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5.5 Using LIDAR-derived Local Relief Models (LRM) as a new tool for archaeological prospection

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Abstract

High-resolution Digital Elevation Models (DEM) based on airborne LiDAR have emerged as a valuable new data source in archaeology. While such data are becoming increasingly available on a regional to national scale, their potential is far from being fully utilised. One field in which improvements can be expected is the optimisation of data processing with the goal of extracting anthropogenic features for archaeological prospection. Until recent years, however, most archaeological applications of LiDAR have been limited to the visual interpretation of the DEM. In this case, the detection of potential archaeological features depends to a large degree on the chosen illumination angles. Here, a data processing approach is presented which produces Local Relief Models (LRM) from LiDAR-derived high-resolution DEM. The LRM represents local, small-scale elevation differences after removing the large-scale landscape forms from the data. The LRM greatly enhances the visibility of small-scale, shallow topographic features irrespective of the illumination angle and allows their relative elevations as well as their volumes to be directly measured. This makes the LRM an improved basis for spatially extensive archaeological prospection over a wide range of landscapes. The LRM raster map of local positive and negative relief variations can be used for the mapping and prospecting of archaeological features such as burial mounds, linear and circular earthworks, sunken roads, agricultural terraces, ridge and furrow fields, kiln podia and mining sites. This approach is currently being used in a project aimed at the spatially complete archaeological mapping and prospection of Baden-Württemberg, covering an area of 35,751 km². The goal is the verification and extension of the existing archaeological data base. An object-based local relief vector layer is produced as a by-product; however, due to the common agglutination of natural and anthropogenic features this cannot be efficiently used for archaeological prospection at present.
KEYWORDS

LiDAR, Local Relief Model, LRM, archaeological prospection, Baden-Württemberg, Germany

INTRODUCTION

The federal state Baden-Württemberg in south-western Germany is rich in archaeological heritage from the Palaeolithic onwards. Numerous Neolithic, Bronze and Iron Age, Roman, Merovingian, medieval and early modern sites make Baden-Württemberg a region of great archaeological importance (cf. LAD 2009, for an overview of recent archaeological research in Baden-Württemberg). Of particular importance are sites dating to the early Celtic period like the hill fort Heuneburg – perhaps the earliest urban settlement north of the Alps – and the Upper German and Rhætian segment of the Roman Limes, a part of the UNESCO World Heritage system.

However, it is unknown to what extent the current state of knowledge approximates the actual number of sites. This is particularly relevant given the high forest cover of 39% of the state which renders large areas as blank spaces for archaeological prospection by aerial photography. Residential and industrial sprawl, construction of roads, railway lines and pipelines, mechanised agriculture and forestry practices as well as looting pose serious threats to known and unknown archaeological sites. Before this backdrop of the urgent necessity for spatially extensive archaeological prospection, in 2009 the State Office for Cultural Heritage Management Baden-Württemberg launched a project aimed at the complete archaeological mapping of Baden-Württemberg using high-resolution airborne LiDAR (Light Detection And Ranging) data, covering an area of 35,751 km². The goal is the verification and extension of the existing archaeological data base. While it is recognised that aerial approaches to archaeological prospection have serious limitations for certain types of sites and particularly in areas of sediment accumulation, no other type of prospection allows a complete coverage of large areas with a single and consistent methodology.

METHODOLOGY

High-resolution Digital Elevation Models (DEM) based on airborne LiDAR (Light Detection And Ranging, also known as Airborne Laser Scanning, ALS) have in recent years become an important data source for the prospection, mapping and monitoring of archaeological sites. Such data are now becoming increasingly available on a regional or even national scale. In most archaeological applications, LiDAR is applied to relatively small areas (up to a few square kilometres). LiDAR DEM are mostly visualised as shaded relief images which allow viewing the land surface under different simulated lighting conditions (elevation and azimuth) as well as vertical exaggeration (e.g. Harmon et al. 2006; Bofinger et al. 2006; Boos et al. 2008; Risbøl et al. 2006). While the experimental manipulation of lighting conditions allows a visual optimisation of individual features, it is a time-consuming process as the visibility of potential archaeological features depends to a large degree on the chosen illumination angles (e.g. Devereux et al. 2005). For a spatially extensive prospection project covering thousands of square kilometres – like the present
project in Baden-Württemberg – time is an important constraint. Therefore, and to enhance the reliability of the prospection results, improved visualisation techniques are required in archaeological applications of LiDAR. Experimentation with approaches for improved visualisation from other disciplines (Hiller & Smith 2008; Loisios et al. 2007; Rusinkiewicz et al. 2006) did not deliver satisfactory result for archaeological prospection.

