Chapter 4
LiDAR for Archaeological Research and the Study of Historical Landscapes

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Abstract Remote sensing technologies have helped to revolutionize archaeology. LiDAR (light detection and ranging), a remote sensing technology in which lasers are used as topographic scanners that can penetrate foliage, has particularly influenced researchers in the field of settlement or landscape archaeology. LiDAR provides detailed landscape data for broad spatial areas and permits visualization of these landscapes in ways that were never before possible. These data and visualizations have been widely utilized to gain a better understanding of historical landscapes and their past uses by ancient peoples.

Keywords LiDAR • Visualization techniques • Landscapes • Archaeology

4.1 Introduction

Archaeological survey and settlement pattern research is becoming increasingly dependent on LiDAR (light detection and ranging) for enhancing the interpretation of historical landscapes. LiDAR is of value even in areas of the world where there is a long tradition of studying ancient landscapes in the context of environment and history. In Europe, LiDAR has been utilized to aid cultural heritage analysis in conjunction with written historic records. Within European countries, LiDAR has enabled researchers to gain detailed information on specific features such as castles, cairns, furrows, and coal pits that were obscured by covering vegetation. LiDAR has been perhaps even more significant for research in tropical and subtropical areas such as Mesoamerica and Southeast Asia where there is often neither great time depth to the written history of landscapes nor a detailed understanding of the specific spatial parameters being investigated. In the tropics, LiDAR has dramatically changed perceptions of largely unknown landscapes, serving to document both the settlement and the spatial parameters of anthropogenic activity and tropical urbanism. Thus, the focus, applications, and effects of LiDAR to archaeological

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data have varied markedly in different parts of the world. In temperate zones, LiDAR is often used to focus on specific features or areas that are historically known or identified, whereas in the tropics LiDAR is used to understand a largely undocumented settlement distribution on an ancient landscape. Not only is LiDAR moving forward in archaeological interpretation, but its use by archaeologists is also changing the way in which LiDAR is collected and subsequently analyzed in an attempt to maximize interpretations within different environmental parameters.

4.2 What Is LiDAR?

LiDAR uses laser pulses to measure discrete distances and is able to produce three-dimensional (3D) points that measure both the canopy and earth surface (Glennie et al. 2013). Although new in the field of archaeology, LiDAR has actually been in use for more than half a century and directly derives from optics research with lasers. Even though initially unable to penetrate these bodies of vapor, LiDAR was utilized for meteorological remote sensing of clouds (Goyer and Watson 1963). The use of lasers in this technology eventually resulted in the word LiDAR, which originally stood for "light radar" (Ring 1963). Because RADAR was an acronym for "radio detection and ranging," the technology was ultimately called "light detection and ranging" or LiDAR. The public became aware of the impact of this technology as early as 1971, when a laser altimeter was used to map the surface of the moon by the Apollo 15 mission; a descendant system was also used to map the surface of Mars (Zuber et al. 1998). In the 1980s, NASA developed two airborne laser instruments that were precursors for modern LiDAR systems: (1) Atmospheric Oceanographic LiDAR (AOL) and (2) Airborne Topographic Mapper (ATM) (Anderson et al. 2010: 875). Most of the airborne systems used today derive from the ATM.

Modern researchers use various filtering algorithms to classify ground returns for future analysis. This method provides LiDAR with a distinct advantage over traditional aerial photography within forested survey regions (Fernandez-Diaz et al. 2014: 9971–9986). Early comparisons of different vegetation classification and removal algorithms (Sithole and Vosselman 2004) have facilitated archaeological LiDAR use by European researchers (Devereux et al. 2005; Risbøl et al. 2006; Sittler 2004). In parallel with new algorithms and advances in classification and removal algorithms, many researchers have highlighted—time and time again—the importance of considering the vegetation of the survey region when selecting which filtering algorithms to use (Crow et al. 2007; Prufer et al. 2015; Raber et al. 2002). After raw data collection, many additional processes and analyses facilitate the creation of useful LiDAR data; however, to determine the best processes to use, researchers must balance the vegetation in their study region in conjunction with the features they wish to study (Fernandez-Diaz et al. 2014).

