including changes in land use and environment, as well as the presence or absence of related topographic or proxy features (i.e. soil or vegetation marks).

Complementary sources of data could include:

- modern and historic maps at different scales
- remote sensing data (satellite imagery, aerial oblique photographs and orthophotos)
- local, regional and national archaeological records and cultural heritage catalogues
- geophysical prospection data
- reports from archaeological evaluation and excavation projects undertaken in advance of construction
- and other relevant research, scientific or academic publication or project

Context is particularly important to understand the form, origin and possible function of features. For example, a mound, defined as an upstanding domed or coned feature with a circular footprint, could either be natural, archaeological or modern in origin. By examining the context of the feature in other sources we may more clearly identify the type of mound and its cultural heritage significance.

- Single mounds surrounded by streets are usually roundabouts.
- Mounds in forests that have not been exposed to activities such as ploughing that reduce or remove upstanding topography may be ancient and therefore archaeologically relevant.
- Groups of geometrically perfect mounds in a modern agricultural landscape are most likely foundations for windmills rather than undiscovered burials.



### Mound feature

**Figure 18:** Complementary dataset such as aerial imagery, modern and historic maps support interpretation and provide context ALS data © Environment Agency copyright and/or database right 2022, aerial image ©2024 Maxar technologies, historic map © National Library of Scotland

Besides evaluating single classifications, comparative datasets also allow a strategic reduction of the area of investigation (Meyer-Heß, 2020; Verschoof-van der Vaart et al., 2020). For example, national or regional mapping of contemporary land use will help the observer to understand how archaeological remains may present in the landscape (e.g. as cropmarks in arable areas or as topographic features in rough uncultivated ground).

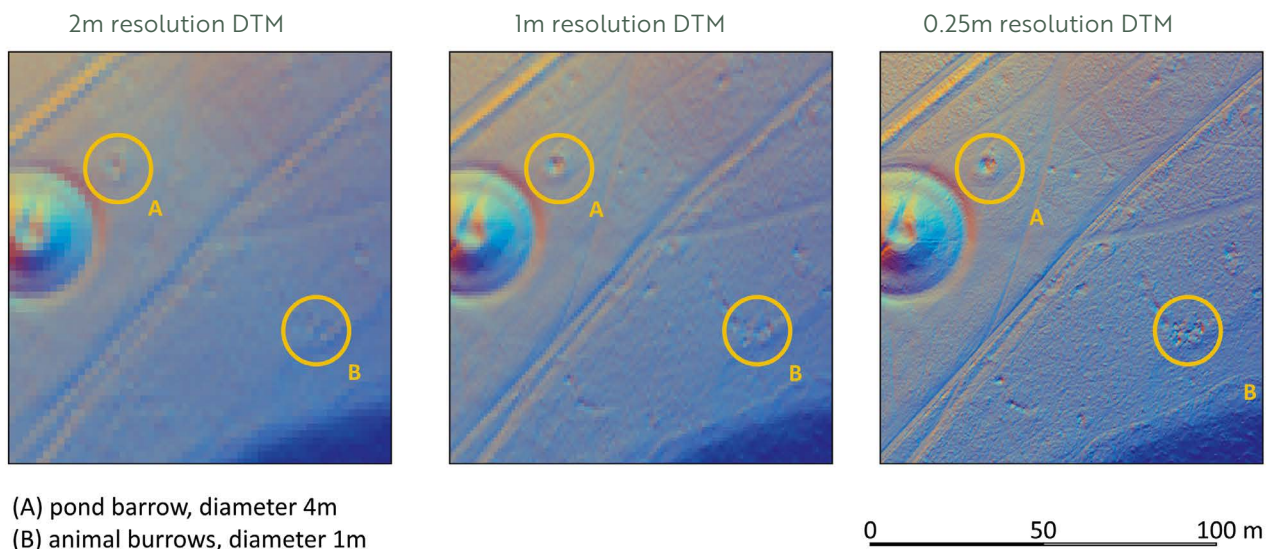
### Vectorisation Process

Vectorisation is the process of converting the content of images of ALS-derived data, which consist of cells or pixels, into a series of vector shapes, including points, lines, and polygons. The vectors give a digital spatial representation to a feature of interest allowing for its inclusion in a geospatial database for further analysis. The process of vectorisation is essential for effectively and unambiguously capturing observed information in the image and conveying it to future users. It is an invaluable step in the analysis of ALS data for purposes such as landscape modelling, heritage management, and archaeological research.

The approach to vectorisation is heavily influenced by the research questions of the project. These questions determine the approach and necessary balance of expediency and detail that is best summarised as a finding the correct balance between precision, accuracy, representation and scale.

**Precision** refers to the level of detail and exactness in capturing and representing features, which involves accurately delineating their spatial attributes in the ALS-derived data. **Accuracy** relates to how closely the vectorised elements align with the true locations and extent of the features. It indicates the degree of correctness in their spatial positioning and attribute representation.

**Representation** refers to the choice of geometric form (point, line, or polygon) and encoding the relevant attributes to represent features in the vectorised data. The analyst must select the most appropriate representation that effectively captures and communicates the desired information for a feature. Finally, scale refers to the relative size of the features captured in the ALS-data and their subsequent depiction as vectors. It involves considering the appropriate level of detail and resolution for the specific research objectives, taking account of factors such as the desired level of generalisation or simplification and the comprehensiveness of the final geospatial entities. Analysts should be careful not to zoom so far into an image that they are unsure of the context and form of the features they are vectorising – and end up vectorising random groups of pixels rather than archaeological features. When evaluating what is an appropriate scale, it is also important to consider that the real world dimensions of the features should be at least **three times larger** than the resolution of the data in any single direction to provide certainty that the feature could be captured in the data and is not a rogue pixel or artefact.



**Figure 19:** Figure illustrating the impact of resolution on the interpretation features of different scales. The 4m pond barrow can be defined from the 1m data whereas the 1m animal burrows are only better interpreted from the 0.25m data (ALS data © South Downs National Park Authority)

### Further Guidance of Vectorisation

With respect to more detailed guidance on the topic of digitisation, the availability of geospatial standards and guidance varies between countries, however Historic Environment Scotland has an accessible and well-established set of Standards for polygonization, specifically for site areas which can be viewed as a good example (Middleton, 2010)

### Approaching the vectorisation process

Deciding on the level of detail that is required is a vital first step. For example, if we want to digitise a cluster of cairns into a representative vector, we could choose to create

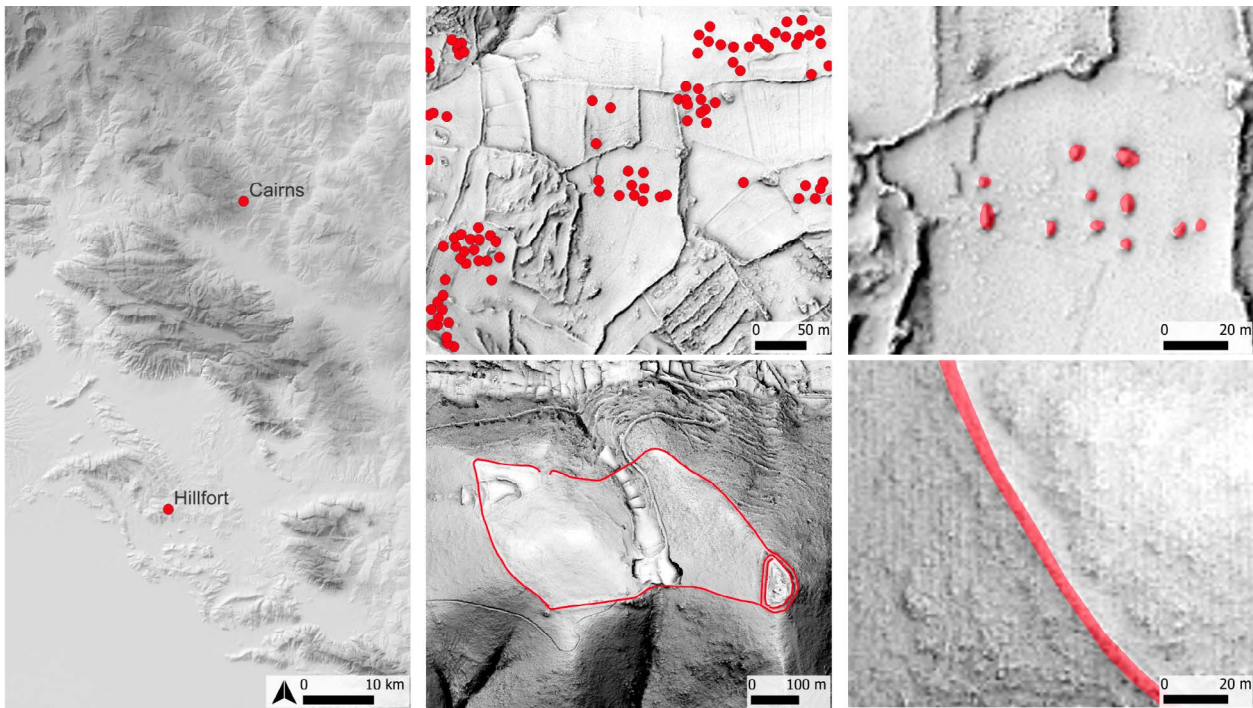
- (a) a single central point indicating their location
- (b) a buffered polygon taking in all the observed features
- (c) a polygon for each individual cairn.

The first approach (a) would be appropriate for a rapid assessment where a general location is sufficient for the purpose of the work. Approach (b) provides additional information about the context surrounding the site, but it also significantly increases the time required for vectorisation without adding new data

on the individual cairns. The third approach (c) gives significantly more detail for each cairn but is time-consuming. Depending on the project objectives, such level of detail about this particular feature type may not be necessary.

Figure 20 illustrates the different approaches for vectorisation at various scales. Each of these choices carries with it implications for a different scale and level of precision in digitising the data, which, in turn, influences how we can use the geospatial entities in further analysis and presentation. Digitising each cairn with a polygon allows for a more detailed understanding of their spatial attributes, facilitating the calculation of areas and volumes for each mound for example. However, this method would not be very effective if study of the spatial clustering of cairn sites across a site or landscape is required. In contrast, using points to represent them simplifies the digitisation process and allows for easier analysis at the site level. However, this approach would over-represent the individual cairns in a landscape-scale analysis, where representing the entire group of cairns as a single point may be more appropriate.

This simple example highlights the importance of considering these factors and having a clear understanding of the research objectives before initiating the digitisation process. Doing so ensures that the chosen approach aligns with the desired outcomes and optimises the use of time and resources.



**Figure 20:** Different approaches to vectorisation of stone cairns and hillforts at various scales. ALS data from Italian Ministry of the Environment, reprocessed and visualised using VAT (see Fontana, 2022)

Figure 20 illustrates different approaches to vectorisation based on scale, progressing from regional to local. In the first column the concentration of cairns and the hillfort are both vectorised as a single point. In the middle column individual cairns are vectorised as points, and fortifications are represented as lines. In the third column the individual cairns are depicted as polygons, and fortification walls are represented as polygons in the bottom row.

It is important to standardise and document the approach taken to vectorisation in any project. An example of levels of recording as applied by Historic Environment Scotland is given below (Table

7 after Cowley et al., 2020) which could be used to help indicate the detail and scale required of the vectorisation process.

If multiple approaches to vectorisation are to be taken, and particularly if multiple people are working on the project simultaneously, it is important to have an agreed vectorisation **schema** (a plan or diagram detailing structure of the data and how it is to be organised) for consistency. Figure 21 gives an example schema for vectorisation based on the form of the feature from Historic England based on Aerial Investigation and Mapping Technical Specification.

## 2.3 VISUAL ANALYSIS AND MAPPING (VECTORISATION)

Level of Survey	Scale	Map Accuracy	Outputs
1: Landscape Characterisation	1:25,000	± c.25m	<ul style="list-style-type: none"> <li>Location polygons</li> <li>Classification</li> <li>Period</li> </ul>
2: Core Information for National Record of the Historic Environment	1:10,000	± c.10m	As level 1, plus: <ul style="list-style-type: none"> <li>Project event (description of why and how a project was undertaken, including statement of methodology and accuracy)</li> </ul>
3: Basic Record	1:10,000 1:2500	± c.10m ± c.1m	As level 1 and 2, plus: <ul style="list-style-type: none"> <li>Recording Event (description of how a record was created, including source data and personnel / organisation)</li> <li>Brief written description</li> <li>Survey at scale that indicated moment or landscape form</li> </ul>
4: Detailed Record	1:2500 1:1000 or larger	± c.1m	As level 1, 2 and 3, plus: <ul style="list-style-type: none"> <li>Detailed analysis and interpretation</li> <li>Survey at a scale suitable to depict the character and complexity of the monument</li> <li>Photographic record as appropriate</li> </ul>

**Table 7:** Summary of Historic Environment Scotland levels of survey with a generalised indication of the suitability for area coverage and resource requirements. In simple terms, the resource requirement by area covered increases from Level 1 to Level 4 (Cowley et al., 2020)

Form of Feature	Type of Digitisation	Use Cases	Accessible HEX Colour	Opacity	Line Style	Example
Structure	Polygon	Use to outline structures including stone, concrete, metal and timber constructions	F46D43	20%	solid	
Bank	Polygon	Use to outline banks, platforms, mounds and spoil heaps.	A50026	25%	solid	
Ditch	Polygon	Use to outline cut features such as ditches, ponds, pits or hollow ways.	313695	25%	solid	
Feature Extent	Polygon	Use to depict the extent of large area features such as airfields, military camps, or major extraction/deposition.	FDAE61	90%	dot dash	
Ridge and Furrow (area)	Polygon	Use to outline a block of ridge and furrow.	74ADD1	90%	dot	
Ridge and Furrow Direction	Line	Line depicting the direction of the rigs in a block of ridge and furrow.	74ADD1	0%	solid	
Slope Edge	Line	Use to depict scarps, edges of platforms and other large earthworks.	4575B4	0%	solid	

**Figure 21:** An example schema for vectorisation at the scale of 1:1000 or larger based on the form of the feature from Historic England based on Aerial Investigation and Mapping Technical Specification (adapted from Historic England research report 16/2023 Carpenter et al., 2023)

### Core metadata and paradata for vectorised features

A key aim of vectorisation is to communicate one analyst's evaluation and interpretation of the data to others. To ensure that each vectorised feature is comprehensible to other researchers, a formal and comprehensive metadata description is necessary (see also sections 3.4 and 3.5). The aim of this "data about the data" is to provide information about the identified feature and its definition, allowing the record and interpretation to be understood and reviewed.

Conveying the analyst's understanding of the vectorisation process via the metadata is significant to the outcomes of the project. This understanding informs future interpretation and also the spatial representation and reuse of the feature within a GIS, providing future users with the means to assess the character of the outputs.

The basic analytical metadata encompasses the following components:

- **PID, a persistent identifier** of the project or collection
- **Feature identifier** (ideally also a persistent identifier, but based on specific needs this can also be a local identifier (ID) linked to the PID of the dataset)
- Distinction between natural and man-made features
- Distinction between features of archaeological origin and recent features
- **Description of the morphological character of the features** (convex/concave/uneven/flat terrain)
- **Expression of the visibility** of feature in the data
- **Expression of the reliability** of feature identification
- **Expression of the accuracy** of the spatial definition of the feature

In addition, the feature description should include paradata, i.e., data of a procedural nature that gives information about the processing of the data and the actors involved. At minimum, it should include:

- Reference to the **data source** (may be described on the project level, if it is the same for all data, but should include date of capture and resolution)
- **Scale** at which the vectorisation was made, e.g. 1:1500
- Date of vectorisation
- **Data on the analyst** (e.g. ORCID)
- **State of processing**, e.g. distinction between work-in-progress and validated / finalised data

## 2.4 Archaeological Interpretation

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### Introduction

This section focuses on the archaeological interpretation of features identified from ALS-derived data. Archaeological interpretation requires the assignment of features to a particular class or type of archaeological remains based on the interpreter's best understanding of the past activities that these physical features represent. Such interpretation requires careful consideration of the landscape processes, past and contemporary, that have influenced the appearance of the features e.g. ploughing, sediment accretion or erosion (Mlekuz, 2013).

Without meaningful data and interpretations nested behind them, vectors digitised on a map will remain just shapes without sense. By adding an interpretation to a vectorised feature, we can explore our process of understanding the landscape and data, add clarity to our decision making processes and give meaning to elements of the past landscape.

While it may seem that feature interpretation is an obvious end-point of the use of ALS in cultural heritage management, it is important to remember that ongoing process of interpretation is both complex and iterative. Observations and interpretation made from study of the digital models and visualisations is often the first interpretation of a feature, and depending on resource, may remain as the only interpretation. Interpretation is a repeatable process that can be conducted for various purposes and from diverse perspectives (Opitz and Cowley, 2013). Interpreters should ensure that the feature data is recorded in a systematic way so that it can be revisited, reviewed and added to given additional time and resource (Banaszek et al., 2018). Attention should be always paid to the integration of standardised vocabularies and thesauri where these exist to facilitate data interoperability. Measures of confidence can assist in understanding and re-interpreting the features and the confidence of interpretation can often be improved if there is scope for the integration of field observations into the interpretations (see section 2.7).

Key to useful archaeological interpretation is the experience of the personnel (section 2.8) involved who should ideally have both a clear understanding of ALS data and derived products and of the landscape and cultural heritage of the area in which they are working (Opitz and Cowley, 2013). Each interpreter brings their own experiences to bear and thus beyond description of the physical nature of a feature, the process is both individual and subjective. This means that collaborative working practices, where interpretations can be discussed and cross-checked within a team, produces more useful systematic and holistic results in which greater confidence can be placed than a single interpreter working alone (Cowley et al., 2020). Where interpreters are working in isolation, peer review of mapping and interpretations is strongly encouraged through engagement with wider specialist networks such as the Aerial Archaeology Research Group.

### Observation: Brain-eye System Biases

The human brain-eye system is designed to observe and process information quickly and accurately and to identify patterns within it. Therefore, the steps of interpretation can be hard to pinpoint as the viewer reads the landscape for relevant features of many shapes, forms, textures and sizes while also comparing to their internal catalogue of known information on feature forms, types, land use and taphonomy. However an attempt to break these "natural" steps down into a process is helpful, not only to inform the training of new interpreters, but also to help established interpreters reflect on their own practice to identify and address biases and partiality in their work.

It is also key to note that the human eye actively and subconsciously scans a scene presented by the ALS data, flitting around and focussing most time on recognisable features. This means that to view and interpret the whole scene equitably, the observer must make a conscious effort to look at every part, a process that is often aided by the application of a grid to the scene (Kokalj and Hesse, 2017).

None-the-less, experiments in eye-tracking demonstrate that it is difficult for human to assess an entire scene systematically (e.g. Michalik, 2014).

The bias towards identifying features that are familiar to us has also been noted, most clearly in the tendency to “close the gap” i.e. to map a feature as a closed form when in fact it is incomplete or to group features based on similarity to a known form (Kokalj and Hesse, 2017). The in-built functionality of the human brain-eye system cannot be completely over-ruled but with understanding of how this might affect the task of interpretation the observer can aspire to achieve greater consistency.

### Interpretation as an Iterative Process

Typically, interpretation starts with **physical observations first**: what is the size, form and topographic presentation of the feature? Then the question of origin comes into play. Starting with a binary question of whether a feature is **likely to be natural or human in origin**, then moving onto the layers of archaeological interpretation that are underpinned by **analogy to similar examples and understanding of how the traces of past human interactions with the landscape are typically observed**. Experience in aerial photograph and archaeological landscape interpretation are valuable skillsets in this regard.

Interpreters should keep in mind “false friends”, natural and modern anthropogenic features that may resemble forms commonly associated with archaeological features (Crutchley, 2018, pp. 47–48). There are two elements that can be incorporated into the process of interpretation that will help to increase the confidence of feature interpretations. The first is full consideration of the topographic form for a feature. This can be achieved through review of different representations of the feature using several visualisations (see 2.1 and 3.2) and by extracting profiles of the feature from the DTM model.

The second is by incorporating thorough assessment of a variety of supporting data such as modern and historic aerial photographs, cartographic sources and existing heritage records, along with integration of field observations if possible (Doneus et al., 2022b)

These data will enrich the detail that can be given to the interpretative text for any features and provide additional sources for future observers to reference.

### What to record

A key attribute of an interpretative record of observed features and groups of features, is the **descriptive text** giving the detail of and the reasoning for the interpretation - **“What did you observe from the data that led you to this interpretation?”**. The coherence of the description matters to ensure that future users of the data have confidence in the interpretations and text should be structured in a consistent way and clearly expressed to be easily understood by others. Text should be of an appropriate length to the level of survey (too much detail can be confusing, but equally important information must be conveyed) and contain due acknowledgment to relevant sources.

It may be beneficial to first outline the descriptive evidence, (i.e. describing morphology, size, shape or form of the site) and progress from general overview to detail. Describing any morphological, spatial or stratigraphic relationships between archaeological features may strengthen period or date interpretations. Discussion of the topographic setting or background geology may lead you to suggest a site type, for example in areas of mineral extraction where the local geology allows you to pinpoint the type of mine. Where supplementary sources, such as historic mapping, have assisted your interpretation including that information is important. Reference to similar, previously dated and interpreted features will help clarify aspects of the interpretative process, and a good description will clearly express ambiguity in both evidence and interpretation.

It is good practice to ensure that feature records are created with reference to controlled vocabularies, for example archaeological feature types and chronological period. This is especially important for the data to be useful in making comparisons with other areas, and will make it easier to assimilate outcomes in national or regional historic environment records. In creating feature records, it should be noted that these will benefit from elements of the description being recorded as separate fields, as this allows for easier access, analysis and amendment of these categories, ensuring greater reusability of the data.

Attribute	Description	Sample Feature Data
Feature PID	Historic England Research Record Unique Identifier (UID)	79060
Existing Cultural Heritage Record Number	Number for those features concorded with existing local, regional or national records	MHU1513
Description	Free text containing observations and interpretation	Surviving earthworks of moats and fishponds can be seen on the ALS data. a triangular enclosure contains, on its northern side, three interlinked rectilinear fishponds. these lie parallel to the main enclosing moat and are linked to it, each other, and adjacent drainage ditches by well-preserved sluice channels. the westernmost pond measures 24m by 9m and is 1m deep; the middle pond is slightly smaller and measures 27m by 10m by 1m deep; the easternmost pond measures 27m by 7m wide and is 0.75m deep. These ponds would have been used to rear fish which formed an important element of the medieval monks' diet.
Period	Date of feature (controlled vocabulary from HE Thesaurus). Single or dual indexed terms	Medieval
Narrow Type	Monument Type (controlled vocabulary HE Thesaurus). Specific monument type for individual features	Fishpond
Broad Type	Monument Type (controlled vocabulary HE Thesaurus). Broader monument type to enable grouping of individual features	Cistercian monastery
Evidence 1	Form of remains (controlled vocabulary HE Thesaurus) as seen on PHOTO 1	Earthwork
Photo 1	Source feature was mapped from (aerial photograph or ALS)	Environment Agency ALS data 2021 1m
Evidence 2	Form of remains (HE Thesaurus) as seen on PHOTO 2	Levelled earthwork
Photo 2	Latest available source (aerial photograph or ALS) to give indication of current state of preservation. Not applicable for cropmark sites	NMR 28225/36 19-oct-2011

**Figure 22:** An example feature record adapted from Historic England research report 16/2023 (Carpenter et al., 2023)

## Controlled Vocabularies

The feature data recorded for attributes such as feature type should use **established archaeological/cultural heritage controlled vocabularies** specific to your nation, region or institution. Examples of these vocabularies include the [PACTOLS Thesaurus](#) in France, or [TEATER](#) in the Czech Republic and the and the UK Linked Data Vocabularies for Cultural Heritage.

Best practice is to use a thesaurus that is FAIR compliant, allowing humans or computers to **Find, Access, Interoperate and Reuse** the terms themselves (Wilkinson et al., 2016). To be FAIR compliant, the controlled vocabulary used to describe datasets needs to be documented and resolvable using globally unique and persistent identifiers.<sup>6</sup>

In some cases, users may not have access to a national or region specific controlled vocabulary. In these cases, they may wish to consider using the [Getty Art and Architecture Thesaurus](#) (AAT). The [AriadnePlus](#) project has successfully used the AAT to map conceptual subjects from multilingual domain vocabularies to allow cross searching. The Getty AAT is FAIR compliant and provides at least broad terminologies to describe most forms of monuments or resources encountered in airborne lidar surveys.

## Interpretation and Scale

One crucial consideration is the chosen scale for interpretation. The outcome of interpretation varies considerably depending on whether the focus is on individual features and their morphological parameters (e.g., the precise shape of mining pits or the internal structure of ruined buildings) or on the identification of more complex units, such as groups of features (e.g., individual farmsteads) or entire activity areas (e.g., hillforts, barrow grounds, mining fields). The digital outcomes and feature records will be determined by the choices made at a project management level, so the chosen scale of interpretation must be explicitly defined and consistently applied within the methodology. Additionally, the scales of vectorisation and interpretation must be explicit in the associated paradata and project reporting.

While interpretation at multiple scales is permissible, users must work with distinct geospatial layers and

establish feature hierarchies to ensure the usability of the resulting dataset. Furthermore, it is crucial to effectively distinguish and describe evidence of sequence in the archaeological remains (for example, the superimposition of one field system over a more ancient one). The ability to record such sequence is determined during the process of creating vectors for the features, where it is advisable to digitise overlapping features separately and handle their sequencing through metadata relations or by grouping them into higher-order features (Doneus et al., 2022b; Johnson and Ouimet, 2018; Vletter and Schloen, 2017).

## Core Metadata and Paradata for Interpretation

As with the process of vectorisation, the interpretation should generate attributes that document the feature record for subsequent analysis and ensure the data can be understood and used by others. These may take the form of supplementary attributes appended to a digital feature set or included in a distinct interpretive geospatial database linked to the relevant vectors via a PID.

Given the complexity of many archaeological landscapes, it is likely that a number of parent-child relationships in the record structure will be required. For example, a single feature may require multiple types or dates to be recorded in addition to the PIDs of multiple related features. These relationships need to be managed by many to one structures within the data schema. Metadata schemas and controlled vocabularies should be applied to recorded attributes throughout the interpretation in accordance with local, national and international standards (see sections 3.3, 3.4 and 3.5)

It is best practice to ensure that the following core interpretation metadata attributes are always included in addition to those detailed in section 2.3:

- **Archaeological interpretation** of the feature origin (e.g. burial mound, mining pit, fortification, etc.)
- **Type of activity area or broader classification of site type** that the feature is part (settlement, cemetery, castle, etc.)

<sup>6</sup> For example <http://ark.frantqi.fr/ark:/26678/pctrtjt6t6tah9> or [http://purl.org/heritagedata/schemes/eh\\_tmt2/concepts/70407](http://purl.org/heritagedata/schemes/eh_tmt2/concepts/70407)

- **Chronological classification**
- **Crossreferences / PID links** to features that are linked to the record in a parent or child relationship (e.g. feature to complex; complex to site, etc.)
- Expression of the **reliability** of interpretation or the confidence that the observer places in their interpretation. This measure is often represented by a Likert point scale, such as in Table 8 and is of course subjective.

1	Strongly Not Confident
2	Not Confident
3	Neutral
4	Confident
5	Strongly Confident

**Table 8:** Example Likert Confidence Scale

The paradata should include:

- Reference to the **data sources** consulted for the interpretation (including supplementary data used during interpretation)
- **Scale** at which the interpretation was made, e.g. 1:1500
- **Date of interpretation**
- **Data on the interpreter** (e.g. ORCID)

These latter three elements of scale, date and identification may not be needed if the process of vectorisation and interpretation are contiguous and they are therefore duplicate entries of the paradata recommended in section 2.3. However, care should always be given to a schema that allows the paradata relating to later revisions to the interpretation to be recorded.

## Symbology and Presentation

### – Bringing vectorisation and Interpretation together

When considering how the interpretation of features from ALS-data can best be communicated to professional and wider audiences, the use of a standardised visual schema is recommended to ensure visual coherence of the vectorised data. The use of a colour palette designed to be accessible by those with visual impairment is good practice, especially where the feature data or illustrations will be shared with the general public.

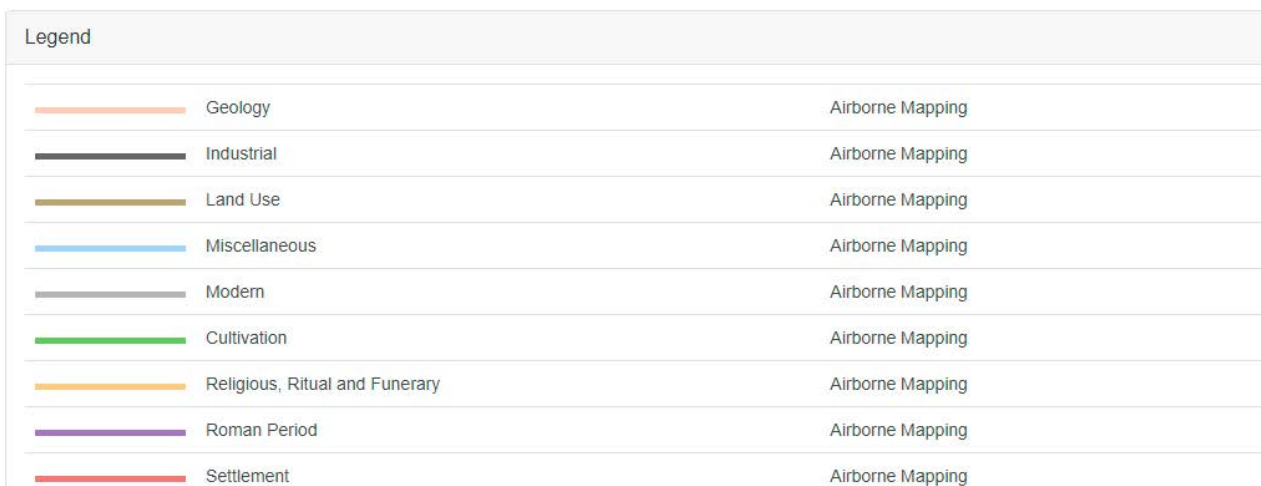
One approach is to use consistent symbology or style for the individual form of the features making up a monument e.g. the feature is banked/convex or ditched/concave or a structure (see Figure 23 and Figure 24). This reflects the topographic presentation of the feature, (the first step of the interpretation and that which is least likely to change) and can sometimes reflect the limit of our understanding of the feature if no specific archaeological interpretation is possible. Some schematic conventions may be required where mapping the features more accurately is challenging, for example the use of a pecked line where a feature is poorly defined. Extensive archaeological monuments which would otherwise mask underlying features may be best visualised as an unfilled polygon outlining the extents but not obscuring the area enclosed. Examples of where this approach would be valuable include areas of quarrying / mineral extraction, large-scale military remains such as airfields, or contiguous blocks of ridge and furrow. Other common presentation approaches include thematic symbology based on recorded feature attributes, for example producing a phased diagram based on period or by broad feature class e.g. industrial, funerary, settlement).



**Figure 23:** An example presentation schema based on form of the site as developed by Historic England



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**Figure 24:** An example presentation schema based on broad feature type as developed by Historic Environment Scotland

## 2.5 Integrating Automation for the detection of Archaeological Features

Anthony Corns, Iris Kramer, Lucy Killoran, M. Fabian Meyer-Heß, Øivind Due Trier, Wouter Verschoof-van der Vaart

As the use of artificial intelligence and machine learning have developed there has been a steady increase in archaeological applications, and inevitably some debate about if and how such approaches should be used (see Bennett et al., 2014; Cowley, 2012; Palmer and Cowley, 2010; Parcak, 2009). Nevertheless, it is fair to state that there is now widespread acceptance in the cultural heritage and archaeological sectors that such approaches have a place and that future development of 'automation' will see improving outcomes. Underlying this position is a recognition that methods have improved, and continue to do so at a rapid rate, and that information in vast datasets is inaccessible through human analysis necessitating the inclusion of computational tools in the archaeologist's toolkit.

### What do we mean by "automation"?

ALS data comprise a raster/grid of numerical values, which we then transform into human-readable images. Both the data and the derived images are well suited for analysis by computational methods. This section

provides guidance on using computational methods to assist with the analysis and interpretation of ALS data by reducing human involvement in specific tasks. Suitable tasks include the detection, classification, and delineation of archaeological features among others (see section 4.5 for more details). There is not one set approach to using automation to perform these tasks. For example, simple tasks can be automated by rules written in a programming language like python, while more complex tasks (with less clear rules) generally use more complex algorithms, based on a large quantity of data, to provide evidence for patterns. When we talk about automation, we are generally referring to semi-automation, i.e. partial automation, where a certain degree of human involvement is (and should remain) necessary in the process.

### What automation technique should I use?

There are a broad range of automated methods that have been developed over the last two decades, and are likely to be applicable in archaeological contexts. These are summarised in Table 9, which sets out those automation techniques that are applicable to the analysis of ALS data and have been used in the cultural heritage sector. Further details of these techniques can be found in section 4.5.

Technique	What is it for?	What data does it use?
Pixel-based	Texture patterns	Gray level co-occurrence matrix
Pixel-based	Features that stand out in the landscape	Local relief model
Template matching	Features that may be modelled by a template; requires only a few training examples	Digital terrain model
Object-based Image Analysis (OBIA)	Identifying and separating out features in an image (Instance)	Openness
Object-based Image Analysis (OBIA)	Instance segmentation	Trend Removal

Technique	What is it for?	What data does it use?
Machine learning	Classification	Multispectral satellite images
Deep learning; requires a large number of training examples	Classification	
	Object detection	Digital terrain model or visualisation (e.g. local relief model)
	Instance segmentation	

**Table 9:** Summary of automation techniques that are applicable to the analysis of ALS data

### How best to prepare data for automated methods?

Feature detection using automated methods depends heavily on 'reference data' that can be used to train or otherwise design the approach. Such reference data might be a corpus of earthwork barrows or settlement enclosures defined by polygons and supported by attribute data, or point data derived from an Historic Environment Record (see sections 2.3 and 2.4). The more reference data available and the better their quality, the greater the chances of success with automated methods. The greater the degree of variance in the reference dataset, the greater the challenge of using it to inform automated methods and that is especially true as many archaeological datasets are derived and aggregated from multiple archaeological record databases. These data are unlikely to have been prepared for use with automated methods and may lack geospatial or semantic precision, have inconsistencies in formatting and unavoidable (human) errors (Davis, 2020; Gattiglia, 2015). As we have seen in section 2.3, there are many different choices that can be made when digitising an archaeological feature into a vector. For example, a group of burial mounds may be represented by a single large and irregular polygon denoting the group, instead of individual polygons that are more representative of the feature morphology that is required as input for an automated process. Therefore, manual checking and correction of the input datasets is essential for successful use.

Target features must be visible in the data. ALS data resolution must be adequate to represent the size of the desired features (see sections 1.3, 1.4 and 1.5). Point cloud classification and subsequent filtering must be carried out very precisely in order to reveal features without filtering them out. Although computers do not 'see' the terrain as the human eye does, target features still need to be visible as a numerical anomaly to have the potential to be detected. Considering the choice of terrain visualisation(s) is key for the successful use of automated methods. This not only relates to their effectiveness, (i.e. how well the target feature is represented), but also on computational demands. For instance, a 'computationally lighter' visualisation might be needed when working on very large-scale datasets. There is an underlying question of whether the ALS terrain visualisations preferable by humans are the best choice for automated methods (Guyot

et al., 2021; Kazimi et al., 2020; Somrak et al., 2020), as visualisations not only enhance the visible contrast but also manipulate pixel values. This issue remains unresolved and requires further exploration.

### How can I future-proof my automation practices?

The field of automated data and image analysis is rapidly developing, and that trend will continue. Thus, rather than trying to chase developments in automation technologies, choices made about the integration of automated methods are more likely to be future-proofed if they are grounded in an understanding of archaeological practice and the requirements of its practitioners. For projects connected to the provision of historic environment services, an understanding of potential future impacts on end users is advised. Following best practices for reproducible, ethical and collaborative data science will increase the longevity of work which uses automated methods and make it easier for others to build on prior work. [The Turing Way](#) (2022), for example, is an accessible online resource to get started with this.

## 2.6 Citizen Science and Crowdsourcing

Karsten Lambers, Rebecca Bennett, Wouter Verschoof-van der Vaart

Citizen Science has different definitions (Vohland et al., 2021) but essentially refers to the involvement of avocational volunteers, or citizen researchers, in scientific research. Going beyond dissemination and outreach, citizen science aims at a close collaboration and participatory knowledge production between scientists and citizen researchers. Volunteer contributions can help to bypass professional bottlenecks in data collection (hence 'crowdsourcing', short for 'outsourcing to the crowd'). Citizen science projects can also benefit from the ideas, knowledge and skills of citizen researchers in project design, data analysis and interpretation, and dissemination and outreach, although not many projects reach that level of involvement yet.

In archaeology, citizen science can take on different forms (Gibb, 2019; Smith, 2014). An increasingly common application is the search for archaeological target features in remote sensing data (e.g. Duckers, 2013). ALS-derived digital elevation models (DEMs, i.e. the broad term that includes DTM, DFM and DSM) are particularly well suited for citizen science projects. For example when visualised as shaded relief models, DTM and DSM are intuitively readable with little or no prior training. ALS models also provide an unusual and engaging way for people to view a landscape and the sense of discovery and exploration provided by this new perspective is very attractive to participants.

While the quality of crowdsourced data from such projects has been debated (e.g. Casana, 2020), suitable technical and project design can help ensure it has value (Bourgeois et al., 2024; Sims and Knight, 2021). However, the process of designing high quality, engaging and valuable citizen science research is complex. A number of aspects have to be taken into account in order to ensure that citizen researchers and heritage professionals alike benefit from a citizen science project:

- **Establishing the scope of the project:** The range of archaeological feature classes visible in ALS-generated DEMs is broad (section 2.4) comprising features on or

close to the surface that leave traces in the microtopography (section 1.3). Neither more deeply buried features nor indirect traces such as vegetation or soil marks are usually visible. The character of features that are being sought and the way in which they are expressed in the data needs to be clearly explained to participants. Supporting heritage management professionals also need to understand from the outset the likely character of the outputs.

