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Airborne LiDAR acquisition, post-processing and accuracy-checking for a 3D WebGIS of Copan, Honduras

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Abstract

Archaeological projects increasingly collect airborne LiDAR data to use as a remote sensing tool for survey and analysis. Publication possibilities for LiDAR datasets, however, are limited due to the large size and often proprietary nature of the data. Fortunately, web-based, geographic information systems (WebGIS) that can securely manage temporal and spatial data hold great promise as virtual research environments for working with and publishing LiDAR data. To test this and to obtain new data for archaeological research, in 2013, the MayaArch3D Project – <http://www.mayaarch3d.org> – collected LiDAR data for the archaeological site of Copan, Honduras. Results include: 1) more accurate archaeological maps, 2) identification of unrecorded archaeological features, 3) an assessment of combining LiDAR and ground-checking to increase data accuracy in ecologically and topographically diverse landscapes, and 4) new LiDAR datasets that are hosted in a 3DWebGIS and integrated with other archaeological data to enhance data accessibility and collaborative research.

Keywords: Landscape Archaeology, LiDAR, 3DWebGIS, Data integration, Maya archaeology, Copan, Settlement patterns

1. Introduction

In May 2013, the MayaArch3D Project – <http://www.mayaarch3d.org> – under the direction of the German Archaeological Institute (DAI), commissioned an airborne LiDAR (Light Detection and Ranging) mission to collect remotely-sensed data of the landscape surrounding the UNESCO World Heritage site and ancient Maya city at Copan, Honduras. This mission had four objectives: First, generate new, more accurate archaeological maps for research and cultural resource management at Copan. Second, locate previously unrecorded archaeological structures or features. Third, combine LiDAR and ground-checked data to increase data accuracy in an ecologically and topographically diverse landscape. Fourth, develop new LiDAR datasets that can be integrated with other archaeological data and hosted in a 3D WebGIS to enhance data accessibility and research possibilities for researchers, cultural heritage managers, and the public, while at the same time protecting proprietary data by offering appropriate levels of access to different user groups.

Airborne LiDAR—a remote-sensing method that captures 3D data points from a laser mounted on an aircraft—is revolutionizing landscape archaeology (e.g., Chase et al., 2011, Chase et al., 2012, Chase et al., 2014a,b, Johnson and Ouimet, 2014, Prufer et al., 2015). LiDAR rapidly acquires high-resolution topographic data across landscapes, partly penetrates forest canopy and captures many features generally difficult to identify from a ground-perspective. These capabilities allow archaeologists to locate, map, and contextualize archaeological sites within their broader cultural and environmental landscapes and to generate high resolution Digital Terrain Models (DTMs) that are essential for accurate spatial and visual analysis. However, archaeological projects engage with widely varying environmental conditions, logistics, and research questions, and so the methods used to acquire, post-process, and integrate LiDAR data into archaeological projects vary across the globe (Opitz and Cowley, 2012).

What is common among researchers working with airborne LiDAR is that they conduct GIS analyses offline in 2D or 2.5D-views; online 3D analytical tools do not exist because the data are often too

heavy for online visualization (Fernandez-Diaz et al., 2014; Rosenswig et al., 2014). The data must be optimized for online visualization but in doing so many details in the data are lost that are often necessary for analysis. Moreover, it is a particular challenge to make these data available to researchers or cultural heritage managers who may not have the technical tools or training to work with the data, yet whose work would benefit in efficiency and quality through access to more accurate information. There are many ways that aerial LiDAR data can enhance archaeological research and cultural heritage management. Archaeologists can use the data to improve their settlement pattern maps, to do hydrological modeling, test landscape reconstructions, and if integrated with 3D architectural data, run visibility studies. Cultural heritage managers can use it to monitor their archaeological sites for damage, or to label archaeological sites with information. Increasingly workshops and summer schools are training archaeologists to work with LiDAR data, but generally the possibilities for accessing or publishing LiDAR data are limited to 2D, non-interactive publications. Now that archaeologists can carry out 3D surveys and are becoming accustomed to 3D perspectives, they are calling for 3D or even 4D GIS tools (Bodenhamer et al., 2013; De Roo et al., 2013, 2014; Desjardin et al., 2014; von Schwerin et al., 2012). Such tools would enable researchers to integrate LiDAR data with other archaeological, architectural and environmental data into a Geodata Infrastructure (GDI) with interactive features for 3D analysis and visualization. Moreover, if archaeologists could integrate LiDAR data with their own datasets on a 3D WebGIS tool, they could carry out more accurate and comprehensive spatial analyses.

A central goal of the MayaArch3D Project (Billen et al., 2013, Loos et al., 2013, Reindel et al., 2013, 2014, von Schwerin et al., 2013) is to develop a 3DWebGIS tool for researchers to integrate and query complex archaeological data online. In 2012 the project

adapted the DAI's archaeological database (iDAI.field) for Mesoamerican archaeology and to record 3D metadata and linked the database to a PostgreSQL with PostGIS database containing the project's 3D data. These are linked to a 2D Geobrowser and 3D Scene Viewer that give users access to view and analyze a test-set of data from Copan including shapefiles, 3D models, images, and attributes on archaeological sites, structures, architectural sculpture, monuments, and inscriptions. Queries of settlement plans, topographic features, orientation, and artifact distribution – that until now were carried out in 2D – are now possible in an online 3D environment with a 4D (temporal) time-slider. Additionally, 3D WebGIS visibility tools in the system enable the user to investigate in the 3D Scene Viewer, for example, the intervisibility of Copan's stelae, alignments of structures to topographic features, or alternate lighting on 3D models of sculpture to reveal details of inscriptions. The tool, "QueryArch3D-WebGIS", is a 3D WebGIS visualization and analytical tool that can be adapted for other archaeological sites worldwide.