LiDAR has quickly become useful in a wide variety of disciplines. Modern agriculture uses LiDAR to determine how fertilizer should be applied to crop fields based on previous yield, land slope, and sun intensity (Hammerle and Hofle 2014).

Atmospheric sciences first used LiDAR for profiling clouds and measuring winds (Rees and McDermid 1990), eventually for studying aerosols and the quantification of atmospheric components (Ansmann and Muller 2006). In biology, LiDAR permits measurement of canopy heights, biomass, and leaf area (Drake et al. 2002). Geologists leverage LiDAR in landform surveys and in studies of the physical and chemical processes that shape landscapes (Bellina et al. 2005); in mining, LiDAR terrestrial scanning has been used to calculate ore volumes (Lato et al. 2009: 194). In everyday life, law enforcement uses LiDAR in speed guns. LiDAR use is known for both unmanned drones and the detection of biological agents (Veerabuthiran and Razdan 2011). LiDAR has multiple uses in physics as well; it is used for robotics, cruise control, rangefinding, and the spaceflight detection of cloud droplets and industrial pollution (Glennie et al. 2013; Grob et al. 2013). Finally, in archaeology (the field focused upon in this chapter), LiDAR has provided a level of spatial understanding of the past that did not exist previously and which helps researchers to refine and redefine the settlement models that are applied to ancient societies (A. Chase et al. 2012).

Various kinds of LiDAR are being used by archaeologists, as well as a host of different visualization techniques for post-processing the collected data. Archaeologists have used three different forms of LiDAR: airborne LiDAR to investigate the surfaces of ground; terrestrial LiDAR to gain detailed scans of features; and bathymetric LiDAR to gain information from underwater. Terrestrial LiDAR usually involves the laser scanning of specific features such as monuments or buildings (Cheng et al. 2013) but has also been extended to the level of scanning complete sites (Romero and Bray 2014; Weber and Powis 2014). Terrestrial LiDAR has also been used to make reconstructions of archaeological stratigraphy, with successive scans being undertaken during excavation (Galeazzi et al. 2014). Although terrestrial LiDAR generally has limited use when analyzing large-scale historical landscapes because of scale, it does have application in terms of hydrological modeling of landscapes for potential flooding (Fewtrell et al. 2010). Bathymetric LiDAR works with features that are underwater and thus has application for shipwrecks (Shih et al. 2014) and submerged sites (Doneus et al. 2013). Airborne LiDAR has been successfully applied to historical landscapes throughout the world, ranging from Europe (Bernardini et al. 2013; Cifani et al. 2007; Masini and Lasaponara 2013; Risbøl et al. 2013) to North America (Harmon et al. 2006; Johnson and Ouimet 2013; Rochelo et al. 2015; Wienhold 2013) to Mesoamerica (Chase et al. 2011, 2012, 2014a, b) to Pacific islands (McCoy et al. 2011) to Southeast Asia (Evans et al. 2013).

4.3 Visualization of Landscapes with LiDAR

Much general background material has been written about the interpretation and analysis of LiDAR data (Challis et al. 2011; Glennie et al. 2013; Fernandez et al. 2014). The most basic product of airborne LiDAR is the creation of a