- **Data and visualisation:** For better visibility, certain target feature classes and/or terrain types require different visualisations of the ALS-derived DEM (see section 2.2) that might be less easy to interpret for citizen researchers than a shaded relief. This can be overcome by providing multiple visualisations side by side and enhanced training.
- **Comparative data:** It is important for citizen researchers to have access to additional information to assist interpretation. Google or Bing feeds provide easy access to contemporary aerial photography and are a minimum requirement to reduce false identifications. Ideally access to historic mapping and a simplified version of existing historic environment records should also be provided to enrich the user experience and reduce false identifications.
- **Defining the task:** Data interpretation is often time-consuming, repetitive and tedious. To keep citizen researchers engaged, prior consideration should be given to classes of archaeological target features that are easily recognizable. Features with recurring traits are best suited as targets. A careful delimitation of the study area can help to ensure a minimum number of instances. While such choices facilitate a learning effect (and also recognition of "objects of confusion" i.e. modern or natural features that may have the same form as archaeological ones), they may at the same time limit the research potential.

- **Grade of engagement and training:** Data collection needs to be regularised and standardised to ensure comparable output, which often requires training. Apart from such minimum requirements, citizen researchers should be free to choose their own level of engagement in order to facilitate a broad participation. This level may be determined by the invested time or by the level of training they are willing to take. Thus, simple tasks should be defined such that even a brief engagement generates useful data, while more time and/or training enables citizen researchers to engage in more complex tasks. The gradation and continuation of training and support has been shown to be key to volunteer researcher engagement and satisfaction.
- **Communication:** Citizen researchers should be well informed about the scientific purpose to which they are invited to contribute. The entire project needs to be clearly outlined, including steps that may not involve citizen researchers. Ideally, citizen researchers can interact with the scientists in easy and straightforward ways, to comment on their work and to contribute their own ideas, and they are kept informed about and engaged with the progress until the end. Increasingly it is seen as desirable to allow citizen researchers to fully connect with all aspects of the research design, data capture, evaluation and outputs of a project, but this requires commensurate resources and skill from the professional team.
- **Impact:** There should be adequate engagement of local/national heritage data managers in the project planning processes to ensure that digital outputs of the citizen scientists' work can contribute to publicly available cultural heritage datasets, ensuring long term accessibility and impact.

In the following we discuss recent examples of archaeological citizen science projects that used ALS data, focussing on applications, challenges and benefits.

### Thinking about feature types

While a trained and experienced cultural heritage professional might be expected to record all features that are of potential importance from the ALS data, a more selective approach is needed for the successful integration of citizen science into mapping projects as not every archaeological feature type is suitable. Principally feature types for identification need to be:

- recognisable in the data (i.e. of appropriate size and scale in comparison to the resolution of the ALS)
- and
- appear in a high enough quantity that the volunteers remain engaged. The quantity of a particular feature type also ensures that volunteers become familiar enough to detect potential features with increasing confidence and reject possible objects of confusion, e.g., roundabouts and round barrows.

Careful consideration should be given to establishing the framework of archaeological feature types that citizen scientists are being asked to identify so that by and large they meet these criteria of recognisability and quantity. For example, while Roman marching camps may have distinctive attributes in their most common form (such as complex entrances, parallel sides and rounded corners) that meet the recognisability criteria, if these features are very rare in the study area, (for example the Netherlands where only a handful are known) they fail to meet the quantity threshold required for a good feature type candidate for citizen science projects.

## Heritage Quest, Netherlands

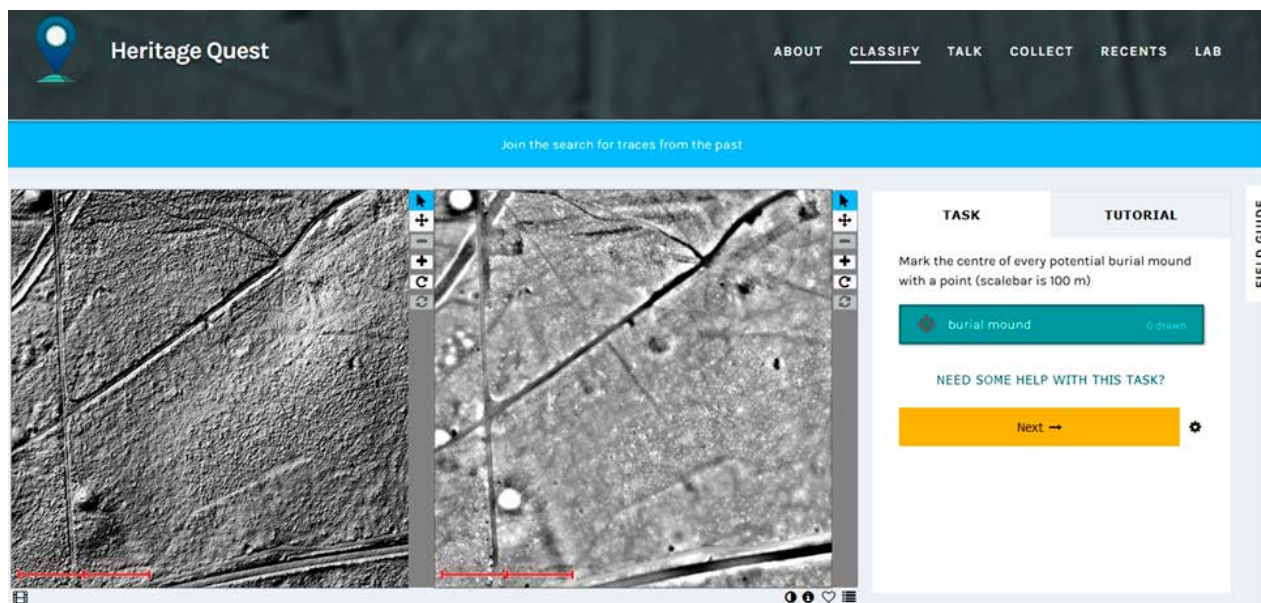
Heritage Quest (Erfgoed gezocht in Dutch) was a large-scale citizen science project in the central Netherlands collaboratively conducted 2019–2022 by Leiden University, Erfgoed Gelderland and Landschap Erfgoed Utrecht (Bourgeois et al., 2024; Lambers et al., 2019). Its goal was to map archaeological remains of frequently occurring feature classes in about 2100 km<sup>2</sup> of the hilly and forested terrain of the Veluwe (Gelderland) and the Utrechtse Heuvelrug (Utrecht). Earlier research had uncovered important prehistoric and medieval remains in these regions, but the extent of the study area and the good preservation under forest cover necessitated an upscaling of archaeological research well beyond previous efforts. Two parallel approaches were chosen: an automation project using computational methods (see section 2.5 and 4.5) and a citizen science project, both based on the same set of open ALS data (AHN2, see [www.pdok.nl](http://www.pdok.nl)).

The citizen science project consisted of two parts, online and on-site. Considering the size of the task, the online project was designed to enable a broad international participation. The project team chose the Zooniverse ([www.zooniverse.org](http://www.zooniverse.org)) in order to reach the large community of citizen researchers active on that platform. Since most Zooniverse projects are not related to archaeology, the project

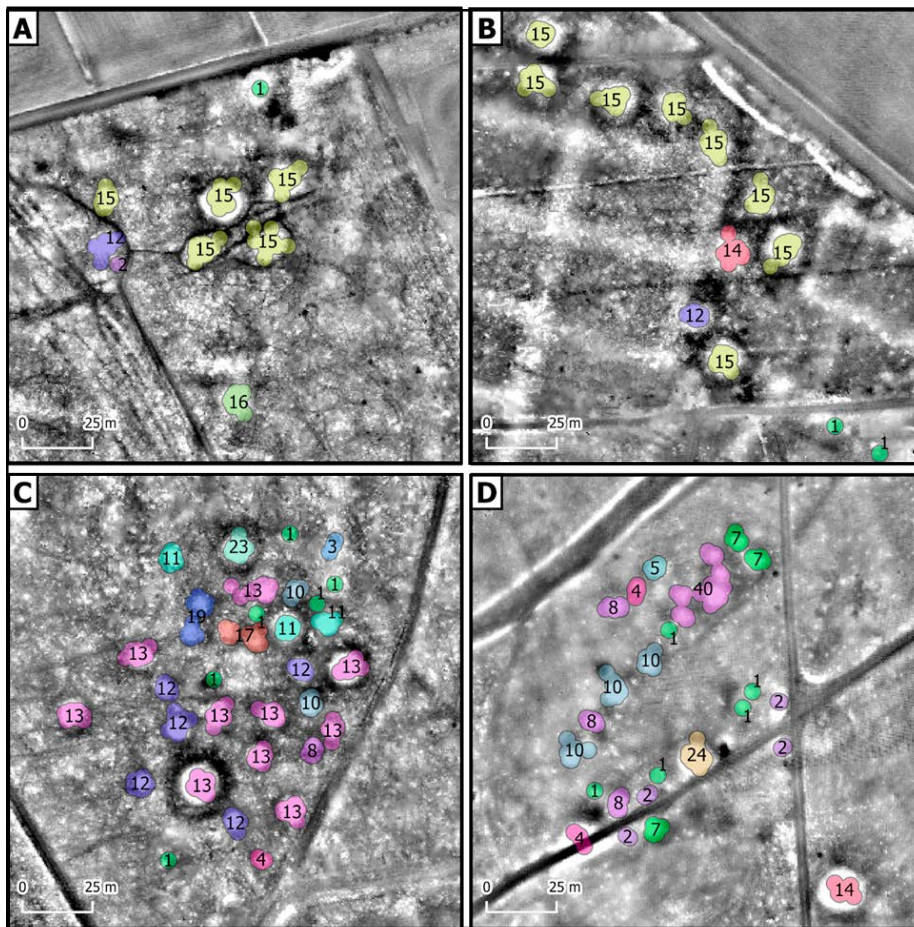
team expected little prior knowledge and thus designed a low-threshold task. For the Veluwe three archaeological target classes were defined: prehistoric barrows, Celtic fields and early modern charcoal kilns (in Utrecht replaced by mediaeval cart tracks). These classes account for a large portion of the archaeological record of the region, are clearly visible in ALS-derived models and have easily recognisable, repetitive traits. On Zooniverse two visualisations of the ALS-derived DTM were provided: the more intuitive shaded relief and the more abstract, yet often clearer, simple local relief model (Figure 25).

After a brief introduction, the citizen researchers were asked to mark first any barrow that they saw, then any Celtic field, then any charcoal kiln (or cart track) in either visualisation before they moved on to the next image pair. The intuitive bilingual user interface was completed by a tutorial, information about the project, a forum, and contact details.

Thanks to the low threshold and the easy yet attractive task, over the course of five and a half months more than 6600 citizen researchers participated online and marked more than 315,000 instances of potential archaeological features across all target classes. The project team aggregated transcriptions where multiple



**Figure 25:** The Heritage Quest mapping interface on Zooniverse showing the two ALS-derived images with different visualizations and the current task (after Lambers, Verschoof-van der Vaart, and Bourgeois 2019)



**Figure 26:** Various results from the aggregation of dense concentrations of potential barrows marked in the Heritage Quest project. The numbers refer to how many different users marked the same location (after Bourgeois et al., 2024)

markings referred to the same feature (Figure 26). The aggregated results were then evaluated in the second, on-site phase of the project. Over six weeks, the project team visited almost 450 potential barrows in the field with the help of local volunteers, many of whom had participated in the online project. Through field observation and coring, it was determined whether the marked spots were barrows or not. Since the field-checked barrows had been carefully selected to span the whole range from one-to-many markings, this gave us a reliable indication of the correlation between the number of online identifications and the probability of the marked feature being a barrow, which could then be extrapolated to the remaining barrows. Counting only barrows with a probability above 50%, the citizen science project more than doubled the number of barrows (918 known plus 1351 newly discovered), with similar numbers achieved for Celtic fields (14.2 km<sup>2</sup> plus 23.8 km<sup>2</sup>).

At the end of the project, the corresponding data were handed over to the responsible heritage authorities for further use, along with a metadata explaining their origin and nature.

Heritage Quest was designed as a low-threshold citizen science project that generated simple output. Yet, thanks to high participation and careful evaluation, the large amount of generated data could be turned into qualitative knowledge gain (Bourgeois et al., 2024). The correlation evidenced between the number of markings by citizen researchers and the actual presence of archaeological features is a good example of the ‘wisdom of the crowd’, and the citizen researchers made valuable contributions well beyond their assigned tasks. For example, their interest in World War Two remains prompted a follow-up project (“Scars of War”) dedicated to mapping traces of modern conflict in the same set of ALS data (Verschoof-van der Vaart and Kaptijn, n.d.)

### Community ALS Portals, UK

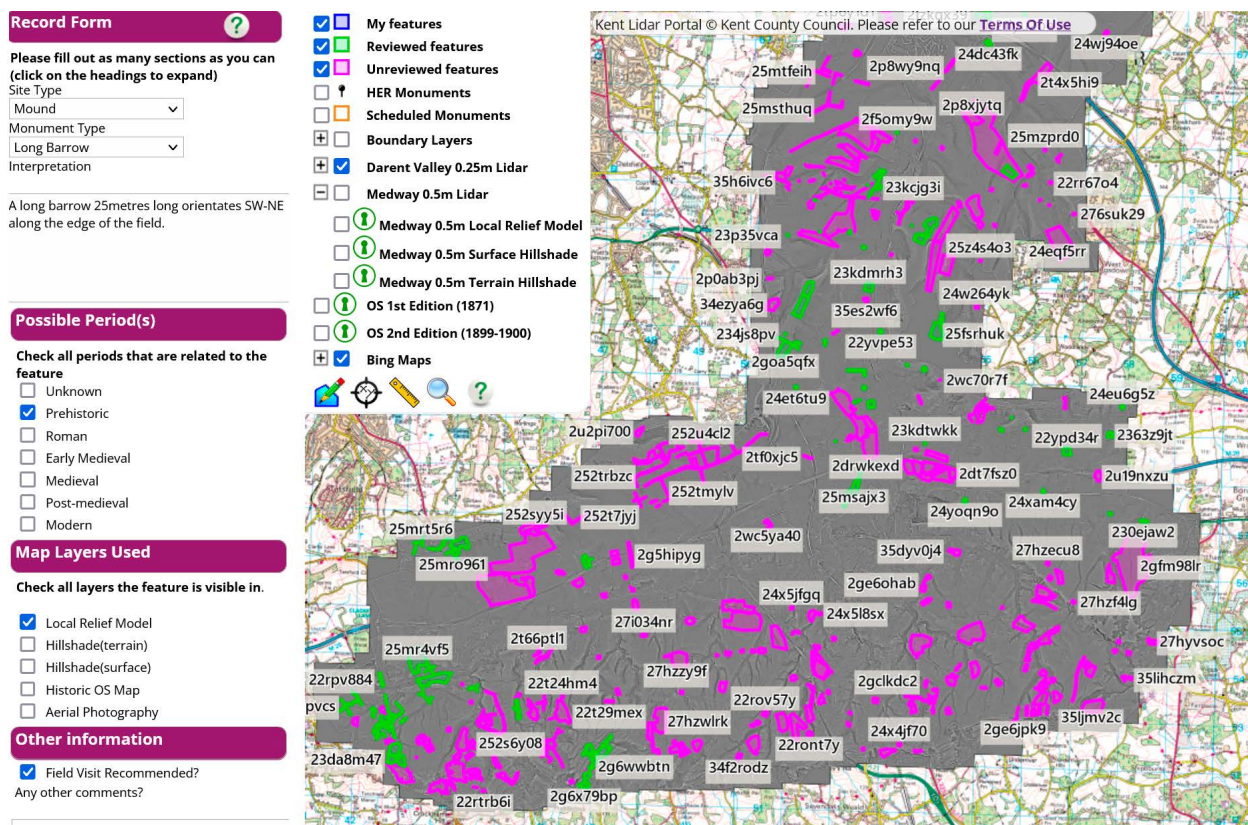
Over the last 10 years in the UK there has been a lot of interest in engaging local communities with the cultural and natural heritage of their landscapes, principally through partnership projects financed by the National Lottery Fund. Commissioned ALS surveys have often been a key tenet of the archaeological projects funded in this way, in order to broaden engagement with and understanding of the historic environment, often for areas with no existing ALS coverage. The tasks available and level of engagement of citizen scientists have varied between projects and have undoubtedly matured as these projects have progressed, had their outcomes evaluated and learnt from each other. This decade of community ALS project delivery is providing a wealth of collective knowledge that has rarely been featured in academic publications, due to the lack of formal participation of universities and academics in the community heritage sector. Consequently the evaluation and lessons learnt from these projects is not easily found in the public domain, for example being subsumed into the general project evaluation reports to funding organisations (Lees, 2017; Romain, 2017), and spread of best practice relying on professional networks and word of mouth (Sims and Knight, 2021). Consequently, a strong recommendation for any project considering a citizen science element would be to seek out professionals from a range of such projects for advice and support at an early stage.

Projects in the south of England provide examples of how the practice of citizen science ALS projects has evolved over recent years. Most of the earliest UK projects integrated volunteers in a traditional role of ground observations to augment the records of features identified by professional specialists, such as the “Secrets of the High Woods” project based in the South Downs National Park (Figure 27). The value of the local knowledge and broad expertise of citizen researchers was recognised early in the fieldwork phases, allowing feedback to the professional team who were concurrently transcribing further areas of the 325 km<sup>2</sup> ALS coverage (Carpenter et al., 2016).

Subsequent projects, including the Kent Lidar Portal and Cranborne Chase Lidar Portal have sought to include citizen scientists in data assessment as well, using an online interactive webmap to facilitate transcriptions. The webmap presents a variety of ALS visualisations (multidirection hillshades of the DTM and DSM and a local relief model of the DTM), alongside historic maps, aerial photographs, and historic environment records. In contrast to the Heritage Quest project, the aim of the portals is to facilitate the recording of a wide range of potential archaeological features visible in the ALS-derived visualisations, though the categories of features are prescribed by drop-down lists to make data recording swifter and more consistent. A team of professionals and trained volunteers undertake the quality assessment of the feature transcriptions and give ongoing feedback and support to the volunteer community.



**Figure 27:** Volunteers with tablets adding field observations to features identified from the ALS-derived visualisations © South Downs National Park Authority / Anne Purkiss



**Figure 28:** Interactive mapping interface for Kent Lidar Portal showing feature data form and range of comparative data including modern and historic maps and aerial photographs. Features are coloured by review status

To facilitate data management and review to professional heritage standards, portals have been designed using open-source Historic Environment Records Open System software (Figure 28). This allows for the easy use of linked vocabulary and standardised geospatial and data formats, facilitating import and export from and to regional historic environment records (HERs). The latter helps to ensure the legacy of the citizen scientists' work by directly contributing to the official record of the historic environment, ensuring access to the data for future research and supporting its protection via the planning process. Key to the success of data structure and transfer to the HERs has been the inclusion of regional curators at the planning stage to formulate and review the suggested data schema, particularly the monument typologies.

The Kent and Cranborne Chase projects are ongoing at the time of writing (2024) so full reporting and evaluation has yet to be completed. However, interim evaluation suggests that the portals have been very successful both in the engagement, training and enjoyment of volunteers and in the contributions of previously unknown features to the archaeological

record. The outcomes have also underpinned field survey and excavation work involving volunteers, contributing to an improved understanding of the landscape by both local people and professionals.

In conclusion, citizen science has the potential to mobilise substantial numbers of volunteers who contribute a broad range of interests, skills and knowledge and bring a lot of time and dedication to the archaeological analysis of ALS data. Just like automation (section 2.5), this can lead to an enriched understanding (in quantitative and qualitative terms) of the archaeology of even well studied landscapes, and also to higher levels of engagement of citizens with their heritage. It is important to underline two key aspects of successful citizen science projects: 1) a high level of engagement on the part of the involved researchers and heritage managers and; 2) a careful project design appropriate for the task at hand. As the examples above show, there is not a standard approach but rather many different ways of doing citizen science. Archaeology and heritage management have only begun to realise the full potential of citizen science, and the archaeological analysis of ALS data is a particularly promising application.

## 2.7 Integration with Fieldwork

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Archaeological fieldwork carried out in the context of a ALS-based study typically serves to validate feature interpretations conducted remotely and gather additional information. The significant volume of ALS-generated data poses challenges for traditional archaeological fieldwork, as the extensive amount of data collected can easily surpass the available time and resources, and processing workflows include various techniques that can vary significantly in terms of intensity and costs. To ensure the success of any fieldwork element, it is crucial to establish specific strategic approaches and employ meticulous sampling methods that are tailored to achieve the study's objectives (see Lee, 2015 for a detailed guide to project management in the cultural heritage sector). It is important to recognise that archaeological knowledge creation through survey is most usefully seen as an iterative process, with different methods and approaches complementing each other, rather than being seen in a competitive framework (see the following for a range of perspectives on this issue: Ainsworth et al., 2013; Halliday, 2013; Opitz and Cowley, 2013)

The primary motivations for conducting fieldwork include:

1. validating and contextualising new discoveries from the ALS-data, specifically adding observations about form, function, building material, vegetation and land use or other properties that ALS data cannot provide
2. providing additional detail on stratigraphic and spatial relationships between features
3. collecting data on previously unknown features
4. assessing gaps in areas where ALS data is unavailable or of poorer quality
5. assessing current preservation of the feature and any apparent risks to it
6. a recognition of the importance of building up knowledge of features on the ground with reference to their expression in the visualisations and of improved understanding of the landscape.

Each of these objectives necessitates different scales of analysis and techniques. For instance, validating discoveries may involve field visits to examine features, while filling gaps might require extensive work such as systematic surveys (Halliday, 2013) or acquiring additional topographic data via deployment of UAV ALS or photogrammetric survey.

This section introduces a range of common fieldwork techniques used in conjunction with ALS analyses. It highlights the varying scales at which each technique is most effective, the relative costs and time requirements, and the potential benefits and limitations it can bring to a study. These details are summarised for quick reference in tabular form to assist with project planning. Despite fieldwork typically being regarded as the final step in an ALS-based study, it is important to remember that ALS analysis and fieldwork are not a two-step approach; rather, they constitute an ongoing, iterative and reflective process of data collection and interpretation. Fieldwork data often prompt the reinterpretation of features identified in the ALS data, which, in turn, can uncover new issues to investigate in the field.

While there are clear benefits to integrating field observations to projects using ALS data there are also clear challenges. Fieldwork activities depend on managing factors including physical and legal access requirements, human resources available, the overall cost of the project and the characteristics of the region (e.g. altitude, weather conditions, and vegetation). Any limiting factors should be recorded in the project paradata for transparency (e.g. Cowley et al., 2020 see also section 3.4).

### Prioritisation and Targeting

Spatial and descriptive data derived from analysis of ALS visualisations provide a framework for targeting ground-based fieldwork. To varying degrees, fieldwork methods are more resource-intensive and costly than desk-based analysis so it is essential that they are targeted to provide the greatest benefit. These constraints also determine the scale at which they can be deployed. Although validation of features recorded from ALS data can be an appropriate objective in

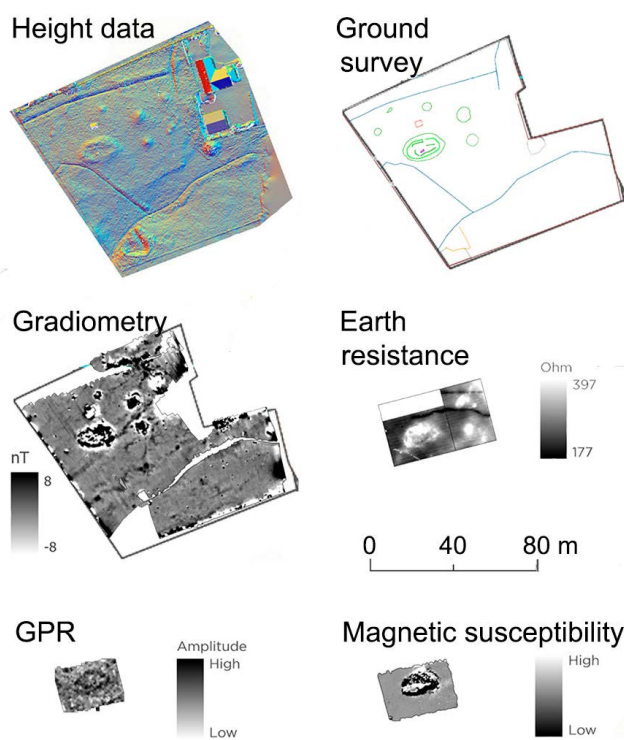
certain contexts, the greatest value of fieldwork is the enhanced understanding that different techniques can bring to sites and landscapes. This includes the specific knowledge that comes from physically experiencing the landscape and features within it at a human scale. For example a better understanding of contemporary land use practice gained from discussion with local farmers or the subtle observations of feature scale and location gained by the observer standing within or alongside it.

Key to successful integration of fieldwork and ALS data analysis is the definition of carefully considered research questions. Ideally, a staged approach to multi-disciplinary survey should be taken which allows for an evaluation of each stage in the context of the research questions, prior to the next stage being initiated. This then helps focus resources on remaining knowledge gaps and prioritise further work. Careful consideration should be given to what level of understanding is required to meet research objectives or inform appropriate heritage management to avoid fieldwork which will provide little or no additional benefit.

**Field Survey** techniques range from rapid walkovers to analytical earthwork survey and may incorporate localised collection of additional data (e.g. via drone survey or artefact collection). Fieldwork can result in targeted or generalised data collection over larger areas, making it a cost-effective and flexible complementary technique to ALS data analysis. Sites where interpretation from ALS data is ambiguous or where ground-based observations can help refine subtleties of phasing or morphology are useful criteria for targeting field survey. It can also be useful where the quality or coverage of ALS data is inadequate.

**Geophysical survey** can add information to sites identified from ALS data, and to areas where ALS data has not yielded results due to poor earthwork preservation. It should always be remembered that earthworks are only one expression of the archaeological remains in an area, and that complementary techniques such as magnetometry or GPR can also provide enhanced information where the topographic remains seen in the ALS are ambiguous and difficult to interpret. However, in woodland and areas with dense and low vegetation it may be challenging or impossible to apply geophysical methods.

**Excavation, scientific dating and paleoenvironmental work** are likely to be the most costly techniques in terms of personnel time and money. Carefully targeted small interventions have the potential to answer landscape research questions by dating, phasing and characterising features. Prioritisation should ideally be based on synthesis of the results from all previous stages of investigation.



**Figure 29:** Whether or not an oval earthwork on Shetland was a Viking Age ship burial could not be established from the surface topography alone, but depended on multi-sensor geophysical data. This is not to make a competitive comparison between techniques, but to demonstrate that while in many cases classifications can be made from ALS-derived visualisations or field observation, on some occasions other techniques, including excavation, are required to create certainty. © Historic Environment Scotland

## Fieldwork Techniques – Walkover and Analytical Survey

Walkover survey, defined as a rapid collection of visual observations of features identified in a landscape, is perhaps the field work technique most commonly paired with analysis of ALS visualisations. This is because walkover survey methods can be very flexible, and range from rapid landscape-wide review of features to more detailed observations and data collection for strategically selected feature types or environments. The surveys typically use pre-prepared digital or paper attribute forms and are enhanced by being able to take digital data into the field (i.e. ALS visualisations and transcriptions on mobile devices). The fieldwork provides an opportunity to enhance the record of the site or landscape by taking scaled photographs and measurements. The survey can be designed in such a way that records can be made of newly recognised features as well as those already recorded from the ALS data and also provides a means by which to assess the current condition of the features and any threats to them.

It is important for any project incorporating field survey into wider ALS analysis to employ a strategic approach that allows for targeting finite financial and personnel resources. Many projects take the opportunity to enhance their resources by encouraging field observations by local communities (see section 2.6). This invariably has the added benefit of improving interpretations with local knowledge that can inform the ALS analysis as part of an iterative process. Community engagement done well is not a cost-saving device, but rather a means by which to upskill and enhance understanding of all participants. It requires careful project and data management to succeed.

Data collection in the field is benefited from access to the ALS-derived visualisations and existing vector transcriptions and for this reason the use of tablets and mobile GIS is recommended. Using recording forms in mobile GIS recording software (such as QGIS QField or ArcGIS FieldMap) allows for the swift and accurate collection of geospatial data with defined attributes in the field. Regardless of whether field records are digital or paper-based, effort should be put into a data management plan for the fieldwork elements that accounts for whether the feature records created in the field will be “born digital” and how the data schema of the records will

be structured to link to and complement the existing transcription records. An example of a field survey data schema is given in Table 10, noting that the different attributes should be tailored according to prior knowledge of specific regional characteristics (i.e. different environmental conditions, presence of specific site types).

For some features and complexes of features, analytical earthwork survey will undoubtedly complement the ALS-derived topographic models and GIS based transcription. Guidelines developed in a UK context for this approach are available (Jamieson et al., 2017) and have relevance to the detailed interpretation of earthworks. Detailed analytical survey, through which sequences of earthwork construction, for example, may be carefully considered, is helpful for analysis and understanding of the complex remains and is a key tool for communication of interpretation to others. However, it is time consuming and requires personnel experienced in both reading and drawing landscape features and therefore is used sparingly to complement to ALS-derived transcriptions.

### Where is it? Thinking about accuracy

When combining ALS survey and field work thought needs to be given to the accuracy that can be given to each spatial record. The accuracy of the ALS data and vectorisations are discussed in detail elsewhere (sections 2.1 and 2.3), and this metadata should be available to the field team to aid location and expected presentation of features.

There are a variety of ways to geolocate field records. Smartphone, tablet and handheld GPS (e.g. Garmin) are common choices for regional survey and their accuracy is usually between 3 and 5m based on manufacturer’s specification. However, this stated accuracy is usually only achieved in open areas and with cloud-free skies. Smartphone and tablet accuracy often also depends on the mobile network coverage. In forested areas the accuracy could fall to 20-30m, with concordant issues not only for correctly geolocating any records made but also for navigation to known features. While these

technologies are accessible and low-cost, in some cases there could be difficulties in field validation and accurate geolocation of features, especially in woodland or more remote areas.

The accuracy of high-precision GNSS receivers' accuracy is less than 5 cm, depending on national network coverages. Such RTK-GNSS or fixed GNSS<sup>5</sup> stations are more expensive and are heavier to carry in comparison to a single tablet, but in recent years they have become more and more accessible in terms of weight and affordability. They are most often used for detailed work such as excavations, to geolocate geophysical surveys and for analytical earthwork survey. These technologies make it easier to identify marked features regardless of their size and to accurately geolocate additional features that have not been recorded by the ALS transcription.

### 3D data from other Techniques

Other sources of 3D data can be effectively integrated with ALS datasets. Foremost of these sources is imagery captured by drone which can be photogrammetrically processed to create 3D models (Bedford, 2017; Campana, 2017; Stylianidis and Remondino, 2016), but terrestrial laser scanners can also be deployed in this way (Grussenmeyer et al., 2018). Although these techniques are not typically suitable for studies with a large geographical extent, they provide an excellent resource for collecting new information and enhancing data resolution in specific areas.

Low-cost UAVs have democratised access to 3D data and are highly effective in open areas. While more expensive, larger UAVs can carry passive sensors, such as multispectral and hyperspectral sensors, with the capability to gather additional information that may not be visible in ALS data. Examples of this include buried features that may be evidenced through soil and crop marks and can provide valuable supplementary information for interpreting features visible in ALS-derived models (see section 3.1 in Bedford, (2017).

Large UAVs can also be equipped with laser scanners, that can help fill in gaps in the original ALS data coverage and provide increased resolution

for selected, small areas where the original data encountered limitations. For example, areas covered by dense vegetation, such as with the characteristic Mediterranean maquis (see Fontana, 2022) are often challenging for airborne laser scanners, and may not be well captured by the specifications of a lower resolution ALS survey (such as might be captured for nation-wide coverage). In such cases, UAV flights at lower altitudes and with increased point density can significantly enhance the data quality for these areas.

Terrestrial laser scanners, also play an important role in collecting data in areas where airborne lidar sensors cannot reach, such as cavities and the internal portions of structures. In this regard, they serve as indispensable tools in the archaeological toolkit, complementing the information obtainable from the ALS data.

### Geophysical Survey Techniques

Since many archaeological features are located below ground it can be highly beneficial to carry out additional geophysical survey in areas where the ALS-data have been analysed. The selection of the most appropriate geophysical technique to complement ALS projects is governed by a variety of factors including the size, depth and type of target feature, as well as the size of the study area and the nature of the environment in question.

Some techniques more readily lend themselves to landscape analysis, (for instance, cart-mounted or vehicle towed devices, such as magnetometers or electromagnetic arrays), while more focused geophysical survey applications (such as Ground Penetrating Radar, Earth Resistance survey or Electrical Resistivity Tomography), may be useful to characterise specific sites, features or deposits complementing information gathered from the ALS survey. A full discussion of techniques is beyond the scope of this document and readers are advised to consult the EAC good practice documentation for geophysics (Schmidt et al., 2015), but it is worth noting that all survey techniques will be more difficult in vegetated areas which are often the primary target of ALS survey.

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<sup>5</sup> RTK GNSS: Real Time Kinematic Global Navigation Satellite System. A location measurement system which combines recorded GNSS signals along with a correction stream to achieve 1cm positional accuracy.

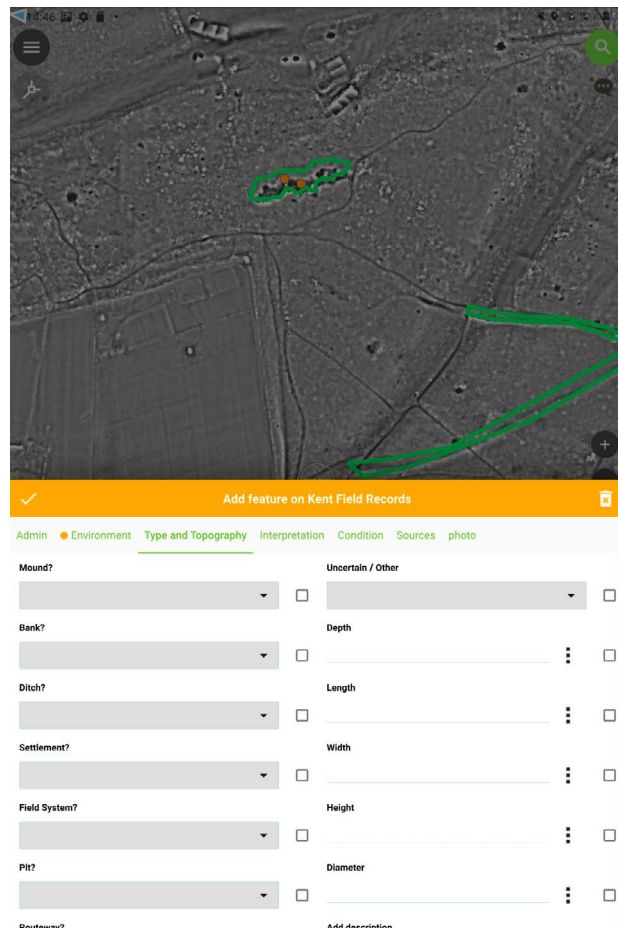
## Intrusive Investigations

Excavation has long been synonymous with archaeology as was the its main method of research investigation. However, with the development of a range of sensing techniques, excavations are beginning to find a new place in the research workflow. The development of landscape archaeology (David and Thomas, 2016) and the increasing range and availability of geospatial information has extended the focus of research beyond site discovery to analysis and reconstruction of historical landscapes. In this context, targeted excavations can focus on specific areas of interest based on a broad view of the landscape and provide materials to date and establish cultural associations, thus optimising the use of resources.

In complex depositional settings (e.g. alluvial, colluvial, estuarine, lacustrine, and urban environments), augering and boreholes can add stratigraphic detail and depositional context for surface landforms visible in ALS data (see sections 4.6 and Case Study 4). Through careful targeting of key archaeological features, scientific dating can be used to establish dates which can be extrapolated to the wider landscape on the basis of morphology. It can also be used to tie down floating chronologies where relative stratigraphic relationships can be established from ALS data and other non-intrusive methods but the phases of activity are uncertain (Hazell et al., 2017).

## Summary

Fieldwork can provide many potential complementary data sets to enhance understanding of features and landscapes mapped using ALS data. It is important to recognise that there is no single technique or determinative workflow that will provide “the answers” for every site. While in some paradigms data collected from excavation is regarded as higher value than that from survey, an integrated approach that maximises the opportunities to enhance interpretations by strategic use of the most appropriate additional data collection techniques is emerging as a mature recognition of how archaeological knowledge at multiple scales is created. The most appropriate approach should be determined on a project by project basis and invariably balances both research and practical considerations. The most useful outputs are those that are transparent, integrated, well recorded and well communicated. This facilitates the ongoing and reflective process of interpretation that is most beneficial to our understanding of past communities and their interactions with the landscape.



