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Abstract

Airborne LiDAR, or airborne *Light Detection and Ranging*, is a remote sensing technique that measures, among other things, the terrain elevation. In the past two decades, it has become an indispensable component of landscape archaeology, especially for archaeological prospection. However, it is still infrequently used in mountain archaeology. This is especially true in the high mountains, where technical challenges make its use difficult. We can anticipate more successful applications in the future due to the ever-improving quality of data. At present, the greatest untapped potential of LiDAR data for mountain archaeology, we argue, lies in "deep" interpretation or analysis of archaeological features in their landscape context. This approach is illustrated by the case study Vodotočnik (Slovenia). We used this high mountain pasture to test the hypothesis for site location choice, which was put forward by experienced mountain archaeologists. Based on the results of six distinct geomorphometric analyses we reinterpreted the site and demonstrated the benefits of LiDAR data for modelling landscape context at the scale of individual buildings and activity areas.

Keywords

LiDAR, airborne laser scanning, ALS, mountain archaeology, methodology

Introduction

Airborne LiDAR, also known as airborne laser scanning, is a remote sensing method that measures the terrain elevation. Every second, the laser scanner emits hundreds of thousands of laser light pulses toward the earth's surface. At least some pulses avoid obstacles like tree canopies and reach the ground, allowing LiDAR to "penetrate" vegetation. The distance between the laser and the ground is determined by how long it takes for a pulse to return to the sensor. The measurements are then georeferenced to an accuracy of up to 0.01 metres, creating an accurate 3D point cloud model. This is further processed into digital terrain model, canopy height models, digital surface models, etc. (e.g., Dong and Chen 2018). Additionally, LiDAR sensors can provide information on intensity, vegetation, and bathymetry. This article focuses on topographic data of solid ground, as this remains the most prevalent use in archaeology and mountain archaeology.

LiDAR data have become an indispensable component of landscape archaeology over the past two decades. Archaeologists interpret enhanced visualisations of high-resolution digital elevation models (DEM) or digital feature models (DFM) using a combination of perception and comprehension (e.g., Štular, Lozić, and Eichert 2021). The results have already transformed our understanding of archaeological sites, monuments, and landscapes as they have proven to be highly effective in detecting archaeological features. Successful examples include an entire cityscape in a tropical forest (Evans et al. 2013; Evans 2016), over one hundred thousand potential archaeological sites in a single German state (Bofinger and Hesse 2011), and thousands of prehistoric features detected in the Knežak region of Slovenia (Laharnar, Lozić, and Štular 2019).

LiDAR's ability to "penetrate" the vegetation canopy is of particular interest to mountain archaeology because no other remote sensing technique in archaeology can match it. In forested areas, it can be stated unequivocally that LiDAR has surpassed previous incremental improvements in remote sensing. In addition to the archaeological prospection, LiDAR data can be utilized for landscape reconstruction and to better understand the archaeological features in their landscape context (Lozić 2021).

However, caution against overly optimistic expectations is warranted (Crutchley 2009), as LiDAR data are only suitable for detecting archaeological features that are detectable in the terrain morphology (Štular, Lozić, and Eichert 2021) (Figure 1). Therefore, the benefits of LiDAR are unevenly distributed across the discipline and mountain archaeology is one of the fields where LiDAR is yet to make a significant impact.