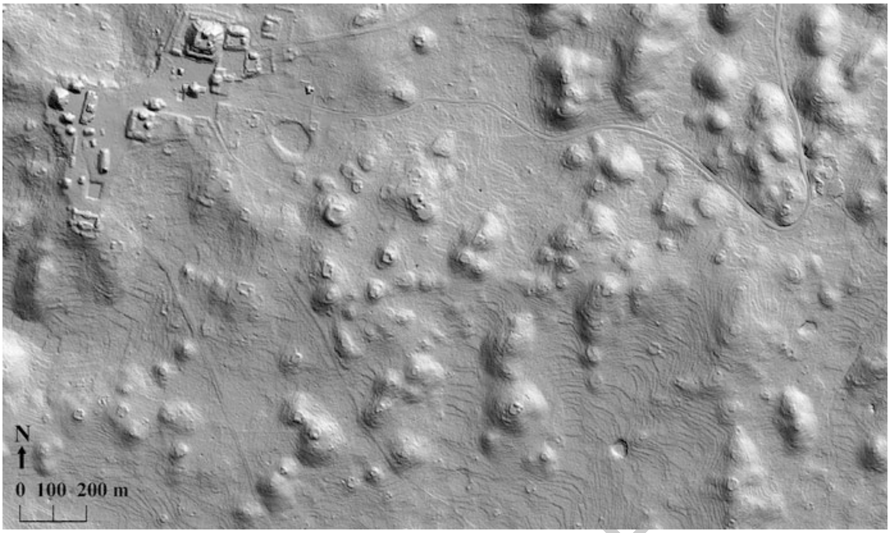

Fig. 4.1 A standard two-dimensional (2D) hillshade of the central part of Caracol, Belize

DEM (digital elevation model), which "has a precise meaning as an xyz elevation raster" (A. Chase et al. 2011: 391). Analysis is made easier by applying various visualization techniques. Those that have been developed to view these data range from the traditional hill-shaded terrain model (Yoeli 1967) to slope analysis (McCoy et al. 2011) to local relief modeling (Hesse 2010) to sky-view factor (Kokalj et al. 2011) to geomorphons (Stepinski and Jasiewicz 2011).

The hill-shaded terrain model is one of the original visualizations applied to LiDAR (Devereux et al. 2008; also see Yoeli 1967 for detailed analytical hill-shading methods). This analysis is based on techniques that were used for traditional aerial photography, where flights where often scheduled to take advantage of the naturally raking light during different times of the year. The similarity between hill-shades and aerial photographs facilitated interpretation. There is also a long history of artists creating hill-shades from elevation maps (Yoeli 1967). The effect of a hill-shade is the same as raking a flashlight over a three-dimensional (3D) printout of the DEM, and this is essentially the computation process behind hill-shading (Fig. 4.1). Shadows highlight elevation differences that reveal natural hills and human-made features. This visualization type sees very common use because of the ease of manual interpretation; however, multiple hill-shades with variable azimuths and altitudes are required to see all the features on the landscape (White 2013). Future use of this analysis type has been superseded both by principal components analysis (PCA) hill-shades (Devereux et al. 2008) and more recently by sky-view factor (Kokalj et al. 2011).

Slope analysis (McCoy et al. 2011: 2148) uses the value of the angle representing the change in elevation between cells and reclassifies the slope into expected classes. In general, both slope and aspect, the compass direction of a cell's slope, find use in hydrological DEM applications. Additional measurements created from slope include the curvature along a cell's slope, the curvature perpendicular to a cell's slope, the first derivative of cell slopes along a specified direction, and the second derivative of cell slopes along a specified direction. These measures help identify anomalous slopes that may be archaeological features of interest, data errors, or changes in the underlying regional topography. After running these analyses, reclassification of the varying datasets of slopes into types can help further visualization and identification of features within these datasets. For example, the simplest classification utilizing only slope could be flat, low slope, and high slope; however, more complex systems utilizing various slope datasets mentioned earlier can be used in tandem to create more complex classifications based on research interests.

The local relief model (Hesse 2010) considers the microtopography of a DEM. Although the output is often considered noisy and messy, it also includes many of the humanly constructed features of archaeological interest. A small moving window of analysis is applied over every cell in the DEM to observe the difference between average elevation around a cell and the elevation of the cell itself. This technique effectively, but not actually, flattens hills and raises valleys so that only the minor landscape variations are visible.

Since being introduced by Kokalj and his colleagues (2011), sky-view factor has become the visualization of choice in airborne LiDAR. Sky-view factor asks one question: what proportion of the sky can I see from my location? Each point is analyzed looking at the full horizon. The angles from where the sky can be seen along the horizon are taken and recorded. This is a very good alternative to traditional hill-shaded terrain models.