Until 2013, the 3D data collected for QueryArch3D-WebGIS included reality-based 3D models of selected structures, architectural sculpture, and monuments at Copan ranging from 3 cm–0.5 mm resolution (Agugiaro et al., 2011; Remondino et al., 2009; see also: <http://www.mayaarch3d.org/research/tools-in-development/3d-object-viewer>), but the Digital Terrain Model (DTM) of the bare-earth features of the Copan valley landscape had been generated from scanned and georeferenced survey maps (Fash and Long, 1983) with accuracy ranging from 2 to 10 m. To analyze relationships between architecture and landscape in three-dimensions, the project needed a more accurate DTM of bare-earth, as well as a Digital Elevation Model (DEM) including bare-earth and architectural features; hence, the 2013 LiDAR mission.

This paper summarizes how these LiDAR data have been post-processed, partially ground-checked, and further processed for inte-

Figure 1. Map of Copan's location on southeast periphery of Maya region.

Figure 2. Copan GIS data showing LiDAR collection area [after PAC 1 (1983) and Hohmann and Vogrin (1982)].

Figure 3. MayaArch3D LiDAR acquisition (25 km²), Copan, Honduras.

Figure 4. Ground-return density map for Copan, Honduras (100 m × 100 m cells) (courtesy WSI).

gration and web-publication in QueryArch3D-WebGIS. The goal is to expand knowledge about ancient Copan by making LiDAR data more usable and accessible, and to facilitate collaborative research, sparking new insights and innovative lines of inquiry.

2. A brief history of mapping at the Maya kingdom of Copan

Copan was an important center on the southeastern periphery of the Maya world. The landscape is ecologically and topographically diverse, which, as shall be shown, makes for more challenges in post-processing LiDAR data. Within the Copan valley are alluvial terraces, foothills, and mountains, as well as diverse vegetation ranging from sub-tropical coverage on the valley floor to pine forests in the mountains (Figure 1). Since 1885 archaeologists have carried out numerous surveys and excavations at Copan (e.g. Fash, 2001). From these investigations, they have reconstructed the history of a kingdom ruled by seventeen kings between AD 426 and 822, each of whom continually re-shaped the design of the city.

Early investigations focused on the city's main-civic ceremonial zone — the Principal Group of ruins on the valley floor. Between 1978 and 1980, however, the Copan Archaeological Project (PAC 1)

surveyed and instrument-mapped 24 km² surrounding the Principal Group (Fash and Long, 1983) (Figure 2). Contour lines and hydrological features were drawn from 1:4000 maps produced from stereoscopic aerial photographs. The result of the PAC 1 survey is twenty-four maps (scale 1:2000) with hydrological features, contour lines, and over 3000 archaeological structures. Since then subsequent pedestrian mapping campaigns have been done in other parts of the valley (e.g. Freter, 1988, Landau, 2014; Maca, 2002). A LiDAR mission flown in 2000 for flood and landslide analysis following Hurricane Mitch captured Copan's main-civic ceremonial group at a 1m-resolution (Gutierrez et al., 2001) but these data did not capture the majority of archaeological sites.

From 2006 to 2008, the PAC 1 maps as well as photogrammetric maps of the Principal Group (Hohmann and Vogrin, 1982) were digitized, georeferenced, and attributed to create shapefiles to perform accessibility and visibility studies of the Copan settlement (Richards-Rissetto, 2010, 2013). The MayaArch3D project is now comparing these digitized ground survey data from the late 1970s/early 1980s with the 2013 LiDAR data, editing the shapefiles of the ancient settlement where necessary, and linking these to archaeological data in the 3DWebGIS.

Figure 5. WSI survey marker, Trimble base unit and the roving Trimble R8 GNSS receiver (photo credit: WSI).

Table 1. Absolute and relative accuracies of LiDAR acquisition, Copan, Honduras.

	Absolute accuracy (meters)	Relative accuracy (meters)
Sample	292 points	84 surfaces
Average	0.002	0.042
Median	0.003	0.043
RMSE	0.027	0.043
1σ	0.027	0.003
2σ	0.054	0.006

3. Data & methods

3.1. LiDAR data acquisition

The LiDAR data collection took place during four days in May 2013. Watershed Sciences Inc. (WSI) from Oregon, USA collected LiDAR data for 25 km² of the Copan valley, with the main archaeological park approximately at the center (Figure 3). WSI used a Leica ALS50 Phase II system mounted in a Piper Aztec aircraft. The target point density was ≥ 15 pulses/m² and all areas were surveyed with an opposing flight line sidalap overlap of ≥ 50%. The average first-return density for the LiDAR data for Copan was 21.57 points/m². While ground return density averaged 2.91 points/m², Figure 4 shows marked differences in first and ground return density across the valley. These differences are correlated to topography and vegetation density (see Section 4.3). Several operational procedures were taken to increase absolute accuracy (i.e. to minimize divergence of ground surface model from ground survey coordinates) and relative accuracy (i.e., maximize internal consistency of data) of the LiDAR data. Positional coordinates of the airborne sensor and the aircraft’s altitude were recorded continuously and indexed by GPS time. To geospatially correct the LiDAR data, WSI set two permanent survey monuments and used a Trimble R7 base unit and a roving Trimble R8 GNSS receiver to collect GPS data across the valley (Figure 5). Table 1 lists the absolute and relative accuracies.