**Figure 30:** Screen Shot of ALS-derived visualisation and feature form in QField (source: Darent Valley Landscape Partnership Scheme, Kent Downs National Landscape, UK)

## QField Data Schema Example

(Southern England Temperate Woodland and Mixed agriculture)

Section Name	Field Name	Options	Type
Admin	UID		autogenerated
	Surveyor		free text mandatory
	Transcription Feature Reference		free text
	OS grid ref		pick from map
	Location / Site Name		free text
	Recording date		autogenerated
Photographs	File name		Take / upload photo
	Caption		free text
Environment	Woodland Type	coppice (managed), coppice (overgrown), coppice with standards, plantation – conifer, plantation – deciduous, mixed woodland, yew wood, arable, pasture	list pick one
	Understory	dense, moderate, negligible	list pick one
	Description		free text
	Problem Species	Yes, no	list pick one
		Yew	check box
		Holly	check box
		Rhododendron	check box
Topography	bank		check box
	ditch		check box
	mound		check box
	pit		check box
	lynchet		check box
	terrace		check box
	other		check box
	Description		free text
	length		free text
	width		free text
	diameter		free text
	height		free text
	Interpretation	interpretation	
period		Later Prehistoric, Roman, Medieval, Post medieval, Modern, Unknown	list pick one
Condition	Condition	Good, Fair, Eroded Damaged	list pick one
	Threats	none	check box
		animal burrowing	check box
		collapse	check box
		natural erosion	check box
		scrub	check box
		development	check box
		forestry activity	check box
		extraction	check box
		dig/dump	check box
		visitor erosion	check box
		vandalism	check box
		vehicles	check box
	agriculture	check box	
Sources	Visible in ALS data	yes/no	list pick one
	description		free text

**Table 10:** Field Survey Data Schema Example (Southern England Temperate Woodland and Mixed agriculture)

Method	Scale of analysis	Technique(s)	Relative Cost	Relative Time	Potential Benefits	Potential Limitations
<b>Field visits (ground observations)</b>	Land-scape	Targeted field visits	Moderate / High	Moderate / High	<p>Validating interpretations.</p> <p>Detail specific attributes of the ALS data.</p> <p>Disambiguation of potential archaeological features</p> <p>Record of environment, condition and threat</p> <p>Can be a helpful stage of ALS interpretation and feature identification process feeding back into the desk-based interpretations.</p> <p>Ploughed areas often present as without features in ALS data.</p> <p>Walkover survey so may give important additional evidence.</p> <p>Local knowledge / information can only be collected in this way</p> <p>"field" observations also possible for bathymetric ALS data. Underwater investigations /survey/ excavations may add value just as in terrestrial contexts.</p>	<p>Time consuming so requires a strategy for prioritisation considering accessibility.</p> <p>Physical access to sites often problematic (for a variety of reasons including land ownership, environment, land use, vegetation cover, seasonality).</p> <p>Requiring specific permissions according to national laws.</p>
	Site	Site walkover / photography	Low	Low		
	Feature	Feature walkover / photography	Low	Low		
<b>Remote sensing</b>					<p>Enhance the understanding of features.</p> <p>Corroborate interpretations or highlight any features. (cropmarks) that are not readily observed as earthworks.</p> <p>Provide additional clarity for specific sites, features or monuments.</p>	<p>Cost, availability and accessibility, (seasonality, cloud cover, access to appropriate data).</p> <p>Time consuming, how to prioritise data that will complement ALS data, law of diminishing returns, value of additional new data needs to be considered.</p> <p>Capacity within sector to commission new survey.</p>
	Site	UAV sensor (active and passive)	High	Moderate		
	Feature	UAV sensor (active and passive) / terrestrial laser scanning	High	Moderate		

Table 11 continued overpage...

Method	Scale of analysis	Technique(s)	Relative Cost	Relative Time	Potential Benefits	Potential Limitations
<b>Geophysical survey</b>	Land-scape	Electromagnetic Array, Magnetometer	Low	Moderate	Provision of measurements of the physical properties of the ground. Corroborate interpretations and highlight any subsurface features with no topographic expression.	Practicalities, land cover, seasonality. Understanding of environmental factors that limit the applications of certain geophysical survey techniques. Requirement for specialist equipment High level of expertise in geophysical survey and RS integration required to attain meaningful results
	Site	Earth resistance, Magnetometer, Ground Penetrating Radar	Moderate	Moderate		
	Feature	Multi-channel GPR, Earth Resistance, Earth Resistance Tomography	High	High		
<b>Intrusive investigations</b>	Land-scape	Targeted test-pitting / augering / boreholes	Low / moderate	Low	Analysis of specific chronologies of features, sites, deposits, and landscapes. Answer site specific or feature-scale research questions.	Most resource intensive. Organisation / permission / restrictions / permits. Destructive process. Consider scale of sampling strategy. Ongoing costs, post ex & archiving. Data integration a challenge sometimes due to timescales and publication methods.
	Site	Trial trenching / Excavation	Moderate	Moderate		
	Feature	Open area Excavation	High	High		

**Table 11:** Considerations for integrating ALS data with other complementary methods and their potential benefits and limitations. Time and costs indicated are relative assessments with respect to each other, and absolute cost will depend on many factors

## 2.8 Skill and Expertise of Staff

These guidelines cover a range of tasks whose execution requires skilled archaeologists to undertake them with the quality and reliability of the outcomes depending on both expertise and good management. In most European national contexts, there is no formal legal or regulatory guidance for the qualifications or accreditations that are needed to practice as a specialist in archaeological remote sensing or to undertake specialist technical work (e.g. processing and analysis of ALS data), beyond the general requirements to practice as an archaeologist (Belford and Wait, 2018). For example, professional accreditation for general practice as an archaeologist is recommended but not required in the UK, while in Poland all archaeologists must have a degree in Archaeology (Aitchison and al, 2014). In Bulgaria a Masters degree in Archaeology and permanent employment in a relevant institution are necessary (Kecheva, 2019). In some contexts, even general requirements may be unclear, vary across the sector, or be unenforced (Dans, 2019; Knobloch, 2019). This section provides a guide to the qualifications and experience most relevant for a professional specialising in work with archaeological ALS data in four key roles:

### **Practitioner, Specialist, Data Commissioner and Project Manager**

**Table 12** provides a breakdown of essential skills required to work effectively with ALS data in the heritage sector for each of these roles. These criteria have been designed to help individuals looking to develop their own skills and managers looking to build a team to work with ALS data, as well as supporting decision makers in assessing and building the capacity of their organisations. Potential training and career pathways are also laid out in Figure 31 to help identify the routes to building skills and expertise.

Throughout the process of recruitment, team development and project delivery, it should be understood that commissioning, working with and interpreting archaeological features from ALS data is a specialism that requires specific skills and experience. As a sector it is vital that we support professional development via collaboration and engagement with professional networks. In this way we can future-proof the skillsets and availability of skilled professionals against the rising quantity of data available and demand for interpretation. We can also build resilience as a sector to smooth the path through disruptive

changes to accepted practice that will emerge via the wider implementation of technological advances such as AI and automation.

### **Essential Skills and Competencies**

ALS-derived imagery can appear deceptively easy to interpret but in reality, interpretation requires specialist skills, knowledge and expertise. An appropriate level of technical knowledge is essential to understand the limitations of the data (e.g. the influence of vegetation on its effectiveness, effects of data processing) and potential interpretation pitfalls (e.g. processing artefacts, misinterpretation of non-archaeological features). However, it is important to recognise that analysis and mapping from ALS data is not just a technical exercise but a process of knowledge-based image interpretation (see Palmer, 2011 for a relevant discussion of these issues for aerial archaeology). Practitioners should have a grounding in landscape archaeology and an understanding of how natural and anthropogenic topographic features are manifested in the ground surface and how these are expressed in visualisations. An appreciation of the environment and cultural heritage of the specific region in which they are working is also important, as this will provide a corpus of the types of remains that may be expected, the potential objects of confusion and an appreciation of land use processes. While most mapping and interpretation of ALS-derived visualisations will be a desk-based exercise, experience of observing archaeological earthwork remains in the field is vital to ensure that interpretations are reliable. Where this is lacking ALS based projects should ensure project staff go into the field in the early stages of the project, or, if this is not possible, to consider how to compensate for a lack of field observation experience.

Interpreting ALS and other imagery derived from airborne platforms requires a structured and critical approach that draws on a broad range of observations to reach an informed interpretation of the archaeological features. These skills also enable the interpreter to more effectively use complementary sources to inform the interpretation of ALS derived visualisations. Underpinning good practice in aerial imagery and ALS data analysis is a sound understanding of landscape archaeology. This

provides the skills required to synthesise multi-period archaeological data at a landscape scale, drawing out chronological and spatial relationships between archaeological monuments as part of a continuum of landscape development that recognises that past landscapes exist in contemporary ones and are a product of many complex processes.

A degree of technical understanding and proficiency are essential for anyone involved in commissioning, managing or undertaking projects using ALS data, but the level of technical knowledge required will vary depending on role (see Table 12). **Practitioners** and **Specialists** need the technical knowledge to interpret a range of visualisations, assess how limitations of the data and choice of visualisation may determine what is visible, appreciate how processing may have affected the data and effectively combine ALS with other survey data. The ability to make informed judgments on the suitability of ALS data and derived visualisations is key to enabling survey **Commissioners** to act as an 'informed client'. An informed client can specify survey parameters and outcomes and make decisions on whether ALS is an appropriate and cost-effective survey technique. Likewise, **Managers** need to take on the role of informed client for their teams and organisations, but their technical knowledge should be balanced by the project management and communication expertise that enables integration of ALS into wider project designs and workflows.

### Role-Specific Skills and Competencies

The competence of cultural heritage professionals working with archaeological ALS can be divided as follows:

**Practitioner:** A heritage professional familiar with the process of analysing ALS-derived visualisations and creating geospatial data.

**Specialist:** A heritage professional who specialises in the use of ALS data for cultural heritage project. They can work with ALS data at a more advanced level, for example by training colleagues, taking responsibility for metadata and archiving.

**ALS Data Commissioner:** This role will typically be present in countries where access to project-based finance determines ALS data acquisition. The commissioner requires specific technical understanding of the process of acquisition and the impacts of ALS data processing for cultural heritage

projects in order to draw up the ALS specification, review contractor submissions and act as the informed client.

**ALS Project Manager:** This role requires specific technical understanding of ALS data, combined with project and team management skills. In many organisations the Data commissioner and project manager may be the same individual.

The essential and desirable skills for each role (Table 12) can be used as a tool to guide recruitment, and for the development and upskilling of specialist teams.

It is worth noting that the skills of Practitioner and Specialist lead on from one another, providing a potential career path. The ALS Commissioner role may be brought in as a specialist consultant but in some circumstances could also be executed by the ALS Project Manager. However, the specific skills of the ALS Project Manager must be separated from the practitioner and the specialist, since the manager must have the capacity and expertise to deliver the overarching project processes, from project planning to archiving and dissemination. This includes competence and experience in choosing the right staff, but is unlikely to require the level of technical experience of the Specialist.

ALS Practitioner		ALS Specialist	
Essential Skills	Desirable Skills	Essential Skills	Desirable Skills
<p>Visual interpretation of the landscape using ALS together with complementary data sources</p> <p>Understanding of the archaeology of the area being studied</p> <p>Familiarity with GIS</p> <p>Strengths and weaknesses of different visualisations</p> <p>Basic understanding of challenges and pitfalls of ALS data processing which can affect interpretability</p> <p>Awareness of applicable data standards and recording conventions for the area, if they exist</p>	<p>Knowledge of alternative sources of ALS and complementary data</p> <p>Awareness of relevant guidelines and reporting conventions for archaeological ALS</p> <p>Capacity to generate a range of visualisations as needed for the task at hand</p> <p>Knowledge of applicability of ALS for their use cases</p> <p>Willingness to engage in training opportunities to broaden their skills</p>	<p><b>All the essential and desirable practitioner skills plus:</b></p> <p>Solid understanding of the full ALS data lifecycle, from project planning to archiving and dissemination</p> <p>Ability to process ALS from point cloud to visualisation</p> <p>Can read and create relevant metadata for ALS</p> <p>Understanding and experience of the practice of landscape archaeology</p> <p>Capacity to provide advice to colleagues on the acquisition, processing and use of ALS</p> <p>Maintains up to date knowledge of technical and methodological developments relevant to archaeological ALS through continuing professional development</p>	<p>Understanding of a range of applications of ALS in different environments</p> <p>Active participation in a relevant professional network</p> <p>Capacity to deliver basic training to colleagues in ALS interpretation and processing</p> <p>Ability to advise on data requirements and technical specifications for archaeological ALS applications</p> <p>Ability to lead development of interpretive strategies and workflows for archaeological ALS</p> <p>Ability to communicate good practice in the archaeological use of ALS to others</p> <p>Awareness of the importance of, and good practice in, disseminating and archiving the outputs of ALS data analysis and interpretation</p>

**Table 12** Competencies Matrix for Practitioner, Specialist, Commissioner and Manager Roles

ALS Data Commissioner		ALS Project Manager	
Essential Skills	Desirable Skills	Essential Skills	Desirable Skills
<p>Clear understanding of the specific requirements of the project</p> <p>Solid understanding of the full ALS data lifecycle, from project planning to archiving and dissemination</p> <p>Awareness of relevant guidelines and reporting conventions for archaeological ALS</p> <p>Ability to identify relevant experts and required expertise for projects using archaeological ALS</p>	<p>Ability to balance the quality of data with cost to ensure the data are fit for purpose</p> <p>Ability to identify and build a consortium of data users and balance their differing needs with respect to the data acquisition</p> <p>Knowledge of sources of archive data and ability to identify when new survey is required</p>	<p><b>All the essential commissioner skills plus:</b></p> <p>Ability to source appropriate training and skills development opportunities for themselves and their employees</p> <p>Ability to integrate ALS into project designs and workflows</p> <p>Ability to lead projects promoting the development of good practice and methodological innovation</p> <p>Awareness of the importance of and good practice in disseminating and archiving the outputs of ALS analysis and interpretation</p>	<p>Capacity to develop and deliver training to specialists and practitioners in archaeological ALS</p> <p>Capacity to support and contribute to the network of project managers using ALS for archaeological research and heritage management</p> <p>Effective communication of good practice in the archaeological use of ALS to a range of audiences</p>

Table 12 continued

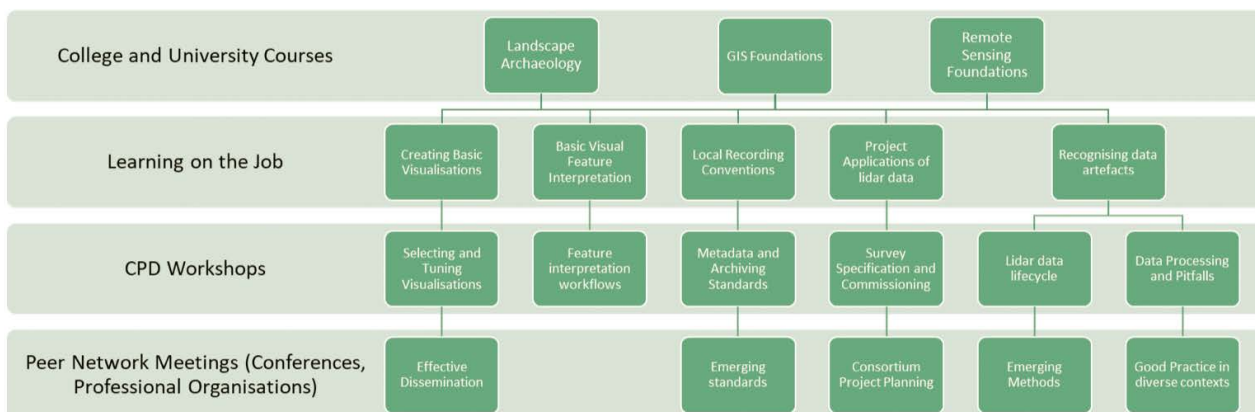


Figure 31: Career and Learning Pathways

## Building skills through supervision and quality assurance

Appropriate supervision and quality assurance procedures are key to maintaining standards and ensuring consistency of products derived from analysis of ALS data. Quality assurance in the form of review takes place throughout a project lifecycle and includes informal knowledge exchange, peer-to-peer review and structured evaluation of compliance with procedures. Review does not have to be hierarchical – it can take place between peers, within or outside your organisation. For project teams comprising two or more specialists, it helps promote consistency of approach and products. In its essence, it is a collaborative process of cross-checking.

Quality assurance processes provide a way to draw upon the skills and expertise of other specialists (including other disciplines) draw on a collective knowledge base of regional, thematic or period specialisms. They also provide an opportunity for knowledge sharing and growth in the sector where practitioners may number only a few individuals in any region. These processes ensure that appropriate standards are met and interpretations and mapping from ALS data are robust.

The level of quality assurance is determined by factors including the size of the project, the stages it contains (both desk-based and fieldwork) available resources and the experience of the practitioner. Complete review of 100% of the work produced may be practical over projects with a limited spatial extent, but for large-area projects a more common approach is to review a sample of the work. In any context, it is important to devise an appropriate quality assurance strategy that is achievable and ensures the data is fit for purpose.

In training contexts, review processes can help create opportunities for learning while ensuring data integrity. When reviewing the work of an inexperienced practitioner or trainee, the sample reviewed should initially be high (i.e. up to 100%), and gradually reduced as proficiency and experience increases. Sampling a larger proportion of the data for review should be considered when dealing with unfamiliar landscapes or types of archaeology, even for experienced practitioners, to ensure that bad habits and assumptions about interpretation are minimised. There are several approaches to selecting the subset of the data to include in the sample that will be reviewed,

including random, stratified, probability and purposive sampling (Banning, 2020).

When machine learning and computer vision are integrated into archaeological prospection and monitoring workflows, quality assurance processes should be adapted. These processes should include suitably experienced staff reviewing a large sample of the identifications (referred to as predictions in the machine learning literature) made by an algorithm as part of the model training. Such review allows the team to assess the accuracy and precision of model underlying the AI identifications. Reviews during model training should also consider possible sources of bias in the training data, for example the over-representation of a specific class of features (see section 1.3). When using a fully trained model, quality assurance may focus on the review of a sample predominantly comprised of identifications where the predictions have lower confidence scores.

Review and quality assurance processes should consider if:

- The analysis uses an appropriate range of available complementary sources of information.
- Appropriate visualisations of the ALS data have been used.
- All features of interest have been identified as per the project aims.
- Interpretation of recorded features is plausible.
- Graphical depiction of features is accurate and meets the standards outlined in the brief or project design.
- GIS attribute data and textual records are complete, accurate and consistent.

Professional bodies or networks provide valuable forums for discussion and advice. For example in addition to conferences, they may facilitate live workshops where participants can discuss issues or queries, or online forums where questions can be posted. It is recommended that specialist practitioners engage with and support such networks, which can be particularly valuable for independent specialists who do not have the support of other team members.

## SECTION 3

### Reporting and Archiving

Making the results of the work undertaken with ALS data available and accessible is key to effective integration into heritage management. This section provides guidance for the management, reporting and archiving both ALS data and the many products derived from it including:

- good practice for the data management plans to ensure data is compliant with FAIR (Findable, Accessible, Interoperable, and Reusable) principles of archiving.
- advice on the content and structure of reports using ALS to meet national and regional standards.
- good practice examples for the presentation of ALS-derived data in reports and other outputs.
- detailed guidance on the process of archiving ALS data and derived products including standards for data interchange and the importance of recording metadata and paradata and tools that can support this.
- guidance and ideas for dissemination and public outreach, including explaining technical topics to diverse audiences.

### 3.1 Best Practice for Reporting

Tom Fildes, Bruce Mann, Sally Evans

#### Introduction

The reporting of cultural heritage information derived from ALS data is a crucial step in making the data readily available to colleagues and the wider community. This communication is essential whether the project originated in the commercial, government or public sector, and the results of the assessment are typically presented in the form of a report, alongside a feature inventory. Incorporating ALS data into the process of development-led archaeology significantly contributes to the public benefit thus derived (European Archaeological Council, 2024).

Due to the high value of complementary data when assessing ALS-derived visualisations (see sections 1.3 and 2.4), ALS-based research reports are frequently integrated into archaeological assessments with broader scope. This is especially true for work undertaken as part of the planning and development control process (see section 4.2). Typically, such desk-based assessments bring together evidence from a variety of sources and provide essential information about the history and development of an area, including known and potential archaeology, as a precursor to ground disturbance and development. This process helps identify and evaluate potential features of archaeological interest, historic buildings,

and environmental features that may not otherwise be considered or protected.

By evaluating pre-existing data and resources, the assessment enables developers, local authorities, planning departments, and other stakeholders to make informed decisions regarding about potential effects on sensitive archaeological or landscape features, preventing loss or damage of valuable assets through timely mitigation measures. As a result, this preliminary assessment plays a critical role in effective planning procedures, ensuring sustainability and cultural sensitivity while minimising negative consequences to our shared heritage and environment. This section gives specific guidance that will allow the results of ALS-derived archaeological mapping and interpretation to be effectively reported and integrated into these assessments.

#### National and Regional Standards

To be effective, an assessment report should have a well-defined objective and maintain a clear and coherent narrative. Below we provide a suggested structure for reporting ALS projects (Table 13), along with details of the content for each section. Typically, the results of interpretation will also be represented as a gazetteer of sites and this should be formatted as an appendix to the report. It is good practice for reports to be presented in digital formats that make

cross-referencing from the main text to supporting information such as the appendix and figures easy for the reader.

Standards for archaeological reports vary between countries or regions, with variations in approach such

as scoping objectives, accessibility of required data sources, assessing impact levels, reporting formats etc. Consequently, authors should familiarise themselves with the national and regional guidance and working practices in addition to the general guidance presented here.

### Content Structure for ALS Reports

Report section	Contents
<b>1 Title page</b>	Project name Client Archaeological Consultant Report author(s) Geospatial location (Coordinates / National Grid Reference as specified) Report status (draft/final) Date of issue
<b>2 Contents</b>	List of contents. List of illustrations.
<b>3 Summary</b>	A non-technical summary of less than 1000 words.
<b>4 Acknowledgements</b>	As appropriate.
<b>5 Introduction</b>	Brief description of the project and its aims. Brief outline of the topography, geology, soils and hydrology of the Study Area. Brief outline of the major forms of land-use in the Study Area. Brief outline of the recorded archaeological heritage of the Study Area.
<b>6 Method statement</b>	Description of the ALS data, including survey company, date of survey, survey parameters (ppm, resolution of DTM, DFM, DSM etc.) etc. Description of data processing and visualisation methods, including the parameters applied in generating raster models (e.g. azimuth, sun elevation, trend assessment radius etc., as appropriate), model overlays etc. feature classification and numbering system. Constraints on methods. Quality Assurance procedures. Personnel, equipment and software.
<b>7 Results</b>	Overview of the quantity, location, character, interpretation and significance of the features assessed/identified by the study, supported by appropriate illustrations (which can include graphs, bar-charts and/or pie-charts). Illustrations based on relevant extracts from the DTM, ALS-derived models, historic maps and/or aerial photos showing significant areas, sites or features, as appropriate.
<b>8 Discussion</b>	Interpretative discussion of the results considering alternative possible interpretations where appropriate; highlighting features of potentially high significance; and comparing the results to the nature and distribution of the previously known archaeological heritage of the study area. Recommendations for further fieldwork (such as the validation of identified potential features) could also be included here.
<b>9 Bibliography</b>	References to all maps and published, printed or online sources referred to in the report.

Report section	Contents
<b>10 Illustrations</b>	<p>Scheme location map(s).</p> <p>Atlas of site location maps of the Study Area as a basemap at an appropriate scale, with both previously recorded and newly identified sites mapped and labelled.</p> <p>Relevant extracts from the DTM, ALS-derived models, historic maps and/or aerial photos showing significant areas or sites, as appropriate.</p>
<b>11 Appendix 1 - Inventory of Sites</b>	<p>Descriptive inventory of all sites within the Study Area, listed in numerical order by unique identifier reference. Inventory to include location (coordinates), placename, site type, description (including dimensions), confidence score (0-4), and any other relevant remarks.</p> <p>Each site to be cross-referenced with the reference number assigned to the record in any heritage inventory, where relevant.</p>
<b>12 Appendix 2 – Image Catalogue</b>	<p>Catalogue of large-scale images extracted from the processed DTM and/or ALS-derived models, each showing a clear, detailed view of a site or cluster of sites (all sites listed in Appendix 1 are to appear on at least one image).</p> <p>Semi-transparent overlays of historic maps, aerial photos or other appropriate imagery to be used where relevant.</p> <p>Cross-sectional profiles derived from the DTM to be included for significant sites, and for sites where such profiles would support the proposed interpretation.</p>

**Table 13:** Suggested structure and content of Archaeological Examination of ALS Data Report

## Scope of Report Content

### Summary (non-technical)

This should be a short summary of the principal objectives of the ALS survey and the extent to which they were achieved. The language used should be readily understood by a general audience, which means that any technical terms should be explained or defined as appropriate.

- Begin by briefly outlining the background and context for the ALS survey and clearly stating the purpose of the study.
- Provide a high-level overview of the methods used, avoiding technical details at this stage.
- Summarise the key results of the ALS-based research, focussing on the most significant aspects of survey and highlighting trends.
- Briefly mention any limitations of the study.
- Offer a summary conclusion that reinforces the main points discussed in the technical summary. If applicable, suggest avenues for future research.

### Introduction

This should provide a description of the project and its aims. It should also provide a summary of the previously known archaeological background of the study area.

- Describe the reasons for the survey addressing any local, regional or national research questions that the project impacts.
- The size and location of the project area should be described paying attention to the geology, soils and hydrology.
- Provide a brief outline of the current land use within the study area. Describe the potential impacts of land use, geology and topography on the survival and visibility of archaeological earthworks and on the effectiveness of ALS survey in that area.
- Consider how topography can impact the value of varied ALS visualisations.
- Summarise key previous archaeological survey and research and sites known from cultural heritage records and relevant publications.

### Method Statement

The method statement should be a concise account of the survey techniques and methodologies used. Referring to an appendix, published standards or to other appropriate sources for a more detailed description of standard techniques and methodologies may be appropriate.

- Describe the ALS data used by the project, including the survey company, date of the survey and survey parameters. Include the resolution of the ALS data and available models (DSM/DTM/DFM) (see sections 1.4 and 2.1).
- Describe the software used to view the ALS data or to produce any 2D raster outputs and data processing and visualisation methods. These should include the parameters applied in generating raster models (e.g. azimuth, sun elevation, trend assessment radius etc., as appropriate).
- Describe the process of ALS interpretation and mapping, providing detail about the scope of the survey and the periods of archaeology covered. Include a summary of additional sources such as example aerial photographs or historical mapping where they were used to aid interpretation.
- Present details of the methods used to identify and classify sites, and describe any constraints on the methods used. Where interpretative spatial mapping has been produced, describe the depiction methods (or reference an accepted standard where one was used), symbology, attributes recorded and numbering systems used.
- Describe and reference (e.g. by DOI) any outputs from the project such as GIS data and descriptive monument records.
- Include information on personnel and their experience and competency to carry out ALS-based research, such as professional qualifications or equivalent experience. Describe any quality assurance procedures undertaken to enhance confidence in project results.

### Results

The content of this section is dictated by the specifics of the investigation itself – both in terms of survey methodology and the observed subject matter. In general the results should provide a comprehensive overview of the areas, sites and features characterised in the assessment of the ALS data, with reference to the data used for the interpretation and any corresponding relevant material. It is expected that the results section will be supported by a **geospatial dataset** and **Inventory of Sites**. This section should provide clear synthesis of the numbers and type of features recorded, providing examples of routine sites alongside challenging or extraordinary cases.

The structure of the section will often depend on the nature of the ALS data as well as the number of datasets presented for analysis. If several surveys are being reported on, it is typical for these elements to be dealt with under separate subsections, so that any discrepancies can be clearly presented.

While the description of results will vary according to the individual style of an author or the requirements of their employer or commissioning organisation, it is important that the details of the survey interpretation are supported by referenced illustrations. Language should be clear, with each site or feature described in relatively concise language, appropriate to the complexity of the feature.

The rationale behind the data interpretation should be included with each element (both textual and visual), and the author should define how the conclusion was reached based on the associated dataset. While parameters such as these are often pre-determined and defined in a specification document (or similar), it is important that the results can be read in isolation, as sometimes such associated literature is unavailable.

Whilst the resulting narrative of the report should primarily be presented in the subsequent section (Discussion), it is reasonable for the author to give a level of confidence on any given feature within the results section. This could include reference to ancillary material (aerial photography, mapping, other surveys etc), or indeed more generic comments on the data itself, and how it (or the conditions in which it was conducted) may impact interpretation.

### Discussion and Conclusions

The concluding section should draw on the previous analytical section present a more descriptive assessment of the survey with reference to the initial objectives of the project. For the identified historic features, this section allows a wider context to be sought, and for results to be presented with reference to comparative sites and previous work. This could include ancillary material or existing literature relevant to the exposition of the results.

A closing summary should be included that brings together the findings of the report, however big or small. Significance can be highlighted, especially where sites may be at risk from external factors (such as development or climate change). Whilst recommendations can be helpful, it should be noted that in some instances curatorial oversight falls to a regional or national authority and therefore explicit instruction may be omitted in these cases.

### Bibliography

References should include any material used within the report that is not original to the active investigation, and in some instances it still be helpful to include references to forthcoming or cross-collaborative work. All maps (printed or digital) should be referenced appropriately, and any literature (academic, grey, or otherwise) must be fully referenced with respect to the agreed bibliographic format. Guidelines and standards should also be included, and if pro-forma are used it may be useful to describe them in this section (or in the appendices as appropriate).

### Illustrations

**Survey Location Maps** – Whether as part of a stand-alone ALS report or part of a wider report, such as a cultural heritage assessment, a map should be included showing the geographic extents of the study area and of the ALS data used. The map(s) should include reference to the location in relation to the country, region, and local landmarks. Appropriate copyright must be obtained where relevant. A north-arrow, scale, and explanatory key should also be included.

**Site Location Maps** – Archaeological landscapes, sites and features identified from ALS data should be shown using an ALS-derived visualisation (see section 3.2) as a

basemap at an appropriate scale. These maps should show both previously recorded and newly identified features, with the feature's unique identifier (UID) used in the inventory of sites (included as an appendix to the report). A north-arrow, scale, and an explanatory key should also be included, as well as a clear indication of the type of visualisation used.

**Site Plans** – Interpretation of archaeological landscapes, sites and features identified from the ALS data should be presented in a clear and consistent way. In some cases an illustration of the site or features comprising the ALS-derived visualisation may be adequate, but careful consideration should be given to the need for graphical representations of interpretations (see section 2.4). Where this is done, two plans should be used, one for the original ALS visualisation showing the site or feature, the other showing the graphical interpretation. For this second type of plan, it is important that the graphics convey the nuances of the interpretation and are not misleading where there is ambiguity or uncertainty. For instance, bold lines and sharp edges should be avoided when attempting to delineate features that can only be interpreted tentatively. It is good practice to consider how accessible illustrative material is, for example to colour blind people, as it is important to ensure that users can easily and quickly understand illustrations. The use of too many conventions or colours can be confusing and should be avoided (see section 2.4). As with the other diagrams, a north-arrow, scale, and explanatory key should also be included.

**Additional Imagery** – In addition to the site plans described above, it may also be appropriate to include specific illustrations to illustrate or otherwise support the interpretation. These might include cross-section profiles of the DTM / DFM / DSM models for significant sites, historic mapping, or aerial photographs to help inform the interpretation. Where such additional images are used, it must be clear which site they are referring to (cross-referenced with the feature UIDs used in the feature inventory), and include reference to their source (with copyright permission where required).

All sites listed in the Inventory of Sites should be illustrated on at least one of the feature plans accompanying the report.

### Appendix 1 - Inventory of Features

A descriptive inventory of all archaeological landscapes, sites and features, both previously known and newly identified, within the Study Area, listed in numerical order by unique identifier reference should be supplied as an appendix. The inventory must include location (coordinates), placename, feature type, feature description (including dimensions), confidence score (e.g. 0-4) based on the interpretation of the data and the certainty that the feature is archaeological, and any other relevant remarks. Each feature should be cross-referenced with the UID number assigned to the feature in any public inventory or record, where relevant. It is critical that all features referred to in the body of the text are checked against the inventory, and vice-versa.

### Appendix 2 - Image Catalogue

A catalogue of images, each showing a clear, detailed view of the identified archaeological landscape, site or feature. All sites listed in Appendix 1 should appear on at least one image. Each image should be cross-referenced and labelled accordingly with the Inventory of Sites as detailed in Appendix 1 above.

### Other Guidance for Reporting in the Heritage Sector

Republic of Ireland: Transport Infrastructure Ireland has published guidance notes called [PE-ARC-02009 - Guidelines for Cultural Heritage Impact Assessment of TII National Roads and Greenway Projects](#) (2024).

The Chartered Institute for Archaeologists in the UK has a standard for Desk-Based Assessments [https://www.archaeologists.net/sites/default/files/CIAS%26GDBA\\_4.pdf](https://www.archaeologists.net/sites/default/files/CIAS%26GDBA_4.pdf) which is a useful reference for overarching report structures.

## 3.2 Data Presentation

Žiga Kokalj, Rebecca Bennett

As discussed in section 2.2, it is essential that ALS data are processed into visualisations to aid archaeological interpretation. When reporting on the use of visualisations, it is desirable to understand the parameters and presentation of the images for wider comparability and reliable research outputs. All the illustrations created using ALS-derived visualisations should be supplied with the following metadata:

- the applied algorithm - for example Shaded relief, Local relief Model, Skyview factor
- vertical exaggeration factor (if used) - Numeric value representing the scale exaggeration factor e.g. 1= no exaggeration, 10 = 10x exaggeration
- technical parameters used in the algorithm - When calculating the local relief model the user must define a radius for the algorithm e.g. 20m. For shaded relief models the user must define the angle, and azimuth of the light source

The list of parameters to record are reasonably short for basic visualisations as listed in section 2.2 and therefore easily added to the name of the file or provided in the figure caption. If the aim is solely to provide an illustration, some of the technical parameters may be omitted, but the visualisation type should always be included in the caption.

If the aim of the illustration is a quantitative analysis of specific features, a discussion of feature details, or a comparison of different visualisations, more parameters have to be provided to enable understanding of the image and reproducibility. For example, a parameter such as illumination azimuth in a shaded relief model, has a huge impact on the perception of the landscape and must be reported to viewers of the image (Kokalj and Hesse, 2017).

Archaeological interpretations that are accompanied by appropriate metadata on the visualisations used can be robustly re-assessed in the future. However the requirement to record and make available the metadata for combined visualisation is more complex because the process involves many decisions that all have an important effect on the appearance of the combined visualisation. Therefore, the choice of 'basic' visualisations, their individual computation parameters, the type of histogram stretch, saturation of minimum and maximum values, blending methods,

order of blending, and opacity settings all have to be documented (see section 2.2 Table 6 for examples).

While the list of recorded parameters can seem excessive, replicating the appearance of the combined image is only possible if this information is stored in an accessible way and published with the combined visualisation and project report.

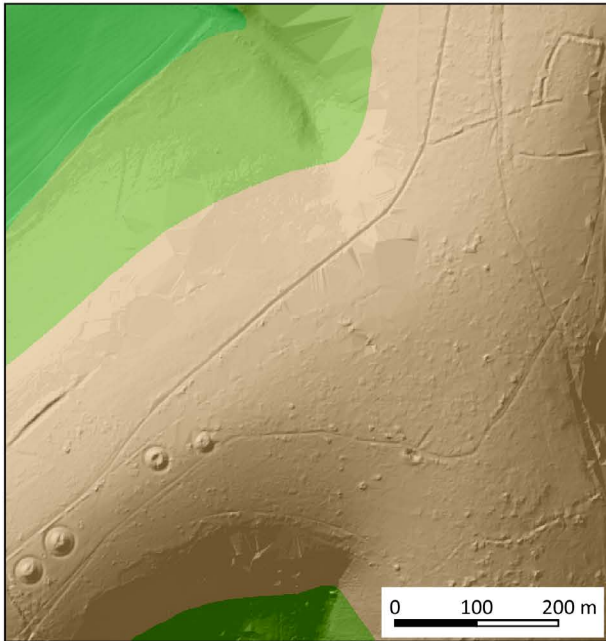
If providing details for individual figures is judged to be impractical when preparing images for publications it may be necessary to standardise the visualisation used across a report. For publication in scientific and technical literature, we strongly encourage replacing shaded relief models with the combined visualisation for archaeological topography (VAT) which offers similar benefits in terms of legibility to the non-specialist but is better suited to illustrating archaeological topography. Definitions of more complex visualisations can also be shared through RVT settings files (QGIS) or chained function models (QGIS, ArcGIS Pro).

