Full-waveform airborne laser scanning as a tool for archaeological reconnaissance

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1 Introduction

Airborne Laser Scanning (ALS), also referred to as LiDAR, is a rather new technique to produce dense and high precision measurements of the topography of the Earth's surface (Ackermann, 1999; Kraus, 2004, 449-470; Wehr and Lohr, 1999). The scanning device is typically mounted at the bottom or below an aeroplane or helicopter. For the determination of object points, the laserscanner emits short infrared pulses into different directions across the flight path towards the earth's surface and a photodiode records the backscattered echo and determines the distance to the reflecting object by the determination of the travel time.

ALS finds application in archaeology because working with archaeological sites and landscapes involves also the description of topography. So far, ALS was used as a tool to produce detailed maps of archaeological sites showing in relief. But it has also a high potential to be used for detection of archaeological sites, especially in densely vegetated areas.

This paper therefore deals with the reconnaissance aspects of ALS. In April 2006, the project "LiDAR-Supported Archaeological Prospection in Woodland" was launched, which is funded by the Austrian Science Fund (FWF P18674-G02). The goal of the project is to explore the potential of ALS for archaeological reconnaissance in a densely forested area; specifically, to evaluate an approx. 190 km² forest area within an archaeological case study. Using the data of a test scan, some issues are presented that have to be decided upon during its workflow, in order to use the output for the detection of archaeological sites.

2 ALS and archaeological surveying

The archaeological application of ALS so far showed that it is extremely useful to measure extensive archaeological sites showing in relief (Bewley, 2003; Challis, 2006; Holden et al., 2002; Motkin, 2001; Shell and Roughley, 2004). The short time needed for the production of data and the detail and high accuracy of the derived DTM made it also a tool to monitor sites and map the occurrence and extent of damage or destruction (Barnes, 2003). Various applications demonstrated that when using ALS it was possible to depict subtle features in relief, which are hardly detectable and comprehensible when surveying terrestrially. In several cases, previously unknown features were detected in ALS data. This expands the potential of ALS from a plain measurement technique to a tool for archaeological reconnaissance.

Recent publications examined its possibility to survey sites in relief even under dense vegetation. Already known archaeological sites, as for example an Iron Age hillfort (Devereux et al., 2005), ridge and furrow (Sittler, 2004), or round barrows (Doneus and Briese, 2006) were scanned using conventional and full-waveform recording systems. The results were more than promising and will have a substantial impact on future archaeological investigations in woodland. Even under difficult canopy, as deciduous trees with dense understorey, or conifers, the archaeological features could be measured in detail. Especially the latest generation of full-waveform recording scanners proved to be extremely useful. The consequent step forward will be to test ALS as a method of archaeological reconnaissance in forests, i.e. to evaluate its potential to detect previously unknown sites.

3 ALS as an archaeological prospection technique

Currently, archaeologists use only two prospection methods for the systematic (i.e. not coincidental) discovery of archaeological sites: field survey and aerial archaeology. Both methods come to their limit in woodland, which results in the fact that we usually know only large and well preserved sites in these areas.

As a prospection technique, ALS takes an intermediate position between aerial archaeology and topographical surveying. With aerial archaeology it has in common that it is an airborne method recording sites in relief in a way, which is similar to vertical aerial photography (where sites are showing as shadow-, flood-, or snow-marks). Both the aerial photograph and the derived DTM from an ALS scan need *interpretation* to identify potential archaeological sites and features. The main difference lies in the fact that aerial photography is a passive remote sensing technique recording the reflected part of the visible and near infrared range of the electromagnetic spectrum on film or a digital sensor. A photo-pixel is a mixture of all radiation within a certain back-scattering area. ALS, on the other hand, is an active technique measuring a dense network of 3d-points of the Earth's surface. A laser pulse can penetrate vegetation to a certain degree and offers the possibility to discriminate different objects within the footprint.