In the first phase of the present project, a new approach was therefore developed and implemented (Hesse 2010). It is based on the observation that archaeologically relevant structures are usually characterised by very low relief relative to the elevation range of the surrounding landscape. Because they thus often only appear as subtle features in the conventional shaded relief visualisation, one goal of LiDAR data processing for archaeological prospection was identified as the problem of extracting local small-scale, low-relief features from the DEM and eliminate as far as possible the large-scale landscape forms from the data.

Several data processing steps (fig. 1) have to be applied to extract small-scale (detail) topographic features for archaeological interpretation:

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Figure 1. Data processing steps for the generation of the Local Relief Model (LRM). See text for the description of data processing. The image series shows a group of burial mounds in the Schönbuch area. See also the full colour section in this book.
a. A DEM is produced from the vegetation-filtered LiDAR point cloud data (in the present case with a pixel size of 1 x 1m).

b. A low pass filter is applied to the DEM. This smoothed elevation model represents a first approximation of the large-scale landscape forms. The kernel size of the low pass filter determines the spatial scale of features which will be captured in the LRM. In the present case, a kernel size of 25 metres is used for the low pass filter. This size was found experimentally to result in a good representation of many previously known archaeological features and is therefore assumed to work well for the detection of previously unknown features. Features much larger in diameter or cross-section are uncommon; furthermore, they would be conspicuous in conventional shaded relief images of the DEM. Degraded representation for much smaller features than the kernel size may become a serious issue if they are underlain by strongly convex or concave terrain (e.g. hilltops or ridges, valley bottoms), but is less pronounced on smooth slopes.

c. By subtracting this smoothed elevation model from the DEM, a first approximation of the local relief is achieved: only small-scale topographic features are preserved in the model while the large-scale landscape forms are eliminated. However, because small-scale features are smoothed rather than eliminated by the low pass filter, the model derived by this approach is biased towards small features, i.e. the local relief elevations are progressively underestimated as spatial extent of the features increases.

d. The zero-metre contour lines in the difference map represent the boundaries between positive and negative relief anomalies. Potentially, these lines can be used in vector data processing to derive shape parameters for individual anomalies.

e. The elevation values of the DEM are extracted along these lines. This results in a set of elevation values that do not belong to – positive or negative – relief anomalies.

f. A purged DEM is created from the extracted DEM point elevations by interpolation. This purged DEM represents the large-scale landscape forms after cutting out rather than smoothing small-scale features.

g. Subtraction of this purged DEM from the original DEM results in the final LRM which reflects less biased elevation information of small-scale features relative to the landscape at large. The visual rendering of positive and negative relief anomalies can be enhanced by colour-coding.

In comparison to using a simple difference map between the DEM and its low pass or median filtered derivate (Doneus & Briese 2006; Hiller & Smith 2008), the LRM derived using this approach results in a less biased representation of small-scale topographic features which reflects more truthfully the elevations of these features relative to the surrounding landscape and thus allows the direct measurement of feature volumes and heights. On the other hand, it is less computationally expensive and easier to implement than the kriging based filtering suggested by Humme et al. (2006) if an efficient workflow for data processing is applied.
DATA MANAGEMENT AND APPLICATION OF THE LRM WORKFLOW

The German state Baden-Württemberg has an area of 35,751 km². Vegetation-filtered LiDAR point cloud data were supplied by the State Surveying Office Baden-Württemberg. The enormous amount of data that had to be processed (more than one terabyte in approx. 160,000 separate files) required the acquisition of capable hardware (8-core Xeron with 16 GB RAM and 4.5 TB hard disc) and software (ENVI). Dedicated software for the efficient management of the data and the semi-automatic implementation of the LRM workflow was not available at the outset of the project.