3.2. Post-processing: filtering and deliverables

In August 2013, WSI delivered a technical report (WSI, 2013) and deliverables including raw 3D data points (LAS and ASCII), classified LAS data (Table 2), and raster data. To classify the unstructured 3D point clouds, WSI employed proprietary automated and manual techniques, and also compared the LiDAR data to the shapefile of archaeological structures generated from the PAC 1 survey. From these classified points, WSI generated a bare earth model (Digital Terrain Model—DTM) that removes the archaeological mounds and a DEM (Digital Elevation Model) that includes bare earth as well as still-standing archaeological buildings and mounds that together represent the archaeological surface (Figure 6). WSI’s filtering algorithms were developed to distinguish bare earth (DTM) from vegetation, i.e., to generate topographic models (Figure 7), and not to delineate archaeological features from bare earth. While WSI did perform a semi-automatic approach to separate archaeological mounds from topographic features (such as natural hills), their postprocessing was not able to distinguish many lower archaeological mounds (b0.80 m) from natural terrain (bare earth). In addition, the results showed some inconsistencies (Figure 7). In the Great Plaza, one of the largest structures—Structure 4—was missing (Figure 6). This is a typical problem of many LiDAR filters that are customized ad-hoc to segment out vegetation and human-made structures. Therefore, the LiDAR data needed to be further post-processed. For this task, the DAI collaborated with the 3D Optical Metrology unit of the Bruno Kessler Foundation (FBK) in Trento, Italy. In 2013, FBK refined and applied different filter methodologies based on landform and vegetation cover in order to correctly extract a DTM and human-made structures from the LiDAR data. Indeed, comparing WSI’s classified data to known sites provided by the PAC 1 shapefile (Richards-Rissetto, 2010), FBK calculated that 14% of the features classified as purely ground were actually archaeological mounds. Therefore the LiDAR data were processed with the aim of preserving all archaeological features and to unveil hidden structures. Using the software Laser data LIS, the LiDAR point cloud was segmented with a classification workflow based on various steps:

Table 2. 3D point classifications of LiDAR data.

Classification number	Name	Classification description
1	Default/unclassified	Points not in ground class and not dismissed as noise
2	Ground	Determined as ground using automated/manual filtering algorithms
6	Archaeological features	Excavated features and mounds recorded in PAC 1 survey
27	Ruin ground	Secondary ground classification to preserve ground model integrity and differentiate archaeological features from true ground

Figure 6. 3D view looking southwest over Principal Group. Left: LiDAR point cloud classified by elevation and intensity. Right: Digital Elevation Model (DEM) classified by elevation (courtesy: WSI).

Figure 7. Inconsistencies among DSM (left) and DEM (ground & structures — right) of the Great Plaza.

(i) segmentation of the point cloud by means of planes: for a certain amount of neighborhood points, a plane is robustly fitted and then the normal vector of each point are calculated thus to group all points sharing the same vector orientation into segments; (ii) identification of ground points (called seeds points) located on planar surfaces; (iii) use of a region growing method to search within the immediate neighborhood of seed points for segments that share approximately the same surface plane orientation and add these points to the ground class; (iv) apply the Enhanced Point Cloud Classification module of LIS to extract two attributes of the non-ground points: planarity and 3D/2D neighborhood ratio (useful to better distinguish between buildings and vegetation).

Using this workflow, three classes (Figure 8) were finally identified (ground, building, vegetation).

To evaluate the derived archaeological structures, the points clas-

sified as structures were isolated with an open module of Lastool (“las2las keep” class structures). Afterwards the structures were loaded in a GIS environment and compared with the shapefile derived from the PAC 1 mapped structures and the WSI’s classified data. The comparisons revealed a number of new structures (see Section 4.2) but also some shifts in the positions of known structures (see Section 4). Furthermore, some profiles were derived and the analysis showed that most of the new structures have a height between 0.5 and 1 m.

At the end of the new filtering strategy, new Digital Elevation Models were produced — ground only (DTM) and ground + archaeological structures (DEM) — (Figure 9) as well as DEMs with 0.2 m, 1 m, and 5m contour lines. The DTM and DEM were divided into 16 tiles each for geoscientists from the University of Heidelberg to further post-process for visualization and analysis in the 3DWebGIS (see Section 3.4).

Figure 8. Results of new classification approach: ground–building–vegetation (left), building–ground (right).

Figure 9. Intensity image (top), highest hit or Digital Surface Model (DSM) (middle), and DEM (bare-earth + archaeological structures) (bottom).