During aerial archaeological reconnaissance flights, only a few parameters, as date and time of flight, flying height, direction of view, and type of sensor can be influenced to improve the detectability of sites. Once an aerial photograph is made, there is only a limited variety of possibilities to enhance it for easier interpretation.

The raw data of an ALS scan are composed of both terrain and off-terrain measurements, which can be modelled as a digital surface model (DSM) and digital terrain model (DTM). The high-resolution models of an ALS scan have a wider range of possibilities for interpretation. It is for example possible to virtually influence factors of shadow characteristic (preserved height and alignment of the structures to the angle of insolation; position of the sun) that we cannot influence in real life, or to derive secondary models like slope, aspect, and curvature in a desk-based environment later on.

The common point of ALS with surveying is that both methods take measurements and both methods should result in an *interpretation* map. The important difference lies in the fact that the archaeological surveyor is literally in touch with an *already known site* and for reasons of time usually only records what is interpreted on site as archaeologically relevant. During an ALS scan, the total area of interest will be documented with the same high point density (3 to 8 points per m^2), regardless if it contains archaeological features or not.

Throughout the process of terrestrially recording a site, an interpretation is already taking place. The interpretation of an ALS scan is a desk-based analysis of the data later on in a remote place. Being in touch with the site has many advantages and it will be no difficulty for the surveyor to distinguish a pile of wood from a barrow. This can be a very difficult task when working with ALS data. On the other hand, what the surveyor doesn't see during the recording procedure at the site (e.g. because of the faint relief or the dense vegetation cover) will be lost in the final record. In an ALS point cloud, all features within the range discrimination of the instrument and which are sampled within the given point density are documented, regardless whether they are observed during the interpretation process or not. Anybody, who afterwards (re)interprets the data, will see the terrain in the same condition, regardless, if this happens the day after or years later. The data can be interpreted time and again and, as experience and knowledge increases and perception changes, more and more information will be probably found.

Re-interpretation of a site (i.e. re-measuring it) is theoretically also possible when surveying it terrestrially, but it is certainly not common practice. More often than wanted, sites cannot be re-measured because they were subject to damage or destruction. In these cases, previously not recorded features are lost for ever.

4 Using ALS for archaeological reconnaissance in forests

With human occupation, the landscape usually gets shaped: pits and ditches are dug, banks and mounds erected, slopes are terraced, houses built, etc. When a site is abandoned, the structures will start to deteriorate. Without human interaction (especially agriculture), the process of decay can be stabilised by vegetation and the archaeological structures will form part of the ground's surface. Therefore, in a forest, we can expect sites, which are still surviving in relief and can be consequently detected in a DTM derived from ALS data.

ALS works in forested areas because it is possible to differ between the first and the last light echo that follow a single measurement pulse. The first echo (= first pulse) is reflected by the earth's surface (also from treetops, high voltage transmission lines, or roof edges), the last echo (= last pulse) usually from the ground beneath. For the time being, the application of ALS seems to be the only possibility to gain elevation information at an acceptable cost to systematically search for unknown archaeological traces in woodland.

To evaluate the potential of ALS to detect previously unknown sites in forests, the project "LiDAR-supported archaeological prospection in woodland" tries to evaluate an approx. 190 km^2 forest area within the Leitha mountain range, 50 km southeast of Vienna, in an archaeological case study. The area is almost entirely covered with mixed woodland of mainly oak and beech trees with a varying range of understorey.

To test the configuration and parameters of the scanning system and the methods of data processing, filtering, and visualisation, a test scan was conducted during the pilot phase of the project. During the workflow of the test scan from data acquisition to the visualisation for final interpretation, several considerations and decisions had to be made, which had a considerable impact on the quality of the result. In the following some of these issues will be discussed.

4.1 Choice of sensor

At the moment, there are two different types of sensor systems available: so called conventional scanners and full-waveform recording systems.