### Printable Checklist for the Presentation / Publication of ALS Visualisations

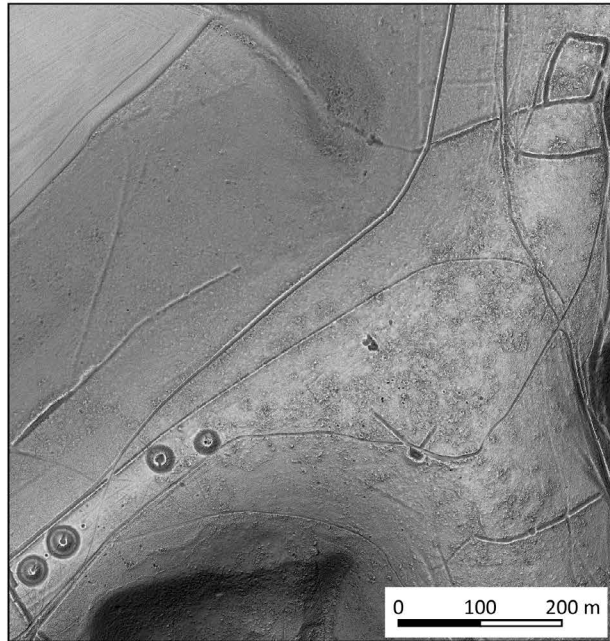
The following checklist can be used to guide the creation of illustrations using ALS derived visualisations:

- ✓ legibility (select the appropriate scale to illustrate the subject)
- ✓ scale bar
- ✓ title / legend
- ✓ data source acknowledgment
- ✓ appropriate metadata:
  - ✓ model used (DTM, DSM, DFM)
  - ✓ resolution
  - ✓ date of capture
  - ✓ visualisation used
  - ✓ visualisation parameters

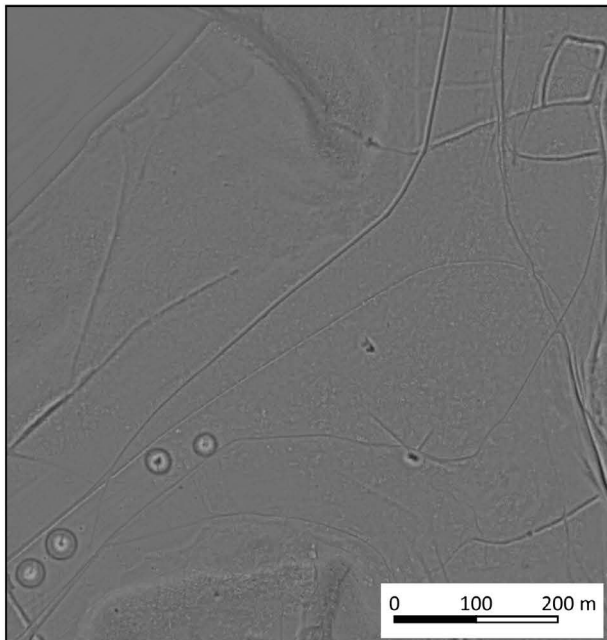
**Kingley Vale Barrow Cemetery and Nature Reserve as visualised in Airborne Laser Scanned Data**



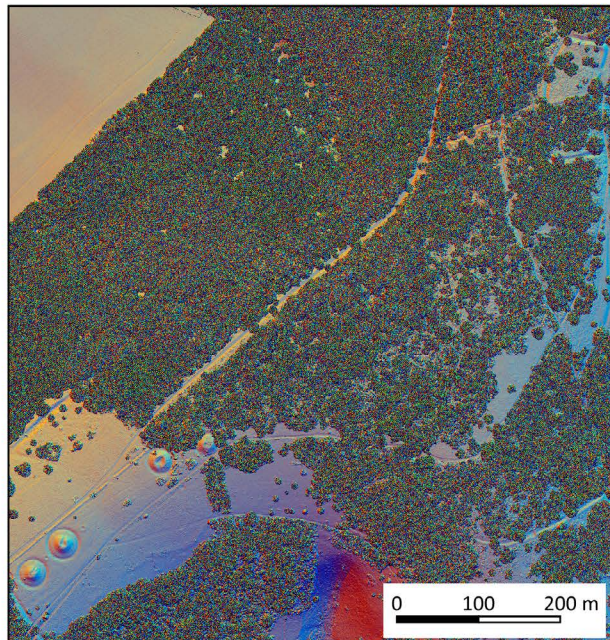
ALS Data Attribution: © Environment Agency copyright and/or database right 2020.  
 Resolution: 1m at DSM  
 Date of Capture: Composite coverage (multiple dates)  
 Model: DTM  
 Visualisation: shaded relief / elevation blend provided via wms (parameters unknown)



ALS Data Attribution: © South Downs National Park  
 Resolution: 0.25m at DTM  
 Date of Capture: spring 2014  
 Model: DTM  
 Visualisation: archaeological VAT (blended visualisation) created using RVT default parameters



ALS Data Attribution: © South Downs National Park  
 Resolution: 0.25m at DTM  
 Date of Capture: spring 2014  
 Model: DTM  
 Visualisation: simple Local Relief Model created using RVT  
 Parameters: radius 10m



ALS Data Attribution: © South Downs National Park  
 Resolution: 0.25m at DTM  
 Date of Capture: spring 2014  
 Model: DSM  
 Visualisation: multi-directional hillshade created using RVT  
 Parameters: elevation angle = 35°  
 Azimuths Red band = 315° Green band = 22.5° Blue band = 90°

**Figure 32:** Example of illustrations incorporating ALS with informative captions

## 3.3 Data Archiving

David Novák, Teagan Zoldoske, Anthony Corns

As the increasing use of ALS-data and widespread use of archive historical aerial photographs illustrates, remote sensing data supports many lines of archaeological investigation. Our methods of inquiry and transform over time, as does the landscape itself and so the archiving of source data and interpretations is vital to ensuring that the value of data and interpretations is maintained for the future. Ensuring transparency and reproducibility of scientific workflows throughout a project further increases this value and re-use potential. The primary goal of archiving is to guarantee that all essential data outputs of research projects are preserved for future use and accountability. This necessitates long-term preservation of data in trusted digital repositories under the care of competent institutions. However, storing data is only one aspect of ensuring its future usability. Good data management must be established from the start, and this is the responsibility of both the data originators and the users.

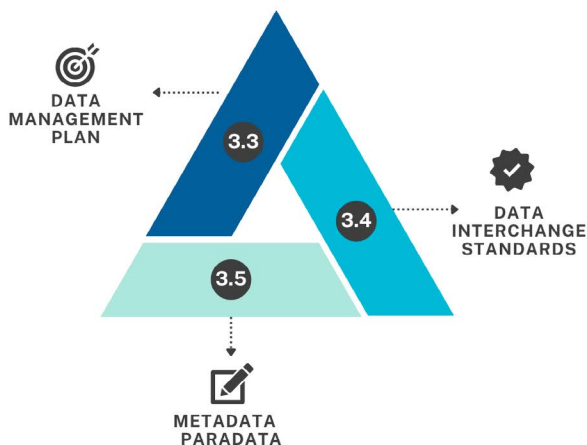
Several outputs are produced during data collection and ALS data processing. Consequently it is necessary to clarify in advance how the data will be handled and stored during and after the project. Users are referred to the detailed guidance in the EAC Standard and Guide to Best Practice in Archaeological Archiving in Europe (Perrin et al., 2014) as a benchmark document. This section provides specific additional advice on archiving practice for ALS-derived data and projects through the implementation of a Data Management Plan based on FAIR principles. It is supported by detailed guidance in sections 3.4 and 3.5 that cover data interchange and metadata and paradata. Each of these elements are vital to ensuring FAIR data.

### Data Management Plans

A Data Management Plan (DMP) is a written document outlining how research data will be managed both during and after a research project. The plan should address what types of data will be collected and how the data will be documented, stored, shared and preserved. A well-designed and well-implemented data management plan is crucial for ensuring data is compliant with FAIR principles.

The DMP is formulated at the outset of a project and implemented throughout its lifecycle. It is a dynamic document that must be adaptable to unexpected situations and responsive to evolving needs as a project progresses. The underlying principle is that all data handling processes must be deliberate, thoughtful, compliant with established guidelines and accompanied by proper documentation at every stage. Data lifecycle management represents an important process that involves applying and updating the DMP. It is essential for all team members involved in the project to have a thorough understanding of the DMP, as the implementation of the plan is the collective responsibility of the team, and adherence to the DMP is crucial for achieving FAIR data. Several excellent online tools and examples of good practice are available for creating a DMP (see Table 14).

Three Pillars of FAIR Data Archiving for ALS Projects



**Figure 33:** The three pillars of FAIR Data Archiving for ALS projects: the data management plan (section 3.3), data interchange standards (section 3.4) and metadata / paradata (section 3.5)

	Tools	Originator
Dig Digital (DigVentures, 2019)	A guidance document and online resource created specifically for archaeological data management. Cultural Heritage specific.	DigVentures, supported by Archaeological Archives Forum, Historic England and the Chartered Institute for Archaeologists (UK)
ARIADNEplus Data Management Plan Tools	Online tools to assist archaeologists in making data management plans, including a Protocol for Archaeological Data Management and DMP Template to allow data creators to check compliance. Cultural Heritage specific.	ARIADNE Research Infrastructure AISBL
The Data Stewardship Wizard (Pergl et al., 2019)	A combined knowledge model and interactive online software tool that supports guidance, decision making, and learning. Cross-discipline.	ELIXIR, ELIXIR CZ and the Ministry of Education, Youth and Sports of the Czech Republic
DMP Online	An online tool to create, review, and share data management plans that meet institutional and funder requirements. Cross-discipline.	Digital Curation Centre and California Digital Library (CDL)
Standardized checklist	A Checklist which defines the essential topics in data stewardship planning. Cross-discipline.	Digital Curation Centre

**Table 14:** Guidance and online tools for creating Data Management Plans

In some cases, ALS data may not form archaeological archives on their own, but rather form part of them. As a result, the data management and archiving process for the ALS data must be linked to the wider framework and the DMP of the research project. A well-prepared DMP can streamline the execution of a project by allowing for automation of workflows, facilitating both human and machine readability, ultimately leading to well-described, properly organized, and appropriately stored FAIR data. The DMP also establishes responsibilities, encompassing both general data management and individual tasks, including validation, and can rely on both internal and third party repositories, while meeting their requirements.

While also considering relevant regulations such as those set by funders and laws, a DMP should always be based on research and data preservation needs. The DMP should include a clear consideration for selection and retention of data (Oniszczyk et al., 2021) which involves defining which datasets will be archived for perpetuity and which need not be. Consideration should be given to streamlining the deposition to archive, to facilitate future access and to reduce the environmental impact of long-term digital storage. Additionally, the DMP should address basic administrative data, data collection methods, creation procedures for documentation and metadata,

legal and ethical considerations, data storage and backup, and anticipated methods of data sharing. It is essential that the DMP identifies a target repository where the data will be permanently stored and takes into account its capabilities and requirements. Early planning will minimize the need for retrospective data editing and correction, leading to more efficient work and reduced potential for errors. The DMP, along with other reporting outputs, should be part of the final digital archive.

### Licensing and Data Sharing

Adopting standard practices for ALS data creation and management within the community can enable easy sharing, aggregation and reuse of data. However, this requires appropriate licensing that should be as open as possible. Without appropriate licensing, good data management is virtually impossible. Licensing should reference the original source of the data (cited within the metadata) and should explicitly cover the reuse of the ALS data, derived visualisations and the derived archaeological interpretation for archiving and reuse. Examples of appropriate licenses include Creative Commons licenses and their equivalents.

### How FAIR is your repository?

It is essential to address the need for FAIR data at all levels, as the entire archaeological archive will only be as FAIR as its weakest component. It is thus important that the repository holding and preserving the data also adheres to FAIR principles (Wilkinson et al., 2016) as well as striving for openness.

### Data Repositories

A key issue to consider at an early stage of the DMP and ideally before data is captured, processed and/or analysed, is the requirements of the repository archiving the end products. Depending on how and where the data was created, there may be institutional or national requirements which can include which repositories data can be deposited with, how it is to be stored, and dissemination requirements. In cases where data creators can choose where to archive their data, careful consideration should go into the selection of a **digital repository**.

Before the selection of the repository, there are a few things that should be considered:

- Is the ALS data being deposited as a part of a larger collection, or as a single entity?
- How long should the data be retained?
- How often will the data be accessed and what level of security is required?
- What formats will the data be deposited in (see section 3.4)?
- What metadata will be needed for the data and are workflows in place to facilitate metadata creation and retention (see section 3.5)?

The repository will be able to help with these questions and may have requirements of their own which will need to be met prior to deposit, ideally at data creation. This information should be incorporated into the DMP to allow for a better workflow and the opportunity to deposit data at any point in its life cycle. It is important to keep in mind, however, that for data to make it to the repository, care for data in the short and medium term by data creators is necessary. Data should be backed up, monitored, and access to the data should be agreed on in advance within the DMP.

The digital repository should be a trusted institutional or national repository, ideally with certification such as [CoreTrustSeal](#) or relevant national certification. The repository should have backups of all data it holds, both on-premises and offsite storage, and should have clear plans on how it checks for and would handle data loss while promoting suitability in the way it stores the data (Lin et al., 2020). Additionally, in accordance with the retention period of the deposited data, any relevant normalisation and migration policies of data should be documented and made available on request (Consultative Committee for Space Data Systems, 2012). Another important consideration is how the repository disseminates the data it holds. This can vary widely based on the institution from limited to no public access to being fully open access. In either case, the data and metadata within the repository should follow FAIR principles (Wilkinson et al., 2016).

## 3.4 Standards for Data Interchange

Teagan Zoldoske, David Novák

ALS data will be transferred many times during the phases of collection, processing, interpretation and archiving, and then potentially many subsequent reuses of all or some of the data and project outputs. It is therefore important to apply good practice for data exchange throughout the ALS lifecycle to support the FAIR principles of interoperability and reusability and ensure that data can be shared and remain accessible in future. This section covers the process and formats for ALS data exchange at each phase as detailed in Figure 35.

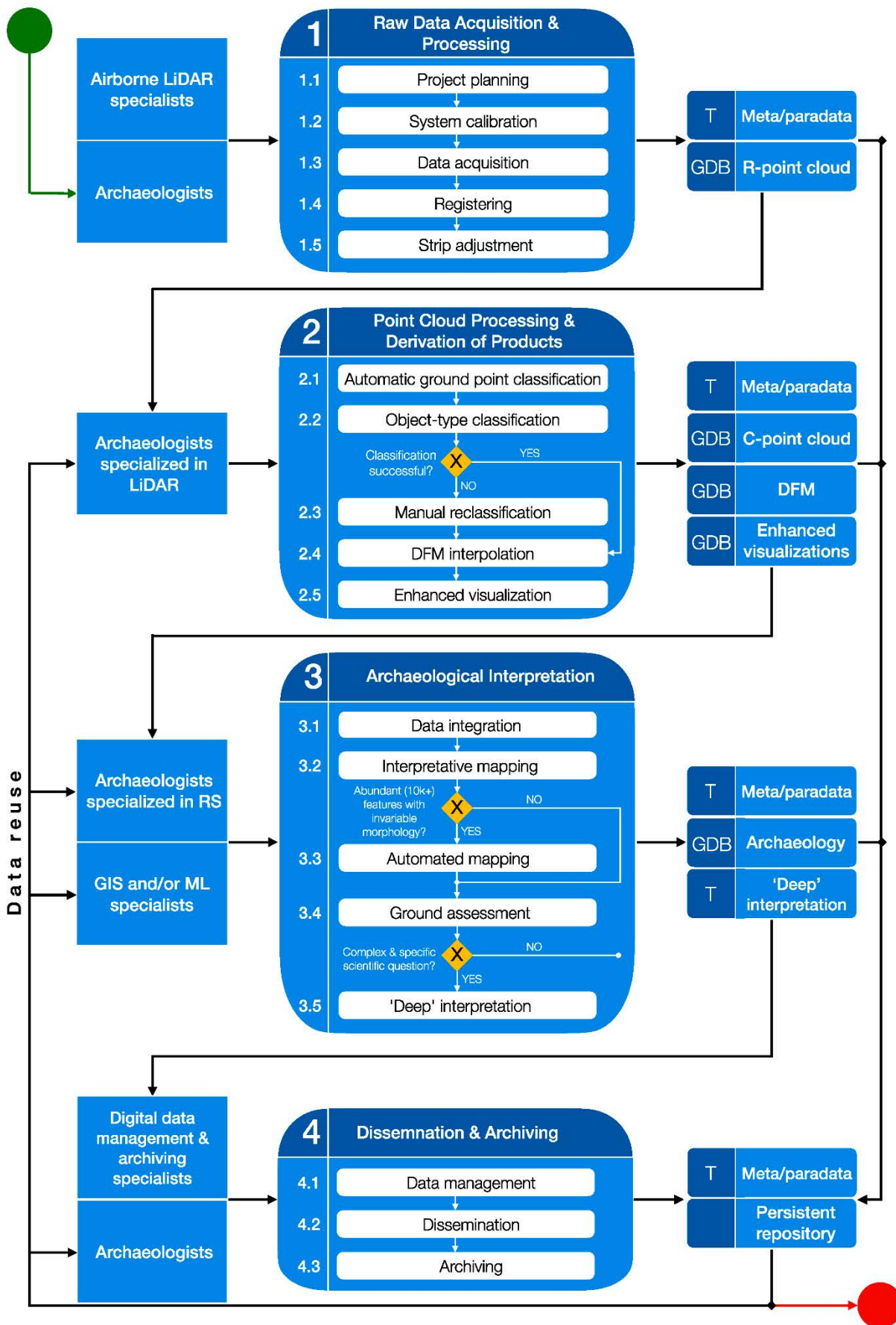
ALS data takes on various forms, from transient to stable archival versions, at different stages of processing, yet it is always inherently spatial data (Lozić and Štular, 2021). In Phase 1, ALS data may be sourced from a range of platforms and sensors and can also include data acquired during the project from data archives. The data acquisition and initial processing phase tends to be highly project specific or is undertaken done by specialists without an archaeological background, so shared standards for data acquisition and distribution are necessary (see sections 1.4 and 1.5 of this guidance and Fernandez-Diaz et al., 2014).

In Phases 2 and 3 the ALS data is being actively used and the data should be formats that suit the project's needs. During this phase point cloud processing, classification, manual reclassification, and interpolation are typically undertaken increasing both the amount of data associated with the project and the number of formats. Archaeological interpretation at Phase 3 may require additional integration and the creation of vectorised maps, tasks that can produce data in many of potential formats (LAS, GeoTIFF, Shapefiles, geopackage etc.). While these formats may be most appropriate within the project's workflow, there are often proprietary formats in use that are not suitable for long term preservation purposes. Therefore, files may need to be exported to a standardised format at the end of Phase 3 before archiving to ensure data exchange and data interoperability. This important step should be recognised in the Data Management Plan (see section 3.3, Figure 34).

### Looking to the future, the importance of Data Exchange and Data Interoperability

The exchange of data in archaeology continues to be a mix of downloading datasets from online repositories and portals and requesting them from data creators. It would be more efficient to facilitate and automate data exchange (processing, modification, visualisation or publication) by connecting systems that provide services for data transfer and manipulation. In a world of interconnected online data, technical interoperability is a crucial feature of data and services that enables machine processing and the creation of efficient, reproducible workflows. **This is only possible if standards for data interchange are applied to each project.**

One of the significant benefits of high levels of interoperability is the ability to use distributed resources, both for data storage and processing. The principle of interoperability involves a mutual understanding between systems that manage and process data. Interoperability requires the standardisation of the language used and information presented so that no information beyond the metadata is required for further processing of the data. Technical (syntactic) interoperability is mainly based on the use of standard data formats and communication protocols, such application programming interfaces (APIs) that support two or more computer programs communicating with each other. On the semantic (content) level, it is based on the use of standardised vocabularies and ontologies. The semantic interoperability of interpretations obtained from ALS data is explored in more detail by the [ARIADNE Research Infrastructure](#) and comparable initiatives as well as in section 2.4.



**Figure 35:** Context data-flow diagram for archaeology-specific airborne lidar data processing (after Lozić and Štular, 2021). Notations: GDB—geodatabase, T—(textual) descriptive data store

## Formats for Data Exchange

In an effort to support data exchange, a range of shared standards for spatial data provided are by the Open Geospatial Consortium (OGC). The OGC standards are extensively applied and form the most comprehensive library of open standards for spatial data to date. OGC standards can be utilised for archaeological ALS needs, from data visualisation to advanced analyses, as they provide high levels of syntactic and semantic interoperability. Notably, the LAS format is widely used in archaeological research, as it is specifically designed to enable standards-driven exchange and interoperability of point clouds derived from ALS. Compressed versions of LAS (LAZ and COPC) are commonly used as well, though these are not suitable for archival purposes.

Derived models are often created from ALS data. While these are most often created as a GeoTIFF or Cloud Optimised GeoTIFF (COG), the large file size of these means that they may sometimes be saved as other georeferenced image files such as JPG/JGW or PNG/PGW. These smaller image files are not suitable for archival purposes due to their compression.

As ALS data is often managed within a GIS environment, it is common for a variety of geospatial file types including Shapefile, Geopackage, WKT, GML, and GeoJSON files to be created as part of the interpretative process. Of these file types all except shapefiles are suitable for archival purposes (see below). With each of these files, it is important to remember that they should have accompanying metadata and paradata (section 3.5) that explains how the data transformed from the raw ALS data up to that stage in the life cycle.

## Data Sharing via Services

The choice of suitable file formats for a dataset should consider if there is a spatial service that allows data and its metadata to be shared between systems and applications (McKeague et al., 2020). This service can be provided by either the data creators or the digital repository. The OGC has the following interface standards which are widely implemented:

[Web Map Service \(WMS\)](#): allows access to geo-registered map images. Ideal for displaying and interacting with raster data interpretations.

## Why not Shapefiles?

Shapefiles are a very commonly used file format for geospatial data however there are disadvantages to this format that make it less desirable for archival purposes. Shapefile format requires the preservation of multiple component files for every dataset (at least three - a main file (.shp) and index file (.dbx) and a dBASE file (.dbf) but often more). Shapefiles also have a limited capacity to embed metadata. Good alternatives are Geopackage and GeoJSON files which have the benefit of being a single file, are open standard formats and well accepted by the open source community.

[Web Feature Service \(WFS\)](#): allows access to geographic information on a feature and feature property level. Ideal for displaying and interacting with vector data interpretations.

[Web Coverage Service \(WCS\)](#): returns specific, multi-dimensional coverage data. It also performs operations on the data, such as subsetting, reprojection, and resampling.

Current developments in data sharing are moving towards supporting cloud native interface standards and this is likely to be highly relevant to ALS derived dataset in the future. This includes a move towards OGC APIs to replace the web map, feature and coverage services mentioned above.

The method of sharing data heavily depends on the form of the data and the Spatial Data Infrastructure (SDI) that is in place (see the [INSPIRE Directive](#) for further guidance on SDI), and is crucial to ensuring that the future usability of the data. It is therefore important to consider what will happen to each ALS derivative within a project as part of the data management plan and save them to the most suitable file format. As discussed in more detail in sections 3.3 and 3.5, if these file formats are to be shared or archived (as they should be), it is important to ensure that the data and metadata are as open, and stable, as possible.

## 3.5 Metadata and Paradata

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The final element of data management that ensures adherence to FAIR principles is the creation of metadata and paradata. Metadata and paradata records are essential for the understanding, interpretation and reuse of ALS data and ALS-derived data as they allow users to contextualise each element by providing a range of information about the data. This section explains the nature of metadata and paradata for archaeological projects including ALS data and provides best practice for the structure and content of metadata and paradata records.

### Metadata

Metadata provides information about the characteristics and properties of the data, which are key to reusing, understanding and interpreting it. In a geospatial context, the metadata describes the important characteristics of the data including the content, quality and accuracy. This information assists users in understanding the origin, purpose and limitations of data, informing decision-making on the appropriateness of data for specific purposes. It enables individuals to assess the relevance and reliability of data and is therefore an essential part of data processing workflows and the data archive.

Metadata is also important for sharing and integrating geospatial data from different sources. The lack of consistent, universal standards within archaeology-specific ALS workflows necessitates rich metadata. By providing standardised and consistent descriptions of the data, metadata creators facilitate data discovery, access, and interoperability. In light of the growing amount of available geospatial data from different organisations and platforms, it is essential to create metadata in a consistent manner, based on the methodology described in the data management plan (DMP) (see section 3.3).

### Metadata for ALS data and derived models

ALS data can be acquired using different types of platforms and sensors which all have their own formats

and requirements and the data are often processed and re-processed to create digital elevation models and other derived products. This creates variability in metadata format depending on the organisation or agency responsible for collecting and distributing the data and the phase of the ALS data workflow. These formats include: ISO 19115, LiDAR Data Exchange Format (LAS) Specification, LASzip, Federal Geographic Data Committee (FGDC) CSDGM, and Dublin Core. These metadata formats have been broken down into key elements shown in Table 15 and are further described below. There are also several commonly used metadata formats for ALS data, some of which are directly related to a specific file format which have been summarised in Table 16.

The archaeological analysis and interpretation of ALS-derived data requires specific metadata that are beyond the scope of the common standards listed in Table 15 and their format should follow the good practice guidelines laid out in sections 2.2 and 2.3.

### Recommended Metadata Schema

The recommended scheme for geographic metadata is the ISO 19115 standard. It describes a set of metadata elements that can be used to describe ALS data, including its acquisition parameters, quality, and other characteristics. Profile variations on the ISO 19115 metadata schema exist at an international level such as the [UK GEMINI](#) standard and the [EU INSPIRE](#) schema (Table 15).

Within the ISO 19115 schema there are several subsets which are tailored for different geospatial datasets and services.

- **ISO 19115-1:** The basic metadata schema for geographic information. It includes information about the data quality, spatial and temporal characteristics, data distribution, and other descriptive information.
- **ISO 19115-2:** This schema is used to describe imagery and gridded data, including satellite imagery, aerial photography, and digital elevation models.

### 3.5 METADATA AND PARADATA

ISO 19115 Core	Required?	INSPIRE Implementing Rules for Metadata	Required?	uk gemini (ukinspire)	Required?	Dublin Core Equivalent (not recommended)
						Contributor
						Coverage
Geographic location of the dataset	Conditional	Part B 4.1 Geographic Bounding Box	Mandatory	Bounding box	Mandatory	Coverage: Box
Spatial resolution of the dataset	Optional	Part B 6.2 Spatial Resolution	Conditional	Spatial resolution	Conditional	
Additional extent information for the dataset (vertical and temporal)	Optional	Part B 5.1 Temporal extent	Conditional	Temporal extent	Mandatory	Coverage: Temporal
				Extent	Optional	
				Vertical extent information	Optional	
Spatial representation type	Optional			Spatial representation type	Mandatory	
Reference system	Optional			Spatial reference system	Mandatory	
				Equivalent scale	Optional	
Dataset responsible party	Optional	Part B 9 Responsible organisation	Mandatory	Responsible organisation	Mandatory	Creator
Dataset reference date	Mandatory	Part B 5 Temporal Reference	Conditional	Dataset reference date	Mandatory	Date
Metadata date stamp	Mandatory	Part B 10.2 Metadata Date	Mandatory	Metadata date	Mandatory	
Abstract describing the dataset	Mandatory	Part B 1.2 Resource abstract	Mandatory	Abstract	Mandatory	Description
				Quality scope	Mandatory	
				Data quality	Conditional	
				Maintenance information	Optional	
Distribution format	Optional			Data format	Mandatory	Format
		Part B 2.2 Spatial Data Service Type	Mandatory	Spatial data service type	Mandatory	
		Part B 7 Conformity	Mandatory	Conformity	Mandatory	
Metadata character set	Conditional			Character encoding	Conditional	
Dataset character set	Conditional					
		Part B 1.5 Unique Resource Identifier	Mandatory	Resource identifier	Mandatory	Identifier
On-line resource	Optional	Part B 1.4 Resource Locator	Conditional	Resource locator	Conditional	Identifier: URI

ISO 19115 Core	Required?	INSPIRE Implementing Rules for Metadata	Required?	uk gemini (ukinspire)	Required?	Dublin Core Equivalent (not recommended)
Metadata file identifier	Optional			File Identifier	Mandatory	
Metadata point of contact	Mandatory	Part B 10.1 Metadata point of contact	Mandatory	Metadata point of contact	Mandatory	Publisher
Dataset language	Mandatory	Part B 1.7 Resource Language	Conditional	Dataset language	Mandatory	Language
Metadata language	Conditional	Part B 10.3 Metadata Language	Mandatory	Metadata language	Mandatory	
		Part B 1.6 Coupled Resource	Optional	Coupled resource	Conditional	Relation
				Parent identifier	Optional	
		Part B 8.1 Conditions for access and use	Mandatory	Use constraints	Mandatory	Rights
		Part B 8.2 Limitations on public access	Conditional	Limitations on public access	Mandatory	
Lineage	Optional	Part B 6.1 Lineage	Mandatory	Lineage	Mandatory	Source
				Hierarchy level name	Conditional	
		Part B 3 Keyword	Mandatory	Keyword	Mandatory	Subject
Dataset topic category	Mandatory	Part B 2.1 Topic Category	Mandatory	Topic Category	Optional	
Dataset title	Mandatory	Part B 1.1 Resource Title	Mandatory	Title	Mandatory	Title
				Alternative title	Optional	
		Part B 1.3 Resource Type	Mandatory	Resource type	Mandatory	Type
Metadata standard name	Optional			Metadata standard name	Optional	
Metadata standard version	Optional			Metadata standard version	Optional	

**Table 15:** Table of metadata requirements for Dublin Core, ISO 19115 Core, INSPIRE, and UK GEMINI schema. Elements that are the same, appear on the same row and the requirement for their inclusion as per each standard for is shown in the “Required?” column

LiDAR Data Exchange Format (LAS) Specification	The LAS specification developed by the American Society for Photogrammetry and Remote Sensing (ASPRS) is widely used to exchange and store ALS data. Among the metadata elements are those describing the data's acquisition parameters, classification, and other characteristics.
LASzip	LASzip is a lossless compression format for ALS data that is compatible with the ASPRS LAS specification. It includes metadata elements that describe the data's compression method and other properties. <b>LASzip should not be confused with the LAZ file format which is unsuitable for archiving due to the lossy compression used.</b>
Federal Geographic Data Committee (FGDC) CSDGM	The FGDC CSDGM is a metadata standard developed by the U.S. federal government for describing geospatial data, including ALS data. It includes metadata elements that describe the data's source, quality, and other characteristics.

**Table 16:** Metadata Schema related to specific ALS file formats

Although ISO 19115-2 was specifically designed for imagery and gridded data, it can also be used to describe other types of remotely sensed data, including ALS data. ALS data can be described using the basic metadata elements defined in ISO 19115, which includes information on identification, data quality, spatial representation, reference system, distribution, metadata extension, and contact. In addition, the following metadata elements in ISO 19115-2 can be used to provide more specific information about the ALS data:

- Platform and Sensor Information: altitude, scan frequency, pulse repetition rate, and beam divergence
- Data Acquisition Information: flight lines or survey grids, point spacing, and the type of data collected (e.g. topographic or bathymetric)
- Processing Information: filtering algorithms, interpolation methods, and error models
- Data Quality Information: accuracy, precision, and completeness

Dublin Core is a general schema which provides a set of metadata elements used to describe digital resources such as documents, images, and web pages. It provides a simple and standardised way to describe information resources and is widely used across different domains such as libraries, archives, museums, and the web. While Dublin Core is often used for exchange and aggregation of metadata across domains, **it is not recommended to use this schema** as the default for describing geospatial data as it does not require enough geospatial information to allow for easy re-use (see Table 15).

## Paradata

The term paradata refers to information, including metadata, logs, and other documentation, that defines or characterises data collection procedures. By documenting and retaining paradata during data creation and any associated derived data, it is possible to provide the means to assess the data's characteristics against its intended purpose, including recognising limitations or uncertainties. The paradata may need to be collated from a number of sources for example the paradata elements listed for point cloud data below should typically contained in the survey report for ALS data acquisitions (see also section 1.5) where the paradata for ALS-derived models may be in a processing or project report (Table 17).

## Tools for Recording Metadata and Paradata

Different metadata tools offer a range of features and capabilities. When choosing a tool, it is important to consider the features that are most important to you. Several factors such as cost, automated capture capabilities and the integration within your GIS systems may decide which platform you use. Some of the more common tools include:

### GeoNetwork

GeoNetwork is a web-based metadata management system that provides a platform for creating, editing, and sharing metadata for geospatial data. It supports the ISO 19115 metadata standard and provides a range of features for managing metadata, including advanced search and discovery tools.

Paradata for point cloud data	Paradata for elevation data
<p>Some instances of possible paradata for ALS point cloud data include:</p> <ul style="list-style-type: none"> <li>• Sensor specifications: laser wavelength, pulse repetition rate, field of view, and scan angle</li> <li>• Flight parameters: altitude, airspeed, and flight route of the plane or drone that collected the ALS data</li> <li>• Scan settings: rate of laser shots, the scan angle, and the scan direction</li> <li>• Calibration data: precision of the range estimations and the laser beam alignment</li> <li>• Quality control: GNSS data, quantity of control points georeferencing the data, and the precision of the point cloud</li> </ul>	<p>Instances of where paradata for elevation data can be found include:</p> <ul style="list-style-type: none"> <li>• Information about the data's original source: the date and time it was acquired, the type of sensor used to measure elevation (such as a ALS or photogrammetry), and the spatial resolution of the source data</li> <li>• Information on data processing: the procedures used to transform raw elevation data into a DEM, the software and techniques used, any filtering or smoothing, and corrections for mistakes or inconsistencies in the data</li> <li>• Information on accuracy assessment: the root mean square error (RMSE), the vertical accuracy, the error statistics for various DEM components, quality assurance procedures, and ground control points</li> <li>• Provenance data: the history of the DEM data, updates made to the data, and ownership or lineage</li> </ul>

**Table 17:** Examples of paradata for point clouds and elevation models

### ArcGIS Metadata Editor

ArcGIS Metadata Editor is a desktop application that allows users to create and edit metadata for geospatial data in a variety of formats, including Shapefile and File Geodatabase. It supports the ISO 19115 and 19139 metadata standards and includes a range of tools for managing metadata, including automated metadata generation and batch editing.

### QGIS metadata tools

QGIS is a free and open-source desktop GIS software that includes tools for creating and editing metadata for geospatial data. It supports a range of metadata standards, including ISO 19115, FGDC, and Dublin Core, and includes a range of tools for managing metadata, including automated metadata generation and batch editing. Several plugins exist to improve and extend the core functionality of metadata within QGIS.

### FGDC Metadata Editor

FGDC Metadata Editor is a desktop application that allows users to create and edit metadata for geospatial data in the Federal Geographic Data Committee (FGDC) metadata standard. It includes a range of features for managing metadata, including batch editing and automated metadata generation.

### Metadata and Paradata in Practice

During the process of working with ALS data, recording metadata and paradata can be easy to overlook. As the ALS is captured and processed, the knowledge of who, when, and how is often available to the team and yet these pieces of information can be difficult and time consuming to document if not planned for properly. It's for this reason that including how to document metadata and paradata within the DMP is vital. As discussed in section 3.3, a DMP is a dynamic document that helps set out the lifecycle of the project. Without metadata and paradata the ALS-data and derivatives have significantly less value and may be rendered unusable.

Updating and collecting the metadata and paradata is a continuous activity and should accompany the data from raw data to interpretive derivatives. Some of the metadata can be generated automatically (e.g. processing reports during data transformations) and both can be embedded within the data or may need to be exported during creation and accompany the data. Alternatively, some information such as weather conditions will need to be manually created. The

tools listed above can be helpful for embedding some of the metadata and paradata within the data itself. Alternatively, separate external documents or spreadsheets can be created to accompany that data. For online catalogues, the metadata can be presented in the form of a webpage or interactive dashboard which aids accessibility as the example metadata from the UK Environment Agency lidar catalogue in Figure 36 shows.

**LIDAR DTM Time Stamped Tiles**

**Summary**  
The LIDAR DTM (Digital Terrain Model) Time Stamped Tiles product is an archive of raster elevation data produced by the Environment Agency. Site specific LIDAR surveys have been carried out across England since 1998, with certain areas, such as the coastal zone, being surveyed multiple times. Data is available at varying resolutions of 25cm, 50cm, 1m and 2m, depending on project requirements.

**Categories**  
environment, elevation

**Keywords**  
Elevation, mapping, flood, mapping, GIS digital format, remote sensing, LIDAR

**Use limitation statement**  
There are no public access constraints to this data. Use of this data is subject to the licence identified.

**License**  
Open Government Licence

**Attribution statement**  
© Environment Agency copyright and/or database right 2020. All rights reserved.

**Technical information** Show ▶

**Spatial information** Show ▶

**Metadata information** Show ▶

**Data and Supporting Information** Hide ▼

Data services and download by area of interest	Link	Action
Full downloads and supporting documentation	Format	Action
OSGM02_to_OSGM15_Adjustment_Grid.zip	ZIP	<a href="#">Download</a>

**Technical information** Hide ▼

**Update frequency**  
quarterly

**Lineage**  
Light Detection and Ranging (LIDAR) is an airborne mapping technique, which uses a laser to measure the height of the terrain and surface objects on the ground such as trees and buildings. Hundreds of thousands of measurements per second are made of the ground allowing highly detailed terrain models to be generated at spatial resolutions of between 25cm and 2 metres. The vertical accuracy of the LIDAR dataset is +/-15cm RMSE.

**Spatial information** Hide ▼

**Coordinate reference system**  
<http://www.opengis.net/def/crs/EPSG/0/27700>

**Geographic extent**

Latitude from: 50 to 55.8  
Longitude from: -5.7 to 1.8

**Metadata information** Hide ▼

**Language**  
English

**Metadata identifier**  
dbadf364-0192-4bcf-a223-f3d403f08682

**Environment Agency LIDAR Capture Programme**

**Filter by Capture Season**  
No category selected

**Filter by Project Type**  
Show All

**Filter by Project Name**  
National LIDAR Programme

**Search**  
Search...

**Surveys**  
P\_10696 - Surveyed 04/04/2021 - 05/04/2021

**Map**  
Select a polygon from the list to zoom to it on the map and view its ground truth result.

Polygon ID	RMSE (m)	Surface	Ground Truth Survey ID	Ground Truth Survey Date	Standard Deviation	Random Error
P_10696	0.06	Tarmac	P_10696_TRA_21042	11/02/2021	-0.05	0.02

**Pop-up**

Survey ID	P_10696
Survey Name	
Project ID	PM_1692
Project Name	National LIDAR Programme
Coastal Work Package	
Capture Status	Surveyed
LIDAR Resolution (m)	1.00
LIDAR Accuracy (m)	0.15
Capture Season	2020/2021
Survey Area (km2)	675.77
Product Type	National LIDAR Programme - Phase 1
First Survey Date	04/04/2021
Last Survey Date	05/04/2021
Survey ID's	21-091   2021/04/04   21-093   2021/04/05
Released To DSP	Yes
GT Result	Yes
Number of GTs	4

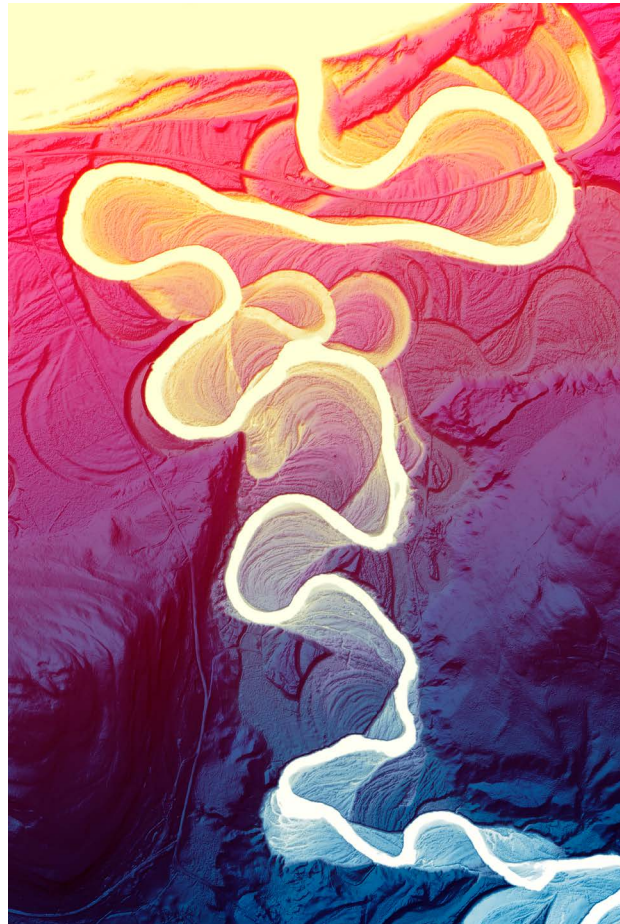
**Figure 36:** Metadata for the UK Environment Agency ALS data presented as a webpage (top) with additional detailed metadata for the UK Environment Agency ALS data capture program presented as an interactive ArcGIS web app (bottom).