3.3. Post-processing in the Lab and in the field: Archaeological inspection & ground-checking

In December 2013, FBK delivered the newly post-processed LiDAR data. Project archaeologists are iteratively working with these data in the lab and in the field to achieve three main objectives: (a) update the GIS shapefiles, (b) locate new sites and archaeological features, and (c) evaluate the accuracy of post-processed LiDAR data. In the lab, we are visually comparing the PAC 1 survey data shapefile to FBK's post-processed LiDAR data and noting areas that are not consistent. In the field, we compare a LiDAR-generated map to archaeological features on the ground. From January 16 to March 14, 2014 a two-month field campaign was carried out in Copan in

collaboration with the Honduran Institute of Anthropology and History (IAAH). The field work was directed by Markus Reindel, Jennifer von Schwerin, and Heather Richards-Rissetto. After agreeing with IAAH on areas to be ground-checked, a workflow was devised that combined analog and digital technologies. Paper maps, digital PDFs, and GIS data were brought into the field and the older PAC 1 maps were overlaid using the Relief Visualization Toolbox v 1.1. (RVT) to explore the utility of different visualization methods including LiDAR-derived hillshades, PCA (principal component analysis) hillshading, slope gradient, local relief model, and Sky-View Factors (SVF) for comparing mound size, location, and orientation and identifying unmapped features (Figure 10) (Kokalj et al., 2011; McCoy et al., 2011; Opitz, 2013; Zaksek et al., 2011). The utility of the differ-

Figure 10. Visualization methods employed to identify new sites — example from Group 9R-1, Copan. Average mound height 1.5 m.

ent visualization techniques varied based on feature type; for example, Slope and Sky-View Factor techniques worked best to delineate low-lying architectural mounds and the Sky-View Factor was the best method to identify terraces (Figure 18).

During our fieldwork, we ground-checked 5.6% (1.414 km²) of the 25 km² surveyed with LiDAR—transecting 1.5% (0.375 km²) and spotchecking 4.1% (1.039 km²). (The modern town of Copan Ruínas comprises ~9.9% [2.507 km²] of the LiDAR survey area and Principal Group ~0.5% [0.127 km²].)

3.4. Data integration into the 3D WebGIS

The final step in our methodological approach is to make the LiDAR data and improved archaeological maps available in our 3D WebGIS so that researchers can incorporate the LiDAR data into their archaeological analyses. The GIScience working group at the Institute of Geography at the University of Heidelberg further post-processed the LiDAR data into datasets that they then integrated into QueryArch3D-WebGIS to be visualized in two front-end components—the 2D Geobrowser and the 3D Scene Viewer (Figure 11).

The 2D Geobrowser is based on the open source web mapping framework Geomajas (www.geomajas.org) and PostgreSQL/PostGIS and offers a set of 2D data layers for visualization and spatio-temporal queries against the archaeological database iDAI.field (Loos et al., 2013). Six LiDAR-derived data layers (intensity image, DEM, DSM

colorshade, DSM ground structure, hillshade ground structures, and colorshade ground structures) have been added (Figure 12), which can be overlaid with other archaeological datasets (see Section 4.4).

The 3D Scene Viewer uses GIScene.js, a 3D Geovisualization framework. It is mainly based on WebGL (a Web Graphics Library for rendering 2D and 3D graphics without plug-ins) and the JavaScript 3D library Three.js (Khronos Group, 2014; <http://threejs.org/>). The 3DScene Viewer presents a schematic virtual reconstruction of Copan circa AD 822, which comprises extruded building footprints from the PAC 1 maps, photogrammetric architectural drawings (Hohmann and Vogrin, 1982), and SketchUp reconstructions (Richards-Rissetto, 2013). The LiDAR data then was integrated into the virtual environment to replace the previous landscape model made from the PAC 1 maps. Users now have more accurate terrain data to run 3D analyses on both the architecture and the terrain for landscape archaeology (see Section 4.4) (Figure 13). To integrate the LiDAR data, the 3D point clouds (classified as ground points) were converted using several intermediate steps into a series of simplified 3D triangle meshes. Meshes were prepared at several levels of detail (LoDs 1–6) to allow for distance-dependent loading that: (1) enables large datasets to be streamed dynamically in nearly real-time, (2) allows higher-resolution tile loads so that as users approach landscape features they can examine them in high detail, and (3) permits 3D landscape analysis using high-resolution data to maintain data accuracy and integrity.

Figure 11. QueryArch 3D-WebGIS infrastructure. Shaded components handle LiDAR data. (System built by the GIScience Group, Heidelberg University).

4. Results and discussion

4.1. Updated archaeological maps

Of the 521 mounds from the PAC 1 maps that were checked in the 2014 ground-survey, 468 were relocated in the LiDAR data and/or ground-checking. The project's lab and field results show that while the PAC 1 maps capture almost all of Copan's visible sites, at least 80% of the architectural groups that we checked on the PAC 1 maps differed from the LiDAR data and/or ground-checked architectural groups in five possible ways: internal composition, location, structure orientation, structure size, and/or mound height. These differences most likely are due to the state of the art surveying technologies in the late 1970s that lacked an exact topographic reference system to compile data collected at various scales, over several years, and by different mappers as well as from subsequent scanning, georeferencing, and digitizing of the PAC 1 maps.