Conventional systems record typically up to four distinct echoes from multiple targets (e.g. treetop, second level of vegetation, surface) touched by a single laser pulse using analogue detectors in real time during the acquisition process. As a result, these systems provide "only" an irregular 3D point cloud containing coordinates of scattering targets and usually the respective un-calibrated intensity information. For the classification of the point cloud into terrain and off-terrain points, only the location information of the individual points is typically used. Therefore, the developed filtering techniques are all based on the local spatial relationships of the 3D points (Wagner et al., 2004, 101). Usually, the height difference of the scanned objects must be 1.5 m to be able to distinguish the returns, which makes it difficult to get the surface height in areas e.g. covered with dense low bushes (Kraus, 2004).

The latest generation of commercially available ALS systems, the so called full-waveform recording scanners, sample the entire echo waveform for each emitted laser beam (typically with an interval of 1 ns) and convert the signal in a digital data stream, which can be post-processed later (Wagner et al., 2004, 105).

The echo-waveform allows gaining further physical observations of the reflecting surface elements, which can be useful for subsequent object classification. As a result, in comparison with the conventional ALS data, a more reliable classification of the laser points and a higher accuracy of the terrain points can be expected.

4.2 Data acquisition

In a forest, only part of the laser pulses will penetrate through to the actual ground. To get a high density of ground points, a slow moving platform with a high frequency scanner was used. The data acquisition took place in the dormant period beginning of April 2006 using a RIEGL Airborne Laser Scanner LMS-Q560 operated by the company *Mi*lan Flug GmbH. Its multi-target range discrimination is 0.6 m.

Flight altitude was about 600 m above ground, which resulted in a laser footprint size of 30 cm on ground. A total area of 9 km² was covered with a scan angle of 45 degrees by 26 parallel flight tracks, which had a width of approximately 500 m and an overlap of 50%. The real scan rate was 66 kHz that resulted in an overall mean point density of eight measurements per m².

Although it is often argued that scanning a forest demands a narrow opening angle of the scanner to receive only nadir or near-nadir returns, the test scan was done using the maximum scan angle of 45 degrees with an overlap of 50%. This resulted in a large overlapping area of two neighbouring strips, which can be an advantage when georeferencing. Due to the large overlap, it was also ascertained that every object on the ground would be hit at least twice from two sides and there is a good chance, that some of the oblique laser pulses will hit the ground below conifers where the almost vertical laser pulses of a system operating with a narrow scan angle would not get through. The drawback of a wide opening angle with a large overlapping area is the huge amount of data that have to be processed. In this case the entire point cloud had a density of 8 points per m^2 resulting in 22.5 GB of raw data for $9km^2$. The remaining point density when considering only the last pulses was still 5 points per m^2. Due to the wide opening angle, especially near the borders of the scanning strip a high number of last pulses were returned from tree trunks and consequently had to be filtered out later on.

4.3 Georeferencing

Georeferencing of the laser data is usually done by the data providers, where a calibration over asphalt or areas with sparse, very low vegetation is usually performed (Pfeifer et al., 2004, 2). This was also the case with the test scan.

The georeferencing process still causes a few problems (Kager, 2004), which usually introduce inaccuracies into the resulting point cloud. These inaccuracies will lead to discrepancies between overlapping laser scanner strips, which can result in noise, and formation of non existing structures (sinusoidal curves, but also edges), which consequently can irritate during the process of interpretation.

These inaccuracies can be improved doing a simultaneous 3D adjustment by least squares. For this, tying features between the overlapping stripes are used analogously to tie points in aerotriangulation. As tying features, homologous planes and straight lines with low noise from covering vegetation are used (e.g. roofs, meadows, roads).

In order to have a reliable description of the plane, there should be a sufficient number of last pulse ALS points (at least 15 points). Furthermore, the plane should be of minimal steepness. It should have not too many outliers (chimneys, trees etc.) (Kager, 2004). In a forest, it can be more difficult to find appropriate tying features. Therefore, a large overlapping area between scan strips is an advantage.

At the time of writing, a simultaneous 3D adjustment by least squares is being performed with the data of the test scan. The results will be presented in a future publication.