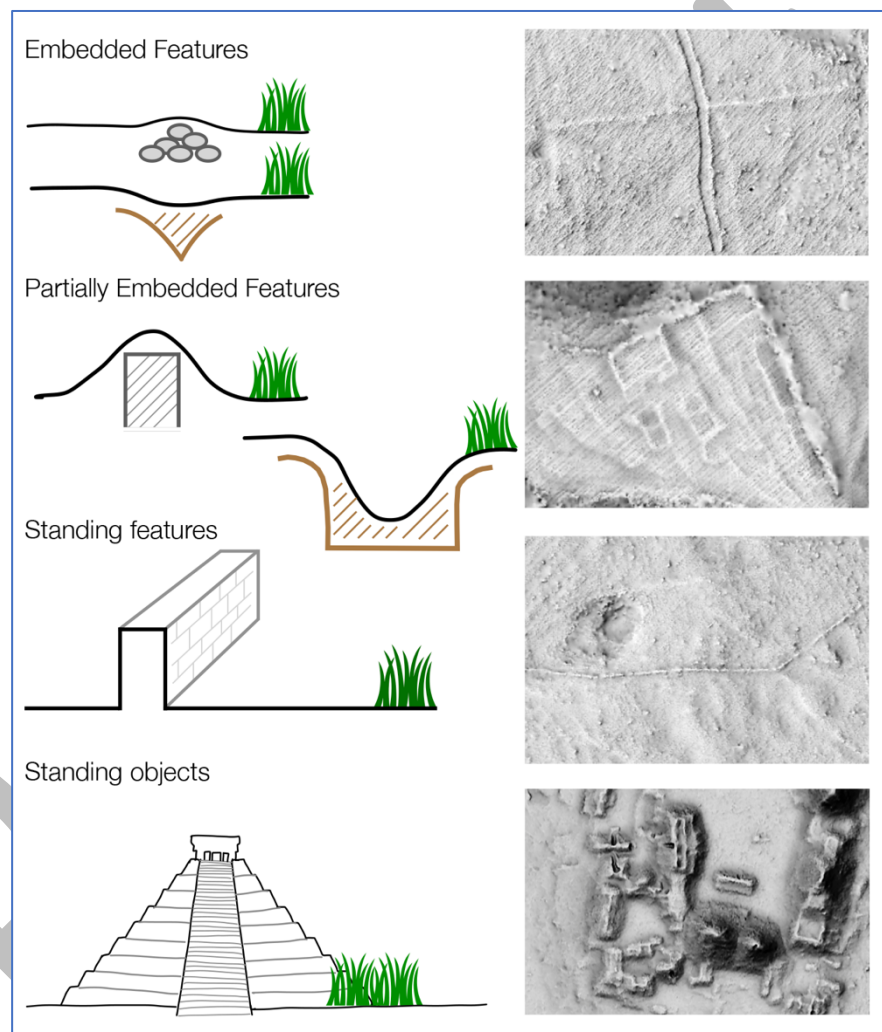


Figure 1. Morphological types of archaeological features detectable via DFM (Štular, Lozić, and Eichert 2021), Figure 5).

This chapter describes the application of airborne LiDAR to mountain archaeology. It is divided into three parts. After a brief history of archaeological LiDAR, the processing of LiDAR data for mountain archaeology is described. In conclusion, we present a case study illustrating a good practise example for LiDAR interpretation in mountain archaeology.

History of research

While the first attempts to use LiDAR for archaeological mapping occurred in the mid-1980s, archaeological practise is much more recent. In the 2000s, research centred on archaeology-specific data processing. The next step was to solve archaeology-specific technical problems, particularly those involving the visualisation of DEMs and DFMs. When the first methodological overview volume was published in 2013, most of the technical issues with using LiDAR in archaeological prospection had been resolved (Opitz and Cowley 2013; for more references see Lozić and Štular 2021).

The first theoretical considerations of LiDAR in archaeology appeared early on (Brown 2008; Crutchley 2006), but landscape archaeology considerations (e.g., not mentioned in: Head 2008; Johnson 2007), as well as research-led studies in which LiDAR data would be fully integrated into archaeological research, were lacking (some early exceptions are (Chase et al. 2011; Štular 2011).

Two factors characterise the period since 2010. Particularly in the EU and North America, LiDAR data are becoming accessible at a low cost or for free. Additionally, free or low-cost software for processing LiDAR data has evolved to include open-access software packages designed specifically for archaeological LiDAR (Kokalj and Somrak 2019; Štular, Eichert, and Lozić 2021). Recently, three significant development trends have emerged. The first is the mapping of archaeological features using deep learning (e.g., Abdulin 2021; Guyot, Hubert-Moy, and Lorho 2018; Snitker et al. 2022; Fiorucci et al. 2022; der Vaart and Landauer 2020). Deep learning aims to complement interpretative mapping by archaeologists, particularly in situations where there is so much data that it is impossible to map everything manually (Lozić and Štular 2021).

The second is the mounting of LiDAR sensors on unmanned aerial vehicles, also known as "drones". These are highly mobile and acquire much denser data sets, allowing for the exploration of new landscapes (e.g., Miħu-Pintilie, Braşoveanu, and Stoleriu 2022; Schroder et al. 2021), such as the dense evergreen shrubbery typical of mountainsides just above the forest line. Only very recently have systematic efforts been made to make archaeological LiDAR more ethical, theoretically aware, impactful, and reproducible (Cohen, Klassen, and Evans 2020; Dennis 2020). As part of this effort, a standardised methodology for processing archaeological LiDAR data is being developed (Lozić and Štular 2021; Štular, Lozić, and Eichert 2023; Štular and Lozić 2022; 2020; Štular, Eichert, and Lozić 2021).

The specific use of LiDAR data in mountain archaeology is relatively new, and only a handful of studies can be cited.

A methodological study centred on the remains of World War I in the Julian Alps (Slovenia) addressed the specific problems of DEM visualisations for mountain archaeology. It developed a technique for image fusion that enhances the visibility of micro topography, preserves a sense of general topography, and enables the recognition of archaeological features regardless of their position, size, orientation, or shape. The study also noted problems arising from a low data quality combined with locally very rough terrain, which is typical for mountain archaeology (Petrovič, Kozmus Trajkovski, and Kokalj 2018). Building (also) on this study the "visualisation for archaeological topography (VAT)" was developed, where the specifics of visualising mountainous terrain were also considered (Kokalj and Somrak 2019).

The method to map all archaeological features detected within a specific area was employed in five studies of the mountainous terrains. Prehistoric hillforts in the Daunian Mountains (Italy) were the subject of one study, with the vast majority of the sites being below 1000 metres above sea level. The aforementioned VAT visualisation was successfully used in this investigation (Fontana 2022). In the heavily forested Harz Mountains (Germany), diligent and precise analysis of LiDAR data resulted in the mapping of thousands of archaeological features, including tracks,

charcoal kiln sites, and mining relicts (Swieder 2021; 2019). Next similar study targeted settlement structures and cedar wood transportation routes in the Mediterranean mountains near Chekka (Lebanon; Rom 2020). The analysis of Olt Gorge (Romania) was also devoted to mapping all types of archaeological features. The first to be noted were remains of limekilns and their associated modified landscapes that include relicts of quarrying and transport roads. The study revealed that the intense mining and quick-lime production activities were organized at the level of families coming from the adjacent villages (Ştefan et al. 2021). Prehistoric terraces in the Sitno or Tribec mountains and mining landscapes in the alpine parts of Low Tatra mountains (Slovakia) are the subject of ongoing research (Lieskovský et al. 2022).