Therefore, two graphical user interfaces were developed using VBA (Visual Basic for Applications). The first user interface allows the efficient interactive management of all raw, semi-processed and processed data. The current data processing and archaeological prospection status is documented for data segments of ten by ten kilometres. Several data processing steps implemented in VBA can be interactively executed for the selected data segments. For data processing steps that are executed in ENVI, the processing status is also documented in the user interface. Furthermore, relevant metadata like the number of known archaeological sites in each data segment or the average LiDAR raw data quality are displayed in the user interface, preview maps of the data segments can be displayed and short notes can be stored for each data segment.

Finally, data segments can be selected and all relevant data can be opened for visualisation and mapping. This includes:

- the LiDAR-derived DEM, DSM and LRM (DSM = Digital Surface Model);
- raster maps showing the LiDAR raw data quality in terms of point density and data gaps;
- raster maps showing surface depressions (e.g. dolines) derived from the LiDAR DEM;
- topographic and geological maps;
- aerial photographs;
- vector data of present settlements, roads etc.;
- vector data of known archaeological sites and find spots.

The mapping/prospection is based on the visual interpretation of a combination of all relevant data. Known archaeological sites and find points are used as reference for the qualitative and quantitative properties of archaeological features.

A second graphical user interface serves as a toolbox for actual prospection. It allows the orientation within the ten by ten kilometre segment and the documentation of the mapping status on the scale of one square kilometre as well as the interactive manipulation of the illumination in the shaded DEM visualisation. It also provides templates for the creation of new vector objects for the mapping of potential archaeological features.

FIRST RESULTS

After development and implementation of methodology, workflow and data management, the processing of the LiDAR point cloud data, the DEM and LRM for the entire state Baden-Württemberg were generated. Further LiDAR-derived raster maps showing raw data quality, data gaps as well as surface depressions...
were generated. Data processing was largely finished in January 2010. The subsequent archaeological prospection then concentrated on two large test regions, the forest Schönbuch region in the centre of Baden-Württemberg and the southern Black Forest and Upper Rhine region (fig. 2).

The Schönbuch region has an area of 600 km\(^2\). Here, the 2,513 potential archaeological sites identified by LiDAR prospection compare with 1966 previously known sites and find spots. In the region southern Black Forest and Upper Rhine, prospection of an area of 2,700 km\(^2\) resulted in 57,936 potential sites compared with 3,726 previously known sites and find spots.

Most features mapped as potential archaeological sites can be related to historic or prehistoric resource use. Terraced slopes as well as ridge-and-furrow document agricultural use; mining traces and slag heaps as well as thousands of kiln podia allow new insights into spatial patterns of mining, ore processing and related fuel supply. Furthermore, a large number of potential burial mounds as well as several previously unknown fortifications have been detected. Sunken roads as well as former field parcel patterns are also mapped as they allow inferences regarding the location of settlements.
EXAMPLES

The application of the LRM approach to the two extensive test regions Schönbuch and southern Black Forest/Upper Rhine indicates that in particular kiln podia, sunken roads and former agricultural structures (ridge and furrow, fig. 3a; terraced slopes) can in many cases be unambiguously identified because there are no natural morphological equivalents. Characteristics of kiln podia are a roughly circular outline, a steep upslope scar and a downslope lip (fig. 3b). Features created by the uprooting of large trees or mining

Figure 3. LRM colour maps showing (a) ridge and furrow, (b) kiln podia, (c) sunken roads and (d) mining traces. See also the full colour section in this book
scars on slopes may occasionally be misinterpreted as small kiln podia, but in general the confidence of identification is high. The regular spacing typical of many kiln podia clusters can help to avoid misinterpretations. Sunken roads are often well-identified where they occur as swarms of incised linear features which climb slopes at oblique angles (fig. 3c).

