Detection Thresholds of Archaeological Features in Airborne Lidar Data from Central Yucatán

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LIDAR IN FOREST ENVIRONMENTS

The application of lidar technology in archaeology has gained momentum since the first successful projects demonstrated its utility for survey and mapping around the turn of the millennium (Barnes 2003; Bewley 2003; Bewley et al. 2005; Challis 2006; Crow et al. 2007; Crutchley 2006, 2010; Crutchley and Crow 2009; Devereux et al. 2005; Harmon et al. 2006; Holden et al. 2002; Shell and Roughley 2004). Moreover, since the groundbreaking application of lidar technology to tropical forest-shrouded archaeological remains in Belize by the Caracol project (A. Chase et al. 2010, 2012, 2013, 2014; D. Chase et al.

ABSTRACT

In this article we evaluate ~48km$^2$ of airborne lidar data collected at a target density of 15 laser shots/m in central Yucatán, Mexico. This area covers parts of the sites of Chichén Itzá and Yaxuná, a kilometer-wide transect between these two sites, and a transect along the first few kilometers of Sacbé 1 from Yaxuná to Cobá. The results of our ground validation and mapping demonstrate that not all sizable archaeological features can be detected in the lidar images due to: (1) the slightly rolling topography interspersed with 1-6 m-high bedrock hummocks, which morphologically mimic house mounds, further complicated by the presence of low foundations; (2) the complex forest structure in central Yucatán, which has particularly dense near-ground understory resulting in a high number of mixed-signal ground and low vegetation returns which reduces the fidelity and accuracy of the bare-earth digital elevation models; and (3) the predominance of low archaeological features difficult to discern from the textural noise of the near-ground vegetation. In this article we explore different visualization techniques to increase the identification of cultural features, but we conclude that, in this portion of the Maya region, lidar should be used as a complement to traditional on-the-ground survey techniques.

En este trabajo evaluamos datos de lidar recolectados en la parte central de Yucatán. Se mapeó un total de ~48km$^2$ en el mes de mayo 2014. El área mapeada cubre grandes porciones de los sitios de Yaxuná y Chichén Itzá además de un transecto de un kilómetro de ancho entre estos dos sitios y otro transecto a lo largo de los primeros cuatro kilómetros del Sacbé 1 de Yaxuná a Cobá. Los vuelos fueron llevados a cabo por un equipo del Centro Nacional de Mapeo Aéreo por Laser de la Universidad de Houston con una densidad de 15 pulsos de laser por metro cuadrado. Varios de los elementos grandes fueron verificados y confirmados en los sitios de Yaxuná y Chichén Itzá y se recorrió un transecto de 200 m de ancho entre los sitios de Yaxuná y Popolá (una distancia de cinco kilómetros) mapeando todos los elementos culturales. Los resultados de este trabajo demuestran que no todos los elementos de tamaño substancial se pueden identificar en las imágenes del lidar por tres razones principales. Primero, el centro de Yucatán está caracterizado por afloramientos de roca madre muy parecidos a montículos domésticos y a veces sirven como la base de pequeños cimientos. Segundo, la vegetación baja, resultado en gran parte de un sistema agrícola de roza y quema, presenta problemas para distinguir la superficie de la vegetación. Tercero, como muchas de las estructuras son plataformas relativamente bajas, es difícil identificar una gran parte del asentamiento en la región. En este trabajo exploramos varias técnicas de visualización de los datos de lidar, pero concluimos que, aunque esta tecnología cambia la manera en que los arqueólogos buscan y mapean sitios, no es sustituto de las técnicas tradicionales de recorrido y mapeo en esta parte de zona maya.
While research at Caracol (Belize) has demonstrated that lidar technology can be used to collect extremely informative data from high canopy (20–25 m) tropical forests (A. Chase et al. 2010, 2012, 2013, 2014; D. Chase et al. 2011; Weishampel et al. 2010, 2011, 2012, 2013), data from complex canopy environments and areas with dense, low vegetation common in the northern Maya lowlands are much more difficult to acquire and process in order to create bare-earth models. In these instances, there is less of a distinction between the true ground surface and vegetation, as the last returns of conventional discrete lidar data points are distributed throughout a vertical band of the lower understory rather than clustered at the bottom (see Doneus et al. 2008:883). Making matters more difficult, complex terrain with abrupt topographic changes (e.g., karstic collapse features) such as found in central Yucatán, can further complicate the discrimination of archaeological features. While some progress has been made in processing data from areas characterized by a dense understory and terrain with abrupt topographic changes using a progressive densification filtering algorithm (Axelsson 2000; Lasaponara et al. 2011), we have had great difficulty identifying many smaller-scale (< 1-m-high) features in our research area. Where challenging forest conditions can be anticipated, considerations for designing a lidar survey that maximizes canopy penetration probability should be taken into account (Fernandez-Diaz, Carter, et al. 2014; Fernandez-Diaz, Lee, et al. 2014).