An example of a research-question-led approach is the study of the Sowie Mountains (Poland). It utilised a combination of historical aerial photographs and LiDAR data to investigate World War II forced labour camps, successfully identifying the camps (Kamola et al. 2020). In a similar manner, the pre-World War II landscape of mountain villages in southern Poland was analysed. Comparing LiDAR data and historical cadastral maps revealed that the majority of the abandoned rural landscape was well preserved (Affek et al. 2021).

Among the research-question-led LiDAR studies, mining landscapes are a topic of particular interest. The relationship between a Roman military settlement and the surrounding Tresminas mining district was studied in the Padrela Mountains (Portugal). The analysis revealed that the Roman army was directly involved in the control and protection of mining areas, logistical issues, administration, and territorial organisation (Fonte and Costa-García 2016).

Lately, several studies specifically addressed hydraulic mining. In Lumpkin County (Georgia, USA) the nineteenth century gold-rush era water conveyance features were documented on historic maps and LiDAR data were used to detect the features that were still preserved *in situ* (Balco and O'Leary 2018). An even more comprehensive was the study of anthropic landscape imprint around one of the largest Roman period hydraulic gold mines in Europe, Sierra del Teleno (northwestern Spain). These mines were located in a mountainous area with a mean altitude of 1400 m asl. The existence of specific geomorphological features was determined by the study of large and complex hydraulic systems. The knowledge of these characteristics greatly improves the identification of anthropic elements associated with mining (Fernández-Lozano et al. 2022; 2019).

Considering mountain archaeology, the aforementioned studies can be divided into two categories. The majority of studies fall into the first category: those located in low mountains or on the fringes of higher mountains up to approximately 1000 m asl. As such, they differ little from lowland archaeology in terms of subject matter or methodology.

Only two of the presented studies are concerned with high mountain regions: a methodological paper on enhanced visualisations and an examination of Roman hydraulic mining in Spain. The first (Petrovič, Kozmus Trajkovski, and Kokalj 2018) uncovered two significant methodological issues: working with LiDAR data in high mountains requires a specific methodology, and mountain LiDAR data from large-scale data acquisition projects are frequently of poor quality.

The latter (Fernández-Lozano et al. 2019; 2022) is distinct from the others in that it is a research-question-driven study and it relies heavily on interdisciplinarity between archaeological LiDAR and geology, hydrology, and geomorphology. This type of research holds the greatest methodological promise for LiDAR-supported mountain archaeology in the near future. However, before archaeological interpretation can occur, the data processing described below must take place.

LiDAR data processing in mountain archaeology

Archaeology-specific LiDAR data processing is often perceived as a dull, repetitive, and completely objective task. It is neither! Instead, it is subject to a constant stream of subjective archaeology-specific (or non-archaeology-specific) decisions.

This rather complex task consists of four interrelated phases: Raw data acquisition and processing, point cloud processing and derivation of products, archaeological interpretation, and dissemination and archiving. Each phase is further subdivided into several steps (Lozić and Štular 2021, 5-10) (Table 1).

| Phase | Step | Workflow Step | Arch. Engagement |
|---|------|---------------------------------------|------------------|
| 1 Raw data acquisition & Processing | 1.1 | Project planning | + |
| | 1.2 | System calibration | o |
| | 1.3 | Data acquisition | o |
| | 1.4 | Registering | + |
| | 1.5 | Strip adjustment | o |
| 2 Point cloud processing & Derivation of products | 2.1 | Automatic ground point classification | ++ |
| | 2.2 | Object-type classification | ++ |
| | 2.3 | Manual reclassification | +++ |
| | 2.4 | DFM interpolation | + |
| | 2.5 | Enhanced visualization | +++ |
| 3 Archaeological interpretation | 3.1 | Data integration | ++ |
| | 3.2 | Interpretative mapping | +++ |
| | 3.3 | Ground assessment | +++ |
| | 3.4 | "Deep" interpretation | +++ |
| | 3.5 | Automated mapping | ++ |
| 4 Dissemination & Archiving | 4.1 | Data management | + |
| | 4.2 | Dissemination | + |
| | 4.3 | Archiving | + |

Table 1. Archaeology-specific airborne LiDAR data processing workflow. Arch(aeological) engagement: o nonessential; + as consultant; ++ important; +++ essential (modified after Lozić and Štular, 2021, Table 2).

Phase one is a very specialized topic and is usually not tackled by archaeologists and will not be discussed further here (see overview in Lozić and Štular, 2021, 6).