Yet another visualization technique uses geomorphons (Stepinski and Jesiewicz 2011). This visualization does not produce a photograph-like image, as a hill-shade does. Rather, this analysis breaks down the landscape into distinct units that highlight flat space and elevated space. Each location has its unit type determined by the relative elevations of its neighbors along both cardinal and ordinal directions. Neighbors can be higher, lower, or equivalent (i.e., flat). These signatures, called geomorphons, are then classified into one of the 498 possible distinct types (Stepinski and Jesiewicz 2011: 110). This analysis essentially breaks the entire landscape into unique types; it is exceedingly good in differentiating and classifying landscapes by type, thus permitting the interpretation of archaeological landscapes in ways not possible through the previous methods (Fig. 4.2).

4.4 Applications of LiDAR to Landscape Analysis

There is a long history of landscape study using LiDAR, with the first applications occurring in Europe. Stonehenge was one of the earliest sites examined with airborne LiDAR. Examination of LiDAR originally collected for environmental

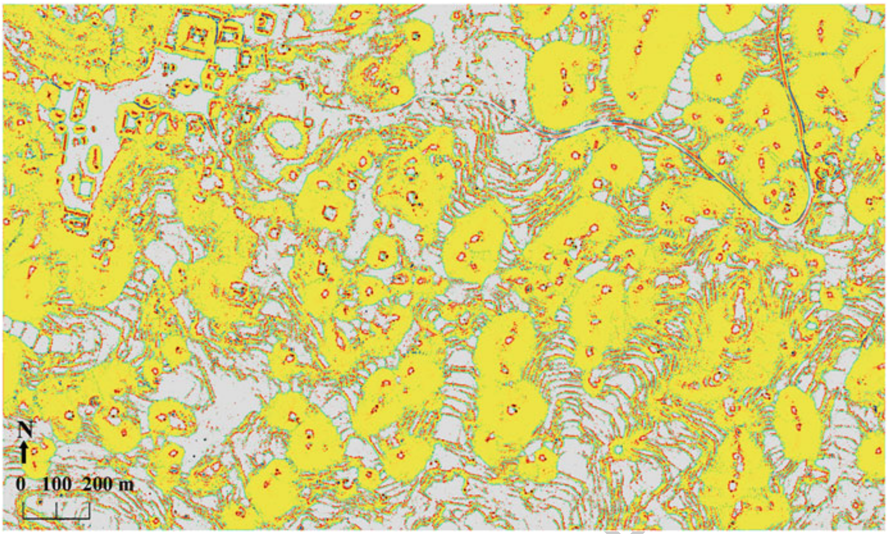

Fig. 4.2 A geomorphon of the central part of Caracol, Belize (same area as Fig. 4.1)

monitoring (rather than archaeological purposes) led to the discovery of previously unidentified archaeological features, agricultural fields, and ditched banks. LiDAR provided surface traces of features with "no visible surface expression" and previously undiscovered data about Stonehenge that caused the researchers to comment that "the technique reveals new details and new levels of survival even in well-researched landscapes" (Bewley et al. 2005: 645).

Italian researchers are quite familiar with the use of LiDAR in terms of landscape analysis (see Masini and Lasaponara 2013 for a brief history of LiDAR research through 2012). As early as 2007, a 100 km^2 survey area in southern Italy showcased the effectiveness of LiDAR in recording archaeological remains in a "complex Mediterranean landscape" (Cifani et al. 2007: 3). LiDAR was also used to build on previous research that had detected a medieval village and led to a reconstruction of its urban boundaries using aerial photographs and Quickbird images. The LiDAR provided additional benefits and permitted researchers to examine "micro-topographic relief linked to archaeological and geomorphological factors" that was related to "the urban shape of a medieval village," allowing researchers to analyze small differences in height that were not visible in the other datasets (Lasaponara et al. 2010: 155). Using LiDAR that had previously been flown for environmental monitoring in 2006 at a low density of 4–5 points/km^2, Bernardini and his colleagues (2013: 2153) analyzed 212 km^2 of hillshaded LiDAR from the Trieste Province in northeastern Italy for examples of prehistoric and historic sites in a karstic area. They identified previously unknown fortified structures, possible funerary barrows, agricultural terraces, and other buildings (Bernardini et al. 2013: 2152, 2159), noting the usefulness of the technique even for "relatively urbanized territories investigated for a long time," concluding that "LiDAR images yield information that surpasses that obtained after years of archaeological surveys." Masini and Lasaponara (2013: 673) also report on the effectiveness of LiDAR in terms of archaeology; the LiDAR that they used at an Etruscan site in Blera under a densely wooded area "made possible the identification of a large number of circular 'craters,' clearly referable to looted tombs or attempts to find and plunder tombs."