Our analysis of lidar data collected in 2014 for a portion of central Yucatán, Mexico (Figure 1A and 1B) indicates that several factors dictate the ability to adequately apply lidar technology to archaeological research in distinct tropical forest landscapes. First, the type of vegetation can significantly complicate the detection of ground returns, which impacts the fidelity of the DEMs (digital elevation models) that can be produced. Fidelity refers to how well the DEMs represent the real world, and it is related but not necessarily determined by the DEM resolution and accuracy (See Fernandez-Diaz, Carter, et al. 2014). Tall tropical forest environments with high canopy (20–25 m) similar to the environment of Caracol are much more amenable to the use of airborne lidar than the lower, compact canopy environments found in central Yucatán (< 15 m). Secondary growth following swidden agriculture, as practiced in Yucatán, can further degrade the quality of lidar data (see Prüfer et al. 2015).

Second, the topography of the terrain can affect the ability to identify certain types of features (see Lasaponara et al. 2011; Lasaponara and Masini 2011). While larger structures in our research zone are easy to spot in lidar imagery, central Yucatán has a low, rolling topography with numerous small bedrock hummocks that tend to look like archaeological features, specifically house-mounds. This situation significantly complicates the use of lidar in this region to discriminate between cultural and natural features compared to many other areas of the Maya lowlands. This particular example serves as a general reminder that lidar provides only an indication of potential elevation anomalies, and additional information is generally needed to properly determine the origin of lidar features. Sometimes this information might come from the spatial arrangement of the features, but sometimes it needs to come from experienced observers on the ground.

Third, the shot density (laser shots fired per unit area) and return or point density (number of laser returns per unit area; a single laser shot can produce multiple returns), which have been used as the de facto figures of merit for lidar surveys, can be a deceptive metric in judging the usefulness of a lidar dataset for archaeological research. In areas with sparse vegetation, the return density is a good predictor of what can be identified in a lidar data product. For example, in low-resolution (5-m DEM) lidar flown by the Instituto Nacional de Estadística y Geografía (INEGI) in Quintana Roo, it is difficult to identify most features, given the coarse-grained coverage (Figure 2); only the large acropolis of El Ramonal (8 m tall and 40 m wide) is visible in the imagery, and buildings of up to 5 m in height in open areas are undetectable in the imagery. On the other extreme, high-density datasets like the case of Mayapan (> 40 returns/m²) can produce extremely high-fidelity products in areas with little or no vegetation (see Fernandez-Diaz, Carter, et al. 2014:Figure 10). However, for areas covered with complex canopies, where the ground return density cannot be accurately predicted based on the nominal laser shot density, the commonly used global density metrics or raster resolutions do not reflect the usefulness of a dataset for identifying archaeological features. Higher-order metrics, such as distribution functions of the spacing between ground returns and percentage of surface illuminated by the laser footprints, might be more appropriate (Fernandez-Diaz, Carter, et al. 2014).

Finally, the size and range of morphologies of archaeological features found in a specific area are important (see Risbel et al. 2013; Stul et al. 2012). For example, many of the domestic contexts found in central Yucatán are low-foundation brace structures that are not easily gleaned from the lidar data or are impossible to identify. More substantially sized patio groups, like those found in the southern lowlands, however, are much easier to identify. In this paper we discuss the data collected by a joint project between the Proyecto de Interacción Política del Centro de Yucatán (PIPCY) and the Instituto Nacional de Antropología e Historia (INAH) between the sites of Yaxúná and Chichén Itzá. While lidar technology has revolutionized the way we locate and map sites, our analysis demonstrates that particular attention must be made to local conditions (topography, vegetation,
FIGURE 1. Overview: (a) location of the Yucatan Peninsula in Mexico; (b) key sites of the Maya lowlands mentioned in the text. Also shown is a vegetation map simplified after Leopold (1950). Topographic data from Shuttle Radar Topography Mission (SRTM); (c) overview of the entire 2014 PIPCY-INAH lidar survey (hillshaded color Digital Elevation Model) with key locations shown.
and type of archaeological features, among others), which may significantly impact the ability to detect certain features.