4.4 Classification and Filtering

To be able to identify archaeological structures, archaeologists have to *interpret* the resulting topographical data of an ALS scan. This does not pose major problems with large structures. Smaller features, however, are much more difficult to identify. Their appearance in an ALS point cloud can be very similar to natural and recent features, as for example dense brushwood, or piles of twigs or wood, which are – other than archaeological structures – actually off-terrain points.

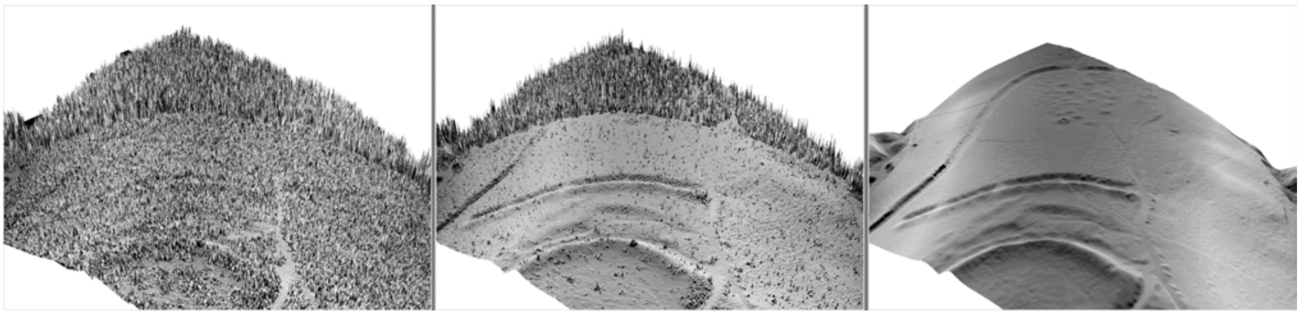

Figure 1 *Left: DSM of the first pulse data showing the canopy of the scanned area. In the foreground, the vegetation consists of dense bushes. In the background there is a dense forest with understorey. Middle: DSM resulting from the unfiltered last echo point-cloud. There are many points, which represent, tree-trunks, very dense vegetation or narrow vegetation, which do not represent the actual ground. Right: filtered DTM showing even faint archaeological traces, as e.g. round barrows with shallow depressions from looting.*

Therefore, to eliminate potential sources of error, a high quality separation of terrain and off-terrain points while maintaining a high point density of the ALS data is essential as a first step before an archaeological interpretation can take place. This can be quite a challenge in densely vegetated (e.g. forested) areas.

The main value of using a full-waveform recording scanner is the availability of additional physical observations of the reflecting surface elements, which can be useful for object classification (see also chapter 4.1).

By modelling the full waveform as a series of Gaussian distribution functions, individual scatterers can be distinguished (Hofton et al., 2000; Wagner et al., 2006). The results are estimates of the location and scattering properties of the individual targets: for each returning echo of a single laser pulse, the estimated coordinates of the scatterer, the echo width, and the amplitude is determined. Using amplitude and echo width, it is possible to investigate the return signal and extract additional ground characteristics. Consequently, much more information is available when classifying the point cloud into solid ground and vegetation cover. In a recent paper, the usage of a simple threshold operation in order to pre-exclude points situated within low vegetation or other structures as for example clearance piles (consisting of twigs and branches) is demonstrated (Doneus and Briese, 2006).

In that way, one has a means to distinguish for example a clearance pile from a round barrow already in the unfiltered data. After eliminating these points, a more reliable DTM will be the result, where most local topographic features are in fact local topographic elevations.

In the data of the test scan, the resulting point-cloud, which was classified as last pulse with narrow echo width, still had a density of 3.7 points per m^2. Many of these points were still off the surface due to random errors (depending on the measurement system), gross errors (due to multi-path effects or buildings, tree-trunks, etc.) and a few systematic errors (vegetation) (Briese et al., 2002). Therefore, for the determination of the DTM additionally advanced filter methods are necessary in order to eliminate remaining off-terrain points from the derived last echo point cloud (Sithole and Vosselman, 2003).