The identification of burial mounds, however, is much less definite. There are many features which may appear as well-defined positive local relief in the LiDAR data, including small natural mounds, slag heaps related to ore processing, waste heaps related to mining or quarrying, wood piles or patches of low vegetation not filtered out by the vegetation removal algorithm. On the other hand, many burial mounds in agricultural areas have been deliberately removed to smooth the terrain or have been unintentionally levelled by ploughing. In these cases, they may survive as very low height anomalies of only a few decimetres. Definite identification of positive local relief features as burial mounds is therefore difficult and has to take into account their distribution in the landscape, with burial mounds often occurring in clusters. Traces of mining activities are often discernible as negative local relief features (fig. 3d); their size, shape and distribution may allow some age assignment based on the technology used. However, some morphological overlap exists between the superficial traces of collapsed mining galleries and geological features (sinkholes).

**ADVANTAGES AND LIMITATIONS**

Because large-scale landscape forms should not be neglected in archaeological prospection, the conventional method of shaded relief representation was used as an auxiliary tool. This allows direct comparison of shaded relief DEM and LRM visualisation and the assessment of advantages and limitations of each method.

While the shaded relief DEM appears visually more 'natural' for the observer, experimenting with variations of illumination elevation and azimuth angles is necessary. Illuminations using azimuth angles between 90° and 270° are often necessary to shed light on south-sloping terrain; however, this commonly leads to the optical illusion of relief inversion. While pronounced features are clearly visible under suitable illumination, the challenge is that a universally suitable illumination does not exist. Subtle features often become visible only under very constrained illumination conditions and therefore tend to be found accidentally rather than systematically.

By comparison, the LRM is well-suited to visualise very low topographic features independent of their topographic location and independent of their alignment. The LRM allows the visualisation of local relief variations in intuitively recognisable colours irrespective of the absolute elevation, making the LRM raster map almost as easily comprehensible as the DEM. Furthermore, by draping the LRM as a colour map over a 3D representation of the DEM, subtle local relief anomalies can be clearly visualised without the distortions caused by strong vertical exaggeration. Another advantage is that the elevations and volumes of small-scale topographic features relative to the surrounding landscape can be directly measured in the LRM. However, natural convex and concave landforms (e.g. hilltops, plateau edges, valley bottoms) also appear as positive or negative features in the LRM. Interpretation therefore requires some experience and the recognition of the effect on the natural landscape forms on the LRM. Furthermore, features on slopes suffer some distortion. Depending of the interpolation algorithm applied for creating the purged DEM,
artefacts may be introduced. Another issue is the fact that the scale of features which are resolved in the LRM ultimately depends on the kernel size of the low pass filter applied in the workflow. Therefore, optimal adaptation of the LRM to features significantly larger or smaller than the standard kernel size used in a particular study may require much of the workflow to be applied repeatedly for different kernel sizes. This task can be partially or fully automated. At the present stage, a kernel standard size of 25 metres is used for the low pass filter. This kernel size was found experimentally to result in a good representation of many previously known archaeological features and is therefore assumed to work well for previously unknown features. Features much larger in diameter or cross-section are uncommon; degraded representation for much smaller features only becomes a serious issue if they are underlain by rather convex or concave terrain (e.g. sharp hilltops or ridges, valley bottoms), but is less pronounced on smooth slopes.

CONCLUSIONS AND OUTLOOK

Extracting Local Relief Models (LRM) from high-resolution LiDAR data has the potential to greatly improve the potential of such data for the prospection, mapping and monitoring of archaeological sites. The value of the LRM approach lies in particular in the representation of local topographic detail detached from the large-scale landscape forms and in avoiding the necessity of experimenting with numerous combinations of illumination azimuth and elevation. Colour-coded maps of the LRM are found to be a valuable tool for the time-efficient prospection of extensive areas, particularly if used in combination (e.g., draped over) shaded relief. Another advantage is that heights and volumes of small-scale features can be directly measured. First results of the project in Baden-Württemberg confirm the feasibility of using LiDAR-derived Local Relief Models (LRM) for the archaeological mapping and prospection of very large areas.

Besides the ongoing archaeological prospection of Baden-Württemberg, further work is planned in the fields of data processing and interpretation. This future work will concentrate on (a) the statistical assessment of size and spatial distribution of sites, (b) the combined processing and interpretation of raster and vector data (i.e. taking into account shape and volume of relief anomalies): One goal of this work is (c) the (semi-)automated detection of selected features.

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