PIPCY-INAH LIDAR DATA COLLECTION AND PROCESSING

The PIPCY-INAH lidar data were collected by the National Center for Airborne Laser Mapping (NCALM) in May of 2014 (Fernandez-Diaz, Carter, et al. 2014:9953). While this time of year is usually the height of the dry season, when the vegetation cover is at its lowest, 2014 was an exceptionally wet year for Yucatán, and the vegetation was considerably denser than in other years. Given the NCALM’s previous experience collecting data in Belize and Mayapán, we decided to collect data at a target density of 15 laser shots/m² (see Fernandez-Diaz, Carter, et al. 2014 for a discussion of data collection and post-production processing). A total of ~48 km² were collected around the large archaeological sites of Yaxúná (12 km²) and Chichén Itzá (18 km²) (Figure 1). A 1-km-wide transect was flown between these two sites (15 km²), which included the secondary site of Popolá, previously investigated by the PIPCY project (Johnson 2012). An additional 1-km-wide transect (3 km²) was conducted along the first few kilometers of Sacbé 1, a 100-km-long causeway connecting Yaxúná to the metropolis of Cobá to the east (Villa Rojas 1934).

Lidar and GPS reference data were collected during three flights that took place between May 19 and 21, 2014. The flight plan consisted of 65 flight lines flown at 500 m above the ground level; the swath of adjacent lines overlap by 50 percent. The collection was performed with an Optech Gemini, which can record up to four discrete returns per laser shot (first, second, third, and last). The system range resolution is about 2 m, which implies that the sensor will not be able to detect distinct returns from objects that are separated by less than this distance along the trajectory of the laser pulse. The sensor was configured with a pulse repetition frequency (PRF) of 125 kHz and a beam divergence of .8 milliradians, which yielded a laser footprint diameter of .4 m from the nominal flight altitude. The scanner was operated at ± 14° and 45 Hz. The combination of all of these parameters yields a nominal shot density of 15 shots/m², which, if distributed uniformly, would yield an 18 percent surface illumination.

For ease of data processing, an orthogonal grid of 1-km-x-1-km bins (tiles) was overlaid over the project area. A total of 83 tiles cover the irregular project area (Figure 1). In aggregate, these tiles contain data from 655.3 million laser shots, which yielded 901.9 million returns (1.38 returns/shot). The returns on the tiles were classified as being ground or non-ground returns using the “classify ground” algorithm in Terrasolid’s Terrascan software and conservative filter parameters. A detailed description on how the algorithm works can be found in Fernandez-Diaz, Carter, et al. (2014:9980–9983). However, in very general terms, the algorithm divides returns as being produced by the ground or not by the ground. This latter class includes building, vegetation, and other non-ground structures. The algorithm will likely classify a group of returns that align in space in a vertical direction as being non-ground, and as such will eliminate structures with vertical elements from the ground surface (see below for a discussion of the accidental removal of archaeological features). Each tile was processed individually but returns within a 10-m buffer around the tile were considered. A total of 92.7 million returns were classified as coming from the ground surface; this represents about 10.3 percent of the returns or 14.2 percent of the laser shots. The first ground returns of each tile were interpolated using the kriging algorithm into 1-m resolution digital surface models (DSM) and 50-cm resolution DEMs respectively. Kriging was selected over other interpolation methods (i.e., nearest neighbor, inverse distance weighting) because of its robustness interpolating sparse datasets and its trend in recognizing characteristics (Fernandez-Diaz, Carter, et al. 2014). Finally, the individual DSM and DEM tiles were joined into larger area rasters and stored in an ArcGIS format.
Assessing the Quality of Bare-Earth DEMs

The lidar data contain several visible milpas (swidden agricultural fields) that were largely free of vegetation at the time of the lidar survey and allow a particularly useful means of qualitatively assessing the true elevation and texture of the bare-earth returns in this landscape, allowing us to estimate the extent of noise that low vegetation introduces into the processed bare-earth DEM (produced by interpolation from lidar points classified as ground). These milpas, cleared from the forest in polygonal areas that cut all existing vegetation from the hummocky landscape, garner excellent ground returns in contrast to the surrounding landscape, and as such are “windows” into the true bare-earth topography (Figure 3). In our processed bare-earth DEM, the cleared milpas are readily visible as apparently lower-elevation polygons with considerably smoother ground texture than their surroundings. Examining profiles across these cleared milpa boundaries indicates that most of the 1-m amplitude, 1–4-m wavelength pockmark texture, which predominates the processed bare-earth data, is in fact mixed ground-vegetation signal returns generated by dense vegetation within 1 m of the ground surface (see discussion on range resolution above). These profiles illustrate that only a small percentage of points