For these tasks the theory of robust interpolation with an eccentric and unsymmetrical weight function (Kraus and Pfeifer, 1998) used within a hierarchic framework, which is implemented into the software package SCOP++ (Kraus and Otepka, 2005), was used (Briese et al., 2002). A brief description of the technique is given in a recent paper (Doneus and Briese, 2006). The whole process of filtering is also demonstrated at the EuroSDR Distance Learning Course "Filtering and Classification of Laser Scanner Data", available under http://www.ipf.tuwien.ac.at/eurosdr/index.htm.

For archaeological purposes, the filter strategies are not allowed to be too rigid. Otherwise, the archaeological objects could be removed, too. Usually, vegetation should be filtered out, while walls, banks, ditches, and smaller archaeological structures should be kept for the resulting DTM. The result of the robust interpolation can be seen in Figure 1. The resulting point cloud had still a density of 2.5 points per m^2, which was sufficient for a grid width of 0.5 m of the final visualisations after DTM interpolation (Figures 2-4).

4.5 Visualisation and Interpretation

The filtering procedure resulted in a DTM, which shows a detailed map of the topography with even fain archaeological structures under the forest canopy. The 260 by 100 m large graveyard with at least 50 round barrows was recorded in detail. The size of the barrows ranges between 5 and 15 m in diameter. The preserved heights vary between 20 cm and 2 m. Many of the barrows even show traces of looting, where shallow depressions (7 - 20 cm deep) on top of the tumuli are interpreted as relics of former treasure hunters.