The majority of methodological considerations in archaeology have centred on the second phase. In fact, for most practitioners, this phase is synonymous with archaeological LiDAR methodology. It consists of five steps, which we have recently discussed in detail (overviews with bibliography in Štular and Lozić 2022; Štular, Eichert, and Lozić 2021) and can be briefly summarised as follows. First, the 3D point cloud is classified into points representing the solid ground (aptly named ground points; step 2.1). Based on the ground points, all other points are classified as either (modern) buildings, (low, medium, or high) vegetation, or other points (step 2.2.). These two steps are performed using general algorithms but with archaeology-specific workflow and settings. However, the accuracy of the automatic algorithms in an archaeology-specific environment can be as low as 37%. Therefore, manual reclassification is sometimes needed (step 2.3). Then, the points classified as either ground, building or archaeology are

interpolated into a raster grid or DFM (step 2.4). In the final step enhanced visualisations of DFM are produced (step 2.5).

Two significant conclusions can be drawn regarding the processing of LiDAR data for mountain archaeology. First, not every archaeology-specific processing step "improves" the final result equally. The greatest added value usually comes from automatic ground point classification and enhanced visualization, and, perhaps specifically for mountain archaeology, from manual reclassification (Table 2).

| Step No. | Step | effort | added value (general) | added value (mountain arch.) |
|----------|---------------------------------------|--------|-----------------------|------------------------------|
| 2.1 | Automatic ground point classification | ++ | +++ | +++ |
| 2.2 | Object-type classification | ++ | + | + |
| 2.3 | Manual reclassification | +++ | + | ++ |
| 2.4 | DFM interpolation | + | + | + |
| 2.5 | Enhanced visualization | + | +++ | +++ |

Table 2. Archaeology-specific airborne LiDAR data processing workflow, phase 2. An estimate of the added value of archaeology-specific processing for mountain archaeology.

Second, automatic ground point classification and DFM interpolation are least accurate when dealing with steep slopes and sharp ridges covered in dense low vegetation (e.g., shrubs or stunted trees). Furthermore, if LiDAR data were not acquired specifically for archaeology, the data for mountain areas tend to be of lower quality (e.g., Petrovič, Kozmus Trajkovski, and Kokalj 2018).

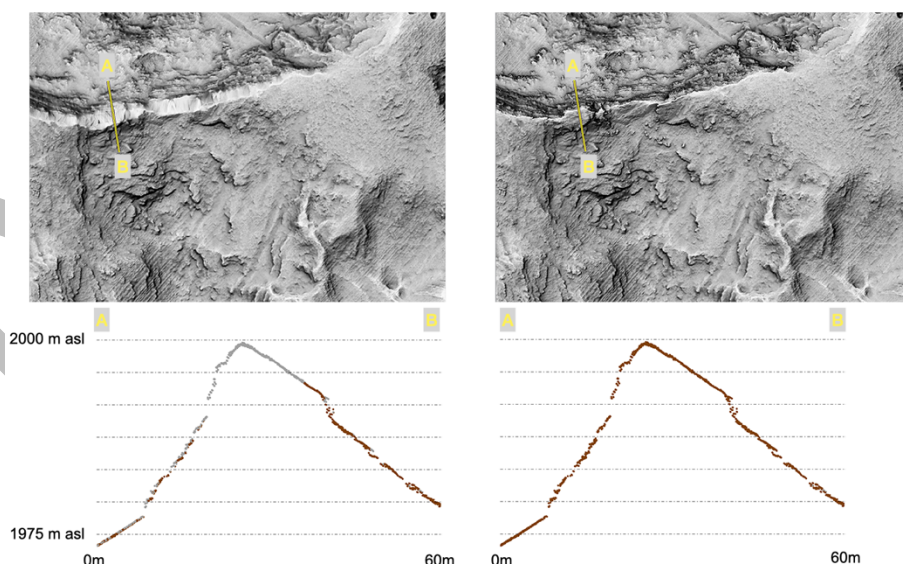


Figure 2. Zeleni vrh (Slovenia; Lon 46° 15' 36.5" Lat 13° 45' 37.7"), an example of automatic ground point classification with the popular `lasground_new`¹ tool (left) and manually reclassified data (right). VAT visualisation of the DFM (top) and profile of the point cloud (bottom) show the significant inadequacy of automatic classification on sharp ridges and steep slopes.

¹ LASStools (Rapidlasso, Gilching, Germany): `Lasground_new`.

Consequently, a typical mountain environment often combines difficult geomorphology with poor data quality, which is the worst-case scenario for data processing. This has a twofold consequence: data processing of the highest possible quality is even more important for mountain archaeology, and more manual reclassification is expected to be required than in other scenarios. Since manual reclassification is by far the most time-intensive step in data processing, (considerably) more time must be allocated to it (Figure 2).

In conclusion, archaeology-specific point cloud processing and derivation of products in mountain archaeology is likely to be more challenging and time-consuming than for average data. However, no additional steps in the workflow are required.

Archaeological Interpretation

The third phase of archaeology-specific LiDAR data processing is archaeological interpretation, which consists of five steps (Table 1). First, the derivatives generated in the second phase are integrated with other relevant data sources - e.g., aerial and satellite imagery, modern and historical maps, geological and archaeological maps - into the GIS environment (step 3.1). This is followed by desk-based archaeological interpretation, which involves identifying, interpreting, and mapping archaeological sites and features; this step is referred to as interpretive mapping (step 3.2). This can be followed by automated mapping often based on deep learning techniques. This step is used when many thousands of morphologically identical features need to be mapped, which is less likely in mountain archaeology (step 3.3). The following step, ground assessment, is essentially a LiDAR guided archaeological topography. Some even consider the entire LiDAR data processing workflow as a preparation step for fieldwork (step 3.4).