FIGURE 3. Testing a bare-earth DEM: (a) 2013 aerial image of a milpa (field) cleared at the time of lidar survey (Google Earth image); (b) “bare-earth” hillshade of the same extent as (a) derived from 2014 lidar data. Note the readily identifiable margins of the milpas, the apparent lower elevation of the milpas, and the difference in topographic texture within the milpa (smooth) compared to outside of it (noisy). This is clear evidence for near-ground vegetation (~1-m height) capturing a high percentage of last returns and thus obscuring the true ground surface with vegetative noise. (c) Slightly oblique view of similar extent as (a) and (b) showing the point cloud classified as last (ideally ground) returns (yellow points on blue background). Notice the significantly higher density of points within the milpas contrasted to regions with dense forest cover. (d) Photograph of a cleared milpa illustrating the true ground texture with bedrock hummocks, the dense vegetation that coats regenerating milpas, and a cross sectional view through forest typical of this area. (e) Profile view through the ground-classed point cloud (white) shown in (c). Region sampled is shown as a box in (b). Note the high accuracy of ground-classed points within the milpa and the relative lack of true ground returns from regions with forest cover. The result is a 1–2-m vegetative noise prevalent throughout the derivative lidar imagery.
classified as ground using default parameters are actually pure ground returns. Another hint that near-ground vegetation noise is prevalent is the visual clarity and apparent lower elevation of trails through the forest. These trails are physically at the same elevation as the ground surrounding them, so the height difference (and contrasting point density) can again be attributed to vegetation within about 1 m of the ground surface prevalent throughout the forest. As pointed out above, this vegetation noise is at or above the height of many of the archaeological structures observed in the field, indicating that these structures will not be seen in the data without further processing.

Further classifying and processing the point-cloud data to target this vegetative roughness (i.e., removing a greater percentage of near-surface vegetation by increasing tolerance of ground classified points compared to default) might result in a considerably lower-resolution DEM (perhaps 1- or 2-m raster cell versus .5 m cell), but with improved vertical accuracy of the ground surface. Such processing could be useful to delineate larger archaeological structures with low heights (≤1 m) above the surrounding landscape (e.g., Hare et al. 2014). While the tendency is to produce one bare-earth DEM at the maximum obtainable resolution, this is an instance where working with processed DEMs of differing resolutions (i.e., different thresholds of vegetation-ground classification) could yield the most complete detection of archaeological structures. This merits further study, but it is outside the scope of this paper.

A Cautionary Example of Ground Classification Algorithms

We noticed an issue with the first round of data processing that bears discussion. At Chichén Itzá, at least eight important monumental structures (the Osario, the Akab Dzib, the Iglesia, the Eagles and Jaguars Platform, the North Temple at the main ball court, the Temple of the Large Tables, the Red House, and most of the Initial Series buildings) were missing from the first bare-earth DEM generated from processing the point-cloud data using standard ground classification algorithms (Figure 4). After identifying this issue, we examined the Yaxuná DEM hillshade again and found that the historic hacienda of Cetelac had also been eliminated. In these cases, we were able to identify a problem, as we already knew the location of these prominent features. This experience, however, serves as a cautionary tale that we must be careful with determining the types of algorithms, level of processing, and kind of data products that are required for archaeological research (Fernandez et al. 2014; Hare et al. 2014).

As described above, DEMs are supposed to model the natural terrain and are created by interpolating returns classified as coming from the ground; returns that align in the vertical direction will be assumed as coming from vegetation, buildings, and other structures and thus won’t be included in the ground class or used in the creation of the DEM. While using these ground classification algorithms is common practice in archaeology and beyond (e.g., geological applications, Langridge et al. 2014), their use for archaeological research requires additional attention and processing to avoid the removal of relevant structures. In Mesoamerica, certain archaeological features such as unconstructed structures or residential mounds will have vertical profiles that are similar to small natural hills, and their returns will most likely be classified as coming from ground. Many of the structures at Chichén Itzá that were not included on the DEM were consolidated by archaeologists and in many ways resemble modern construction with straight vertical walls; and thus their returns are classified as non-ground and not considered in the generation of the DEM.

Based on our experiences, we suggest that standard procedure in archaeological studies should include additional processing steps and algorithms so that potentially important structures are incorporated into the DEMs. Among the additional work, we suggest the generation of minimum elevation rasters, additional classification that will further discriminate the non-ground returns into buildings and vegetation classes such that an enhanced DEM can be generated using the ground and building classified return. If there is good reason to remove modern construction, we suggest that it be done manually. In most cases, modern construction is easily identifiable in readily available aerial photography (including Google Earth). It is imperative for archaeologists to establish close collaboration with the provider of lidar data while the data products are being generated (as important during planning the lidar collection). Finally, it is important to keep in mind that lidar data products are fluid—there is no final DEM or point-cloud classification; point-cloud data can be reclassified and multiple iterations of data products can and should be generated.