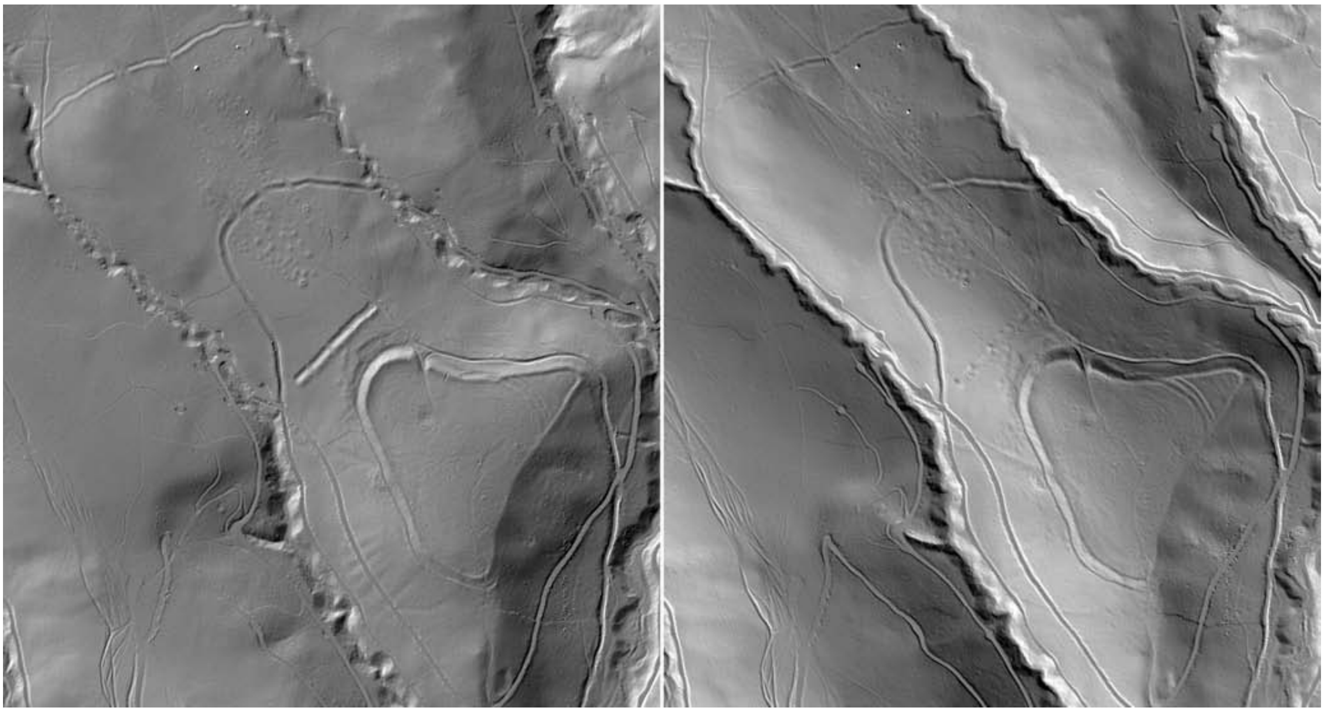

Figure 2 *Shaded DTM after filtering. Note that even large linear features can be missed if they align with the sun and do not cast shadows. Left: illumination from northwest. Right: illumination from southwest.*

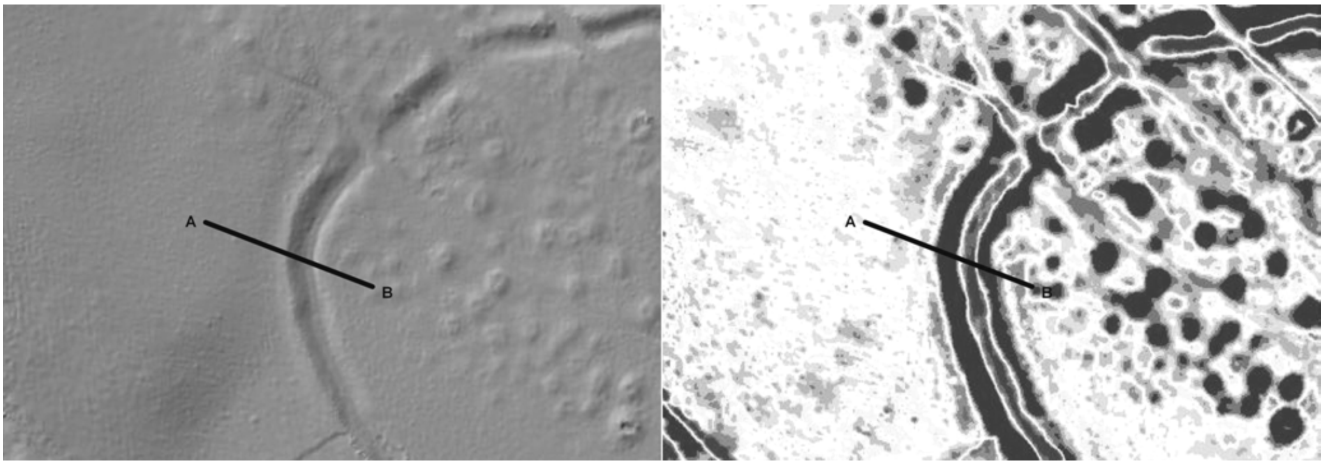

Figure 3 *Left: Shaded DTM (illumination from northwest). Right: Difference model after subtraction of a resampled DTM. The line A-B refers to the cross section in Figure 5. In this case, a point of the 5 m DTM is lying in the ditch of the archaeological fortification. Because of the larger distances between points, the local slope in the resampled terrain is therefore lower than in the original DTM derived from the ALS point-cloud. The resampled DTM will therefore be too low which will result in an "artificial" bank after subtraction from the ALS-derived DTM.*

Although shading of the DTM results in a comprehensible representation of the DTM, there is a certain danger that features will be missed because they align with the sun and do not cast shadows (Figure 2). This problem can be overcome by creating different hillshades with different directions and heights of the illumination source. Another possibility is to subtract a resampled DTM with a crude resolution (in this case: 5 m) from the high resolution DTM with its subtle variations representing banks, ditches, or barrows. The resulting difference model consequently shows only the terrain variations below or above the main topography of the surface, which was flattened by the subtraction. After colour-coding, the difference model is easier to interpret with all features visible regardless of any illumination source (Figure 3).