Researchers in Norway have also utilized LiDAR to better understand the history of their landscapes and have extensively tested how to best employ the technology. Risbøl and his colleagues (2013) utilized airborne laser scanning to observe the effect of point density on hill-shade identifications of linear features as opposed to irregular features; this study comprises a useful demonstration of the effects of size and shape in the detection of archaeological remains through the use of LiDAR. They concluded that "large cultural remains with clear geometrical shape (ovals and circles) and large elevation difference were more successfully detected and classified compared to smaller ones" and further noted that a point density greater than 10 points/m^2 "could potentially contribute to better identification of smaller features" (Risbøl et al. 2013: 4688).

Among the earliest LiDAR applications in the United Sates was its use in historic archaeology to gain information on the spatial layout and gardens of two eighteenth-century Maryland plantations. As a result of investigating these two plantations, the researchers concluded that LiDAR "can be used to identify areas of potential archaeological interest with ephemeral or no surface expression" (Harmon et al. 2006: 668). More recently, LiDAR has been used to examine past landscapes in North America. One of the more interesting applications has been the use of LiDAR data to examine the historic landscape of southern New England. Similar to some of the European applications, the New England study used an already extant database produced for environmental monitoring; even though the point density only averaged 2 points/m^2, the results from the LiDAR analyses were far better than any other database available. Within a heavily forested environment, Johnson and Ouimet (2014) were able to identify stone wall networks, building foundations, farmsteads, dams, mills, and old roads and pathways within the DEMs that they used. They also suggest that the large-scale LiDAR that they are using can be used to "interpret the data or results in terms of theoretical anthropological questions regarding landscape … and how humans have interacted with, shaped, viewed, and even divided the landscape" (Johnson and Ouimet 2014: 19). Their use of field systems and walls in New England mirrors the use of ancient agricultural terraces in the Maya area to answer similar landscape questions (D. Chase and A. Chase 2014).

Another recent study in the United States using LiDAR successfully documented ancient earthworks in the northern Everglades of Florida (Rochelo et al. 2015: 632–634), using post-processing techniques to improve on previous usage of the same LiDAR (Pluckhahn and Thompson 2012). Using lower-resolution 2-m data, Rochelo and his colleagues (2015: 642) were able to process the raw data with alternative software systems to eliminate some of the vegetation problems that were not resolved with originally available DEMs. Their innovative solution only highlights the need for cross-disciplinary fusion in using LiDAR point files not only with other existing off-the-shelf programs but also with specially written algorithms for specific environmental and climatic circumstances.

Another study in North America used LiDAR data in conjunction with archaeological data and a GIS platform to study the hydrology and agricultural practices of the prehistoric Hohokam in the American Southwest (Wienhold 2013). Because of the three-dimensional points produced through LiDAR, it was possible to model the flow of water over the landscape and to demonstrate that prehistoric rock alignments were used to modify both the channel and surface flow of water. Constructed rock alignments "were placed within suitable areas for collecting rainfall and runoff and for maximizing crop production during a time period of substantial drought" (Wienhold 2013: 857). This water harvesting is an example of an ancient complex land-use strategy in a marginal environment.