Visualization of Lidar Data

Once data quality and filtering considerations were addressed, we experimented with a variety of visualization techniques to maximize our ability to detect archaeological features in the lidar data (original bare-earth DEM), summarized briefly in Figure 5. Visualization of lidar-derived data is a prolific area of research with strategies tailored to the features being targeted and the type of terrain in which they occur. Useful comparisons of visualization techniques are provided by Pingel et al. (2015), Bennett et al. (2012), Stular et al. (2012), and Hesse (2010), among others. For our study area, a very helpful way of visualizing the generally flat topography (but also with karst collapse features and bedrock hummocks) was to create a custom-classed color DEM. Based on field observations, we classified elevations into categories that help summarize the landscape; elevations that uniquely must be attributed to cenotes (karstic collapse features, which intersect the water table) were classed red; rejolladas (karstic collapse features above the water table) were classed orange; the average elevations of the generally flat terrain were classed yellow and green; elevations typical of rises and hummocks were classed blue; and elevations of heights necessitating human landscape manipulation (higher than natural features) were classed purple. We layered this custom-classed color DEM with a NW-illuminated hillshade, which proved to be one of the most useful pieces of imagery we produced, with many of the larger features readily identifiable (most archaeological features in the Maya region are aligned a few degrees east of north). Similarly, customizing a colored map of slope (where most natural features have moderate-to-low slopes and anthropogenic features often have steeper slopes) can be a useful technique. Slope aspect maps were found to be particularly useful for identifying linear features, such as causeways, but is comparatively poor at detecting structures. Contours were
not very helpful because of the complex micro-topography and prevalent vegetative noise.

Sky-View Factor analysis (SVF), which analyzes the proportion of the sky visible at a given location overlain with a color DEM is one of the most useful techniques we employed for archaeological interpretation (e.g., Kokalj et al. 2011; Zaksek et al. 2011). SVF is particularly adept at identifying corners and steeper anomalies, both of which tend towards human-made structures in the landscape. We did not find Local Relief Modeling (LRF, e.g., Hesse 2010), a technique that reduces macro-topography effects while retaining micro-topography, to be a useful technique, given the already subdued macro-topography of the study area and vegetative noise dominating the micro-topographic data.

FIGURE 4. Cautions with Ground Classification Algorithms. Overview of the core of Chichén Itzá showing the many important ancient stone structures removed by a standard ground classification algorithm presently employed in most archaeological applications of lidar. We suggest standard practice should be to avoid ground classification algorithms for archaeological studies.
Detection Thresholds of Archaeological Features in Airborne Lidar Data (cont.)

FIGURE 5. Lidar visualization techniques. (a) A standard black-and-white hillshade with NW illumination. (b) Contours can sometimes pick up sharp corners but are largely ineffective due to abundant mounds and depressions, and ~1-m amplitude vegetative noise. (c) A finely tuned slope map can reveal steep-sloped features, many of which are human made. (d) Slope aspect direction can be a very useful technique for delineating linear features. It also best highlights the vegetative noise. (e) A fine-tuned hillshaded color DEM is a useful technique that simultaneously provides ground texture and elevation information. (f) Sky-View Factor (SVF), which images the proportion of the sky visible at a given location, overlain with a color DEM is one of the most useful techniques we employed for archaeological interpretation. (g) Colored SVF image. (h) Another technique that was trialed with some success was an algorithm utilizing a 15-m-wide moving window determining maximum height anomaly.
TABLE 1. Number of residential platforms and isolated structures (non-monumental architecture > 5 x 5 m) mapped by PIPCY, number and percentage of residential platforms and isolated structures identified in the lidar imagery, false positives structures identified in the lidar imagery, their location (see Figure 1) and type of settlement in the Yaxuná-Popola-Tzacauil area.