## 3.6 Dissemination and Public Outreach

Jitte Waagen, Kimberley Teale, Rebecca Bennett, Steve Davis

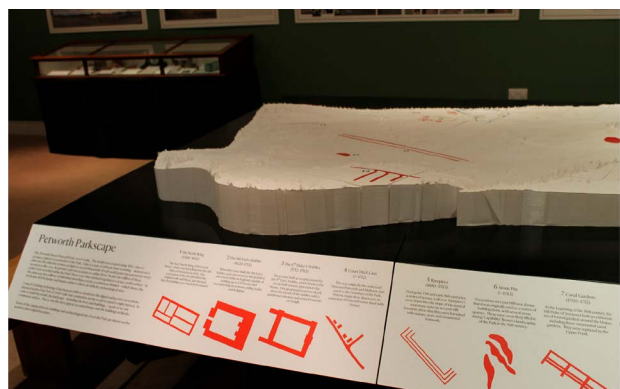
ALS-derived visualisations of archaeological sites and landscapes have the potential to capture the imagination of interested parties beyond the sphere of heritage professionals (Figure 37). With the increasing availability of open data from a wide range of sources it is now common to see social media posts from archaeologists and cultural heritage organisations that feature some form of ALS-derived visualisation, and likewise from interested members of the public exploring the data themselves. This engagement of a broad audience should be welcomed, and has enormous potential to stimulate wider interest in archaeological prospection and encourage greater engagement in the process of identifying sites and understanding landscapes (e.g. via citizen science see section 2.6). Members of the public exploring open source satellite imagery (e.g. Google Earth; Bing) for prospection is already well established, and with appropriate training the use of ALS-derived data is a natural extension of this (see section 2.6).

The use of ALS data for community engagement has broad potential beyond citizen science applications, including projects that bring the archaeological landscape to life in a variety of interpretative forms. These can range from exhibitions including 3D printed landscape models (Figure 38) and interactive displays, to digital mapping, landscape reconstructions and augmented reality 360° digital experiences. It also includes the use of a variety of illustrative materials (such as information boards, posters, books, leaflets and video content) that can help to share not only



**Figure 37:** ALS data as art: the Máskejohka River in Norway, as rendered from ALS data by Daniel Coe, [dancoecarto.com](http://dancoecarto.com)

the outcomes of a project but the story of how ALS data can be used to understand and protect cultural landscapes. An excellent example of the documentation via video of a community archaeology project built around ALS acquisition and analysis is provided by the Secrets of the High Woods Project film.



**Figure 38:** 3D printed model of Petworth House and Park, UK, created using ALS data and used to support the interpretation of the historic landscape for visitors © National Trust

### Innovative Exhibitions

The images below show the exhibition created for the 'Verderers of the New Forest Higher Level Stewardship Scheme', created by UK New Forest National Park Authority in 2015. The exhibition shared work undertaken, and discoveries made during the 10-year project which saw 23,000ha of the National Park surveyed through remote sensing and volunteer terrestrial survey. The exhibition included virtual reconstructions of sites, an interactive touch table where visitors could interpret ALS data, virtual reality treasure hunts and 3D printed digital terrain models of some of the sites found within the New Forest.



**Figure 39:** Exhibition celebrating the methods and results of the UK New Forest National Park's ALS projects

A mobile exhibition was produced for the 'Secrets of the High Woods' project (South Downs National Park, 2013-16) to celebrate and communicate the work undertaken by local communities using ALS data. Jam Creative produced a series of free-standing exhibition panels that could be configured differently depending on the venue they were being taken to, together with a central 'AR-chaecology table' that allowed visitors to peel back the historical layers of the landscape using augmented reality. The exhibition was accompanied by an augmented reality app that allowed visitors to compare the landscape that they know today with that of the past by adding animations of a World War One airship station, a World War Two Canadian training camp and a Bronze Age funerary barrow.

The project also used gaming software to recreate ancient landscapes as 360° interactive experiences from the ALS data. These allowed visitors to virtually walk through time, exploring day to day activity in an Iron Age settlement, a medieval deer park during a hunt and a World War One Canadian lumber camp.

The process of capturing and using the ALS data was also explained in a series of animations, that showed how the technology was used to uncover archaeological features hidden within the wooded areas of the National Park.

Both exhibitions were considered highly successful in conveying a sense of woodland exploration and discovery, and engaging a new generation with their heritage and archaeology.



**Figure 40:** The Interactive Public Exhibition produced for the Secrets of the High Woods Project (© South Downs National Park Authority)

The integration of ALS-derived data and imagery into public interpretation can often be uniquely valuable, providing a perspective on the landscape and cultural heritage that has never been experienced before, even by those who live within it. In addition, the cross-over of the use of science and technology to understand human stories appeals to a broad range of people. Demonstrating how ALS technology can be a tool for discovery can engage non-traditional audiences, younger people or those with less affinity to the countryside for example, inspiring new interest in the cultural environment and archaeological methods to understand it.

The ability to share a landscape and its development over time digitally can also help address some of the accessibility challenges that may restrict wider participation in heritage. Between a quarter and a third of the population may experience physical or health barriers to exploring a landscape in person before accounting for financial barriers (European Commission, 2019). You do not need any level of fitness or mobility to explore a virtual landscape in augmented reality. Additionally, it is often easier to make accommodations for users with sight or hearing loss in a digital environment than in the real world. The use of screens to display and explore interpretative material and integration of interactivity, that allows

the user to control content and pace of change, can provide greater opportunities for assistive technologies and self-led exploration that can improve user experience. Indeed the ability to access interpretative materials from your own location on a personal internet-enabled device all but removes physical location as an inhibiting factor when exploring the cultural heritage of a landscape.

There are strong benefits to sharing ALS-based projects and imagery with the wider community, not least of which are the enhancement of engagement with cultural heritage and community decision making. It is therefore important to ensure that the correct licensing terms are in place for any commissioned data to facilitate sharing it in a variety of ways (see section 1.5) and to integrate public dissemination as part of the project planning and management.

### **Explaining ALS for the non-specialist**

The use of ALS datasets and derived imagery for public interpretation is not without its challenges. As these guidelines show, there are many aspects that require technical understanding or explanation no matter the audience. For example, the most common representation of ALS data is as a shaded relief image and for many non-specialists this style of visualisation

is synonymous with the term “lidar”. Beyond the observation that it looks a bit like an aerial photograph, it is not inherently obvious what the ALS derived images actually represent and this is clearly an obstacle to their correct interpretation. The way that the information about the visualisation is communicated is key and this can be challenging.

When sharing interpretation with the wider community, it is good practice to evaluate the depth of knowledge required to access the information being shared. By taking care to consider such issues, it is more likely that knowledge is shared in an accessible way. If detailed or specialised knowledge is needed, that information should be provided in a way that is accessible, easy to access and free from professional terminology or assumed prior knowledge.

### **Dissemination – Helping others to work with ALS Data**

Working effectively with ALS-derived raster datasets requires some GIS experience that cannot be guaranteed for amongst professionals. Thus providing access to a dataset does not necessarily make it accessible. Although resources can be limited for any scale of community training, the sector benefits by being able to provide advice and support to community groups who want to develop their use of ALS data.

Making provision for training also helps to guide the non-specialist user away from naïve expectations of ALS data. It is common to hear ALS described in misleading terms such as ‘it’s like an X-Ray of the ground’, ‘lidar can see through trees’, or ‘new technology replacing archaeological excavations’. This can lead to bitter disappointment in community projects where money is spent on datasets that show little or nothing of any significance either because of past land use practices or the quality of data. ALS data need to be recognised as a valuable but typical part of the archaeological prospection process, and its place alongside field observation, geophysical survey and aerial photographs properly explained. As professionals and curators we can help to change common misconceptions through open engagement with the general public, offering training and information wherever possible and designing a range of public engagement methods into our projects.

### **Risk of illicit activity vs public interest**

Opening up ALS-derived data and archaeological interpretations to the public inevitably raises questions of the security of sites and the possibility of increased illicit or illegal activity. While there is generally greater social and political acceptance of open data, many landowners fear not only nighthawking and illegal excavation of sites but also trespass and interference with land management on private property. In the UK some community projects with commissioned ALS coverage counter these concerns by requiring registration, training and agreement of terms of use (Figure 41) before allowing access to the ALS-derived data.

Official policies on the balance of public interest and the increased risk of illicit or illegal activity vary with jurisdiction. For example in Ireland the entire Sites and Monuments record is freely available online and to download in geospatial format. This dataset is regularly updated with ‘new’ sites, the legal protection of which is currently questionable. However, national ALS coverage is still some way off and metal detecting of any field, whether a recorded site or not, without a specific detection license for the purpose of finding archaeology is against the law. In some countries descendent communities may not want heritage or archaeological data to be published and projects involving the mapping of such sites and features should consider these cultural sensitivities and respect community views (e.g. Davis et al., 2021a).

In other jurisdictions access to information about known or suspected sites is much more closely regulated. In such circumstances it seems likely that availability of open ALS data could be of significant value to treasure hunters or looters, and is likely regularly interrogated by them. The decision that ALS data are to be made publicly available is often taken a governmental level and in these circumstances cultural heritage managers may find themselves in a reactive rather than proactive position. It is possible that national datasets could be made available but with a requirement for registration and agreement of licensing requirements. However, given the objective of such requirements would be to target heritage crime, and that criminals by definition do not abide by rules and regulations, this is potentially of limited value.

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**Figure 41:** Kent Lidar Portal's Terms of Use. Registering on the portal requires acceptance of these terms before the data can be accessed

Essentially the only viable routes to combat illicit activities are rapid assessment and inclusion of features within open access ALS data to the relevant cultural heritage databases and effective policing of local rules and regulations on looting/unlicensed prospection. However public engagement with local cultural heritage that encourages increased knowledge of and respect for the landscape also plays a part in promoting self-governance of human behaviours, illegal or otherwise, that would prove detrimental to their environs.

## Case Study 3: ALS for Forested and Woodland Environments

Ole Risbøl, Peter Crow, Rebecca Bennett

### Introduction

The ability of ALS to potentially “see through the trees” has been a significant driving factor behind its development and application in cultural environment surveys. Whilst other remote sensing techniques such as Synthetic Aperture Radar (SAR) are capable of mapping below a forest canopy, they do not have the ability to provide the high resolution, landscape-scale results that ALS can produce. Consequently, before the application of ALS, aerial surveillance was limited to visual and photographic records and the cultural heritage assets located within woods and forests were often unknown or not mapped in detail when compared to features in tree-less landscapes. Additionally, a low prioritisation of forested land for archaeological ground based survey strengthened the bias in documentation of cultural heritage assets. This is despite the potential for good preservation of features in woodland where they are protected from many degenerative processes of land management such as ploughing. Wooded environments contain archaeological features that were obscured, unknown and unmapped for the majority of the 20th century and consequently many significant landscapes have been discovered in the last 20 years since the widespread application of surveys.

ALS data can be specifically commissioned for heritage purposes, but as we have seen elsewhere they also have many other potential landscape and environmental applications. In a forestry context, height difference models between the Digital Surface Model and the Digital Terrain Model can be used to map vegetation height, and when combined with reflectance data of the lidar infra-red laser (section 1.2), facilitates the mapping of vegetation types. The cross-disciplinary applications of ALS surveys allow the data and derived models to be shared and enable different potential user groups to collaborate on commissioning new surveys. However different users may have different requirements, affecting the specification of the survey (section 1.5). For example, ALS commissioned to provide information about vegetation e.g. forest inventory, canopy height, crop or biomass modelling will likely be flown in summer when the vegetation is in leaf. For a survey of a deciduous woodland with a heritage interest, a survey during the winter season is preferred as the trees will

be devoid of foliage, allowing better penetration of the laser through the canopy to the forest floor (Crow et al., 2007; Devereux et al., 2005).

### Benefits of ALS Survey in Wooded Environments

There is no doubt that ALS has the potential to produce spectacular results, mapping previously unknown or unrecorded archaeological features hidden under woodland in remarkable detail. When surveyed using a large aircraft, entire landscapes can be mapped in a few days, whilst still collecting sub-metre resolution data. Few other single survey techniques have the potential ability to add so much information to our understanding of the historic environment both within and of the woodland. As modern land use often varies from that of earlier periods, woodlands can contain the remains of many different features and site types. In good conditions with an appropriate survey specification (see section 1.5 and below), distinctive features relating to historic woodland management activities such as saw pits, charcoal hearths, tar kilns, settlement sites, hollow-roads and mineral extraction pits can also be mapped. Linear features and large monuments can be shown in detail and their relationship to the surrounding terrain and landscape examined. Woodlands and forests can also be considered heritage assets in their own right, as part of designed landscapes, or containing old hedgerows or individual ancient trees that can also be recorded using ALS data.

### Vegetation Challenges

The use of ALS to map heritage assets within a wooded environment has proven to be highly effective, but there are many limitations to the technique, and it is important to understand them when considering the acquisition of a new survey, using data from another source, when processing data and interpreting the results. The most important of these is an assessment of the type of vegetation through which the survey is to be applied (Crow et al., 2007; Doneus et al., 2022a). Any dense vegetation, such as evergreen trees like yew (*Taxus accata*), shrubs such as holly (*Ilex aquifolium*), heather (*Calluna vulgaris*) or juniper (*Juniperus communis*) or ground cover such as bracken (*Pteridium aquilinum*), have the potential to block the laser and

prevent it from reaching the forest floor. This is also true for dense conifer forests.

For surveys of deciduous forests, flights during the winter season are preferable and the trees will be devoid of leaves and understory vegetation will be dormant. The optimal time of year is in the months before spring, when any winter storms and snowfall have compressed any ground vegetation and after the snow has melted. Late autumn after defoliation is also an acceptable option in some parts of the world. ALS surveys in the winter season pose other challenges as the weather is less likely to be suitable for flying a survey and any snowfall or flooded areas will prevent the laser from reaching the forest floor. Daylight hours may also be shorter, reducing the ability to collect complementary datasets such as aerial photography. Surveys need to be completed before the vegetation comes into leaf in the spring, so the window of opportunity to acquire the data can be small. Deciduous forests during the summer months will often have a closed, intergrown canopy. ALS surveys or existing data (perhaps obtained for another purpose) can still be useful, but many features on the ground will remain obscured by the canopy and so should be factored into any interpretation of the data.

For surveys of coniferous forests acquisition dates may seem to be more flexible, but this will depend upon the age, type, and density of the forest. Any coniferous or mixed forest as well as a mature, well-thinned plantation may still have many open areas in which light can reach the forest floor. But here ground vegetation is also likely to have grown and whilst a summer survey may be acceptable from a canopy perspective, ground vegetation is likely to be a problem.

In addition to the season and vegetation cover, other survey parameters can be altered to increase the likelihood of a successful survey. The more times a laser pulse is directed at an area of woodland, the greater the chance that some of the laser energy will reach the ground. A survey specified with high DTM point density (the average number of laser points per square meter that can be attributed to ground returns) is therefore desirable to increase the chance of a woodland floor being mapped. Point densities can be increased by raising the sampling frequency of the laser scanner, or the time the system spends over the target area. If the data capture of a survey area requires a series of parallel flight lines, options such as having a large degree of overlap with each flight line can generate more data points. Similarly, using a slower aircraft or

an UAV will also increase the number of data points captured. However, obtaining the optimum point density requires compromise as using slower aircraft, UAV or increasing flight overlaps can increase the time and therefore cost of data capture and increasing the point density will require more data processing time and storage capacity. Therefore there is a tipping point of the ALS survey specification at which there is little to be gained by continuing to increase the point density. The best survey specification will depend upon the nature of the vegetation cover and the probable size of the features of potential interest so it is important for heritage managers to incorporate this information into the development of the ALS specification if there is opportunity to do so (Bollandsås et al., 2012; Risbøl et al., 2013).

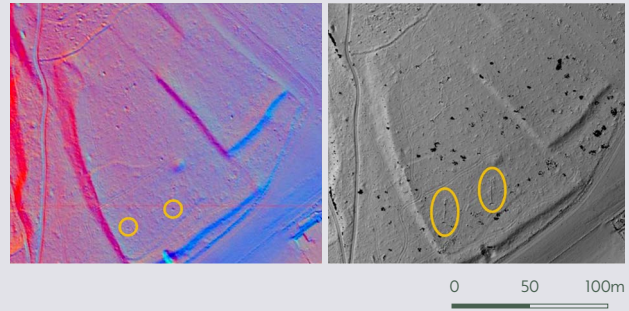
### ALS Processing Challenges in Wooded Environments

The unique strength of ALS data is the ability to filter the reflected points to remove above ground features and model a 'bare earth' DTM below the canopy. There are many ways in which the ALS data can be specified and processed (sections 1.5 and 2.1). In particular the parameters chosen during the process of classification of the point cloud can influence the way in which points relating to vegetation and buildings are identified and removed (see section 2.1). Too harsh a filter risks removing relevant archaeological terrain features from the DTM along with non-ground points but too gentle a filter will result in understory vegetation or features such as wood piles remaining in the DTM model which can complicate archaeological interpretation. Similarly, gaps left in the DTM where above ground data like trees and understory are removed, can be smoothed and infilled as part of the interpolation. This interpolation is an essential step for further processing and visualisation but has the potential disadvantage of masking areas where the ALS survey was less effective at penetrating the canopy.

It is important to know where the laser was less able to penetrate the canopy, as the resulting DTM model may contain areas that don't appear to have any heritage features, but in reality these may simply not have been detected by the sensor. An absence of features in the DTM model is not necessarily an absence of features detectable on the ground. Figure 42 shows a composite image of several hillshades with a number of small pits that may be of archaeological interest alongside a single

hillshaded image of the same area using a different DTM model where the on-ground points were filtered less aggressively and gaps the model left unfilled. In this second image, the trunks of the fallen trees are visible as narrow linear features in the model, allowing the nature of the pits to be identified (see the two highlighted examples with more fallen trees evidenced beside the cluster of pits to the north). A similar result could potentially be achieved by comparing the DTM and DFM. An example of the triangulated appearance that typifies interpolated areas of the DTM model where no ground points were measured can be seen highlighted in the orange boundary in Figure 43, contrasting with the continuous and smoother presentation of the DTM surface in the area if open field to the north. The image shows a wooded area where ALS has revealed a lot of archaeological features, most noticeably the circular features that indicate charcoal kilns. Inside the orange boundary the kilns are much less easily identified due to the lack of ground points. Interpreters should familiarise themselves with this type of data artefact and

may also help to use a “mask layer” showing the pixels that did not contain any ground measurement (Figure 44) as a complementary dataset to the DTM to improve interpretation.



**Figure 42:** Two DTM models showing small pits. The left DTM model has been subject to more aggressive filtering of non-ground points while the right model retains features low to the ground (such as fallen tree trunks) aiding interpretation (image credit: Peter Crow, Forest Research, ALS data: © South Downs National Park Authority)



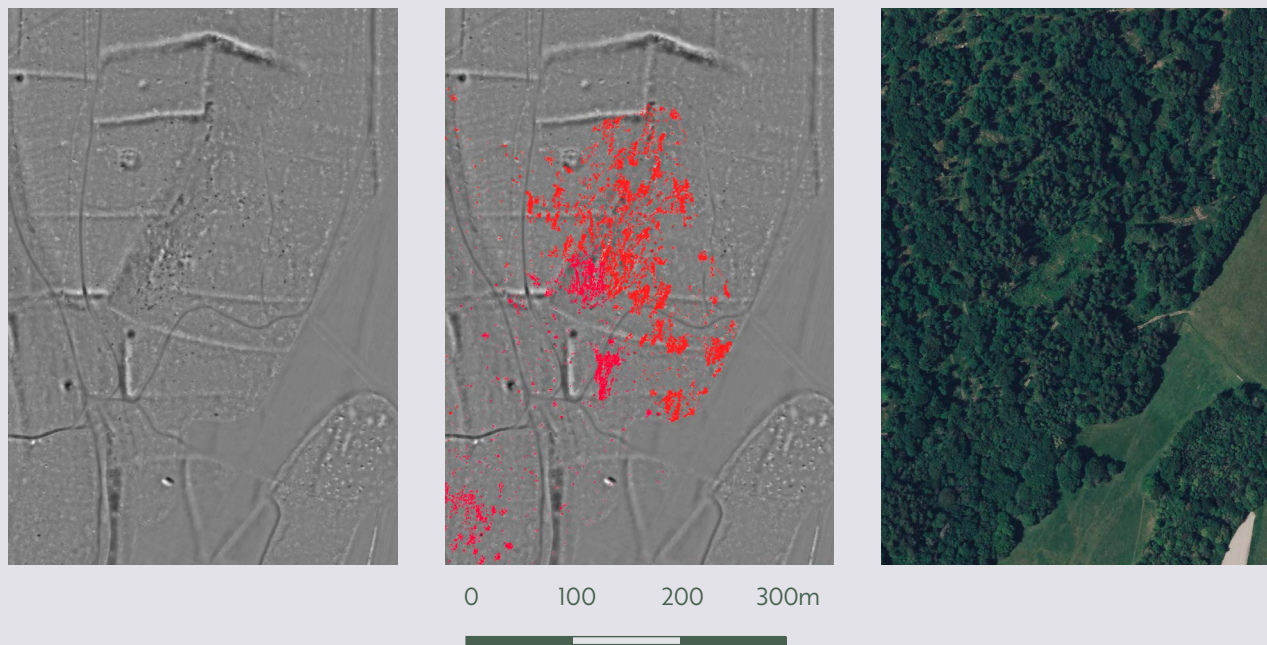
**Figure 43:** Aerial photograph fading into a hillshaded DTM of a wooded area in Norway showing multiple circular charcoal kilns. Triangular artefacts created by interpolation across areas where no ground points were recorded can be seen highlighted in the orange area in this image (credit: Magnar Mojaren Gran, NTNU University Museum)

### Ground Observations

Survey based primarily on remote sensed data benefits from ground observation as it helps to build up knowledge of the survey area and may be essential to understanding ambiguous features. Thus, depending on the specification of the survey, some element of ground observation (section 2.7) is highly desirable, recognising that in some cases (e.g. war zones) this may not be possible. As we have seen above, the challenges posed to accurate DTM creation by woodland canopy and the fact that complementary sources such as aerial imagery is significantly less useful in these environments means that ground observations are even more important. There is a need to validate and add information to features identified from the terrain model, to ensure that they are not products created by the ALS data processing (known as data artefacts) but also to clarify which features are a result of modern forestry activities or the typically more rugged terrain with natural anomalies that could be mistaken for cultural features. A knowledge of the typical vegetation cover of a survey area is strongly recommended as it can guide

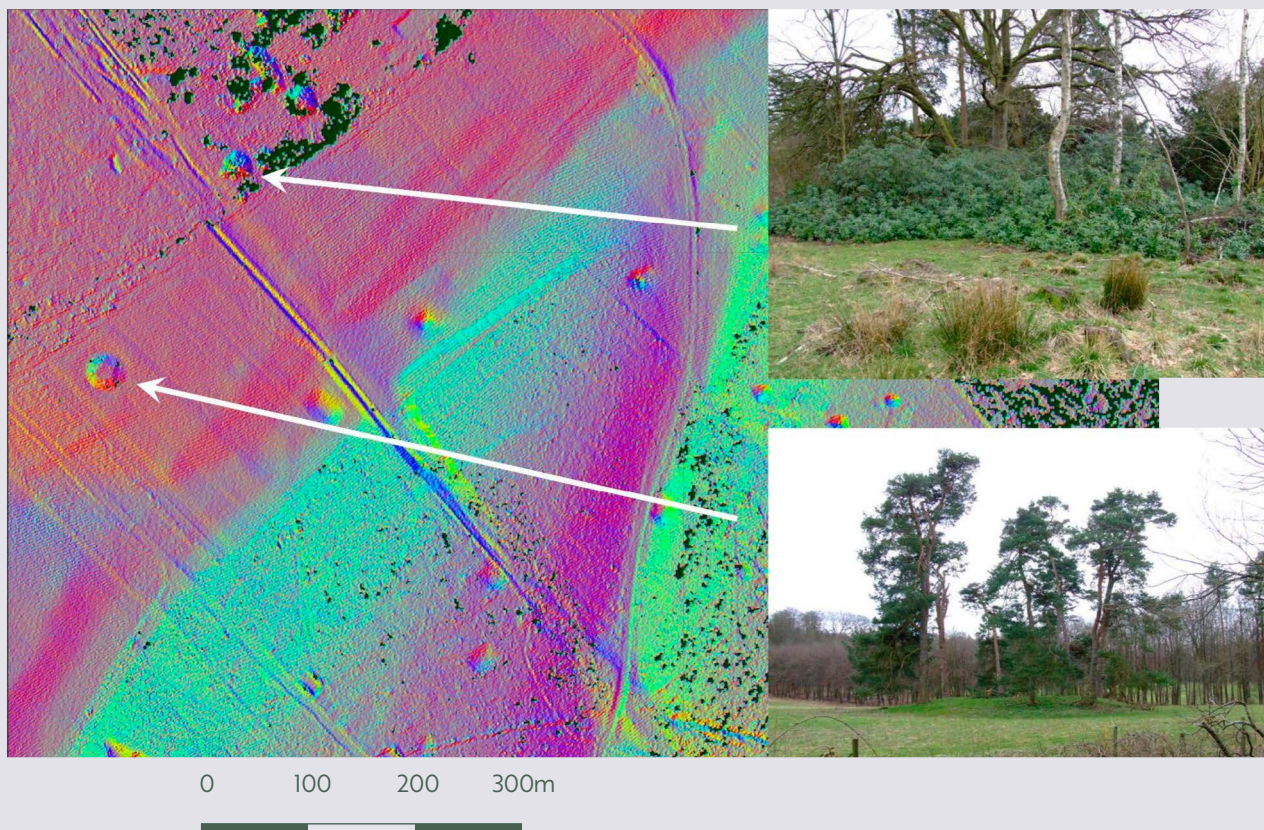
the confidence with which ALS data are interpreted for heritage assets. While there may be existing habitat mapping available, the broad categories typically used will likely need to be complemented by field observations to understand the impact of woodland type and understory on the ALS data and resulting models (Figure 45).

Recording contemporary woodland management is also an important function of ground survey. Areas where the trees have been recently removed as part of routine forest operations may be perceived to be good targets for ALS surveys, however piles of forest waste (often raked into rows or piles) or stacks of timber can resemble cultural features on the terrain model, or mask others beneath them and there is often extensive turbation of the ground surface if the trees have been mechanically harvested. If trees were removed in the preceding years, it is likely that new trees have started to grow, along with other colonising plant species. This regrowth can form a very complex and often dense vegetation layer that inhibits both ALS and ground survey.



**Figure 44:** A mask layer (red) can be overlain on the LRM visualisation of the ALS data as an interpretation aid to show areas where the data did not meet the minimum specification of eight points per metre ALS Data

© Southdowns National Park Authority



**Figure 45:** Ground observations of understory are key to understanding features identified in the DTM as with this example of two mounds in Wiltshire, southern England (image credit: Peter Crow, Forest Research, ALS data © Forestry Commission)

### Key Information for Using ALS in Wooded Environments

There are several factors that must be taken into consideration when assessing ALS data for cultural heritage purposes in wooded environments. The method has a lot of potential but it is essential that users are aware of the limitations to ensure good quality outcomes.

- The cultural heritage of and within wooded environments are typically under-represented in archaeological records due to the difficulties of remote survey and access. ALS survey is the primary tool for mapping and interpreting archaeological heritage in these environments.
- Collecting data in leaf-off condition is critical for ALS survey of woodland and forests. Surveys should be specified with a higher density of pulses to ensure a high-resolution DTM after the removal of vegetation.
- No matter how high the resolution there will always be parts of the DTM model that will be interpolated in wooded environments. Varying the classification parameters, using the DFM in addition to the DTM and incorporating a mask layer to highlight any gaps in the model can aid interpretation.
- Knowledge of the woodland type, condition of the understory and current management is key to contextualising and interpreting the ALS data.
- Ground observations are valuable in wooded environments and allow an assessment of the quality of the DTM model.

## SECTION 4

### Applications and Management Considerations

This section provides guidance for specific applications of ALS data within the heritage sector. Areas covered include planning and landscape management, integration with cultural heritage records, geoarchaeological applications, change monitoring, 3D visualisation, and automated feature detection.

It is supported by the technical information in the preceding sections and by the illustrative case studies throughout the text that cover the application of ALS for cultural heritage management in a range of environments and situations:

- Coastal Environments (page 21)
- Agricultural Environments (page 43)
- Forested and Woodland Environments (page 112)
- Integration with The World Heritage Convention (WHC) UNESCO (page 119)
- Integration with Heritage Building Information Modelling And Restoration Systems (page 130)
- Automatic Detection of Archaeological Features (page 138)
- Wetland Environments (page 147)

## 4.1 ALS for Heritage Management

Keith Challis, Ole Risbøl, Simon Crutchley

### Introduction

For many countries in Europe, documentation and understanding of cultural landscapes at scale and proactive management, are key principles of modern cultural heritage management practice. This is enshrined in The Convention for the Protection of the Archaeological Heritage of Europe in the obligation 'to make or bring up to date surveys, inventories and maps of archaeological sites' (Valetta: Article 7), recognising that identification and recording of cultural landscapes is foundation knowledge, central to investigating, caring for and promoting the historic environment, and is also promoted by The Council of Europe Landscape Convention ([ETS No. 176](#)) promotes the protection, management and planning of the landscapes and organises international co-operation on landscape issues.

The growing recognition of extensive cultural landscapes, comprising not just the remains of traditional archaeological and historical sites such as castles and settlements but rich palimpsests of agricultural and other remains, has been a stimulus to the development of a landscape-based approach in archaeology (Bradford, 1957; David and Thomas, 2016).

The increasing recognition of relict physical remains of past human activity in the contemporary landscape developed alongside a more mature understanding of landscape history. At the same time, the understanding of landscape as an entity shaped by the activities of societies and requiring thoughtful conservation management grew across Europe, informed to varying degrees by differing social and political mores. Therefore proactive management of cultural heritage within dynamic modern landscapes poses significant challenges (Hale and Kersting, 2024).

Landscape archaeology and landscape management has benefited from applications of airborne remote sensed data, whether conventional aerial photography, satellite imagery and increasingly airborne laser scanning, to identify and document cultural landscapes at scale (see section 1.3). Management of cultural landscapes requires both deep and broad knowledge about humans' interaction with their surroundings in the past and how this has changed over time. ALS is a useful tool to underpin this requirement, especially as ALS coverage has increased.

Initial use of ALS data in archaeological studies focussed on identification and documentation of landscape features (see sections 2.3 and 2.4), with a focus also on increasing knowledge about how people interacted with their environments in the past developing thereafter. Thus, an increasingly broad spectrum of archaeological landscape studies are based on, or informed by ALS datasets (e.g. Filzwieser and Eichert, 2020; Meylemans et al., 2017; Mlekuž, 2018), including studies of time-depth and landscape complexity (Bernardini et al., 2020; Doneus et al., 2022b; Vavrouchová et al., 2022; Wallace and Mullen, 2019) and case studies of the specific impacts on landscapes of activities such as mining (Currás and Sánchez-Palencia, 2021; Fonte et al., 2021) and World War Two battlegrounds (Affek et al., 2022; Dolejš et al., 2020).

Landscape scale documentation and understanding requires the consideration of complex human-nature interactions over time. This recognises that the material remains of the past have been modified, destroyed and selectively preserved by ongoing processes of human activity, and are seen in the framework of the contemporary landscape – the ‘past in the present’. Unravelling and understanding this potential complexity requires a wide range of information (e.g. historic maps, aerial imagery; see section 2.4), of which ALS data is a powerful source to develop such an approach, especially as coverage increases (i.e. by national agencies). Several countries have total, or near total coverage, which allows the integration of ALS as a standard tool in any survey across multiple landscape types.

The effectiveness of ALS data varies significantly depending on past and present patterns on land use, which are key factors in the differential survival of relief features expressed in the surface topography. Thus, areas of ancient woodland can routinely preserve the remains of relict landscapes, which is also true of uncultivated upland areas (Doneus and Briese, 2011; Kincey et al., 2014; Kincey and Challis, 2010). In arable landscapes heavily ploughed features can also be detected in ALS data, often exclusively so because their physical remains are so badly degraded by modern agricultural practices it is extremely difficult to detect their presence via other techniques (Gojda and Čulíková, 2016; Poirier et al., 2013). In some cases ALS data may record changes vegetation proxies (changes in biomass, canopy height and /or density) for buried features (e.g. Stott et al.,

2015). Use of ALS data has significantly increased appreciation of many other lowland landscapes and palaeogeographies including the Vale of York (Howard et al., 2008a a) and Trent Valley (Howard et al., 2008b b) in the UK.

The potential value of ALS datasets in a wide range of contexts is amply demonstrated in this volume and elsewhere, with key challenges in ensuring that applications are appropriate, and the characteristics of data sources are well-understood. Such considerations are central to effective integration of information to inform heritage management, whether that is in a framework provided by regional and national planning and development control systems or the UNESCO World Heritage Convention. In these contexts, different requirements for presentation of information will be relevant to effective integration of ALS-derived work with cultural heritage records, and for effective communication of information to stakeholders who may include Development Control Officers and Data Managers (see sections 4.2 and 4.3).

Within the broad range of information that ALS data may provide for landscape archaeology and heritage management, specific approaches are likely to be especially important. Beyond the identification, documentation and understanding of landscapes, ALS can provide a very powerful means of monitoring change at both site and landscape scales, for example in generating different maps that document the erosion of surface features (section 4.4). Such work requires careful assessment of data characteristics to generate accurate outputs, highlighting the need to ensure data processing steps and processes (sections 2.1 and 2.2) are well understood. The same is true of the use of artificial intelligence, machine learning and other automated or semi-automated approaches to data analysis (section 2.5 and 4.5), where decisions taken at all stages in the workflow can have significant impacts on the character of outputs.

Returning to the importance of the wider landscape scale perspective that ALS and other airborne remote sensing data can bring, that wider spatial context includes geoarchaeological applications (section 4.6) that not only provide important context for interpretation of archaeological remains, but also contribute to a broad understanding of landscape history. This highlights the extent to which working at landscape scales with datasets such as ALS requires integration with other disciplines, and a consideration

of how such complex integrated datasets can best be visualised and integrated to communicate outcomes to a range of audiences, including the use of gaming software (section 4.7).

As instructive and useful as ALS data are, they are most effectively deployed to understand the cultural heritage of a landscape when combined and

compared with other sources. It is therefore essential that heritage managers are familiar with best practice principles for the integration of ALS-derived features into landscape management strategies. This following case studies focus explore the development of more accurate conservation policies via the integration of ALS data.

### Integration With The World Heritage Convention (WHC) UNESCO

Carolina Collaro, Antonio Jesús Ortiz Villarejo, Alexandra Bucha Rášová, Ján Zachar

One example of where these roles can be brought together for a specific purpose is those sites that are inscribed on the UNESCO World Heritage List, or those that are being submitted for consideration (e.g. Corns and Shaw, 2013; Evans et al., 2013b; Li et al., 2023; Megarry et al., 2016). A central challenge for such monuments is the preservation of the Outstanding Universal Value (OUV) that the UNESCO inscription recognises. In order to do this, archaeologists must understand how to maintain the OUV (Gullino and Larcher, 2013), and the integrity of the cultural heritage represented by the structures and other features

of a site designated site in the World Heritage Convention (Gu et al., 2023). As has been demonstrated throughout these guidelines, ALS-derived models provide a powerful means to document significant features, also providing a source of baseline data for future monitoring and a means to disseminate understandings of globally important sites more widely. Increasingly ALS data is being captured to support applications to UNESCO, demonstrating the OUV of proposed sites, for example at Carcassonne (Figure 46). Here seven mountain castles ("Les Châteaux Cathares") spread over 60km of mountainous and difficult to access terrain provide a good illustration of why ALS data are a cost effective mapping solution, with added benefits in supporting future monitoring and a range of dissemination and education opportunities.



**Figure 46:** Seven mountain sentinel castles, associated with the fortifications of Carcassonne, were surveyed using ALS to provide a better understanding of land occupation in the medieval period around the fortifications in support of their proposal to UNESCO (Image credit: [www.lavionjaune.com](http://www.lavionjaune.com))

Here ongoing monitoring supported by ALS is very cost-effective compared to traditional methods which present many logistical challenges, and will help to safeguard the features defined as significant. For example, monitoring can allow managers to address the issue of invasive vegetation that damages the stone structures of excavated monuments.

Moreover, since archaeological sites exist in the present-day landscape, they are not isolated from their contexts, be that rural or urban, and the many processes that take place in those landscapes. The World Heritage Convention (UNESCO, 1972) acknowledges the importance

of a “buffer zone” surrounding these sites, which must also be protected and managed according to criteria established by UNESCO (Batisse, 1982). In this respect, ALS datasets demonstrate their benefits in providing landscape context, a broad view that is important to the long-term monitoring of sites protected under the International Convention.. It is not easy, especially in fragile or dynamic environments, to protect heritage from the dangers posed by nature, time, and human activities, but the use of ALS data for the wider landscape can help to define the boundaries of a buffer zone that needs protection and quantify the change through time.

## 4.2 ALS in the Context of Planning and Development Control

Bruce Mann, Jacob Streatfeild-James, James Eogan, Paul O’Keeffe, Tom Fildes, Jan Willem de Kort, Eelco Rensink

### Benefits of ALS within Planning and Development Control

#### Introduction

Examination of ALS-derived data for the detection of archaeological features contributes to a more complete record of the archaeological resource within a given area. In the context of planning and development control, this leads to a better understanding of the cultural heritage of an area and can inform more sustainable planning policies at local, regional and national level, for example, with respect to heritage conservation objectives and land-use zoning.

It can also be a key element in the planning, design and archaeological evaluation of proposed development projects. Adverse impacts from a development, particularly where archaeological remains only become apparent at a late stage, increase project risks including obtaining approval for development, increased costs, extended timescales and negative publicity. These risks can be significantly reduced and more effectively managed by using ALS-derived data to better quantify the extent of known archaeological features (i.e. those listed on regional/national registers), to help understand the wider landscape context within which they occur, and to identify previously unknown features.

By enabling more sustainable planning policy and better-informed project design and mitigation strategies, archaeological examination of ALS-derived data can contribute to improved outcomes for both the archaeological resource and for development projects.