The final step, "deep" interpretation (step 3.5), is an integrated, multi-scale process designed to increase comprehension of archaeological features in their landscape context. It may be helpful to view this as a research-question-driven component of the analysis in which archaeological LiDAR is integrated with any archaeological methods pertinent to the specific case study. In other words, "deep" refers to the use of LiDAR data for archaeological interpretation as opposed to merely feature detection. As we will demonstrate below, this step has great potential for mountain archaeology. Although the steps for archaeological interpretation of LiDAR data are presented in a sequential order, the workflow is recursive and takes the shape of a hermeneutic spiral (Lozić and Štular 2021, 7-9).

The greatest advantage of using LiDAR data for archaeological interpretation is that it provides isolated traces of past human activity with the context of the archaeological landscape, thereby facilitating a better understanding of past human-landscape interactions (Affek et al. 2021, 157). This has been successfully demonstrated time and again in archaeological landscapes rich in evidence of past human activity (e.g., Gheyle et al. 2018; Inomata et al. 2020; Laharnar, Lozić, and Štular 2019). However, reconstructing past landscapes in mountains is specific (and much more difficult) for three reasons.

First, in mountain archaeology, traces of past human activity are usually isolated or, more precisely, located at a considerable distance from each other (e.g., Horvat 2020). Only in rare cases is it possible to identify associated landscape infrastructure such as pathways or landscape division. This diminishes the ability of LiDAR to provide meaningful landscape context and thus add value to the same extent as in other types of archaeological landscapes. There are, however, exceptions, such as hydraulic gold mining (Fernández-Lozano et al. 2022) and the (sole) World War I mountain front line (Košir 2020; 2019).

Second, the archaeological features most frequently detected with archaeological LiDAR, such as, stone structures, sunken roads, field boundaries, cairns, burial mounds, hillforts, and large-scale earthworks, are uncommon or non-existent in mountain archaeology.

Third, the features that can be detected in the mountains are often very specific and nonuniform as well as tangled with geological features. This makes it more difficult to detect them systematically. For example, a modest remains of stone foundations of a wooden hut can be almost indistinguishable from the surrounding glacial cairns. This means that the operator performing the interpretive mapping must be trained to recognise the specific archaeological features and, for the purpose of elimination, the specific geological features. In other words, the operator must be trained in both archaeological LiDAR and mountain archaeology.

The above comments paint a bleak picture for the use of archaeological LiDAR in mountain archaeology, at least as far as detection of archaeological features is concerned. The effort is greater and the results are more modest than in most other environments. Nevertheless, LiDAR remains the sole remote sensing technique in archaeology that consistently produces good results in forested environments. In addition, most of the above problems can be greatly reduced by high quality data acquired specifically for archaeology. Furthermore, mountain archaeologists already have the knowledge to identify archaeological (and geological) features specific to mountains.

Therefore, despite the difficulties, LiDAR is still a very viable and arguably the best remote sensing technique for large-scale archaeological prospection in mountains, especially in mountain forests. However, the data processing and archaeological interpretation effort is greater than in most lowland environments.

These considerations are not limited to mountain archaeology. For example, early medieval archaeology in the Eastern Alps is virtually undetectable in LiDAR archaeological prospection. Nevertheless, LiDAR-derived data have proven to be an invaluable resource for "deep" interpretation that has resolved one of the most important unanswered questions in early mediaeval archaeology (Lozić 2021).

By analogy, we argue that there is significant untapped potential for "deep" interpretation of LiDAR data in mountain archaeology. It entails comprehending why people chose to routinely exploit certain areas of the landscape and what factors played a role. Taking inspiration from mediaeval archaeology, environmental factors such as distance to water, soil quality, wind exposure, and visibility can be contrasted with human agency to address the cognitive space (e.g., Doneus and Kühnle 2013; Štular 2011).