<table>
<thead>
<tr>
<th>Location</th>
<th>Area (km²)</th>
<th>Type of settlement</th>
<th>Number of mapped residential structures</th>
<th>Number of identifiable structures in lidar</th>
<th>Percent of identifiable structures in lidar</th>
<th>Number of false positives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yaxuná (Selz map)</td>
<td>1.0</td>
<td>Central part of major site</td>
<td>122</td>
<td>53</td>
<td>41</td>
<td>5</td>
</tr>
<tr>
<td>Yaxuná Sacbe 1 transect</td>
<td>0.32</td>
<td>Major site</td>
<td>46</td>
<td>13</td>
<td>28</td>
<td>5</td>
</tr>
<tr>
<td>Joya²</td>
<td>0.25</td>
<td>Secondary site</td>
<td>44</td>
<td>10</td>
<td>23</td>
<td>4</td>
</tr>
<tr>
<td>Tzacauil</td>
<td>0.10</td>
<td>Secondary site</td>
<td>13</td>
<td>3</td>
<td>23</td>
<td>6</td>
</tr>
<tr>
<td>Xauil</td>
<td>0.10</td>
<td>Tertiary site</td>
<td>10</td>
<td>2</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>Popola</td>
<td>0.45</td>
<td>Secondary site</td>
<td>46</td>
<td>11</td>
<td>24</td>
<td>6</td>
</tr>
<tr>
<td>Yaxuná-Popola transect4</td>
<td>0.20</td>
<td>N edge of major site (Yaxuná)</td>
<td>28</td>
<td>7</td>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>Yaxuná-Popola transect</td>
<td>0.60</td>
<td>Rural hinterland</td>
<td>6</td>
<td>2</td>
<td>33</td>
<td>7</td>
</tr>
<tr>
<td>Total</td>
<td>3.02</td>
<td>Urban to rural</td>
<td>315</td>
<td>101</td>
<td>32</td>
<td>41</td>
</tr>
</tbody>
</table>

1. The numbers in this column only include residential platforms or isolated structures (> 5 x 5 m) and exclude all monumental architecture which is clearly identifiable in the lidar imagery.

2. The area examined includes only a portion of the site of Joya.

3. Tzacauil is considered a secondary site because of the massive acropolis with a triadic group on top, but the residential settlement is extremely small and characteristic of a tertiary site. We did not include this large triadic group in our count, since it is clearly identifiable on lidar.

4. Three of the identifiable structures in this area were located in a milpa cleared of vegetation, thus with much higher visibility.

Another technique that was trialed with some success was our original algorithm implemented in the mathematical software Matlab. The algorithm utilizes a variable size moving-window to determine the height difference between the actual elevation at the center of the window and a computed elevation, which is derived by fitting a plane using the terrain elevations at the window’s edges. The algorithm considers the edges of the window as natural terrain and, by computing the elevation difference, assesses whether the center of the window has an “anomalous” elevation with respect to natural terrain at the edges. The algorithm computes the height anomalies considering edges in the north-south, east-west, and diagonal directions and reports the maximum height anomaly value obtained for each DEM cell. We found that although this method loses some resolution, it does sharpen the edges of structures (Figure 5h).

The main conclusion we reached through our visualization efforts is that no single visualization technique is best for archaeological interpretation, which seems to be a prevailing theme in recent literature (see also Bennett et al. 2012; Hare et al. 2014; Štular et al. 2012). Each visualization method has something to contribute, and the best interpretation comes from utilizing a wide range of techniques.

RESULTS

In this section, we present some examples of the difficulty of finding non-monumental archaeological features in central Yucatán, as we evaluated the lidar results with comparisons to previously mapped areas and with ground-truthing of one transect. While the limitations of lidar in detecting archaeological features are quite apparent for low-density rural areas, often characterized by small low-lying residential units, we had difficulty locating in the data even some sizable Late-Terminal Classic (A.D. 600–900) communities with political importance. Our results indicate that, while the implementation of lidar technology has marked a tremendous shift in Maya archaeology, making it possible to accomplish in a short amount of time what used to take decades to survey and map (Chase et al. 2010), our enthusiasm must be curbed by the fact that in many areas of the Maya lowlands current lidar technology is not a complete substitute for traditional pedestrian survey techniques. We find that 60 to 80 percent of existing archaeological structures in our targeted areas in central Yucatán are invisible in our data (Table 1; see specific examples below), highlighting the need to use lidar as a complement to traditional survey methods.