4.1.1. Internal composition

(1) We could not relocate some mounds from the PAC 1 maps in the LiDAR data (likely due to landscape changes in the past thirty-five years (Figure 14a), (2) within some groups we identified new **structures** (Figure 14b) as well as (3) small **platforms** linking structures — the latter is important as it suggests greater restricted access to architectural groups (Figure 14c).

4.1.2. Location

In comparison with the LiDAR data, many structures, particularly on the valley slopes, were shifted on the PAC 1 maps (Figure 15). This might be due to the fact the mapping surveys used uncorrected aerial photos (i.e. with distortions towards the edges) or occurred in original georeferencing of PAC 1 maps. This was clearly the case in four structure groups located in the valley's periphery, where the primary error was not in the size and/or spatial relationship of the structures inside of the group, but rather the entire group itself was shifted within the landscape.

4.1.3. Structure orientation

The structure orientation on the PAC 1 maps often varied against that of the LiDAR data; alignments differed by 1°–3° and sometimes up to 15° from the LiDAR data (Figure 15). While it is often difficult to determine the central axis or orientation of an unexcavated structure in which the walls might have collapsed significantly in different directions, it was necessary to rotate approximately 60% of the structures that we ground-checked to at least a slight degree to make them correlate with the LiDAR data. During ground-checking, we compared structure orientations to the LiDAR data using a handheld mapping compass. In all but one case, field measurements corresponded more closely to the LiDAR data than the PAC 1 maps.

4.1.4. Structure size

The dimensions (length and width) of structures on the PAC 1 maps typically corresponded to the LiDAR data. All but a few of the ground-checked structures had a surface area well within the range of $\pm 10\%$ of the PAC 1 mapped structures. Such small differences could be due to the structures having been impacted by erosion and other site disturbances over time. In the few cases where a structure appeared larger in the PAC 1 maps than in the LiDAR visualization, it was typically the case that it was located on a natural slope, which disguised its true size from an aerial perspective. Most likely this phenomenon occurs in areas where the hillshade visualization resulted in small features on the illuminated side of the slope to cast smaller shadows or possibly the algorithm erroneously classified mounds as ground points in some sloped areas. Approximately three structures that we ground-checked were complete outliers to this pattern, having a significantly larger size in the LiDAR data (and on the ground), and being located on a fairly level surface with no visible evidence of disturbances. This must be due either to mapping errors, or to physical changes in the terrain.

4.1.5. Mound height

The PAC 1 maps were published at a smaller-scale than originally recorded. This smaller-scale provides less detail and impacts the representation of height because of tighter angles and shorter

Figure 12. LiDAR intensity image (top) and LiDAR hillshade ground structures (bottom) overlaid with structures shapefile hosted in 2D GeoBrowsers (only structures within the protected archaeological park are shown here).

lines. Moreover, the map is only intended to convey a general idea of mound heights relative to each other. Not a single mound elevation is published in the maps. In addition, erosional processes since the 1980s may account for differences between the PAC 1 maps and the LiDAR data. In the end, the LiDAR data provides highly accurate data for present-day mound height and offers a 3D perspective of mound contours that is unavailable from the two-dimensional PAC 1 maps (Figure 16).

The archaeological structures map or shapefile that is presented in the 2D Geobrowser contains updates and refinements to the PAC 1 maps based on the findings mentioned above and two new sites mentioned in the following section. In addition, we added the site of Cerro de las Mesas to the archaeological structures shapefile. This site is well-known to locals in Copan. A sketch map drawn by Dr. Rene Viel was published in the PAC I volume (1983:266–275), and the site has been discussed by other researchers (e.g., Canuto, 2002,

Figure 13. 3D Scene Viewer with LiDAR-derived terrain and low resolution, georeferenced building models.

Fash, 1983). However, because the site was not included in the series of published oversize PAC I maps, we did not have any geospatial data to situate it within the Copan Valley. The LiDAR data provided us with a georeferenced aerial view of the site that we digitized into the archaeological structures shapefile (Figure 17). We suggest that on-the-ground instrument mapping follow-up this initial GIS map.

4.2. Located new sites, structures, and terraces

In the introduction to the PAC 1 map (Fash and Long, 1983), it was predicted that more unidentified sites might exist in the Copan valley because at that time there were areas where the archaeologists did not have landowners' permission to cut down the grass or crops to do an adequate survey. And indeed, the LiDAR data was able to assist us in identifying new sites. Before the ground campaign, we inspected the LiDAR data visually to identify potential new sites. Some of these sites are on private land and we were unable to gain access to these for ground-checking. However, with the permission

and support of IHAH, we did access several areas in The Valley. While we found that some "sites" were modern features, for example, piles of stones cleared for agricultural fields, we did, in our short field season, confirm the identification of, and map two new sites. These new sites have been named 7K-5 and 9R-1 according to their locations on the PAC grid. Overall, 18 new mounds were discovered in Copan—these include 8 structures from the 2 new groups and 10 structures dispersed among other known groups (not including Cerro de las Mesas).

In addition to locating new structures, we identified unmapped agricultural terraces (Figure 18). Some of these were originally recorded as part of the PAC 1 project in Petapilla and Titichon, but intentionally left out of the published map until such time as they could be excavated to determine terrace antiquity (Fash, 1983: Appendix D, p. 17)). Therefore, only a few comments since have been made in the literature about terracing at Copan (Baudex, 1983; Fash, 1983; Maca, 2002:65; Webster et al., 2002). Fash noted what he believed might be agricultural terraces at Cerro de las Mesas as well as in an

Figure 14. a.) Str. 9M-86 in Group 9M-9 not relocated in ground-checking; b.) Group 11K-9 — previously unmapped structure; c.) Group 8N-10 — three platforms not previously mapped.