In Figure 3, the dark grey indicate upstanding features in relief, while lighter grey resent hollows. This visualisation clearly has advantages with smaller features, as the round barrows of Figure 3. To work also proper with large structures, as for example wide banks and ditches, the resampled point cloud of the coarse DTM should not contain points lying on these features.

Otherwise, non existing features as for example an additional bank in Figure 3 can be introduced.

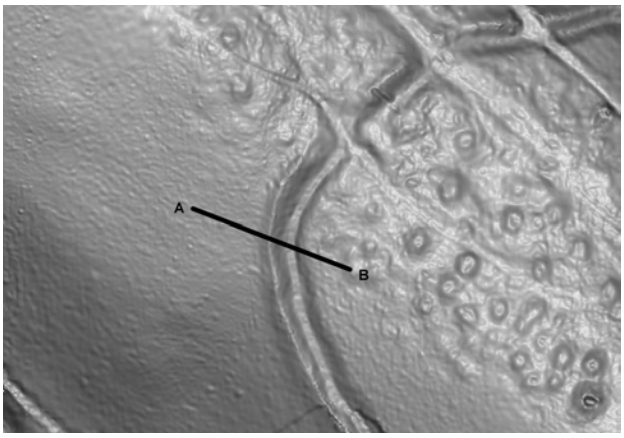

Figure 4 *Slope-map of the area of Figure 3. Dark values indicate steep slopes, while flat areas are represented by bright values. The line A-B refers to the cross section in Figure 5.*

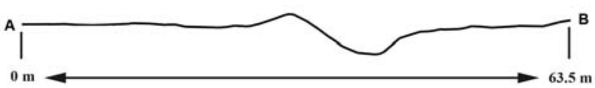

Figure 5 *Cross section of Figures 3 and 4.*

Another possibility is to use a slope mapping, where all features in relief can be clearly distinguished regardless of any illumination source by the change in slope (Figure 4). One problem of using slope mapping is that without additional information it is not possible to tell whether a slope is raising or falling, i.e. whether one sees a bank or a ditch. Additionally, one has to get used to interpret slope maps, because they are similar to shaded images and one therefore tends to "see" shadows.

There are a variety of other possibilities to produce appropriate visualisations for subsequent interpretation and it will be an aim of the current project to develop and investigate the topic of visualisation and interpretation of ALS data.

The interpretation of the visualisations will take place in a GIS-based environment. 'Potential' archaeological sites and features will be identified and drawn. Interpretation is a subjective process and the resulting confidence will vary from site to site. There are many natural and recent features that could affect the interpretation of ALS data. Hence, we maybe identify non-sites as potential archaeological sites or on the other hand give a natural meaning to features, which are in fact of archaeological relevance.

Therefore, to evaluate the accuracy of this identification process, these 'potential' sites will need visiting to ascertain whether they are archaeological sites or not and if not what has caused the response. These visits are essential to the production of an image interpretation key, which should help to improve future interpretation.

5 Conclusion

The project "LiDAR-supported archaeological prospection in woodland" tries to evaluate an approx. 190 km^2 forest area within the Leitha mountain range, 50 km southeast of Vienna, in an archaeological case study. The area is almost entirely covered with forest.

In the course of a test scan over known archaeological sites, which was performed to evaluate the configuration and parameters of the scanning system, several decisions had to be made. Choosing a full-waveform recording scanner for data acquisition and the high point density achieved had the most dramatic effect on the result. In combination with a still rather simple point classification and a sophisticated filtering technique, non-surface points could be reliably eliminated. The potential of ALS to measure even subtle structures in a forested area with dense understorey could be clearly demonstrated. The results were more than promising and will hopefully have a substantial impact on future archaeological investigations in woodland.

The next step of the project will be to test ALS as a method of archaeological reconnaissance in forests, i.e. to evaluate its potential to detect previously unknown sites.

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