In Table 1, we calculated the number of residential platforms and isolated structures that we could identify in the lidar imagery for areas mapped by PIPCY from 2007 to 2015. While counting structures, we included only residential platforms or isolated platforms larger than 5 x 5 m (25 m²), but not pyramids or any monumental architecture (only present at Yaxuná or Tzacauil), which are clearly visible in the lidar imagery. We excluded structures smaller than 5 x 5 m, since these are generally low foundation braces and thus almost impossible to detect in the lidar imagery. Three of the authors, none of whom were involved in the on-the-ground mapping of archaeological features, set out to identify structures on the lidar imagery. The results on
Table 1 are an average of three separate exercises of identifying structures in the lidar imagery by three co-authors. While analyzing the results of the combined exercise, several things became clear: (1) each researcher had a tendency to under-identify (generate a low number of correctly identified structures as well as low numbers of false positives) or to over-identify structures (generate a high number of correctly identified structures as well as high numbers of false positives), indicating a personal bias; (2) in a larger site like Yaxuná, all three researchers had a propensity to identify features that look like structures because structures are part of logical configurational arrangements and because of known higher settlement density (hence the higher percentage of identifiable structures—41 percent); (3) in low settlement areas, there was a tendency to over-identify false positives (in the rural hinterland of the Yaxuná-Popola transect, at Tzacauil, and at X-auil).

Residential Structures at Yaxuná

Yaxuná, a large site with monumental architecture, was occupied from the beginning of the Middle Formative (ca. 1000 B.C.) to the middle of the Terminal Classic (ca. A.D. 900/1000) (Stanton et al. 2010) (Figure 5). A rough sketch map of the site was produced by O’Neil (1933; see Brainerd 1958) in the first half of the twentieth century. During the 1980s, the site center was systematically mapped with a transit by David Freidel’s project (Freidel et al. 1990). Beginning in 2007, the PIPCY project has re-mapped several areas of the site center with a total station and produced Maler-style drawings of many of the architectural groups mapped in the 1980s. Further, other sites in the region, including several included in the lidar survey such as Joya, Popolá, and Tzacauil (see Hutson et al. 2012; Johnson 2012), have been mapped with a total station using standard block survey methods for Yucatán (see below). Pace and compass, instead of a total station, was used in areas of lower residential density.

While large structures such as temples and causeways are quite apparent in the Yaxuná hillshaded color DEM (including two previously unmapped large architectural groups and a sacbé—a raised causeway), it is noticeable that the landscape is covered in low rises (Figure 5). At first glance, these rises may appear to be structures to Maya archaeologists working in other areas. Indeed, many of the rises, especially towards the center of the site, are either structures or natural bedrock outcrops that support structures or foundation braces invisible in the lidar imagery. Yet the rises present a substantial methodological problem for working with lidar data in this area of the Maya lowlands. The entire region is covered in small bedrock hummocks that appear at first glance to be housemounds. These natural rises were preferred by the Maya to situate their domestic life. Thus, many, but not all, of the rises towards the center of the site have evidence of human occupation. Excavations have revealed that many of the large platforms and temples clearly visible in the lidar data were built on rises to take advantage of their volume. In other cases, however, the rises have only small foundations that supported perishable wattle and daub structures that are completely invisible in the lidar. The percentage of rises associated with structural remains drops off gradually away from the site center, and by 2 km out to the east, where we conducted a systematic survey in 2007 and 2008 (Hutson et al. 2012), there is a complete break in the settlement.

To demonstrate what we can and cannot see in the lidar data, we have chosen an area just to the west of the monumental architecture in the site center (Figure 6). This is an area with fairly dense residential remains, but which was covered with low scrubby vegetation, the most challenging vegetation for lidar
Detection Thresholds of Archaeological Features in Airborne Lidar Data (cont.)

detection, at the time of the flights. While some of the structures are visible in the hillshaded DEM, others are clearly not (Figure 6). Several points can be made. First, it is clear that all of the low foundation braces (<1 m in height), by far the majority of the archaeological features identified in the area, are completely undetectable in the hillshade. Even this close to the site center, the majority of domestic settlement is not detectable in the lidar data. Second, the structures that are visible in the hillshade are larger platforms, over 2 m in height, with straight walls and sharp corners (Figure 6). Thus, the portion of Yaxuná shown in Figure 6 shows an area with an extremely low detection rate of archaeological features because of the low scrubby vegetation and the presence of extensive bedrock rise. In the rest of Yaxuná, the detection rate of archaeological features is higher. As has been noted elsewhere (e.g., Hesse 2010; Johnson and Ouimet 2014), linear features such as walls, ditches, and terraces show up better in hillshade imagery. Thus, broader rectangular platforms have a tendency to show up better. More extensive rectangular platforms have a greater chance of being detected in hillshade imagery, regardless of their height, due to the fact that they have a greater degree of “linearity,” or, perhaps more aptly, “rectangularity,” to them. Therefore, when examining the hillshades, we have been sensitized to look for linear features and corners that may be indicative of human construction. The highest percentage of identifiable structures in our lidar imagery (41 percent) at Yaxuná is indeed the result of the presence of larger and taller platforms, with clear corners, square or rectangular shapes, and often with placements in clear configurational arrangements (Table 1).