Figure 15. Illustrates shift and orientation differences between LiDAR and PAC 1 maps (example from Las Sepulturas mapped by Willey and Leventhal in 1976).

area in the foothills 900 m to the southeast of the great plaza (1983: Appendix A p. 112) (which may be the site now named, San Lucas). He concluded that evidence of agricultural intensification that one would expect to find at Copan is lacking, and attributes it to possible deliberate actions by feuding factions (Fash, 1983:72). A widespread explanation for the lack of agricultural terraces is that many have been buried by erosional processes (Webster et al., 2002).

However, with the help of the LiDAR data more unmapped (likely, agricultural) terraces, have been located. Terraces can be seen in the areas of San Rafael, Titichon, Ostuman, Tapescos, Rastrojon, Titoror, San Lucas, and Cerro de Las Mesas. More thorough investigations to determine their age are still required. With regard to construction methods, the most common variations appear to have been building terraces along slopes to catch the eroding soils coming down, and construction dams across quebradas/drainages, except in Cerro de las Mesas, where the slope has been cut away to create planar surfaces. Further investigation of this data may help to expand knowledge about ancient agricultural systems in the valley.

4.3. Analyzed accuracy of post-processed data

We have identified three limitations of the LiDAR data. First, while it is a general problem in archaeological use of LiDAR to delineate archaeological mounds from natural topography (e.g., Prufer et al., 2015), this is particularly challenging at Copan because the ancient Maya often incorporated natural topography into their constructions. Second, identifying archaeological mounds less than ≤ 0.25 m in height is difficult—in some cases, our fieldwork located mounds clearly marked on the PAC 1 maps but not visible in the post-processed LiDAR. Third, in areas with diverse landforms and a range of vegetation types and densities—a particular characteristic of the Copan valley—we found that while the first return from the LiDAR averaged one point every 25–30 cm, areas under dense vegetation resulted in uneven sampling ranging from one point every 50 cm to 1.5 m (Figure 19).

Moreover, we also observed that the further one moves away from the center of the site, the more the PAC 1 maps and the LiDAR data deviate from each other—with the LiDAR data being more accurate.

Figure 16. 2D view of LiDAR points of SE corner of East Court overlaid with shapefile derived from Hohmann and Vogrin (1982) architectural plans, Copan (left); 3D view of LiDAR points highlighting topographic features not visible in 2D (right)

This increasing deviation in the PAC 1 paper maps likely results from several factors: more detailed mapping at site center, increased vegetation in foothills vs. alluvial terraces, increased topography in foothills away from site center, and errors in initial mapping as well as in follow-up georeferencing and digitizing. While it is difficult to tease out the errors introduced from mapping vs. digitizing, we did identify patterns arising from vegetation and topography (Table 3).

The results in Table 4 are as expected. In flat areas such as river terraces with sparse vegetation, the post-processed LiDAR was ac-

curate from 0 to 0.2 m. In flat areas with dense vegetation, the data were less accurate, ranging from 0 to 2.0 m (with worst case scenarios from 1 to 2 m). We found that larger and higher mounds were more accurately delineated than small, low mounds.

In foothills with sparse vegetation the LiDAR data had similar accuracy to flat areas with dense vegetation ranging from 0 to 2.0 m. We identified two sources of error: (1) large structures that incorporated the natural slope appeared larger in LiDAR data than in reality and (2) small structures incorporating natural slope were often

Figure 17. Cerro de las Mesas, a previously-documented site added to the Copan GIS using the LiDAR data.

Figure 18. Unmapped terraces identified from Sky-View Factor of LiDAR (directions— 16, search radius=10m) (top); terraces confirmed at ground-checked location in Titichon (bottom).

not captured in post-processing because they “blended” into the natural terrain. Fortunately, because we had the original PAC 1 maps, we could highlight “missing” archaeological structures in the LiDAR data (and follow-up on them in ground-checking).

These results emphasize that the combination of hilly terrain and dense vegetation can reduce the accuracy of post-processed LiDAR data, highlighting the importance of ground-checking. Yet, it is not possible to do 100% ground-coverage over vast landscapes so calculations of accuracy linked to specific criteria (such as topography and vegetation) can help archeologists to refine post-processing methods and develop new filtering algorithms to increase accuracy. Another approach (when available) is to employ an integrative strategy that incorporates earlier ground survey maps and stratified ground-checking— using this approach we can use the LiDAR data to improve the accuracy of Copan’s maps of *visible surface architecture* to 0.5 m. (Of course, there may be dozens or hundreds of ancient building remains at Copan that are “invisible”, even to LiDAR,

due to the fact that the foundations are buried under the earth, or were washed away by the river, or destroyed by modern land usage.)