The primary advantage of ALS over other forms of prospection is that it can be used to undertake comparatively rapid and cost-effective archaeological assessments over large geographical areas. This can include areas that are not suitable for field survey, whether because of terrain, vegetation cover or lack of access. For planning authorities this can help identify not only archaeological zones or landscapes that are particularly sensitive to change but also potentially archaeological features that were previously unknown. This data helps to inform planning considerations and discussions about future land-use. For developers, identifying areas of heightened archaeological sensitivity can act as an early warning system during the planning and design of projects. This is especially true of large-scale infrastructure developments in sectors such as transportation, renewable energy and utilities. As noted elsewhere in this guidance, not all types of archaeological sites and features can be detected in ALS-derived data, though ALS carries a considerable advantage that it is less impacted by highly variable factors such as those that influence the formation of vegetation proxies (cropmarks) for buried remains.

Incorporating an examination of ALS-derived data into the planning, design and evaluation of a development contributes to better archaeological outcomes and reduced project risks by:

- Ensuring a more robust assessment of likely archaeological impacts;
- Maximising the opportunity to avoid significant archaeological features through design and, in the case linear infrastructure developments, through better-informed route selection;
- Informing the need for and scope of further archaeological investigations to be carried out as part of the evaluation. For example, identifying areas where topographical, geophysical and metal detection surveys, and targeted test excavations need to be undertaken to complement the ALS survey;
- Reducing the overall cost and programme of the required archaeological mitigation.

To achieve maximum benefit, the examination of ALS-derived data should be undertaken as early in the development control process as possible, whether as a stand-alone assessment or as part of a more expansive desk-top study (see section 3.1). However, the timing of the ALS-derived examination will depend to some extent on whether the project can make use of pre-existing ALS-derived data (see section 1.4) or whether new data needs to be commissioned (see section 1.5). If using pre-existing data in a planning context the stakeholders must ensure that both coverage and quality is sufficient for the purposes of the review, and that any relevant access and copyright matters are resolved. The decision to commission a new survey or use existing data should be agreed by the project team with the relevant stakeholders, including regional and national archaeological curators (as appropriate) and archaeological development control officers. It should consider the nature, geographical extent and budget of the project, the project programme, the characteristics of the expected archaeological resource, the perceived sensitivity of the archaeological landscape(s), and the potential for the project to negatively impact the landscape.

### Best Practice in Decision Making

Developers should apply current best practice in their decision making when incorporating ALS survey into pre-development assessment. For example, while a general assumption may be made that commissioning an ALS survey is not cost-effective or proportionate for small or disparate geographical extents due to cost. However it may be that commissioning ALS data capture via UAV provides an appropriate approach (see section 1.5).

Careful assessment of whether the ALS data is fit for purpose is important as ALS data are not equally effective in all environments. For example, there may be less value in the analysis of topographic data for brownfield and urban sites than for rural and agricultural landscapes, so the approach to integrating ALS data should be determined accordingly. Likewise, competing demands from different specialists within the development team may lead to ALS data being captured in conditions that are poorly suited for archaeological assessment (e.g. when vegetation is in leaf), because this may be preferable for some engineering and environmental purposes. In these cases the cultural heritage specialists should document where the approach to ALS data capture has limited or negatively impacted the effectiveness of archaeological analysis.

### Defining the Scope and Approach of a Pre-development Assessment

The scope of the ALS assessment should be agreed by the project team with the relevant stakeholders, and should be appropriate to the nature and extent of the project. It is desirable for ALS-derived data covering the entire project study area to be examined archaeologically. However, this may not always be feasible. A linear infrastructure project, for example, may have an initial study area encompassing hundreds of square kilometres. The time needed to examine such a large area manually may not be compatible with the project programme and, given that much of the study area will fall out of consideration after the first design iterations, it may not be the most efficient use of resources (unless or until the required resource for assessment can be reduced, potentially via the routine integration of automated approaches into the workflow, see sections 2.5 and 4.5). For geographically extensive projects, it may be more appropriate to undertake the ALS-derived data examination once the design has identified confirmed areas of interest (for example, at route selection stage for linear infrastructure projects). Alternatively, given the advances in automated detection of archaeological features (section 2.5 and 4.5) it may be appropriate to design in multiple stages of ALS data assessment that allow human resources to be deployed appropriately while still considering very large areas.

Prior to the start of work, the project team should prepare a method statement for agreement with the relevant stakeholders, describing how the ALS-derived data examination will be undertaken, taking into account whether existing ALS-derived datasets or new ones will be used, the proposed personnel, equipment and software. The proposed approach should be proportionate to the nature and extent of the project, and the expected archaeological features within the landscape. The quality management measures that will be implemented to ensure high-quality results and outputs should also be described. The ALS-derived methodology may be included in a broader project method statement which covers a wider range of techniques for assessing an area, but the embedded ALS-derived method statement should always follow the best-practice outlined in this guidance.

The method statement is also an opportunity to document the agreed aims and scope of the work, which should be tailored to the specific needs and circumstances of the project. The study area should be clearly defined. It could be a large geographical area of interest, a development footprint or, in the case of linear infrastructure, a number of competing route options, or a preferred route option represented by a design corridor of fixed width (e.g. 500m buffer of a proposed route).

### Archaeological Assessment of ALS-derived Data

In general, the aim of the examination of ALS-derived data in a development control context is to:

- determine the morphology, extent and condition of all known archaeological features (i.e. those listed in national/regional registers), and archaeological zones/landscapes within the study area;
- identify, map and describe any previously unknown archaeological features that are discernible in the data. The results of the examination will inform the nature and scope of any further archaeological surveys and investigations to be carried out as part of the overall archaeological evaluation of the area in advance of the development.

The examination should be undertaken by competent personnel (see section 2.8) and should be based on the guidance in this document. For example, the assessment should include analysis of an appropriate range of specialist visualisations (see sections 2.1 and 3.2). The choice of visualisations should be appropriate to the terrain and expected archaeological features of the study area. The visualisations should be incorporated within a Geographical Information System (GIS) for analysis, overlay and comparison with other relevant spatial datasets such as historic maps, aerial imagery, known features and potential archaeological features identified by desk studies and surveys undertaken previously for the project (section 2.2). Other datasets and historic maps should be added to the GIS where these are relevant to feature identification, interpretation, and current condition of survival (section 2.3).

The results of the assessment should be presented to the stakeholders in a manner that clearly defines the nature of the cultural heritage that will be impacted by the development. Standards for writing archaeological reports vary depending on the country or region where the assessment is conducted. However it is particularly important that any assessment in advance of development examines the area systematically and identifies features of archaeological origin. The level of detail required may vary depending on the aims and scope of the examination but it is essential that the morphology, condition and extent of the features identified is recorded along with the feature's relative significance.

### Assessing Archaeological Potential

The relative archaeological potential of the features identified from the ALS-derived data can be expressed as an Archaeological Potential Score (see Table 18) assigned to each feature. The significance score directly contributes to the strategy for subsequent interventions and mitigation in advance of development in determining how to deal with uncertainty in ALS identification. It is expected that features scored as either a '1' or a '2' will require confirmation through additional fieldwork. Analysis of ALS-data has the potential to identify large numbers of possible, probable and certain features. Quantification of this variation in the certainty and nature of site visibility in the ALS-data is key to risk management particularly for large and rural developments.

0	a feature apparent on ALS-derived but not archaeologically significant
1	a previously unknown, possible archaeological feature
2	a previously unknown, probable archaeological feature
3	a newly discovered, previously unknown archaeological feature
4	a known archaeological feature (i.e. listed on national/regional registers) discernible in the ALS-derived data
5	a known archaeological feature that has no expression in the ALS-derived data.

**Table 18:** Example of archaeological potential score for features detected in ALS-derived data

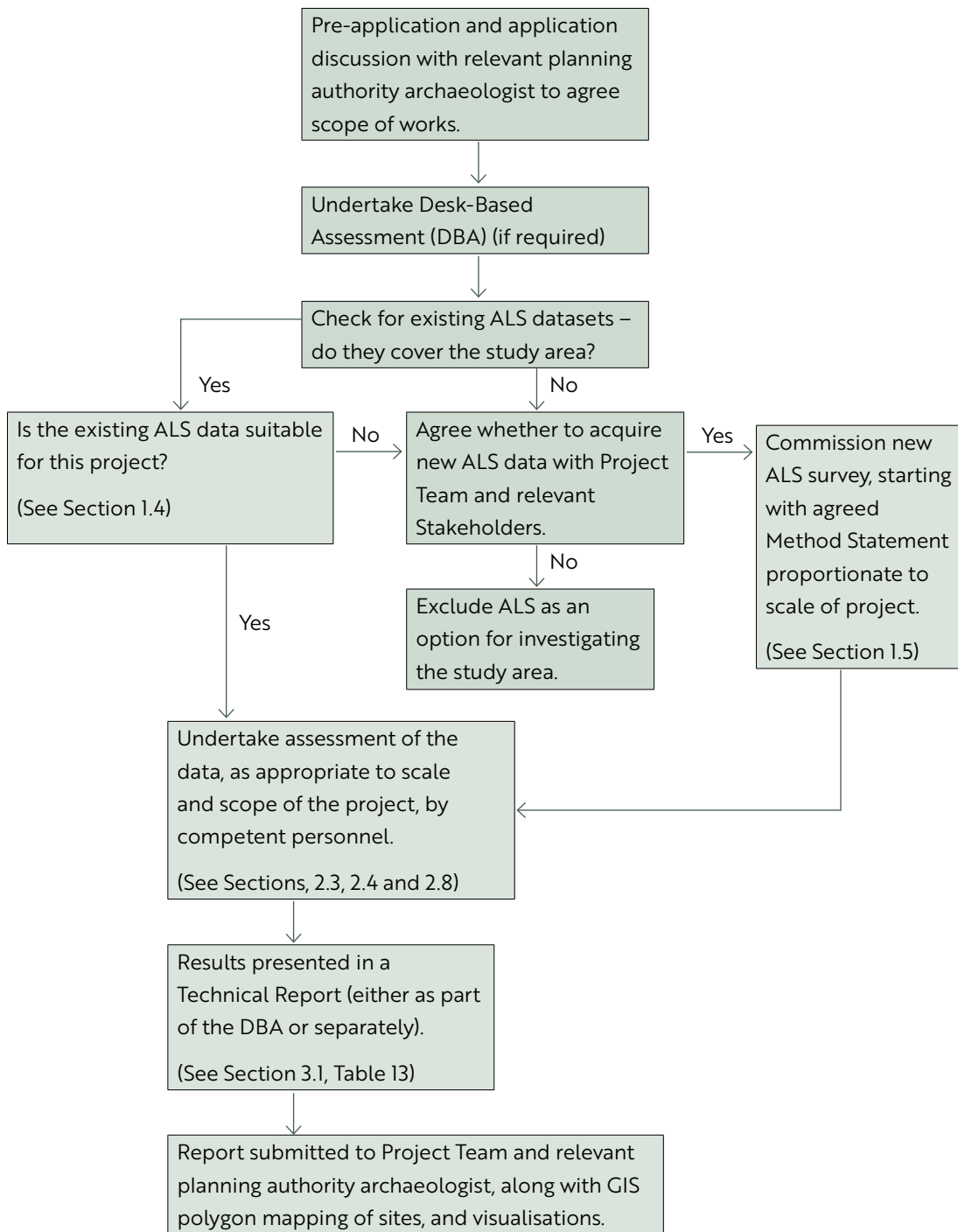


Figure 47: A workflow showing how ALS data assessment can be integrated into the development control process

### Presentation of Results and Digital Data Outputs

The results of archaeological examination of ALS-derived data should be described in an illustrated technical report. The report should generally conform to the structure and content suggested in section 3.1. Where ALS-derived data have been incorporated into a larger body of work (such as a Desk-Based Assessment or similar), the results should be presented in such a way that incorporates the key elements of Table 13, in order to ensure the dataset has been appropriately interpreted and referenced.

To facilitate the integration of the ALS-derived data examination results into the ongoing design process and overall archaeological evaluation pre-development, the following digital data outputs should be provided:

- Vector (polygon) mapping the extents of the archaeological features as discernible in the ALS-derived data as per the guidance in sections 2.3 and 2.4. They should be supplied in archive ready GIS format (see section 3.4). The attributes of the vector file(s) should correspond with the information presented in the Inventory of Features, typically presented as an appendix of the ALS-derived examination report (see section 3.1).
- All visualisations (e.g. Slope, Simple Local Relief, SkyView Factor, Combined VAT etc.) generated as part of the examination in industry standard, GIS compatible, floating point raster format (see section 3.2)
- All other datasets generated as part of the examination or used in the GIS (apart from datasets supplied by the Client) in appropriate industry standard, GIS compatible formats
- Metadata for each dataset, in compliance with the guidelines set out in section 3.5.

### Summary

While planning processes vary across Europe, examination of ALS-derived data can be a powerful tool in the context of planning and development control, resulting in better archaeological outcomes and reduced project risks. The practices detailed in this section are fitted to most formalised planning systems but can be adapted to suit other contexts. Regardless of the process, analysis of ALS-derived data is an important element of the archaeological evaluation of a proposed development, which contributes to robust impact assessments, more informed design and mitigation strategies, and ultimately better decision making.

## 4.3 Integrating ALS with Cultural Heritage Records

Irmela Herzog, Niko Anttiroiko, Marika Kostamovaara, Rebecca Bennett

### Introduction

In most countries information systems have been established on a national or regional scale that store available information on archaeological (or more broadly cultural heritage) data in the corresponding area. The information is usually held in a database with linked geospatial data. In addition to locations of individual heritage feature records, the geospatial information contained in the cultural heritage database may also provide land use, geological or palaeo-geographical information (e.g., ancient shoreline, moraine, or sandy ridges) to contextualise the location of sites and provide additional environmental data for predictive modelling of site location or vulnerability (see sections 4.3 and 4.4). An integrated record system is essential for prioritising further interventions in the context of land use change or research (see section 4.1). It also facilitates decision-making processes supporting archaeological fieldwork, land management, and public engagement in a more efficient and transparent way.

To provide a holistic picture for research and planning purposes, cultural heritage database managers have to integrate the results of ALS data interpretation into the records held on these systems. This section examines current best practice for integration of ALS-derived data and explores the common challenges data managers face undertaking this task.

Cultural heritage databases should support the mapping and recording of archaeological features from ALS data, as equivalent to any other common source of archaeological information (e.g. aerial photographs, excavation reports etc) that contributes to the record. Best practice for the integration of ALS-derived data is through a data management strategy that reflects the two main ways in which ALS can be used to enhance the cultural heritage database. Specifically these are:

1. Amendments to existing feature records which may include updates to the extent, location and description of physical features as evident in the ALS-derived data.
2. Bulk import of features and their attributes mapped from ALS-derived data by external organisations and projects.

The recognition of heritage features in the landscape is the necessary first step to their protection and monitoring. In some countries archaeological features are afforded legislative protection as soon as they are identified (Anttiroiko et al., 2023) and therefore the ability to rapidly identify archaeological features within a landscape may be accompanied by increased levels of legal protection.

### Amendments to Existing Records

Amendments to existing records should form part of the continuous management and improvement of the database. This process is typically constrained by the availability of human and digital resources. Therefore, integration of ALS-derived data can be limited when specialist advice is not available to the database manager to assist with the interpretation and management of ALS data. In many cases access to appropriate ALS-derived visualisations can be challenging as there are limited resources available to the database managers to process ALS data to an appropriate standard for archaeological assessment (see section 3.2). Some cultural heritage information systems have a GIS component that allows the integration of external web mapping services (WMS), but as these are typically provided by non-archaeological institutions they are often limited to shaded relief images of the ALS data which are poorly suited for detailed mapping and interpretation of archaeological features.

In the absence of specialist visualisations however such generic WMS images can and should be used to enhance records providing that appropriate metadata is collected and stored that indicates the limitations of the ALS resource used (see sections 2.2 and 2.3). The database structure should facilitate recording metadata on each feature detected or updated based on the ALS-derived data (see section 3.5). This includes not only the site specific data such as type and period but also metadata on the ALS data used (e.g. the date of acquisition, resolution and visualisations used).

In addition to the metadata, textual description and geospatial definition, if the database is capable of

storing linked files and images it is good practice to include a link to the ALS survey and processing report(s) as sources of information about the feature and georeferenced images presenting a selection of relevant ALS visualisations in the feature records. Where this is not possible, cross-references to PIDs of the reports and imagery hosted or archived elsewhere should be included (see sections 3.3 and 3.4). This facilitates not only later checking and re-interpretation of the features, but also dissemination and communication to a variety of audiences via illustrated reports from the database. It also safeguards against inaccessibility of the ALS data in the future. For instance, an externally hosted WMS (web mapping service) that is the primary source for the mapping may be liable to removal, change or replacement by a third party outside the control of the database managers.

### Bulk Imports of Features from External Projects

A particular challenge associated with integration of ALS data into cultural heritage databases is the increasingly extensive coverage available. Although integration of cultural heritage features from external reports is a key process underpinning the

maintenance of the database, the quantity of ALS data, its increasing use in citizen science mapping projects and applications for automated feature detection challenge database managers to integrate the outcomes of external projects. Without a robust data management strategy, the quantity of feature data derived from a project using ALS survey can easily outstrip the resources of the database manager to deal with it in many cases. A failure to integrate such information into the database in a meaningful way means that the information is lost to the official record and cannot be used to contribute to future management decisions.

There are some data management strategies that help to mitigate the problem of limited resources, thus enabling the integration of data from ALS projects in a timely way. It is highly desirable to produce a set of recommendations for the submission of digital data to the database alongside the project report, and in most instances where these exist specific details can be added to reflect the nature of the data generated from ALS projects (see section 3.5). These recommendations should include preferred geospatial and textual data formats (e.g. gml and xls) for data transfer, agreement on standardised terminologies for monument types and may even include a template data schema.



#### Guidance for the Submission of Data to the Welsh Historic Environment Records (HERs)

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HISTORIC ENVIRONMENT RECORD PROJECT EVENT DATA	
HER Field Name	The assigned PRN number for the work.
EVENT PRN	Usually the title of the Report
EVENT Name Welsh	Usually the title of the Report
EVENT Name English	Usually the title of the Report
Summary Welsh	Who undertook the work? Who was it commissioned by? When was the work undertaken? Where was the work carried out? Why was it undertaken? What work was undertaken? What were the results and conclusions of the work? SEE Guidance Document: Section 4.2 for EVENT Summary Examples
Summary English	Who undertook the work? Who was it commissioned by? When was the work undertaken? Where was the work carried out? Why was it undertaken? What work was undertaken? What were the results and conclusions of the work? SEE Guidance Document: Section 4.2 for EVENT Summary Examples
NGR	Ordnance Survey National Grid Reference for the work undertaken - minimum of 6 figures
Easting	Easting or X coordinate
Northing	Northing or Y coordinate
EVENT Type	See Controlled Term list.
Year	Year the work was undertaken.
Report No.	Report Number.
Project No.	

Figure 48: Example submission guideline contents and spreadsheet proforma for submission of feature data to the Welsh Historic Environment Record database

Database managers are often concerned that the level of recording of features identified solely from ALS data is not comparable to that of existing features in the database and this is especially true of feature data generated by automated or citizen science processes. One method of providing rapid access to the outcomes is a set of layers within the GIS component of the information system that summarise the features identified so they can be consulted for relevant planning and research and copied over to the main database when they have been verified. An alternative, and potentially more integrated method, is to define a new class of “Potential Archaeological Feature” within the database with associated amendments to the schema to reflect certainty and metadata if necessary. ALS-derived features can be imported directly into this class along with their metadata and verified at a later date. The benefit of this method is that it allows the features to be assigned unique identifiers for improved long term management so that they can be interrogated in the same way as existing records while making the source and level of certainty of interpretation apparent. The disadvantages are that without careful sub-setting for existing features, bulk import in this way may create a lot of duplication and such structural changes to the database schema may be beyond the control of the database manager depending on the software used.

### **Cultural Heritage Database Managers as Project Stakeholders**

One important way to influence the quality, format and timing of submission to a cultural heritage database from large scale ALS projects is for the regional or national database manager to be an active stakeholder in the design of the project’s Digital Management Plan (see section 3.3). Engagement at the planning stage can significantly improve the quality of outputs of the project if specialist expertise in feature identification is incorporated from the start. The ability to influence the design of the data schema and output formats will ensure smoother integration with the database on submission, a desirable outcome that ensures best use of often limited resources to make newly-derived information accessible as efficiently as possible.

### **Additional Challenges**

Aside from the practical concerns of integrating large numbers of ALS-derived features to cultural heritage databases, the nature of the features that can be mapped using ALS and their spatial distribution also poses challenges to existing data management regimes. Chief among these is the need to create or adapt protocols for managing large numbers of newly identified sites of specific types, such as the remains of charcoal burning processes, where there are no existing guidelines relating to that site type. If the type has previously been unidentified or little research has been done, it can be difficult to assess the significance. This is especially true when faced with extensive new distributions, derived from national ALS datasets which are often on a scale that was previously impossible.

As automated detection becomes more common (see section 4.5), consideration needs to be given to how to manage such information, where traditional approaches to documenting levels of certainty of interpretation in existing database records may not be suitable. The ability to explicitly communicate the source and degree of certainty of an identification and interpretation will become key to good curation of the cultural heritage database and re-use of the records it contains. This will likely also require substantial re-assessment of existing records held in the database to create a dataset where the measure of certainty assigned to a feature is consistent between those features derived by automated methods and those derived by other means. Key to this is the documentation of source, for example through project metadata and site specific recording events.

Strategic management of sites and landscapes can also be hampered by a lack of dating evidence for site types identified in the analysis of ALS data, but it should be noted that this is also the case for much derived from field survey and aerial photographic interpretation. Most features are dated by analogy of form to existing scientifically dated examples but if the sample size of dated comparators is small, as in the case of newly identified site types, this can lead to huge uncertainty.

When faced with questions about how these “new” sites and site types should be protected it is necessary to update the regional research frameworks to reflect the nature of the changed evidence base. Such regional or national frameworks need to take into account the extent of the ALS data coverage and its availability to cultural heritage managers (European Archaeological

The screenshot shows a web-based form titled 'Event Criteria'. It contains several input fields and a dropdown menu. The 'Event type' dropdown is currently set to 'AUTOMATED OBJECT DETECTION (RECORDING)'. Other fields include 'Event Id', 'Parent Event Id', 'Ref. No.', 'Parent Project', 'Description/Title', 'Event Notes', 'Date From (DD-MON-YYYY)', 'Date To (DD-MON-YYYY)', 'Entered By', 'Entry Date (DD-MON-YYYY)', 'Updated By', and 'Updated Date (DD-MON-YYYY)'. There is also a 'Null' checkbox and a 'Web Access' dropdown.

**Figure 49:** Example of a project metadata (event) record from a heritage database (Historic Environment Scotland)

Council et al., 2024). In countries where ALS data are not open access this severely limits how the data can be re-used and delays widespread adoption of ALS data within the cultural heritage management sector. The issues of data management will be compounded if staff members do not have relevant training

and expertise in the use of ALS data. As ALS data become more accessible and more widely used it is recommended that heritage data managers have access to appropriate training and support to ensure that the benefits of ALS data are fully integrated with national and regional records (see section 2.8).

### ALS data integration with Heritage Building Information Modelling (HBIM)

Antonio Jesús Ortiz Villarejo, Carolina Collaro, Ján Zachar, Alexandra Bucha Rášová

There are a variety of national-level heritage information systems, which are as key platforms for implementing cultural heritage policies. They provide the foundation knowledge for effective management, on the simple basis that you cannot manage what you do not know about, and underpin work to better understand our past and share it with others. Examples elsewhere in these guidelines have shown how effectively ALS datasets can contribute to these objectives. The UNESCO focussed example (section 4.1) illustrates this application in one context where monitoring of condition and change are crucial to long-term management.

Such approaches benefit from clearly-structured, and well understood data, and one tool increasingly utilised by conservation stakeholders is Heritage Building Information Modeling (HBIM). At the core of HBIM is the creation of a 3D model or a shared and collaborative database (Hermoso-Orzáez et al., 2021), which allows project stakeholders to generate and access information easily. The ultimate objective is to

create a graphical model that faithfully represents historical reality, as demonstrated by Heesom in the collaborative development of HBIM for a 19th-century multi-building industrial site in the UK (Heesom et al., 2021). In this study, the authors analyse the use of ALS for collecting 3D morphological data, in comparison with 3D data obtained through high resolution terrestrial laser scanning. Such 3D model is a prerequisite for detailed documentation and subsequent analysis, but terrestrial laser scans have been criticised as time consuming and biased towards recording spatial and topographic detail at the expense of incorporating other elements of cultural and intangible heritage into the model (Counsell and Taylor, 2017; Dore et al., 2015). This is not to make the relationship between point clouds acquired from airborne platforms or through terrestrial scanning, but to more generally identify that the point clouds underpin the creation of surface models with geospatial accuracy, RGB colours, and material properties (Argiolas et al., 2019; Moyano et al., 2022). And, in this context, the increasing resolution of and availability of ALS data requires consideration as a means of cost-effectively enabling the creation of rapid, lower resolution

3D models in an HBIM framework, as one example of how such information can be made more accessible to local, regional and national heritage agencies.

The undesirability of a competitive relationships between different sources of 3D data, such as ALS, terrestrial laser scanning and photogrammetry, is illustrated by the challenges facing the use of ALS data in HBIM. This is primarily in that data from vertical walls and other difficult-to-access areas are missing in the ALS-derived models. And here the benefits of complementarity is illustrated, as ALS can be combined with other technologies, such as photogrammetry, for documentation and visualisation purposes. The choice of 3D data capture methods should be made on a case-

by-case basis to ensure that the HBIM meets management needs. Moreover, to generate a geometric model for a building that closely represents reality, it is necessary to establish automatic conversion algorithms to process the laser scanned data. Developments in BIM software are ongoing in this domain (Moyano et al., 2022) but existing tools designed for this purpose are primarily related to terrestrial laser scanned data, not ALS.

ALS data alone may not be the most suitable technique for detailed documentation of heritage buildings, but these data can serve as a foundation for reconstructing their environment, capturing the setting of a building as part of a multi-scalar approach to a heritage asset.

## 4.4 ALS for Monitoring Change

Carolina Collaro, Irmela Herzog, Niko Anttiroiko, Ole Risbøl

Cultural landscapes and traces of past human activities exist in the contemporary landscape, and so are vulnerable to the many sources of change brought about by many anthropogenic and natural factors. Our landscapes are dynamic, with activities such as land-use change, agricultural practices, urban and transport development, mineral extraction, tourism, war or looting having impacts on both the macro and microtopography. To these can be added factors such as increasingly variable rainfall and regularity of storms with consequential flooding, burrowing animal activity, vegetation encroachment, and coastal erosion, which all have potential to substantially alter the landscape, affecting both known and as yet unrecorded cultural heritage resources. Of particular concern are the effects of climate change on cultural heritage (European Commission, 2022). The need to quantify change caused by drought, forest dieback, extreme floods, peatland degradation and rising sea levels on landscapes and environments are key reasons for both ALS data acquisition and the instigation of monitoring projects using open ALS data.

The impacts on the landscape of these many intertwined factors are often complex and cultural heritage managers have long recognised the importance of archaeological monitoring and recording which provides a baseline from which to design and implement strategies for mitigation. Such an approach requires comparable, multi-temporal datasets, the availability of which is currently very uneven when viewed at a pan-European scale.

### The role of Remote Sensing

Monitoring can be performed in various ways but widespread use has been made of remote sensing data which provides an efficient method for documenting changes on various scales from single sites to whole landscapes, with satellite and aerial photographs being used frequently for this purpose (Luo et al., 2019). Monitoring based on remote sensing is a very efficient approach to large areas or many sites, with the understanding that it will provide less detailed information than may be generated by

terrestrial surveys and so a multi-scale approach to monitoring may also be important. A remote sensing approach is particularly important for areas that are experiencing particularly dynamic landuse change and in also in areas where physical, social and political restrictions limit access (Opitz and Herrmann, 2018).

The main barriers to the application of ALS-derived data for monitoring change are availability and resolution of data. However, more nation-wide and repeated ALS surveys are becoming available, and the acquisition costs of higher resolution data is reducing (e.g. UAV platforms). Multi-temporal ALS allows the comparison of digital elevation models acquired for the same area at different times, allowing changes to topography, landforms, buildings, coastlines, and vegetation to be detected. However, as a metric and repeatable data source, ALS is particularly well suited for monitoring, though use has so far been very limited in contrast to many examples documenting geomorphological changes and surveillance of natural areas (Klemaš, 2013; Okay et al., 2019).

In a cultural heritage context, examples of current practice include both strategic assessments that include a predictive approach to consider potential future scenarios and monitoring of current condition in comparison to past situations. At a strategic level, Rowland et al. (2014) suggest measuring and monitoring negative impacts of sea level rise on cultural heritage sites by the use of ALS. They illustrate the potential by simulating future sea levels on ALS-derived DEMs to create predictive models. A similar straightforward method is suggested by Howey (2020) who studied impacts of sea level rise on archaeological sites and predicted sea levels to illustrate future inundation scenarios.

For monitoring current condition of sites and change over time multi-temporal data sources are required, which can include historical and contemporary aerial photographs. Such an approach was employed in a study of a prehistoric grave field in Norway (Risbøl et al., 2015). ALS data sets from 2008 and 2010 were used, together with aerial photographs from three different dates (1968, 1979 and 1999) from which 3D surface DEMs were generated using a photogrammetric workflow. The data were then used to generate difference models based on automated change detection. The inclusion of photogrammetric

models is an innovative way to remove one of the barriers to using ALS-derived data for longer-term change studies – the lack of historic ALS data.

Not all applications comparing elevation models of different dates have proven successful. An attempt to use ALS for monitoring slope soil erosion rates at archaeological sites in arable land (Huisman et al., 2016), was unsuccessful because but the erosion processes were too small in scale to be detected once the effects of spatial processing errors and tillage were taken into account. However, the ALS-derived models were still useful to indicate areas most vulnerable to soil displacement by surface runoff and tillage, which could be factored into future conservation management.

Danese et al. (2022) have explored the use of ALS for mapping and monitoring detrimental activity, clandestine excavation of burial monuments in a vegetated environment. They employed a combination of ALS data and automatic geomorphon-based pattern recognition to identify 85-95% of looting pits in the Etruscan site of San Giovenale (Northern Lazio, Italy). Despite the good results they identified some key challenges, including the need to test the ALS workflow in other environments, and emphasised that further development is needed to improve the approach, including the acquisition of more frequent and higher resolution data sets using UAVs.

These examples demonstrate the strong potential of ALS for monitoring landscape and site change but routine monitoring of cultural heritage resources using ALS-derived models has yet to be extensively implemented.

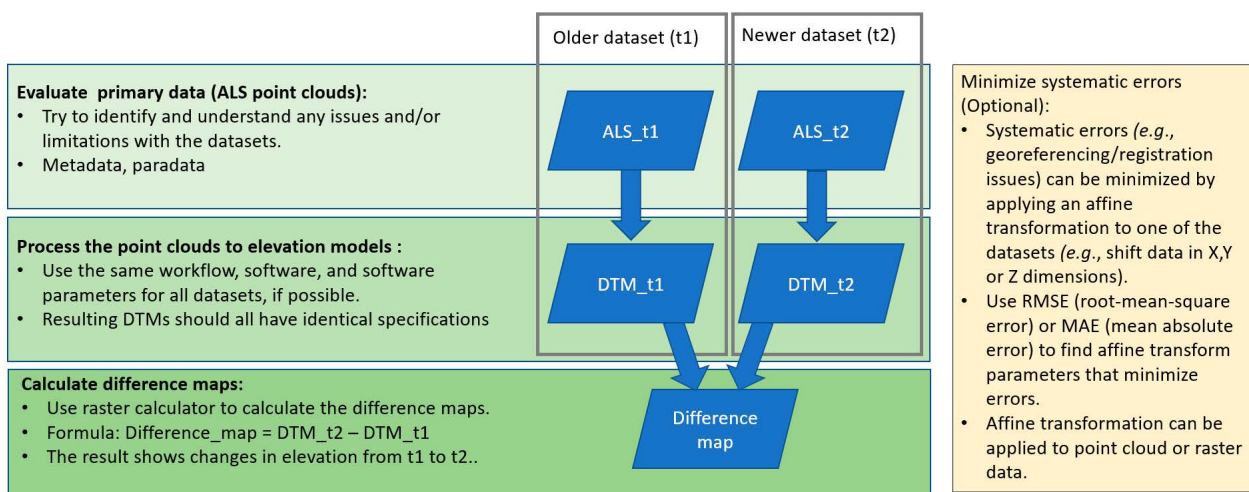
### Using Multi-temporal ALS data to Calculate Difference Maps

Difference maps are typically created by subtracting the DTM models from different ALS surveys. Figure 50 shows the process of subtracting an older DTM from a more recent one resulting in a difference map.

This process results in a difference model where positive values represent increase in height between the two models and negative values represent a loss of height. It is important to make sure all illustrations of difference include a scale for reference and it is best practice to avoid confusion by a colour spectrum not typically used for elevation models (e.g. red-green). Cross-sections can be drawn from the difference model to view profiles of the height change, helping with the interpretation of the results.

Figure 51 shows changes to ramparts and ditches that lie within a protected area in the parish of Oberhausen, Germany. Work was undertaken in advance of the development of an adjacent road which required documenting the surface of the monument (Herzog, 2022, 2021). A comparison of three different terrain models was possible derived from ALS survey in 2011, 2015 and 2020.

The availability of ALS data collected in 2011, 2015 and 2020 allowed a comparison of surface topography over time. The difference maps in Figure 51 shows loss of material from the rampart at the northern border of the site between 2011 to 2015 (highlighted in red on the difference map). Preparation for constructing a road in the western part of the site, required that the western part of the rampart should be covered with

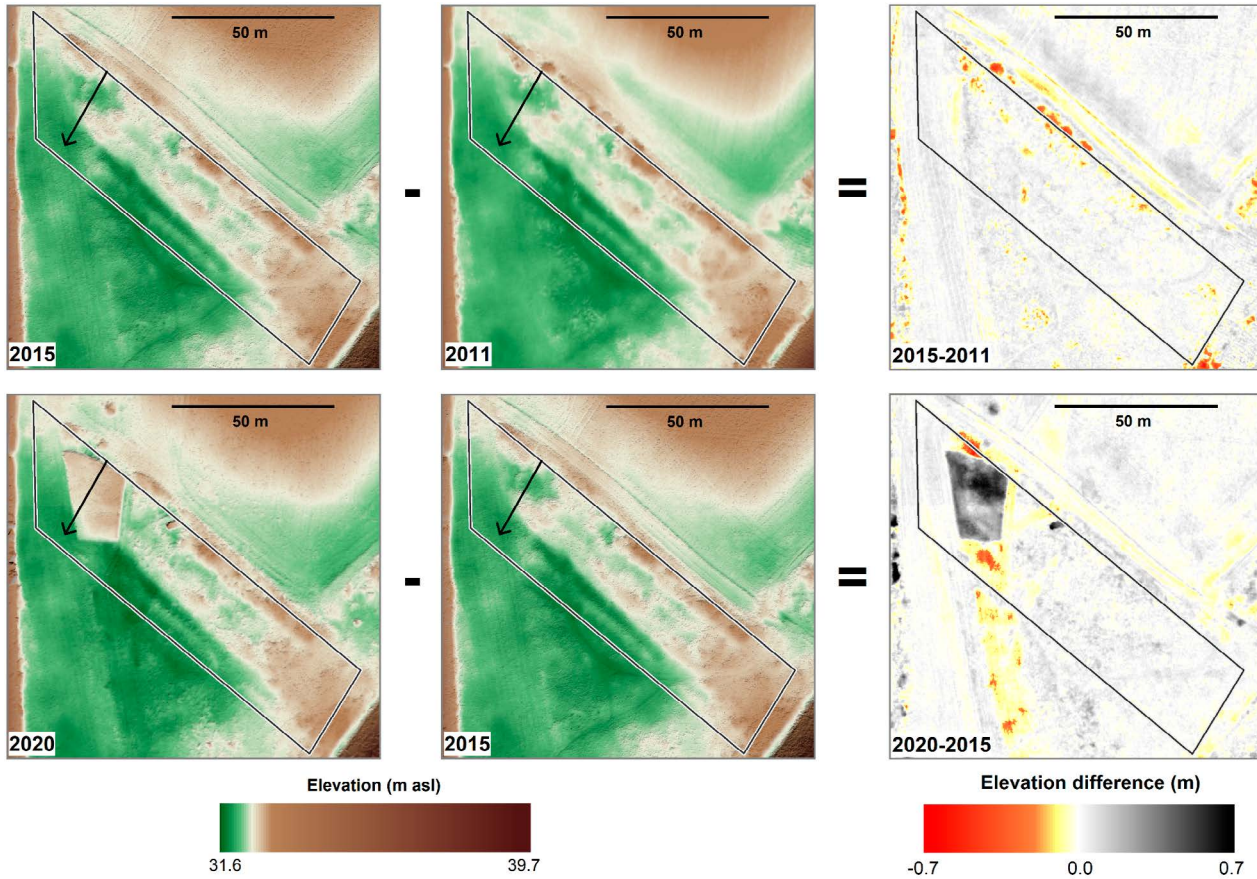


**Figure 50:** Process diagram showing the steps required to create a difference model from two DTMs to study change over time

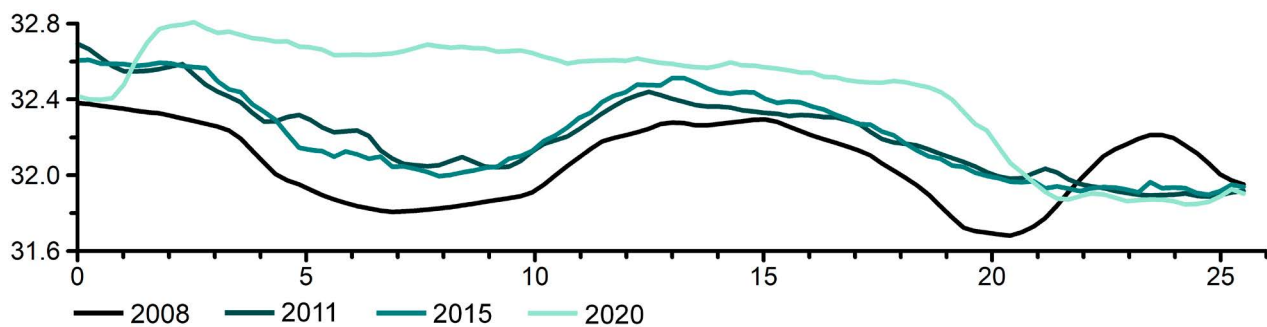
## 4.4 ALS FOR MONITORING CHANGE

a protective bank of earth in 2020. This mitigation can be seen as a regular, raised area on the 2020 ALS data. However the difference map 2020-2015 shows that part of the site was destroyed before it

was covered by the protective bank, as shown by the red values on the map and illustrated by comparison of the cross sections derived from the ALS-derived models (Figure 52).