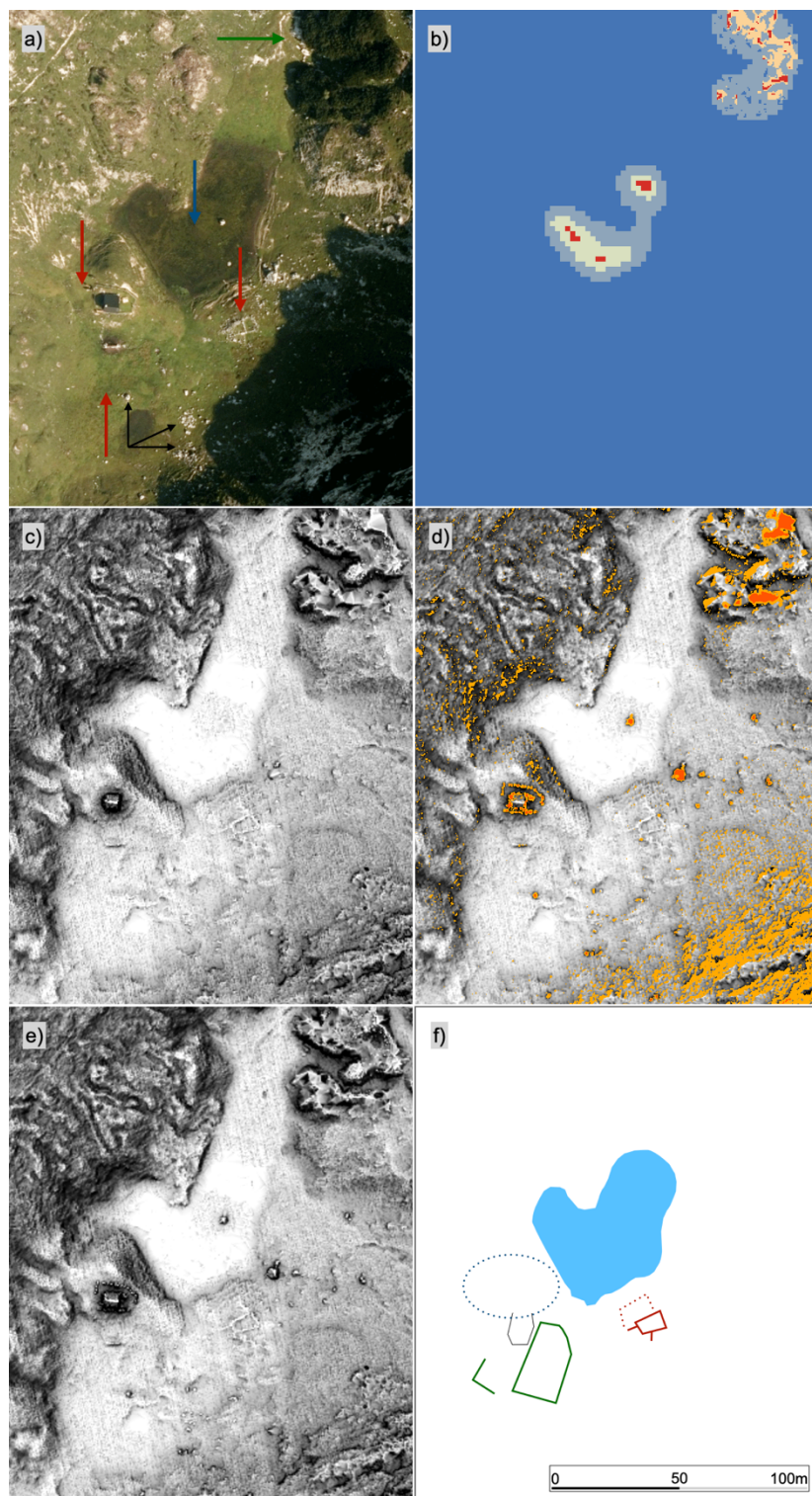
Similar methods have been employed for decades in archaeological GIS (e.g., Gaffney and Slapšak 1991; Lock and Pouncett 2017; Štular and Eichert 2020). However, LiDAR-derived data have an accuracy and precision that represents the landscape at the scale of human behaviour and decision making. In conjunction with the power of modern hardware and software, this not only greatly improves the results, but also enables a shift in focus from (micro)regions to individual habitation- or activity-sized areas. This approach is briefly demonstrated in the case study provided below.

Case study: Vodotočnik

Vodotočnik is a mountain pasture located on the plateau Dleskovška planota in Kamniško-Savinjske Alpe (Slovenia). It is situated at about 1810 m asl, which is the height of the forest line. The place name Vodotočnik, which literally means "water tap place," refers to the small valley filled with colluvial sediments. Since the sediments are impermeable to water, this valley is the main source of drinking water on the otherwise karstic plateau. It was therefore no surprise when archaeological fieldwork there uncovered three buildings from the Roman period (Horvat 2019).

LiDAR data for the case study area were acquired as a part of the Slovenia-wide general purpose dataset in 2014 (Triglav Čekada and Bric 2015); for metadata and paradata of raw data acquisition and processing, see Lozić and Štular, 2021, Table 3). Ground point density ranges

from over 16 points per square metre (pnts/m²) to less than one. The DMF confidence map closely matches the density. The aerial imagery reveals that the areas of low point density, and thus low confidence, are located under the patches of stunted coniferous shrubbery that are virtually impenetrable to LiDAR. Additionally, the aerial photographs are useful for locating scattered boulders and rocky outcrops (Figure 3).



The result of fully automated archaeology-specific data processing using the ONE tool² (Štular, Eichert, and Lozić 2021) was as expected. The areas under the shrubbery showed only general morphology or not even that. In the grassy areas, the results were good, but most of the boulders and rock outcrops were classified as low vegetation. With manual reclassification, it was relatively easy to recover the latter, but the areas under the shrubbery could not be significantly improved. Interpretation of LiDAR data revealed one of the three Roman period buildings conjectured from fieldwork. The north-eastern structure was confirmed with a high degree of certainty, but not the north-western one obscured by the modern hut. The southern potential building proved to be a large rectangular area measuring 25 x 20 m. Its interior was levelled and cleared and there were low banks along the edges (Figure 3).

Figure 3. See next page.

² Open LiDAR toolbox (Research Centre of Slovenian Academy of Sciences and Arts, Ljubljana; Naturhistorisches Museum, Wien): ONE.