4.4. Landscape Archaeology analyses in the 3D WebGIS

By making the LiDAR data available in the 3D WebGIS, this project offers researchers the possibility to engage in new types of 3D geographic analyses that include LiDAR data. Specifically it enables the researcher to analyze the landscape in 3D together with 3D architectural and city models. Going beyond visualization, this 3D WebGIS offers geospatial analyses, such as line-of-sight and orientation analyses. The question whether the resolution of the data provided online suffices depends on the specific research question, the scale of analysis and the purpose. The system does not currently have an automatic download function for the full resolution dataset, but researchers are welcome to contact the lead author regarding access to this dataset, which has been deposited in the DAI archives and IHAH archives.

Figure 19. First return sampling step: average 25–30 cm (*top and middle*); Areas under vegetation — uneven sampling step, from 25 cm to 1.5 m (*bottom*).

4.4.1. 2D Geobrowser — functions and queries

In the 2D Geobrowser, the six LiDAR data layers mentioned in Section 3.4 can be compared with layers that represent the mapping data of the archaeological settlement, including the locations of structures, stelae and altars, with an Open Street Map layer, or with satellite imagery (Figure 12). The layers can be adjusted for

Table 3. Accuracy ranges of LiDAR mapping identified from ground-checking.

	Sparse (low) vegetation	Dense vegetation
“Flat” areas	0–0.2 m	0–2.0 m
Foothills	0–2.0 m	0–3.0 m

Table 4. Characteristics of the different 3D level of detail meshes optimized for visualization.

Level of detail	Number of vertices (rounded to 1000)	Number of triangles (rounded to 1000)	Resolution in vertices per m ²	Average point distance in m
1	33	60	0.001	32.0
2	63	120	0.0019	23.1
3	123	240	0.0037	16.5
4	243	480	0.0073	11.7
5	483	960	0.0144	8.3
6	963	1920	0.0288	5.9

Figure 20. Line of sight tool in 3D Scene Viewer of QueryArch3D-WebGIS.

different levels of opacity to visualize differences between layers. Such an interface that compares for example, a modern street map with both the archaeological settlement map and the LiDAR landscape data can help cultural heritage managers quickly identify ruins that might be in danger from construction projects and then quickly access the database to enter or gather additional information on the endangered structures. For researchers, the LiDAR data can also be analyzed against other data via complex spatial, temporal, and/or attribute queries of the archaeological database, or by clicking on features in the layers (structures, stelae, or altars) that have records in the database.

4.4.2. 3D Scene Viewer — visual, explorative and computational analyses

Because the 3D Scene Viewer integrates the LiDAR-generated DTM with the 3D model of the 9th century Copan settlement (based on the PAC 1 data), users can run a variety of 3D analyses of architecture in the landscape. A lighting feature allows users to examine effects of light and shadow on monuments and the landscape. 3D measurement tools provide easy access to the spatial characteristics and relationships of the monuments and the landscape. Different 3D Visibility (Figure 20) and Orientation analysis tools allow the user to test and visualize hypotheses regarding the relationships of monuments to significant landscape features in a 3D virtual environment. As demonstrated by Auer et al. (2015) and Richards-Rissetto et al. (2015) the testing of hypotheses about ancient stelae in the Copan Valley can be approached by combining the LiDAR derived DTM, the stela locations and the settlement model.

One must remember, however, that the landscape model is made from mesh of triangles that has been reduced in resolution for the different Levels-of-Detail (LoDs) in comparison to the original LiDAR data. In the case of our data for Copan, the original landscape data has a resolution of around 0.5 m. Currently, the 3D Scene Viewer contains LoDs 1–4 (Table 4).

5. Conclusions and future direction

In sum, as a result of working with the LiDAR data we have been able to update maps, locate new features, and evaluate the accuracy

of our LiDAR post-processing methods using a two-prong approach (ground-checking and comparison to legacy survey data) in order to begin to note patterns that could be useful for deriving new filtering algorithms. Moreover, we have collaborated to establish a workflow to process LiDAR data for online visualization with 3D architectural models that fosters spatial and visual research that combines quantitative and qualitative approaches.

5.1. A multi-step iterative process is recommended

Airborne LiDAR offer many applications to archaeology. For our work at Copan, these include:

1. Mapping — including revising and updating older maps and capturing subtle terrain features such as terraces that are difficult to map using traditional techniques. Future ground-checking is necessary to continue to improve the PAC 1 maps.
2. Prospection — From the ground-checking we found that the LiDAR measurements bear great potential for the discovery of new settlement features and a reinterpretation of the cultural landscape even in areas previously ground-surveyed.
3. Analysis — LiDAR captures subtleties in topographic features and with appropriate filtering algorithms offers high resolution data that are important for landscape archaeology.

We cannot stress enough the importance to derive both a Digital Terrain Model (DTM) that shows bare earth without archaeological mounds and a Digital Elevation Model (DEM) that includes bare earth+archaeological structures. These two data sets are crucial, in particular, for 3D visibility studies where it is crucial to “remove” the archaeological mounds in order to accurately place 3D models of architecture in the terrain. Traditional DTM algorithms include archaeological mounds as bare-earth; thus, inducing error into subsequent 3D visibility studies because building heights become artificially increased when 3D models are situated on the surface. To avoid such problems, we recommend a multi-step iterative process that includes ground-checking as well as the testing and application of multiple filtering algorithms, particularly in areas of diverse landforms and vegetation type and density.