**Figure 51:** Difference maps showing changes to the ramparts and ditches in the parish of Oberhausen, Germany (Herzog, 2022, 2021)



**Figure 52:** Cross sections of the DTM models of different dates showing the rampart and protective earth bund (see Figure 51 for the location of the cross section marked by a black arrow). The 2020 data shows the protective bund but a significant deposit from the 2008 (bank that lies between 20m and 26m on the profile) can be seen to have been lost by 2011

## Challenges and Limitations

While it is seemingly a simple task to monitor change by comparing a time series of DTMs, point clouds or other elevation data, there are several challenges and limitations that need to be considered. These include factors contributing to overall cumulative error, which limits the spatial resolution and sensitivity (i.e., smallest change that can be detected) that can be achieved. Spatial resolution, horizontal and vertical accuracy of the available datasets, georeferencing and co-registration issues, differences in data processing as well as environmental conditions during data acquisition are all important factors that need to be understood as part of the processing and interpretation of difference models.

Differences in environmental conditions at the time of ALS data acquisition have a potentially significant negative impact on the comparability of resulting point clouds and DTMs. For example, seasonal variability in vegetation and moisture may affect penetration of laser pulses, and this may have cascading effects on ground point density, point cloud classification and resulting DTMs. When present, such issues could manifest as seemingly systematic errors that may affect only certain parts of the difference map, which makes it harder to detect real changes in ground elevation. For best results, it is preferable to use datasets acquired in the same season or in otherwise similar conditions, especially if the goal is to detect relatively small changes in elevation.

As has been stressed throughout these guidelines, metadata on data acquisition and processing are vital for understanding how comparisons between multiple ALS datasets are impacted by various sources of error, such as instrument errors, flight paths, date of capture, processing steps, software as well as related settings and parameters (see section 3.5). Ideally such metadata should be available for all datasets, for otherwise it might be difficult to assess how each of these factors impacts comparability between the datasets.

Monitoring and mitigation relies on good baseline data so inaccuracies or gaps in prior knowledge of the type, location and spatial extent of the archaeological features to be monitored may negatively impact the outcomes. As with many applications of ALS, the creation of difference models can appear simple but high-quality interpretation requires both archaeological experience and technical specialism to achieve satisfactory results and highlight any problematic outcomes.

## Pre-processing for improved Data Quality

ALS data should be rigorously quality checked before use in difference models, so that differences resulting from classification or systemic errors can be identified and corrected. Below are workflows to support the identification and correction of errors within DTM models.

### Reduce Classification Error

1. Wherever possible the point cloud data from different surveys should be reprocessed to ensure that the same classification parameters are applied.

### Check and Correct Horizontal Error

1. Check for a potential horizontal systematic error of the two DEMs involved via the suggested methods below:
  - a) Find the X and Y offsets that minimize the root mean square error (RMSE) or maximize the correlation coefficient (Hesse, 2016)
  - or
  - b) Check west-east and south-north cross-sections at locations of abrupt elevation change. The X and Y offsets may be deduced from the cross sections. This is easiest, if only one relevant shift parameter exists.
  - Or
  - c) Automatically or manually derive linear features from the DEMs, for instance by flow accumulation calculation. Based on the linear features, the best offsets can be deduced by manual shift operations. This is probably the best method to detect systematic errors that cannot be corrected by shifting the data, e.g., if rotation or some kind of warping or reprojection is required.
2. If needed, shift DEM1 or DEM2 in X and/or Y direction.

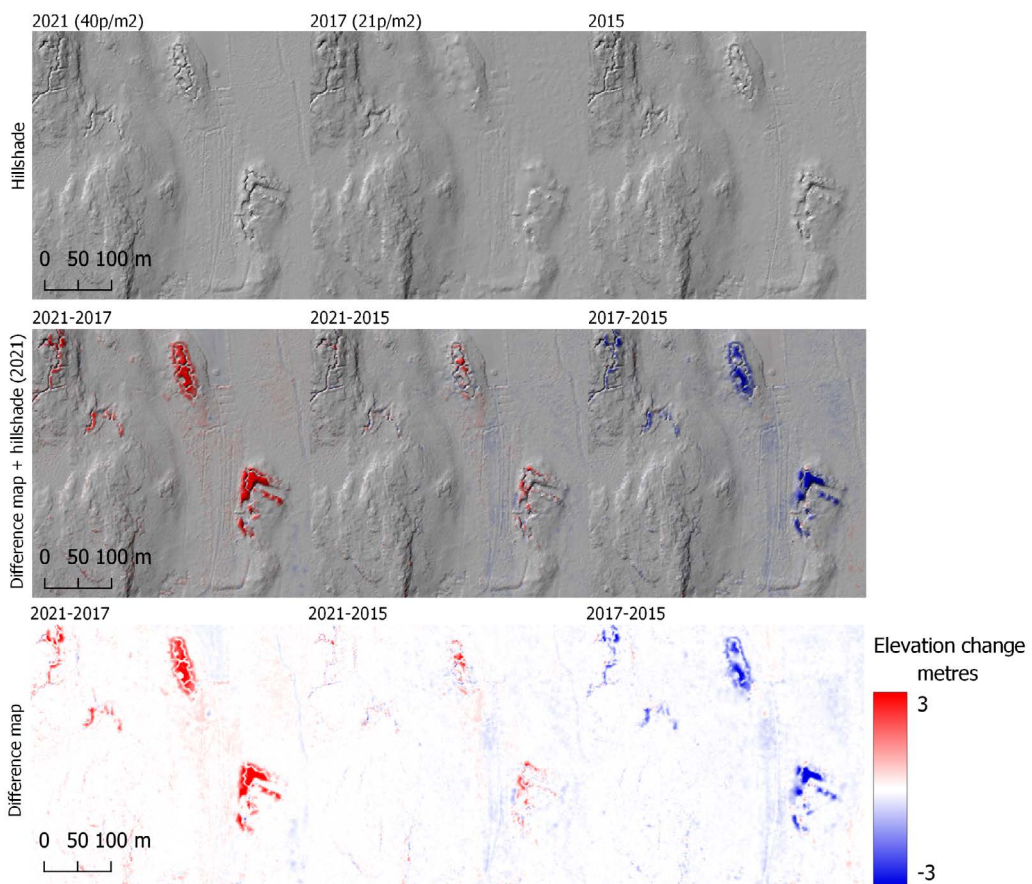
**Checking and Correcting for Vertical Error**

1. Systematic elevation errors may be identified by computing the average vertical difference between the two DEMs (after the horizontal correction, if applicable). However, this produces misleading results in case of either extensive loss or added soil.
2. More reliable results can be derived from assessing the average vertical difference measured on unchanged features such as roads or other fixed points in the landscape.
3. Differences in vegetation may require systematic correction of the elevation area for each area considered.

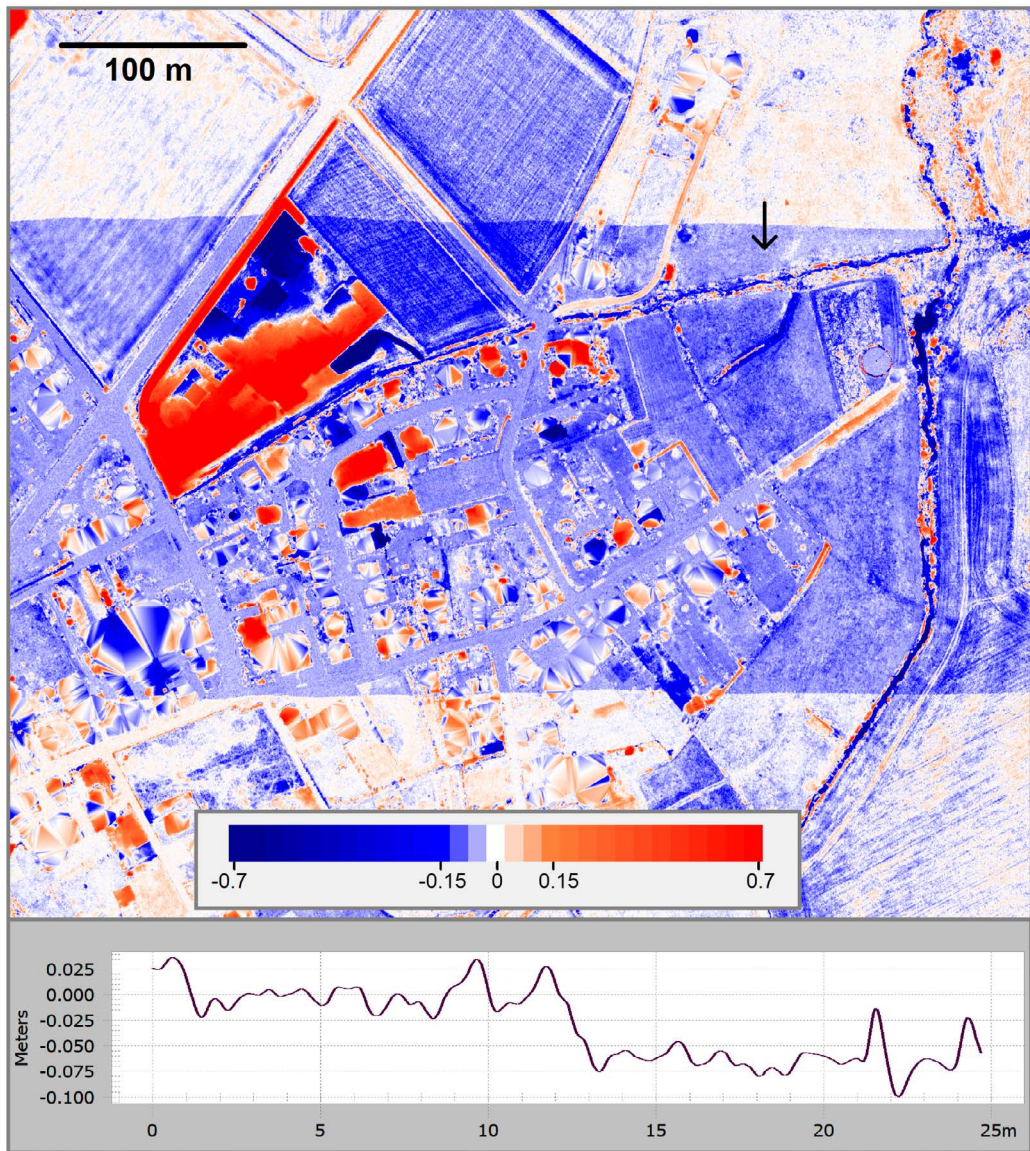
ground elevation in excess of 3m, although there is little or no real change between 2015-2021. This shift is caused by errors in point cloud classification near abrupt changes in elevation, such as steep ridges or World War One trenches, where some of the ground points have been erroneously assigned to other classes. Such errors can be mitigated to some degree by re-classifying the point clouds with identical software parameters.

Figure 54 shows a difference map of two ALS datasets generated by the regional survey organisation in North Rhine-Westphalia (Geobasis NRW) in 2016 and 2022. The two ALS datasets were not preprocessed with respect to systematic horizontal or vertical errors. A systematic vertical error for a band about 250m across can be easily detected in the difference map. The black arrow in the northeast of the difference map corresponds to the cross section shown below the map, which indicates that the systematic error is less than 10cm, (falling within 15cm of the vertical accuracy cited on the Geobasis NRW survey web page). In most cases, global systematic errors are found and corrected, but this example demonstrates that localised errors in the ALS-derived models cannot be ruled out.

Figure 53 shows a comparison of shaded relief models and difference maps based on three ALS datasets from an area with many World War One era fortifications in Finland. The difference models suggest changes in



**Figure 53:** Apparent differences in elevation can be caused by differences in point cloud classification algorithms between ALS datasets (ALS data: City of Helsinki, Urban



**Figure 54:** Apparent differences in elevation can also be caused by systematic horizontal or vertical errors between ALS datasets (Data: Geobasis North Rhine-Westphalia 2016 and 2022)

## 4.5 Using Automation for Feature Detection

M. Fabian Meyer-Heß, Carolina Collaro, Lucy Killoran, Øivind Due Trier, Wouter B. Verschoof-van der Vaart

To paraphrase Cowley et al (2021), after many years of debate the discussion about the use of automated techniques to aid archaeological survey has shifted from the question of feasibility to one of practicality, from the “should we use automation?” to “how should we use automation?”. Section 2.5 introduced the concept, benefits and challenges of integrating automation for the detection of archaeological features and extraction of information from ALS data. In this section the practical applications of automated feature detection are explored to provide context to their development in the cultural heritage sector.

While a proposed workflow and illustrative examples of best practice are included here, the rapid development of automated applications is such that this overview cannot provide more than a current statement that is likely to date quickly. Nevertheless, the most common techniques are briefly described and readers are strongly encouraged to engage with the cited references to deepen their understanding of benefits and challenges.

### What does an automation workflow look like?

Automated detection algorithms are designed to learn from data and iteration to complete tasks such as the identification of potential archaeological features from ALS-derived models. They use this information to make decisions or perform actions autonomously. There are different techniques, but in general the development and deployment of an algorithm adopts the following process (summarised by Figure 55).

1. **Data collection:** The algorithm needs to be fed with training data (i.e. images, text, numerical data or ALS data) that is representative of the problem to be solved.

2. **Algorithm training:** Once the data has been collected, the algorithm is trained to recognize patterns and relationships between the data. The training process involves defining and optimizing a set of parameters to minimize prediction error.
3. **Validation and testing of the algorithm:** After training, the algorithm is tested using a verification dataset. The aim of validation is to verify that the algorithm can generalize and make accurate predictions on data that was not used during training.
4. **Application:** Once trained and validated, the algorithm can perform actions or make decisions autonomously.

It is critical that domain specific expertise is used to collect the training data and evaluate the outcomes. Outputs can suffer from large numbers of false positives (i.e. incorrect identifications) creating “noisy data”. One approach to addressing this issue is to incorporate non-archaeological data such as land use (Meyer-Heß et al., 2019), landscape characteristics and subsoil (Verschoof-van der Vaart and Lambers, 2022) that help to reduce the likelihood that non-archaeological features will be detected and misclassified as archaeological by the algorithm.

### What is the outcome?

The results of the automated detection vary but can be broadly illustrated as follows in order of complexity. As can be seen from comparison to the outputs of manual detection described in sections 2.3 and 2.4, **Instance Segmentation** provides the closest comparator for digitised feature polygons with descriptive attributes.

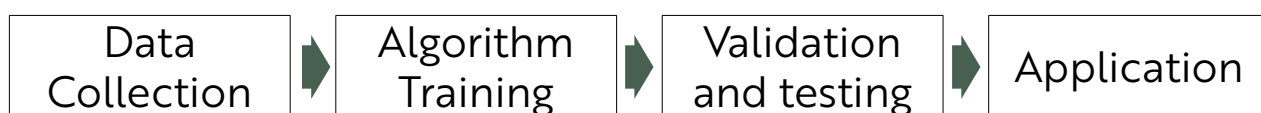


Figure 55: Flowchart showing the steps of an automation workflow

<b>Image Classification</b> Assigns a single class label to the image
<b>Object Detection</b> Not only predicts labels but also localizes each feature instance via bounding boxes
<b>Semantic Segmentation</b> Aims to predict labels for each pixel, without differentiating feature instances
<b>Instance Segmentation</b> Predicts labels for each pixel and differentiates between features by pixel-level segmentation masks

**Table 19:** Comparison of different detection tasks after Verschoof-van der Vaart (2022)

### Correctness Matrix

In order to understand the accuracy of any algorithm, the results of classification should be presented with a correctness matrix that identifies True Positives, False Positives, Correctness, Precision and Recall

**True Positive:** a feature identified by the detection algorithm which is correctly defined e.g. a burial mound classified as a burial mound.

**False Positive:** a feature identified by the detection algorithm which is incorrectly defined e.g. a modern roundabout or a natural mound classified as a burial mound.

**True Negative:** a feature not identified by the detection algorithm which is correctly defined e.g. modern feature that is not classified as a burial mound.

**False Negative:** a feature not identified by the detection algorithm which is incorrectly defined e.g. a burial mound that is not classified as a burial mound.

**Correctness** can be calculated as the number of True Positives ÷ the total number of features.

**Precision** can be calculated as the number of True Positives ÷ (the total number of True Positives + Total Number of False Positives).

**Recall** can be calculated as the number of True Positives ÷ (the total number of True Positives + Total Number of False Negatives).

	Detection / Positive	No Detection / Negative
<b>Reference: Detection</b>	True positives (TP)	False negatives (FN)
<b>Reference: No Detection</b>	False positives (FP)	True negatives (TN)
	Precision: $TP / (TP + FP)$	Recall: $TP / (TP + FN)$

**Table 20:** Correctness Matrix Example

### What automation techniques have been used for cultural heritage applications?

Table 21 provides more detailed information for a series of automation techniques that were introduced in section 2.5 along with references for further reading. The change in row colour indicates the step change in image recognition techniques to incorporate deep learning. This is a rapidly developing field, and while there are several recent publications that review current approaches and applications (Argyrou and Agapiou, 2022; Davis, 2018; Sevara et al., 2016), the reader should note that fresh approaches are inevitable. Never-the less the interested reader should refer to the following key papers to provide an overview of the topic:

Technique	What is it for?	What data does it use?	What does it produce as output?	Suitable evaluation metrics?	Where can I find out more?
Pixel-based	Texture patterns	Gray level co-occurrence matrix	Raster objects	True positive rate, false positive rate	(Haralick et al., 1973)
Pixel-based	Features that stand out in the landscape	Local relief model	Raster objects	Intersection over union (a metric quantification of the overlap between the predicted bounding box and that derived from ground observations)	(Hesse, 2010)
Template matching	Features that may be modelled by a template; requires only a few training examples	Digital terrain model	Location and size of features	True positive rate, false positive rate	(Trier and Pilø, 2012)
Object-based Image Analysis (OBIA)	Instance segmentation	Openness	Raster objects	Intersection over union, true positive rate, false positive rate	(Davis, 2018; Sevara et al., 2016)
Object-based Image Analysis (OBIA)	Instance segmentation	Trend Removal	Vector objects	Intersection over union, true positive rate, false positive rate	(Meyer-Heß et al., 2019)
Machine learning	Classification	Multispectral Satellite Images	Raster Objects	True positive rate, false positive rate,	(Menze and Ur, 2012)
Deep learning; requires a large number of training examples	Classification	Hillshade and digital terrain model	Vector objects	MCC, Recall, Precision, F1-score	(Verschoof-van der Vaart and Landauer, 2021)
	Object detection	Local relief model	Location and size of features	True positive rate, false positive rate, Recall, Precision, F1-score	(Trier et al., 2021)
	Semantic segmentation	Local relief model	Raster objects	Intersection over union	(Bundzel et al., 2020)
	Instance segmentation	Local relief model	Raster objects	Intersection over union, true positive rate, false positive rate	(Guyot et al., 2021)

**Table 21:** Summary of automation techniques used in cultural heritage applications

## Formative Techniques

### Template Matching

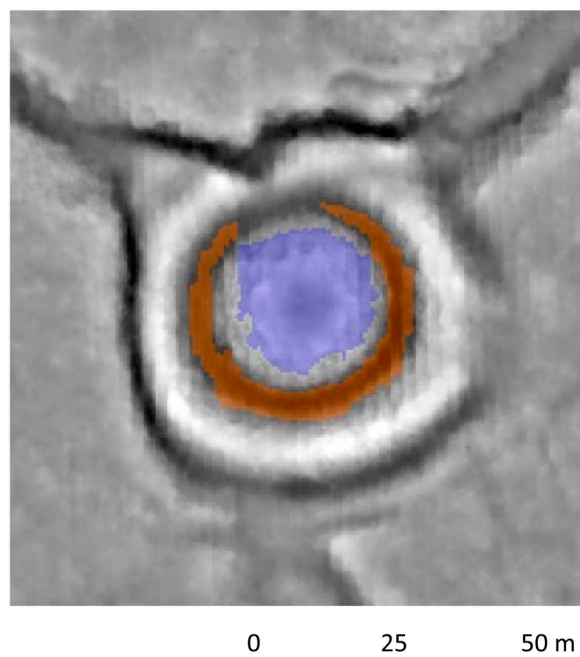
Kernels (convolution matrices) have been used to manipulate images, e.g. blurring or sharpening to better reveal features of interest, for many years. Template Matching uses this mathematical operation as the basis for object detection. The kernel used corresponds to the desired relief feature, which is called a template. This is moved across the terrain model while the similarity of template and terrain model is calculated. In the resulting image, high values represent possible matches. Trier and Pilø (2012) used template matching to detect different relief features (pits, mounds, etc.) in Norway. Multiple templates were applied to the DTM to cover features of different sizes. The comparison to template allowed confidence levels to be ranked with varying precision. Natural hills and ditches pose a significant challenge to this technique as they may look nearly identical to archaeologically relevant features. Although this methodology produces a high number of false positives and is cumbersome, it can be applied to detect archaeological features and may assist manual detection and field work.

### Object-based Image Analysis (OBIA)

Object-based Image Analysis (OBIA) is another possible technique for relief feature detection that use morphometric and spectral parameters (Davis, 2018). OBIA initially merges similar adjacent pixels into homogenous objects. In the case of Digital Terrain Models (DTM), these objects are areas of the same height, which are supposed to represent complete archaeological objects or parts of it. Object-related attributes such as mean pixel value (mean height), shape and relations to other objects then allow the creation of classes. In the language of OBIA, a Motte-and-Bailey castle is composed of two objects. One surrounded by lower objects (a local maxima, the mottes); another in close proximity is a ring-shaped object, that is surrounded by higher objects (a ditch surrounding the motte). Slightly altering the class descriptions further allows evaluations of condition in terms of erosion (Meyer-Heß et al., 2019).

### Convolutional Neural Networks (CNN)

A Convolutional Neural Network (CNN) is a form of Machine Learning. CNNs use the concept of convolution that is already known from Template Matching. Instead of applying only one matrix of a defined shape, they repeatedly apply all kinds of matrices to the input images. The outcome of the first set of convolution is the input for the next set of convolutions, thus forming a network. In the training stage, CNNs observe the outcome of the convolutions and assign given class names (corresponding to archaeological features) to unique signatures of positively (highlighting) and negatively (weakening) triggered kernels (neurons). In the application, an unknown image (a part of the terrain model) will be classified into the class with the most similar signature while a confidence score is calculated. The final results are rectangular markers at locations of possible identifications that are usually combined with the original terrain model. CNNs seem to outperform other detection approaches, but need far more training data and computational power. Among others, CNNs have been used for the detection of barrows, Celtic Fields and charcoal kilns in the Netherlands (Verschoof-van der Vaart, 2022), large tombs in Central Asia (Caspari and Crespo, 2019), roundhouses, shieling huts and cairns in Scotland (Trier et al., 2019) and shell-rings in South Carolina, US (Davis et al., 2021b).



**Figure 56:** OBIA defined topographical objects relating to mound (blue) and ditch (orange) of a Motte and Bailey castle in Paderborn, Germany (after Meyer-Heß et al., 2019 fig. 14)

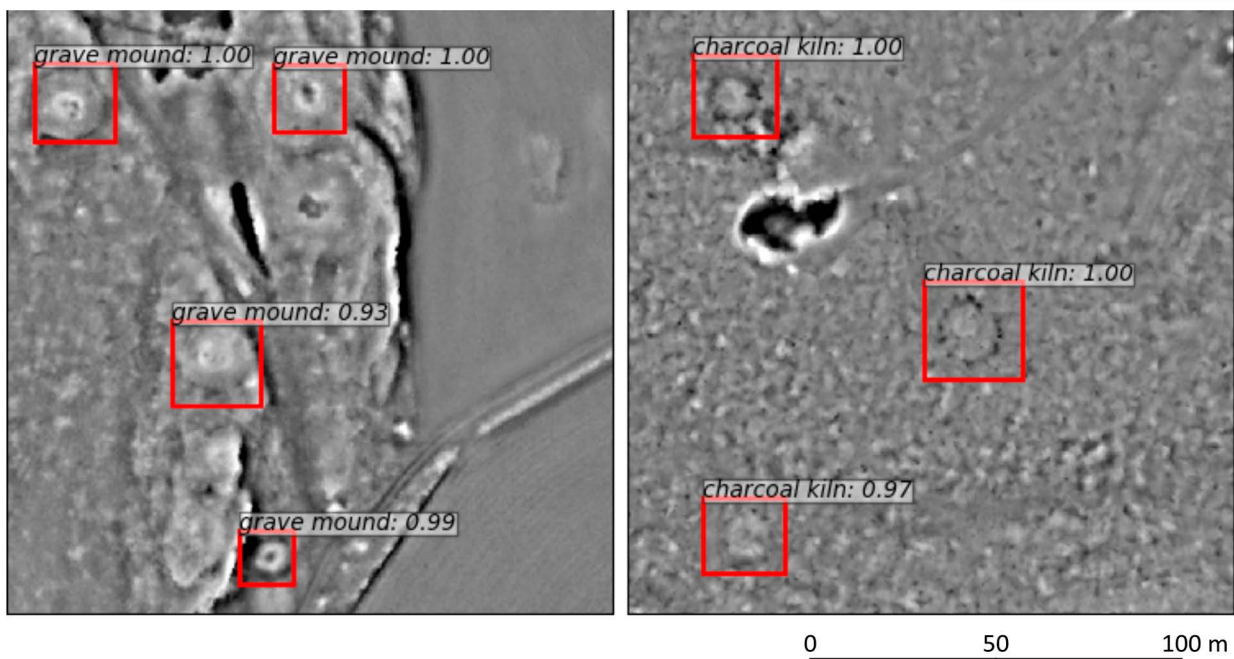
### Deep Learning

Over the past decade deep learning has emerged for image recognition, which mimics the human vision system. The main principle is to train the deep neural network with thousands or millions of examples of images of the objects of interest. The current state-of-the-art of these methods is that they are able to process large amounts of image data, but that the models still require refinement. Thus, a manual visual inspection of the predicted archaeological features is needed. Also, they do not work directly on point cloud data. The ALS data must be converted to a 2D visualisations, e.g. local relief model (Hesse, 2010), before being input to the deep neural network.

The development of deep learning architectures is a very active research field, and so it is premature to suggest one deep neural network method to use for archaeological feature detection. However, a few deep neural networks are worth mentioning, to illustrate possibilities and limitations. YOLO (Redmon et al., 2016) or Faster R-CNN (Ren et al., 2017) may be used to predict the locations, sizes and types of archaeological

features, but not the exact boundaries. However, this is appropriate for some types of archaeological features, such as grave mounds and charcoal kilns, which are usually circular (Figure 57; Trier et al., 2021). On the other hand, for elongated features such as old roads or stone fences, U-Net (Ronneberger et al., 2015) may be more suitable, as it predicts the pixels covered by each type of archaeological feature. However, U-Net is a segmentation method, which means that it does not predict individual features, but rather the union of areas covered by features of the same type (Table 19).

One common challenge in training a deep neural network for feature detection is the availability of a suitably large number of training examples. There are two methods to overcome this challenge. One is to use a pre-trained deep neural network, recognising that the training data may have little or no domain-specific examples in it. The second is to create modified duplicates of the domain specific training data, e.g., rotated, mirrored, scaled, shifted and/or brighter or darker versions of the original images.



**Figure 57:** Local relief model visualisations of ALS data with archaeological feature predictions (red squares) generated by Simple Faster R-CNN. Left image: An area containing five grave mounds, four of which were predicted. The missing prediction is below the top central red square. Right Image: An area containing three charcoal kilns, all of which were predicted (Norwegian Computing Center, using data from <https://hoydedata.no>).

### Artificial Intelligence elsewhere in the processing chain

In the case of ALS data processing, AI algorithms may be used to automatically classify objects in point clouds such as buildings, trees, roads and watercourses. In this case, the training process consists of providing the algorithm with a set of

classified point cloud examples, together with information about the geometric characteristics of the objects. The algorithm then uses this information to automatically identify and classify the objects in the point clouds.

### ADAF – a user-friendly tool for Automatic Detection of Archaeological Features

Žiga Kokalj, Anthony Corns, Paul O’Keeffe

ADAF is an open source software that enables fast and cost-effective archaeological investigation of airborne laser scanning DEMs. The reason for the development of ADAF was Transport Infrastructure Ireland’s need for early identification of previously unknown and potentially significant monuments. This was impossible to achieve without machine learning due to the extent of the survey areas, the constraints of the programme and the limited capacity of the private sector to provide this service.

The ADAF tool consists of Jupyter notebooks for data preparation, training (creation of specific machine learning models), and automatic recognition of archaeological features.

The project involved the creation of a comprehensive training dataset by digitising segmentation polygons for 10,718 recorded monuments and the processing and homogenisation of more than 200 individual ALS datasets. The machine learning models were thoroughly tested for the impact of patch size, visualisation technique, data augmentation and transformation methods, data quality and different architectures for object detection and semantic

segmentation on performance. The currently implemented models are optimised to detect three classes of Irish archaeology (barrows, enclosures, ringforts), but other models can be inserted. The software requires minimal interaction and no prior knowledge of machine learning techniques, which greatly increases its accessibility to the archaeological community.

The project is an important step towards democratising and demystifying machine learning for archaeological applications. The work done so far shows that advanced machine learning models can effectively identify and classify archaeological features in ALS data, reducing the need for manual effort and expert intervention. This progress reflects the development of GIS in the 1990s, which has evolved from specialised tools to widely accessible technologies, encouraging innovation and wider application. Open source software, FAIR machine learning -ready dataset, and open access to methodology aim to opening up new ways for non-experts to engage with and benefit from these advanced technologies.

ADAF can be downloaded from the GitHub repository: <https://github.com/EarthObservation/adaf>

### Summary

The development of automated applications for the cultural heritage sector is perhaps the most rapidly changing aspect in the use of ALS for heritage applications. It is also heavily influenced by wider developments in AI and image processing architectures. This section, when paired with section 2.5, provides the reader with a grounding in the topic,

including benefits and challenges, a methodological overview and indication of the direction of future developments. It cannot give the technical detail required for proficiency of application and as such readers are strongly encouraged to engage with subject specialists and current literature in advance of incorporating these techniques into heritage management.

## 4.6 ALS for Geoarchaeological Applications

Keith Challis, Nicholas Crabb, Steve Davis

Geoarchaeology can be broadly defined as the combined study of archaeological and geomorphological records to investigate how natural and human-induced processes alter landscapes (Banerjea et al., 2019; French, 2003; Ghilardi and Desruelles, 2013; Gilbert et al., 2020). One of the main aims of doing this is to reconstruct and model human-environmental interactions and to interrogate the nature, sequence and causes of human and natural impacts on the landscape. Whilst this is conventionally studied through the study site formation process and soil and sediment stratigraphies, ALS-derived models are increasingly used to define surface features and landforms that provide a record of the evolution of landscapes through the definition of contemporary topography.

ALS data form an important part of what might be considered a standard geoarchaeological toolkit. While it is, of course, of significant interest to archaeologists to understand 'monuments', which are often expressed as micro-topographic deviations from the underlying topography, it should be remembered that one of the greatest strengths of ALS survey is its ability to provide a landscape-scale overview of topographic variation. The landforms and geomorphological processes using ALS-derived models, providing context and enhancement to archaeological interpretations. As with archaeological prospection, there are secondary sources that are for effective interpretation of the ALS data. These might include, but are not limited to:

- other remote sensing data, including aerial or satellite imagery (Crabb et al., 2022)
- geophysical datasets, especially in 3-Dimensions; (Bates and Bates, 2016; Verhegge et al., 2021, 2016)
- borehole/auger data, including palaeoenvironmental data (e.g. Stastney et al., 2023)
- integration of chronological evidence via scientific dating techniques (Pears et al., 2020)

ALS data have been used for geoarchaeological research in a wide range of complex environments

such as wetlands, coastal, alluvial, aeolian, estuarine and lacustrine environments (Bailey et al., 2020; Gregory et al., 2021; Lausanne et al., 2021). The analysis of ALS-derived models is normally targeted towards the identification of specific landforms that influence the distribution of archaeological sites. For example, it has been used in the Samica Valley in Western Poland to identify elevations that may have been associated with islands within former lakes that were the focus of prehistoric settlement (Niebieszczański et al., 2022; Welc et al., 2018). It also helped delineate former beach ridges and jetties contemporary with the late Nordic Iron Age and Viking burial site of Borre in Norway (Draganits et al., 2015). However, ALS has perhaps been most extensively deployed for geoarchaeological purposes in alluvial settings.

Within temperate river systems across Europe, ALS-derived models have been used to considerable effect to reveal the complex morphology of floodplains and assist in identification of areas of differential loss and preservation of cultural remains. They are also valuable for sequencing floodplain morphology and channel development (Challis, 2006; Howard et al., 2008a; Jackson et al., 2011; Ninfo et al., 2011; Passmore et al., 2011, 2006; Van Dinter et al., 2017). The use of ALS data for such investigations is most effective in middle river reaches dominated by lateral channel movement, with upper (erosion dominated) and lower (accretion dominated) river reaches less susceptible to its use (Brown, 2008; Carey et al., 2006; Notebaert et al., 2009). Consequently, within these areas, ALS derived terrain data has been increasingly integrated within geoarchaeological deposit models, providing valuable topographic and stratigraphic control from the contemporary ground surface downwards (Carey et al., 2018; Notebaert et al., 2009).

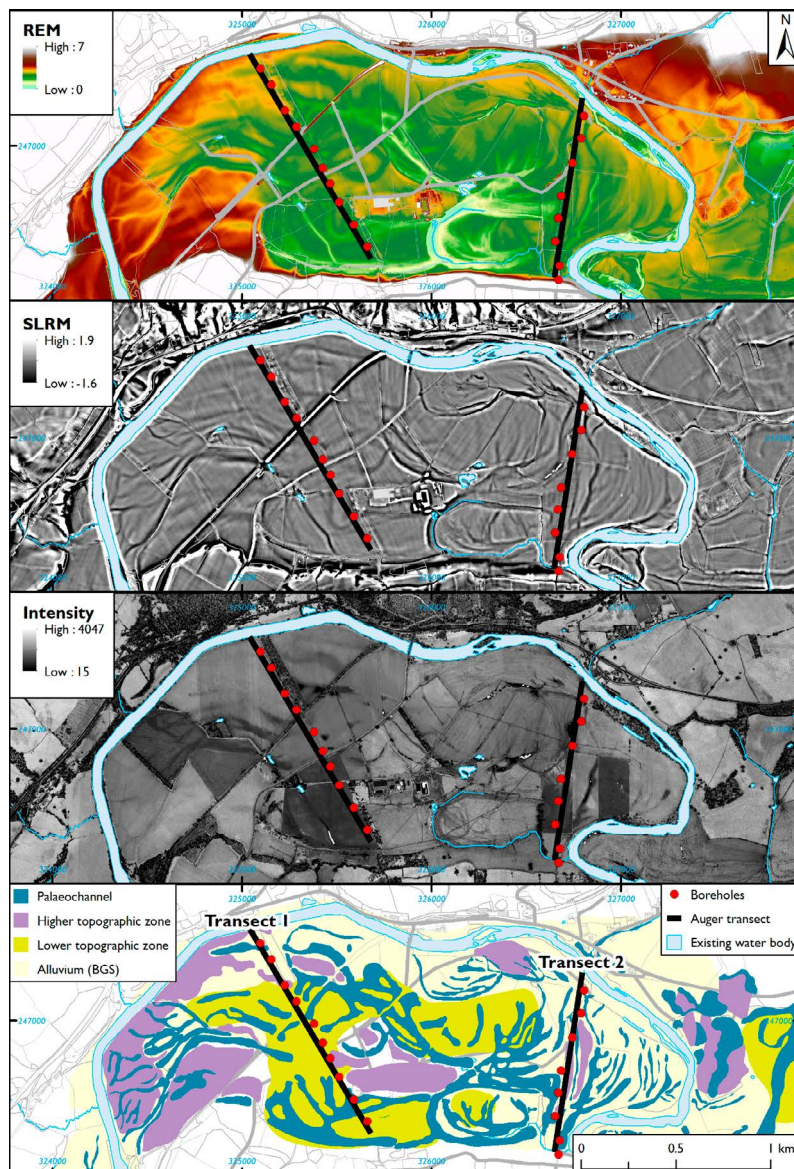
Features and landforms of geoarchaeological interest can be identified using the visualisation techniques outlined in section 2.2. However, within river floodplains, there are a smaller number of appropriate methods that demonstrably improve the detection of geomorphological landforms of geoarchaeological importance. In particular, topographic filters such as Local Relief Models (LRM) and Relative Elevation Models (REM) that reduce the influence of broader topographic trends (e.g. downstream slope) to enhance have been shown to be most effective visualisations for this purpose (Crabb et al., 2023).