Figure 3. Vodotočnik (Slovenia; Lon 46° 20' 48.2" Lat 14° 39' 20.6"): a) aerial photo (DOF2018©GURS); red arrows point to archaeological features identified by (Horvat, 2019), blue to waterhole, green to shrubbery, and black to boulders and stone outcrops; b) DFM confidence map, shades of blue indicate high confidence in LiDAR data and red-orange low confidence; c) VAT visualisation of DFM created with automatic processing using Open LiDAR Toolbox; d) difference map between c and e, orange < 0.5m, red > 0.5m; e) VAT visualisation of DFM created with manual reclassification; f) interpretative mapping of archaeological features, red is a building, green is an activity area, black is a modern activity area, a dotted blue circle surrounds the area of a building identified in the field but not in LiDAR, and blue is the extent of a waterhole.

Thus, the interpretive mapping of the Vodotočnik revealed information that was not discovered during fieldwork. However, the true potential of the LiDAR data lay in "deep" analysis. To this end, we tested the hypothesis put forward by archaeologists based on their extensive field experience: Human dwellings in the mountains were documented in areas of flat terrain, elevated slightly above the surrounding area, exposed to the sun but sheltered from winds, torrential streams, landslides, and avalanches (Horvat, 2019, 4). The hypothesis was tested by conducting six distinct geomorphometric analyses (Figure 4).

Deviation from mean elevation³ is a unitless measure of topographic position and is calculated as the difference between the elevation of the centre of the window and its mean elevation, normalized by the S-factor (Lindsay et al. 2015). Positive values indicate convex or locally elevated areas and negative values indicate concave or locally depressed areas. We used it to show that the two northern potential buildings are indeed locally elevated, while the southern one is not.

Exposure to the sun was calculated as incoming solar radiation.⁴ Because the most important factor in seasonal use of mountain pastures is spring snowmelt, we calculated solar radiation for a three-month period between April and June. All three locations of interest to us are well exposed to solar radiation.

We estimated the topographic exposure to wind⁵ by averaging the effect of wind from 24 directions (Böhner and AntoniĆ 2009). All three locations are relatively well protected from the winds. The north-eastern potential building is the most exposed, but still below average for the case study area. However, a contemporary cabin reveals that any building is immediately exposed to above average wind. Wherever a building is erected it will be exposed to winds. Therefore, the wind factor was probably not a determining factor in the choice of location for erecting buildings.

Exposure to torrential streams was modelled using flow accumulation⁶ calculated as the upslope contributing catchment area using the multiple flow direction approach (Lozić, 2021). The highest values show the areas with the highest accumulated flow, i.e., the areas exposed to potential torrential streams. None of the three observed locations are exposed to such a hazard, as the only area of high flow accumulation is located in the northeast corner of the study area. Landslide hazards can often be detected directly with LiDAR data because any past landslides are clearly visible. In our case study, there are none. Calculating the hazard from snow avalanches with significant accuracy is a complex task. For the purposes of this study, we opted

³ Whitebox tools (Whitebox Geospatial Inc., Guelph, Canada): Deviation from mean elevation.

⁴ ArcGIS Desktop 10.8 (ESRI, Redlands CA, USA): Area Solar Radiation.

⁵ SAGA GIS (Department of Physical Geography, Hamburg and Göttingen, Germany): Wind exposition index.

⁶ SAGA GIS (Department of Physical Geography, Hamburg and Göttingen, Germany): Flow Accumulation (Top-Down).