5.2. LiDAR data delivers more accurate and new data for research and cultural heritage management in Copan

The 2013 LiDAR survey at Copan acquired data resulting in a DTM and DEM with an average accuracy of 0.5m (Figure 21a). The project found that, when available, legacy data are a useful data source for LiDAR postprocessing. However, such data can also contain errors that must be adjusted to ensure accurate GIS and 3D analyses. Moreover, we located and mapped new structures and terraces. Ultimately, using the LiDAR data, in the future, a new, more accurate map could be made of the entire settlement and included in the “Copan structures” layer in the 3D WebGIS. These data would help IHAH staff with cultural resource management at Copan (e.g. looting) (Figure 21b), as well as serve as the basis for further archaeological research, such as hydrological modeling, testing landscape reconstructions, visibility studies, and archaeoastronomical analyses.

5.3. Automated approaches can only assist, not replace visual analysis for LiDAR checking

While LiDAR data enhance the accuracy and efficiency of archaeological investigations and allow for new types of analyses, our research results reaffirm that automated approaches to post-processing can assist, but not replace visual inspection in archaeological feature classification. Because the vegetation density is not consistent across the valley, and because this inconsistency plays out across diverse topography, it is necessary to post-process the data in different ways, despite that the data is from the same acquisition mission and same area. In particular, our findings indicate that archaeologists need to continue to work with specialists to refine existing algorithms and develop new ones to more accurately classify archaeological mounds on slopes, particularly in areas of dense vegetation.

In short, archaeological expertise and ground-checking still are necessary. Ground surveys remain an integral and invaluable part of

landscape archaeology. Earlier surveys offer valuable data on now destroyed or eroded sites and should be consulted even when new LiDAR data is available, and current ground surveys enable ground-checking and data collection on surface finds where aerial surveys fall short. It is important to also include ancillary datasets such as ground survey data, site maps, satellite/aerial imagery, or any other relevant data in archaeological analysis and interpretation of LiDAR data.

5.4. Acropolis point-cloud will be post-processed into a BIM model for online 3D analyses

While we integrated the ground points from the LiDAR data into the 3D Scene Viewer of the 3DWebGIS as a landscape mesh (as explained in Section 3.4), what we have yet to integrate are the points classified as “archaeological structures”. While these data points are being used to create updated maps and a new “Copan structures” shapefile for the 2D Geobrowser, these point clouds also contain 3D data that is far more detailed than the simulation of Copan’s 9th century settlement (based on the PAC 1 data) that currently is in the 3D Scene Viewer. The reality-based, LiDAR data of some of Copan’s larger buildings—if turned into reality-based mesh models—would provide a basis for users to compare existing structures with the simulation.

Moreover, such reality-based models could be of great assistance in planning conservation measures for the Copan Acropolis — a complex structure with 400 years of construction history that is riddled with excavation and tourist tunnels, and whose stability is threatened by vegetal growth and precipitation (Figure 22).

We are now investigating an optimal workflow for post-processing the LiDAR point cloud of the acropolis (removing unnecessary points, generating a mesh, incorporating other 3D datasets and optimizing for offline and online applications), in order to create a CAD model. This model could then be converted to BIM (Building Information Model) and used by architects, engineers, and conservators for

Figure 21. a (left): Map illustrating high resolution (0.5 m) DEM derived from LiDAR; Figure 21b (right): Map illustrating looters pits identified in LiDAR using Sky View Factor visualization

Figure 22. LiDAR point cloud of the Copan Acropolis classified by elevation.

analysis, planning, and record-keeping for cultural resource management and conservation (Hichri et al., 2013) Experts in remote locations could use the BIM to track damaged or threatened areas, and to plan and record conservation interventions.

In collaboration with 7reasons GmbH of Vienna, the LiDAR data was used to test the possibility of making a more accurate simulation of the appearance of the Copan valley landscape in the 9th century that can be employed in educational applications (Figure 23)

5.5. 3D WebGIS supports varied access to Copan LiDAR data for collaborative research, management, and education

Finally, this article emphasizes that hosting LiDAR data in a 3D WebGIS is important to enhance data accessibility in order to support international, collaborative archaeological research and cultural heritage management. In the MayaArch3D-WebGIS, the LiDAR data is available for viewing as a 3D mesh in the 3D Scene Viewer, and as

Figure 23. Test simulation of the Copan valley landscape ca. CE. 800 using the LiDAR DEM bare earth model. Vegetation and river models were subsequently added. Architectural models have not been included. (Courtesy of 7reasons Medien GmbH.)

layers in the 2D Geobrowser. Scholars can submit their own shapefiles to the MayaArch3D project to visualize them against the LiDAR data, or they can annotate existing shapefiles in the 2DGeobrowser. The system is accessible to researchers, cultural heritage managers, and the public at different access levels at <http://www.MayaArch3D.org> (for a log-in and password, please contact the first author of this paper.) Our vision is that archaeologists will be able to integrate and—if desired, publish—a set of their data into this 3D WebGIS system to analyze them with respect to the LiDAR and other published datasets. Therefore this system allows archaeologists to engage with their data in innovative ways that foster the development of new methods and interpretations. In particular, because this system can integrate 3D models of architecture linked to a database within a highly-accurate terrain model, it is now possible to engage in almost real-time 3D landscape archaeology on the web, something not previously possible in ArcGIS or other applications.

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