## 4.6 ALS FOR GEOARCHAEOLOGICAL APPLICATIONS

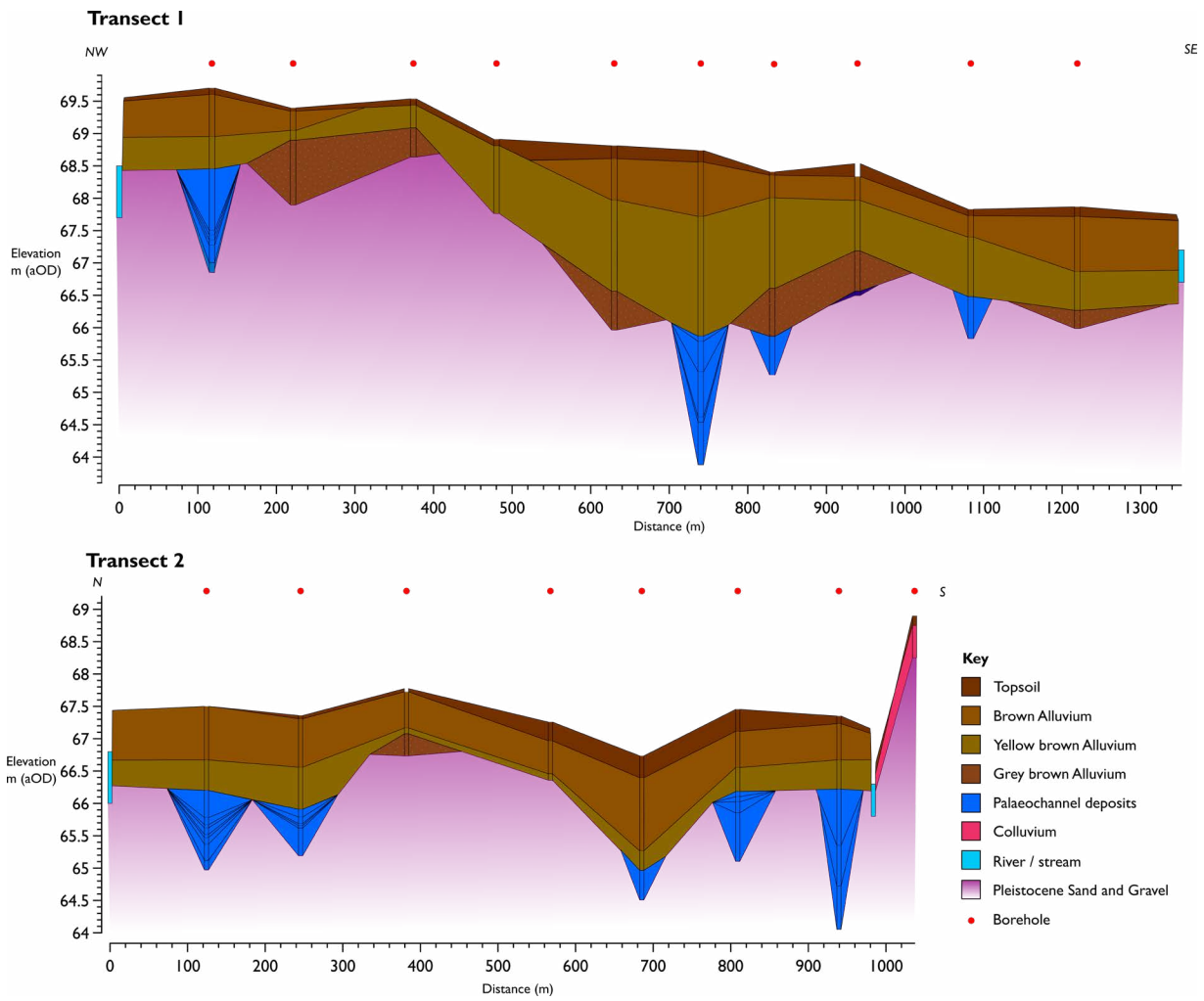
At the River Wye in Herefordshire (UK), the geoarchaeological interpretation of such datasets combined with gouge-core augering enabled the identification of a range of alluvial landforms, comprising a significant number of palaeochannels, widespread higher topographic zones and a small number of lower-lying regions (Figure 58 and Figure 59). This enabled surface expression of these landforms to be defined together with a record of the subsurface sediment architecture, which in turn, allowed for predictions to be made regarding the likely distribution of archaeological resources and definition of regions that have a higher paleoenvironmental preservation capacity.

Some studies have also considered the benefits of ALS intensity data which is a characteristic of the reflected laser beam that is affected by surface characteristics including for example sediment water

content. There is good evidence that intensity data can at least provide a proxy qualitative assessment of the extent of waterlogging and hence preservation potential of alluvial sediments (Carey et al., 2006; Challis et al., 2011b; Challis and Howard, 2013). For example, at the River Wye there is a correlation between areas of low backscatter intensity and deeper (organic-rich) palaeochannel deposits (Figure 58 and Figure 59). Although the study of landscapes where archaeological resources are buried below accumulated sediments is highly challenging, ALS data can be used to map the likely distribution of deposits of archaeological interest. This, in turn, enables the context of archaeological remains to be better understood and subsequent investigations to be more focused, which can be particularly advantageous for management of potential threats and landscape conservation.



**Figure 58:** ALS visualisations of geoarchaeological resources in the Middle Wye Valley, Herefordshire (UK) including a Relative Elevation Model (REM), Simple Local Relief Model and intensity data



**Figure 59:** ALS visualisations of geoarchaeological resources in the Middle Wye Valley, Herefordshire (UK) including a Relative Elevation Model (REM), Simple Local Relief Model and intensity data

## Case Study 4: ALS for Wetland Environments

Nicholas Crabb, Dimitrij Mlekuz

Wetlands can be defined as land surfaces covered by water, or where water is present at or near the surface, either all year round or seasonally (Menotti and O'Sullivan, 2012). They are found across Europe, primarily in lowland, upland and coastal areas and include alluvial, estuarine, lacustrine and peatland environments. Like other complex depositional settings (section 4.6), the distribution and likely character of archaeological evidence within wetland landscapes is closely linked to the hydrological dynamics and geomorphological context of these environments. The environment provides the physical context for past human activities, presenting a range of opportunities and access to natural resources that people may have wished to exploit. Dynamic wetland environments also create hazards that initiate episodic change, such as floods, crevasse splays, and avulsions, which in turn affect and modify anthropogenic features. Thus, understanding the landscape history and hydrological dynamics of wetlands through surface topography, as modelled by ALS, is critical to understanding the nature and extent of archaeological remains, as well as their likely preservation.

### Understanding Sediments

Wetland sediments can deeply bury archaeological features, deposits and natural landforms complicating the interpretation of ALS data. The hydrological dynamics and local topography are critical factors in the choice of location for past human activities, for example permanent settlements located on raised areas in the floodplains or watermeadows in areas where flood water depth can be managed. ALS can only record the modern terrain surface and so the presentation and apparent distribution of cultural heritage features may be significantly impacted by the dynamic and long-term sedimentation and environmental processes in wetlands. It is necessary for users to have an understanding of the sediments and formation processes of the landscape under investigation in order to be able to use ALS data to identify potential site locations.

Archaeological features may have been inundated by blanket bog, raised bog or alluvial sediments and there are a variety of post-depositional effects such as

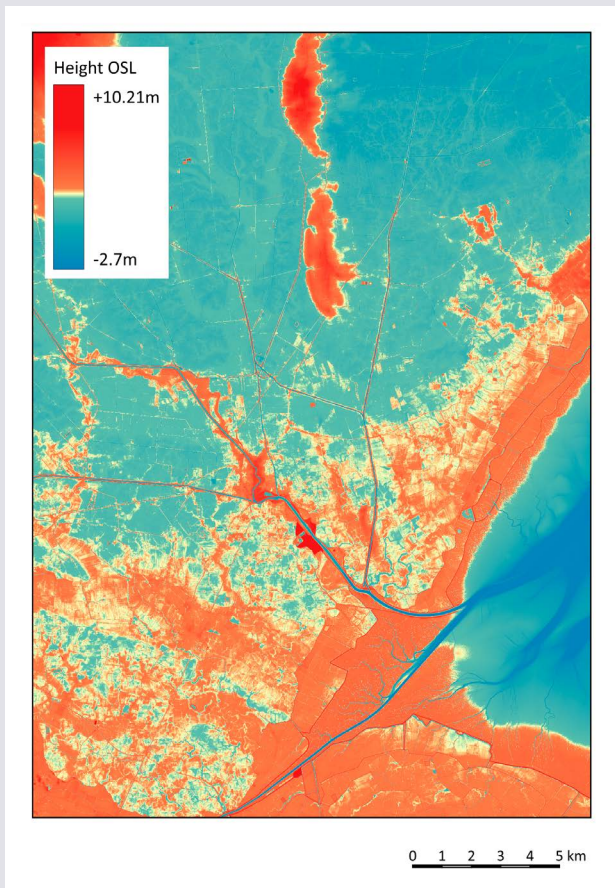
groundwater processes, saturation and modern drainage that can also affect the topographic expressions of these features. For example, within the Lincolnshire Fenland region of the UK, former water courses, known as 'Roddons', represent slightly elevated locations, due to greater shrinkage of surrounding peat, which are key to understanding distribution of archaeological resources as they attracted early and subsequent settlement (Malone, 2001; Smith et al., 2012; Zalasiewicz et al., 2020).



**Figure 60:** "Roddons" (raised former water courses) visible in fields as slight undulations at Splash Drove, near Guyhirn, Cambridgeshire, UK (from Zalasiewicz et al., 2020 fig 6.3)

ALS data can be used in conjunction with complementary datasets to identify natural features and model pre-peat landscapes (Gearey et al., 2023), as well as characterize wetland loss (Rapinel et al., 2019, 2018), and facilitate past landscape reconstructions (Carey et al., 2006; Challis et al., 2011b). As such investigations require an understanding of surface topography, drainage systems and subsurface sediment architecture, the application of ALS within wetlands is most effective when combined with other datasets such as boreholes and deeper methods of geophysical survey, for example EM, ERT and lower frequency GPR, as well as palaeoenvironmental records and dating of sediment units (section 2.7).

Understanding the morphology and sedimentology can help historic environment professionals to assess the distribution of known and possible sites in a landscape. Integrating ALS models into these analyses have been shown to help explain apparent disparities in the distribution of archaeological records and to develop a chronological framework for the development of the landscape (Howard et al., 2008a).



**Figure 61:** Raised former water courses known as “Roddons” viewed at scale on the ALS data for the Boston-Fishtoft and coastal area of Lincolnshire fen, UK (ALS Data: © Environment Agency copyright and/or database right 2024)

### Heritage of and within Wetlands

Wetland heritage comprises a diverse range of evidence that provides rich information regarding past human activity and environmental interaction. For example, some site types, such as wooden trackways, fishponds, salterns, oysterponds, jetties and water meadows, are only found in wetlands. Other more conventional sites, such as settlements, may also be better preserved due to the anoxic burial conditions provided by wetlands or may be found on slightly raised areas as these present more stable land surfaces more suitable for habitation (e.g. Coles et al., 1999; Mainberger, 2017). Settlements may also utilize the high-water tables found within wetlands for defensive purposes, such as moats or more extensive water defences, including natural or artificial lakes, dams, and sluices. In addition, wetlands provide a rare opportunity to study evidence for past communication and transport through the preservation of wooden trackways, causeways, bridges, and platforms that allowed access into or across bogs, rivers, and

estuarine marshes (Farrell and Hazell, 2018). The anoxic conditions of wetland landscapes can also lead to the exceptional preservation of buried soils (peat) and associated plant micro-fossil (pollen, insects, diatoms) and macro-fossil (wood, charcoal, molluscs, bone) records (Matthiesen et al., 2022). As these materials can be securely carbon dated, wetlands present an opportunity to reconstruct detailed sequences of landscape and land-use change (French, 2003).

In Europe, many intertidal wetlands have been reclaimed in the last few centuries which has altered the surface morphology and vegetation regime. In reclaimed wetlands, deposits may be similar to those described above, but drainage, shrinkage and compression may have damaged or destroyed archaeological deposits, particularly in peat wetlands. Such areas, often in agricultural production, typically occur on the fringes of wetlands or in areas subject to seasonal flooding. In some cases, deeply buried, waterlogged or anaerobic soils may retain the preservative qualities of wetland environments and it is perhaps even more critical that these are located. ALS has been established as an effective technique to model the geoarchaeological resource, highlighting the location of palaeochannels and therefore waterlogged deposits with the potential for the preservation of cultural and environmental remains (Carey et al., 2006; Notebaert et al., 2009).

ALS data can also be used to delineate historic landscape features. Wetlands contain rich and fertile soils and are widely utilized for contemporary and historic agriculture, often containing extensive drainage ditches and irrigation systems. Through the analysis of ALS data, this can be spatially or functionally related to a range of historic and contemporary sites, such as farmsteads, religious and manor houses, stately homes, canals, stock enclosures, barns, field systems, landscaped parks, roads, trackways, settlements, watermills, bridges, fords and ponds (e.g. Kirchner et al., 2018). Some wetland landscapes have been modified by extensive hydraulic engineering systems. These systems may have been developed over many centuries and in addition to drains and irrigation systems can consist of features designed to store water, such as moats and reservoirs, and a downstream system of canals designed for the dispersal of stored water, together with spillways and culverts to distribute it. These extensive historic water management features and systems can be mapped and modelled very effectively using ALS, which is often found to complement existing cartographic records and therefore has proven a valuable tool for

understanding modern wetland drainage in advance of restoration projects (Burge et al., 2023). Extensive modern remodelling of wetland environments may limit the applicability of ALS when defining specific archaeological or historic features.

### **Key Information for Using ALS in Wetland Environments**

The capacity of ALS to represent subtle but extensive landforms and anthropogenic features makes it a key tool for understanding wetlands. However to use the ALS data fully requires an understanding of wetland environments, their complex geomorphology, sedimentology and hydrology, and the sometimes dramatic impacts of the most recent centuries of human exploitation. ALS forms an important part of the tool kit for understanding cultural heritage of these dynamic environments, especially with respect to supporting future conservation via predictive modelling and data-led restoration.

## 4.7 3D Visualisation and Data Integration

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The 3D visualisation of terrain data has a long history (Gillings and Goodrick, 1996; McCullagh, 1988), initially for little more than providing a topographical framework (see Wheatley and Gillings, 2000). With the advent of ALS, the sheer volume of data for visualisation increased dramatically (Table 22). Software and hardware have developed in line with this shift in data volume providing an unprecedented and confusing array of tools and options for 3D visualisation. Accessibility of visualisation software varies significantly with some freely available and open source, but many software solutions are expensive and complex for the first time user.

3D visualisation software may work with the ALS point cloud, a raster, a triangulated surface model rendered from the points, or any combination of these products. Broadly software can be divided into that designed specifically for working with point clouds, general GIS software which offer some facility for 3D visualisation and integration of landscape data and more specialised software such as game engines or 3D design and modelling software which either directly, or through appropriate data manipulation, are able to visualise point clouds or surface models. Some of the most used software as of 2024 are listed in Table 23, noting that this is an area of relatively rapid change.

### Point Cloud Visualisation

Here we distinguish between software tools aimed primarily at the processing, filtering and analysis of point clouds (section 2.1) which may or may not include a data visualisation element (e.g. LAsTools rapidlasso GmbH, 2014)e.g. LAsTools and tools primarily intended to allow viewing of point clouds on which we focus. Visualisation and real time

manipulation of ALS point clouds is computationally challenging, requiring the rendering of many millions of 3D points at speed (see Table 22). In most cases software is designed to decimate the data in real-time: a process of discarding points from the data set to improve performance and reduce disk usage. In some software decimation levels can be adjusted by the user, but the process is essential for viewing and manipulating very large datasets. Typically, the reduction in the density of displayed points will be dynamic, with less points displayed during movement of the viewing position and progressively more points displayed once the viewing position is set. The graphics capabilities of the computer in use are crucial here and fast computers with significant RAM memory and powerful graphics capabilities are required for effective point cloud manipulation.

Most point cloud viewing tools allow:

- some form of engagement with the geometric properties of the points e.g. measuring heights, angles, distances, etc.
- display of points coloured by properties such as elevation, intensity, or an externally sourced colour (RGB) value if available (Figure 62)
- filtering of point clouds based on pre-determined classifications (first pulse, last pulse, etc.) (Figure 62)

In addition, generation of profiles through the point cloud is a further common and useful feature (Figure 63). Some point cloud software is designed address specific needs. For example [Fusion](#) and [3D Forest](#), have tools for the extraction of canopy models, identification of tree crowns and even the 3D modelling of individual trees from suitable data to support forest and vegetation modelling.

DSM Resolution	DSM Points 1 km <sup>2</sup>	Point Cloud Resolution	Point Cloud Points in 1 km <sup>2</sup>
0.25m	16 million	26 points per m <sup>2</sup>	26 million
0.5m	4 million	16 points per m <sup>2</sup>	16 million
1m	1 million	10 points per m <sup>2</sup>	10 million
2m	250 000	6 points per m <sup>2</sup>	6 million

**Table 22:** Numbers of individual points in raster terrain models and typical point cloud data for 1km<sup>2</sup> at spatial resolutions typical of ALS data

### 3D GIS

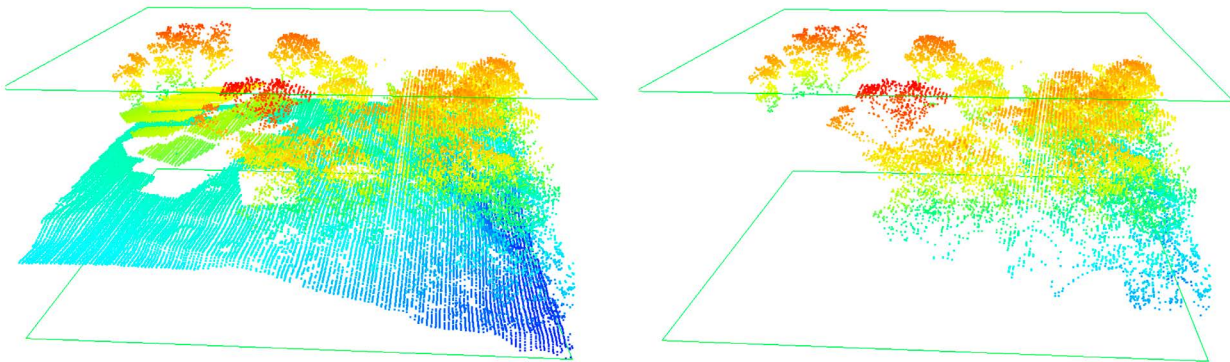
3D visualisation of surface models is a common feature of most modern GIS software. Commonly used products such as ESRI's ArcGIS and the open source QGIS can work with, and render in 3D, raster or TIN surface models generated from ALS data. Fast computers and graphics acceleration mean that these models can be manipulated and explored in real time. Surface models may be integrated with visualisation products derived from ALS data, such as a hillshade or slope severity map, and with other data such as aerial photographs or with ALS-derived intensity images. All software allow integration of ALS-derived models with other forms of vector and raster GIS data, and in some it is possible to manipulate lighting and illumination angles in real time, add 3D rendered objects such as models of trees or buildings, and may include weather effects such as digitally rendered rain. Figure 65 shows the capability of ESRI ArcGIS Online to combine

shaded digital surface models with other data, and then add lighting and atmospheric effects such as fog, rain and snow.

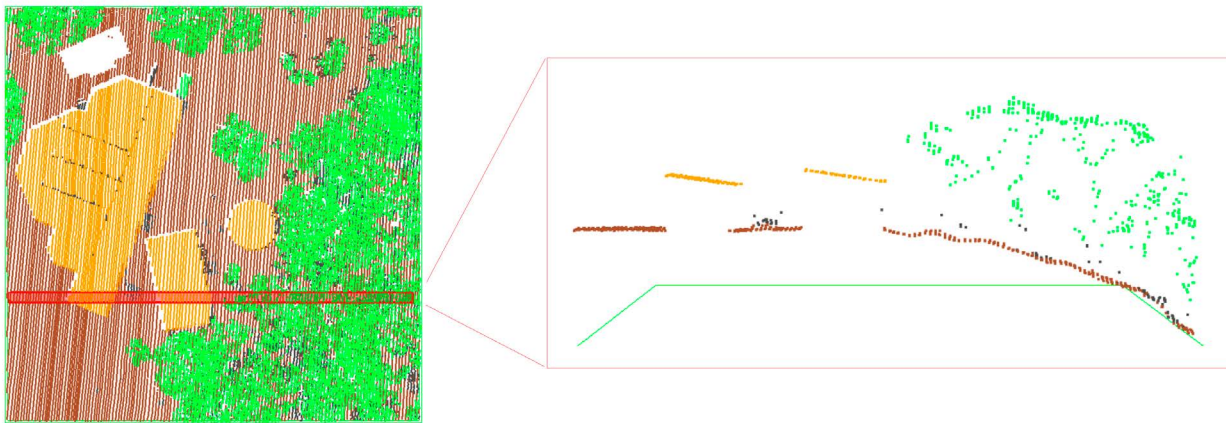
Integration of 3D point clouds within GIS is a relatively new development and some software allows 3D viewing and includes tools for the editing and manipulation of point clouds – blurring the boundary between dedicated point cloud manipulation software and GIS (Figure 64). For QGIS this development takes advantage of the Cloud Optimized Point Cloud specification to organise .las files into a format that is easier for GIS software to read. The functionality within QGIS 3.4 and above includes the ability to visualise native las point cloud data in two and three dimensions and integrate the point cloud with other raster and vector GIS data. QGIS also provides access to a wide range of point cloud processing tools via its toolbox, including native tools and third party add ons such as FUSION and LAStools.

Software	Vendor	Category	Free / Open source	URL
<b>ArcGIS</b>	ESRI	GIS	No	<a href="https://www.esri.com/">https://www.esri.com/</a>
<b>QGIS</b>	Qgis.org	GIS	Yes	<a href="https://www.qgis.org/">https://www.qgis.org/</a>
<b>SAGA GIS</b>	University of Hamburg	GIS	Yes	<a href="https://saga-gis.sourceforge.io/">https://saga-gis.sourceforge.io/</a>
<b>GRASS</b>	GRASS Development team	GIS	Yes	<a href="https://grass.osgeo.org/">https://grass.osgeo.org/</a>
<b>Quick Terrain Modeller</b>	Applied Imagery	Point cloud tools	No	<a href="https://appliedimagery.com/">https://appliedimagery.com/</a>
<b>LASview</b>	Rapidlasso	Point cloud tools	Freeware, not open source	<a href="https://rapidlasso.de/">https://rapidlasso.de/</a>
<b>Cloud Compare</b>	Cloudcompare.org	Point cloud tools	Yes	<a href="https://www.danielgm.net/cc/">https://www.danielgm.net/cc/</a>
<b>Fusion</b>	USDA Forest service	Point cloud tools	Yes	<a href="http://forsys.cfr.washington.edu/fusion/fusion_overview.html">http://forsys.cfr.washington.edu/fusion/fusion_overview.html</a>
<b>Fugro Viewer</b>	Fugro	Point cloud tools	Freeware, not open source	<a href="https://www.fugro.com/expertise/other-expertise/fugroviewer">https://www.fugro.com/expertise/other-expertise/fugroviewer</a>
<b>Blender</b>	Blender.org	3D design	Yes	<a href="https://www.blender.org/">https://www.blender.org/</a>
<b>Unreal Engine</b>	Epic Games	Game engine	Limited	<a href="https://www.unrealengine.com/">https://www.unrealengine.com/</a>
<b>Unity</b>	Unity Technologies	Game engine	Limited	<a href="https://unity.com/">https://unity.com/</a>
<b>CryEngine</b>	Crytek	Game engine	Limited	<a href="https://www.cryengine.com/">https://www.cryengine.com/</a>

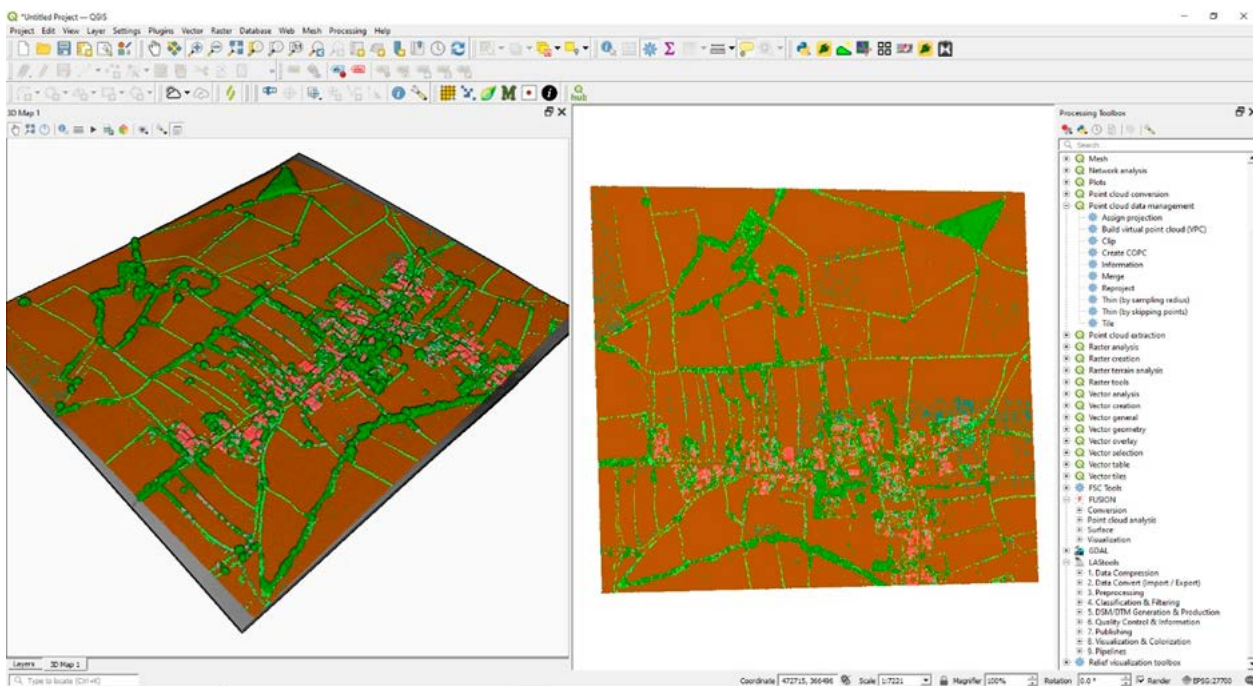
**Table 23:** A selection of software for 3D viewing and manipulation of ALS data in 2023



**Figure 62:** Visualisation of a pointcloud coloured by elevation and filtered by classification (vegetation) in LASview (rapidlasso GmbH, 2014)



**Figure 63:** Visualisation of a profile through a pointcloud in LASview (rapidlasso GmbH, 2014)



**Figure 64:** Using QGIS (v3.4) to visualise native las point cloud data in two and three dimensions and integrate the point cloud with other raster and vector GIS data (ALS data Laxton, Nottinghamshire © Environment Agency copyright and database right 2024)

## Game Engines

Computer game engines offer some of the most highly developed, versatile, and optimised tools available for manipulation of 3D data. Powerful game engines such as Unity, Unreal Engine and CryEngine are free, with licensing that effectively allows unlimited use for research purposes. Modern game engines are designed to make maximum use of graphics accelerator cards. Using sophisticated technology such as real time ray tracing (to simulate different lighting effects) and machine learning derived image enhancements, such as Nvidia's deep learning super sampling (Kapse, 2021) they produce results of startling realism with real-time user interactivity.



**Figure 65:** ESRI's ArcGIS Online has the capability to combine ALS surface models with other data and have atmospheric effects such as rain, fog or snow added for visualisation purposes. Image shows ALS data of earthworks of the Iron Age and Early Medieval hillfort at South Cadbury, Somerset (ALS Data © Environment Agency copyright and database right 2024)

Game engines have been used to visualise ALS terrain data (and indeed other forms of archaeological survey data) for some while (Challis and Kincey, 2013; Fritsch and Kada, 2004; Oikarinen et al., 2016). Early attempts required considerable data manipulation and scaling to transform GIS-derived raster terrain models into the limited range of bitmap-based height maps required by the engine to render terrain. However, transformation of raster terrain data from GIS to game engine environments has been somewhat simplified by the development of middleware products designed to generate terrain for game engines either from scratch through procedural modelling or by conversion of real-world terrain data. The appetite for use of game engines for geospatial data visualisation has driven the production of dedicated plugins designed to streamline the consumption of real-world data. An example of this is the open source GDAL translator library for raster and vector geospatial data, which has been adapted to work within Unreal Engine as a plugin, allowing in-engine access to some geospatial data and tools. Unreal Engine also includes an ALS point cloud plugin, which allows direct integration of point clouds in las format with the engine. Figure 66 illustrates how an ALS point cloud can be directly visualised and point classification accessed within Epic Games Unreal Engine (v5.2), where elevation model views can be manipulated and treated with sophisticated lighting effects to highlight subtle detail.

Most recently ESRI, working in conjunction with Epic Games and Unity Technologies have developed dedicated software development kits allowing the direct integration of GIS data stored in the ESRI ecosystem with [Unreal Engine](#) and Unity. This in effect turns the game engine into a highly sophisticated 3D visualisation tool for GIS data.

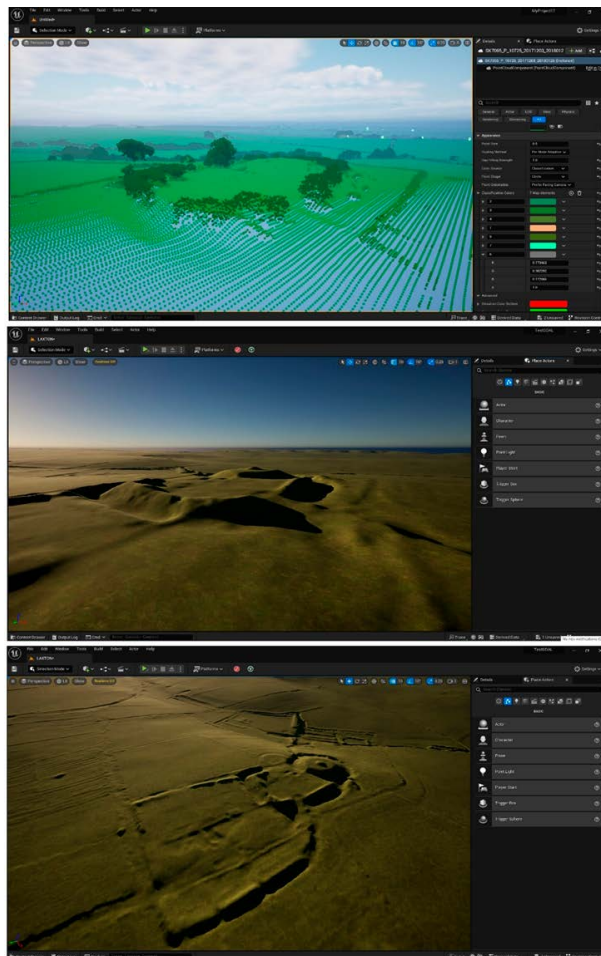
Use of ALS in game engines may serve a variety of purposes (Gabellone et al., 2017; Hatzopoulos et al., 2017; Lercari et al., 2013; Rizvić et al., 2014). While a game engine does not offer access to the full range of tools available in GIS for the analysis and metrical investigation of terrain, game environments offer very high levels of real time interaction, sophisticated illumination and atmospheric rendering tools (for example to facilitate viewshed and visibility studies) and the ability to integrate ALS-derived terrain data with other remotely sensed data, and with 3D models of assets such as historic buildings. Unlike most GIS, game engines allow engagement with landscape

data using a first-person view (Trentholme and Smith, 2008) or through the medium of a third person avatar bringing a different viewpoint to interaction with the data and cultural landscape. These can be used to underpin enhanced user and public outreach experiences such as those showcased in section 3.6.

### Other 3D Software

Suitably manipulated ALS terrain models can be integrated with and displayed in almost any 3D software that is able to consume standard 3D data formats. Common tools such as the open-source Blender, or commercial software such as 3DStudio and Maya, allow terrain data to be rendered in great detail, although such software is aimed at high fidelity static rendering or pre-rendered animation generation, rather than direct user interaction with data. Many of the more specialised 3D modelling and design tools require conversion of ALS-derived terrain data into specific formats to enable data integration (e.g. the SLS / SLA formats favoured by 3D printers), or more common 3D modelling formats such as wavefront.obj or Autodesk .fbx. In some cases, bespoke tools exist to facilitate this (e.g. the [DEMto3D plugin for QGIS](#) which allows export of ALS-derived terrain data to STL format for 3D printing), but in other cases the user is left to establish their own data translation methods to move data between software and this can be a significant barrier to re-use of the ALS-derived models.

Use of ALS terrain data in 3D design software is likely to be for niche applications such as integration with other 3D design work, as the terrain base for a digital reconstruction, for a rendered 3D terrain model making use of specialised lighting and modelling functions offered by this software, or even for film production and VFX, and is probably not for the general user. However it is useful for managers and commissioners to be aware that such outputs can be created especially if the aim of a project is to diversify outputs and engage a wider audience with the cultural landscape captured by the ALS data.



**Figure 66:** Point cloud data directly visualised within Epic Games Unreal Engine (v5.2), allowing the manipulation of model views and lighting. Image shows ALS data for earthworks of the medieval castle at Laxton, Nottinghamshire (ALS Data: © Environment Agency copyright and database right 2024)

# GLOSSARY

Term	Acronym	Definition
Airborne Laser Scanning	ALS	An active remote sensing technique that is used to collect high resolution height data of the ground surface from a plane, helicopter or UAV. From these measurements highly accurate and precise 3D models and visualisations of landscapes can be produced.
ALS-Derived Model		A digital elevation model created from ALS data.
Ambient Occlusion		A scalar value recorded at every surface point indicating the average amount of self-occlusion occurring at the point on the surface. It measures the extent to which a location on the surface is obscured from surrounding light sources
Data Management Plan	DMP	A written document outlining how research data will be managed both during and after a research project. The plan should address what types of data will be collected and how the data will be documented, stored, shared and preserved.
Deep Learning		A subset of machine learning that uses multi-layered neural networks, called deep neural networks, to simulate the complex decision-making power of the human brain.
Digital Elevation Model	DEM	A digital representation of ground surface topography or terrain. DEM is a generic term which can easily be confused use more specific term (DFM, DSM, DTM) when referring to models derived from ALS data.
Digital Feature Model	DFM	A variation of the digital terrain model, incorporating buildings and structures as well as the ground surface, making it relevant to wider cultural heritage applications
Digital Surface Model	DSM	A digital elevation model derived from ALS data points that captures both the natural and built/artificial features of the environment.
Digital Terrain Model	DTM	A digital elevation model derived from ALS data points that have been classified as terrain points and are therefore representative of the ground surface (without vegetation, man made objects etc.).
Discrete Return Lidar System		Records a few, typically up to four, returns for each laser pulse emitted.
FAIR Data		FAIR data are data which meet principles of Findability, Accessibility, Interoperability, and Reusability
False Negative		A feature not identified by the detection algorithm which is incorrectly defined e.g. a burial mound that is not classified as a burial mound.
False Positive		A feature identified by the detection algorithm which is incorrectly defined e.g. a modern roundabout or a natural mound classified as a burial mound.
Full Waveform Lidar System		Records a full profile of a return signal by sampling it at fixed time intervals, typically 1ns (i.e. 15cm).
Global Navigation Satellite System	GNSS	A global navigation satellite system, or GNSS is a network of satellites that broadcasts timing and orbital information, which is used for navigation and measuring the position of an item.
Inertial Measurement Unit	IMU	An electronic device that measures and reports attitude (roll, pitch and yaw), velocity, changes in altitude and gravitational forces acting on an aircraft
Inspire Directive		The Inspire Directive aims to create a European Union spatial data infrastructure for the purposes of EU environmental policies and policies or activities which may have an impact on the environment. It was adopted in May 2007 and forms the template for spatial data interchange across Europe.

Term	Acronym	Definition
Intensity		The return strength of the laser pulse that generated the point height.
Intersection Over Union		A metric quantification of the overlap between the predicted bounding box and that derived from ground observations.
Laser		A device that emits light in a very narrow beam.
Laser Pulse		Laser light emitted for a short duration and usually at a specific repetition rate.
Lidar	lidar	A contraction of Light Detection and Ranging, defined as both the technique of using a laser to measure distance and as the sensor unit that emits and records the laser. Commonly used in the field of cultural heritage to refer to ALS survey, ALS data and ALS-derived products. Use a more specific term instead.
Metadata		A set of data that describes and gives information about other data.
Near-Infrared	NIR	Near-infrared region is a term for the wavelengths of the electromagnetic spectrum from 0.7 $\mu$ m to 1.4 $\mu$ m (700 to 1400nm), just outside the range of the red hues in the visible spectrum.
Open Data		Open data is data that can be freely used, re-used and redistributed by anyone. It may have requirements to attribute the data source and ensure sharealike principles for derived products.
Paradata		Data of a procedural nature that gives information about the processing of the data and the actors involved.
Persistent Identifier	PID	A persistent identifier (PI or PID) is a long-lasting reference to a document, file, web page, or other object.
Phase-Shift Scanning		Phase Shift Scanners emit laser light at alternating frequencies and measure the difference between the emitted and reflected signals to determine the distance to an object.
Point Cloud		A discrete set of data points in space, with values describing their location (x, y, z) and possibly other attributes such as pulse return intensity, return identification, classification, scan angle, etc.
Point Density		The total number of returns per 1 m <sup>2</sup> . Density can be calculated for different categories, e.g. for ground returns only, for a single data strip or for a combined dataset.
Pulse Density		The number of pulses (first and only returns) per 1m <sup>2</sup> recorded by the lidar sensor.
Registration		The process of transforming ALS data points into a co-ordinate reference system. This is done via integration with the data collected via the on-board GNSS unit and ground control points.
Resolution		The spatial resolution of an ALS-derived digital elevation model refers to the area of land being represented by a single grid cell or pixel. A spatial resolution of 1 metres means one grid cell represents an area of 1m x 1m. The appropriate resolution for a ALS model is calculated using the point density and spacing in the point cloud.
Returns		The reflected signal of the lidar sensor which is recorded and processed into height data. One laser pulse may have many returns (partial penetration of vegetation canopy), one return (solid surface) or no returns (water body) depending on the nature of reflecting surfaces.
Secchi Depth		Measurement of the clarity of the water column (and thus light penetration) defined as the maximum depth at which a black and white or all white disk of 30 cm diameter disappears from view by the unaided human eye.

Term	Acronym	Definition
Schema		A plan or diagram detailing structure of the data and how it is to be organised.
Strip Adjustment		Correction of systematic errors in the ALS data collected using geometric adjustment between adjacent swaths of data.
Time-Of-Flight		A time of flight scanner calculates the distance to the surface using the time measurement between when a laser pulse is sent out and when that pulse is reflected from a given surface and returns to the sensor.
Unmanned Aerial Vehicle	UAV	An aircraft piloted by remote control or onboard computers.

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