Studies of Pacific island landscapes have specifically focused on ancient agricultural systems (McCoy et al. 2011; Ladefoged et al. 2011). Ladefoged and his colleagues (2011: 3605) used an area of 173 km^2 of LiDAR to examine "agricultural processes of expansion, segmentation, and intensification" on Hawaii that could then be combined with potential productivity modeling to understand the agricultural development of this area. The landscape that they sampled contained long horizontal walls that were believed to have served as windbreaks for crops planted behind them and also to "result in increased moisture levels ca. 2–3 m immediately upslope of the alignment centerline due to microorographic precipitation" (Ladefoged et al. 2011: 3616). The LiDAR data here also permitted the "identification of the spatial relationships between trails and agricultural alignments" as well as "evidence of segmentation and intensification" in the agricultural landscape, "something that was not apparent in the aerial photograph data" (Ladefoged et al. 2011: 3618). Simultaneously, the LiDAR data from Hawaii also helped identify diverse ancient agricultural strategies that included "terrace complexes used for irrigated agriculture" within small valleys, permitting the development of a new method of "slope contrast mapping" using the LiDAR data "and thus defining where irrigated agriculture could have expanded in the past" (McCoy et al. 2011: 2153). The use of LiDAR for understanding the ancient Hawaiian landscape illustrates how these data can be used for complex environmental reconstructions and modeling.

Finally, we would note that exceedingly successful application of LiDAR to landscapes has occurred in the tropics where it has documented the impressive cities of vanished civilizations, first in the Maya area in Central America at Caracol (A. Chase et al. 2010) and subsequently in Southeast Asia at Angkor (Evans et al. 2013). At Caracol, Belize, a 200 km^2 area was flown in 2009 that revealed a landscape covered with archaeological terraces, urban settlement, and roads (A. Chase et al. 2011). This LiDAR campaign firmly established the usefulness of this technology for understanding a large area of heavily forested landscape and led to a more expansive campaign that covered an additional 1057 km^2 to better understand regional settlement patterns among the ancient Maya (A. Chase et al. 2014a, 2014b; this volume). Spurred on by the success of the Caracol LiDAR results, an area of 370 km^2 was surveyed with LiDAR in 2012 in northwest Cambodia associated with the medieval site of Angkor (Evans et al. 2013: 12, 596). Both the Caracol, Belize and the Angkor, Cambodia LiDAR data indicated the need for reevaluating the nature of urbanism and landscape use within tropical environments (A. Chase et al. 2011: 397; Evans et al. 2013: 12,599). As in the Maya case, a second LiDAR campaign is being carried out in Cambodia by Evans (this volume) to add 1200 km^2 to the previously surveyed area.

4.5 Final Remarks

Because of the ability of LiDAR to accurately detect relatively minor elevation differences and penetrate forest canopy over a vast spatial area, the technology has provided researchers the ability to better understand, model, and survey historical landscapes. In most cases, the application of LiDAR to a landscape has revealed previously unrecorded archaeological features that can then be investigated on the ground, and in some cases LiDAR has truly acted as "a catalytic enabler of rapid transformational change in archaeological research and interpretation" (A. Chase et al. 2012: 12,916), particularly for tropical regions where there is rapid vegetative growth that can obscure a landscape. LiDAR accurately portrays the palimpsest of features that covers the Earth's surface, but more detailed work is necessary to add a temporal dimension to the spatial one. Almost from the inception of the use of LiDAR by archaeologists, this limitation was noted. "The application of these methods will ultimately be most successful when the data are used in conjunction with information derived from the field, the laboratory, and from archival sources ... and reinforces the need for integration of multiple techniques when attempting to understand archaeological landscapes" (Harmon et al. 2006: 668). More than a decade has now passed since LiDAR was first utilized to study archaeological landscapes, and we are now beginning to see the successful fusion and interplay between different scholarly fields (Fernandez et al. 2014; Chase et al. 2016) as new and innovative ways to better utilize LiDAR are developed and tested. In the future, LiDAR use will become even more ubiquitous as the technology is placed into common devices such as phones. The future will also witness the integration of LiDAR data that have been collected at multiple scales (terrestrial, mobile, different altitudes) with other kinds of remotely sensed data (e.g., thermal, hyperspectral, and/or multispectral data and synthetic aperture radar) that will again provide new research avenues and insights into past landscapes.

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