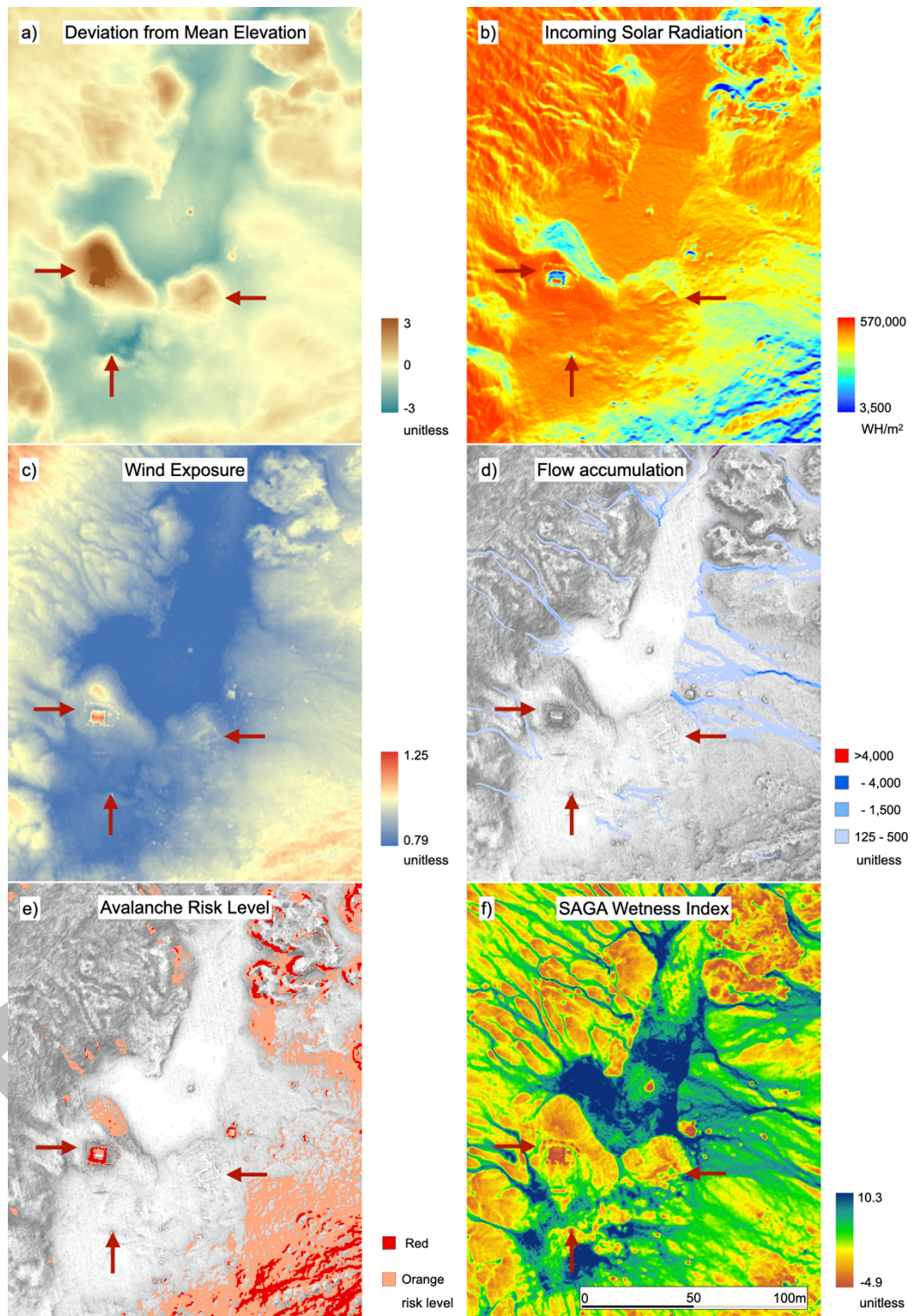


Figure 4. Vodotočnik (Slovenia; Lon 46° 20' 48.2" Lat 14° 39' 20.6"): a) deviation from mean elevation; b) incoming solar radiation; c) wind exposure; d) flow accumulation; e) avalanche risk; f) SAGA wetness index. Red arrows point to archaeological features identified by (Horvat, 2019).

for a simplified estimate. We overlaid areas with steep slopes (value 1: 30 - 45 degrees; value 2: above 45 degrees) with areas with high slope catchment.⁷ Thus, we modelled areas with steep slopes that are upstream from the valley floor. The southern and north-western potential buildings are not at risk, and the north-eastern is protected from potential avalanches by its locally elevated position.

In addition, we modelled the wetness index,⁸ which models a rainfall-runoff model (Lozić, 2021). This model reveals that the southern potential building is located in an area with low runoff. Therefore, given the impermeable geology, this area is prone to waterlogging and possibly flooding after major rain events or during snowmelt.

All three locations of potential Roman period buildings discovered by field archaeologists on Vodotočnik are thus well exposed to sunlight and protected from winds, torrential streams, and possible landslides and avalanches. However, while the two northern locations are locally elevated, the southern one is locally depressed and therefore prone to waterlogging. As such, it is not a suitable location for a building. We interpret this feature as a cleared activity area, most likely an animal enclosure or pen to be used during the summer, which is confirmed by its size of approximately 380 m².

While the results of the "deep interpretation" do not fundamentally change the archaeological interpretation of the Roman period of the Vodotočnik site, new knowledge was created. Not only have we demonstrated that the southern location was an activity area rather than a building, but we have also provided evidence for the interpretation of the entire site as a seasonal pasture. More importantly, however, we have demonstrated that LiDAR data of relatively low quality can be used for high-precision modelling of landscape context at the scale of individual buildings and activity areas.

Conclusion

The use of LiDAR in low mountains is on par with the use in lowlands, both regarding the methods and topics. Especially when low cost or free data is available, it is more and more often used in archaeological surveys.

In high mountains, on the other hand, the use of LiDAR is rare. There are several reasons for that. The effort for data processing is higher than in most other contexts and at the same time the results in terms of archaeological prospection are most often relatively modest. The reason is that typically in high mountains there are fewer archaeological features suitable for detection, they are spaced further apart, and are less preserved. However, with anticipated increasing quality of LiDAR data we can expect to see more successful applications in the future.

Currently, the best use of LiDAR data in the high mountains appears to be "deep" interpretation. Compared to the digital elevation models available to date, even LiDAR data of modest quality can serve as an excellent starting point for testing hypotheses such as why people have habitually exploited certain areas and not others. We briefly demonstrated the potential for such an approach on the Vodotočnik high mountain pasture in the Alps. We reinterpreted one of the potential buildings, gave an indication of the interpretation of the entire site, and demonstrated the usability of LiDAR data for modelling landscape context at the scale of individual buildings and activity areas.

⁷ SAGA GIS (Department of Physical Geography, Hamburg and Göttingen, Germany): SAGA wetness Index (catchment slope).

⁸ SAGA GIS (Department of Physical Geography, Hamburg and Göttingen, Germany): SAGA wetness Index.

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