Residential Structures at Chichén Itzá

Chichén Itzá was one of the largest cities in Mesoamerica at the end of the Classic period and was first systematically researched by the Carnegie Institution of Washington in the early part of the twentieth century. This project produced a map still utilized in great part by the field today (Tozzer 1957). Further total station mapping and ground reconnaissance has been conducted by Cobos (2003) of the Universidad Autónoma de Yucatán and INAH (e.g., González de la Mata et al. 2006) in and around the site. Primarily dating to the Terminal Classic and transition to the Postclassic (A.D. 850–1100), Chichén Itzá represented an incredible opportunity to test the lidar data, given the range of archaeological features known at the site.

As with the Yaxuná lidar data, the monumental architecture at Chichén Itzá is quite apparent (Figure 4). We were also able to identify unregistered structures throughout Chichén Itzá. For example, we identified a series of structures to the east of the Casa Redonda that, although near the modern highway, had escaped notice until now (Figure 7). Yet the same problems discussed for the analysis of the Yaxuná data were also encountered at the Itzáe capital. An area just to the north of the Great Terrace and west of the Sacred Cenote had been surveyed using standard block techniques just weeks prior to the lidar flight. In fact, the hillshade of this central area of the site shows that the gridded brechas (paths) cut through the vegetation as archaeologists combed this zone for cultural remains (Figure 8). The area was characterized by the same bedrock hummocks as found at Yaxuná, clearly seen in the lidar data. Cultural remains, including ceramic scatters and wall lines, were located on these hummocks during the survey, yet none of them clearly look like part of a human landscape in the lidar data, again showing the importance of using lidar as a complement to traditional survey and mapping techniques in central Yucatán. As mentioned above, however, in an area a bit further to the east of the site center numerous, previously unknown structures were detected in the lidar (Figure 7). This area is around the Casa Redonda at the...
the edge of the current registry map. To the east of the Casa Redonda, there are clearly defined platforms. To the west, we see two less-defined platforms, but still visible in the image. Two of these platforms were excavated during a salvage project in 2015 and revealed well-constructed stone architecture, although without complete vaults.

The Case of Popolá

We examined the secondary site of Popolá, located 5 km north of Yaxuná. Popolá does not have large architecture, although it has been considered an important secondary site during the Late and Terminal Classic (A.D. 700–900) periods, given the presence of carved panels (Greene 1986; Freidel 2007; Johnson 2012; Magnoni et al. 2014). The majority of the site is covered in a young forest with a complex canopy. The area of the ruins had been used for patchy swidden agriculture until about 20 years prior to the lidar flights, and the vegetation has recuperated substantially. Nonetheless, the canopy was fairly complex and not as high as areas around other sites such as Tzacauil, to the east of Yaxuná. Popolá was completely mapped with a total station by Johnson (2012) a few years prior to the lidar survey, using standard block survey techniques. We calculate that most, if not all, masonry structures and foundation braces were found within the blocks.

A quick cursory look at the lidar imagery for Popolá does not reveal any obvious buildings (Figure 9a). Much like at Yaxuná and Chichén Itzá, the bedrock hummocks dispersed across the landscape and the vegetative noise obfuscate our view of the structures at the site. It is difficult to distinguish with great confidence structures from natural rises. Overlying the total station map informs us which hummocks were utilized to support low platforms and foundation braces that served to stabilize the walls of structures made of perishable materials (Figure 9b). As is apparent comparing the two images, numerous rises in the landscape were not used for construction, but, as discussed for Yaxuná, there was a tendency for the ancient Maya to situate structures on high ground. The results of Table 1 show that we were able to correctly identify in the lidar imagery only 24 percent of the structures.

A closer look at the images demonstrates that several natural rock outcrops at Popolá have what appear to be sharp corners indicative of habitation platforms (Figure 9). These are natural features checked on the ground during Johnson’s survey. Further, several of the structures do not exhibit straight lines or sharp corners. In part, this is due to bioturbation, specifically tree roots that have ripped the walls of the platforms apart, leaving piles of rubble. Yet, in many cases, this is also due to the fact that the Maya utilized existing outcrops in the architecture. For example, Str. N10E10-1, the platform associated with carved panels to the far north of the site, has a rectangular shape. Yet it is barely identifiable in the hillshaded DEM. The northern part of the platform is quite low and almost blends into the outcrop on which it is situated. By changing the illumination azimuth of the hillshade and using SVF imagery, we can identify a feature worth checking in the field. Since we can detect only a quarter of the structures on the lidar imagery, the only manner in which we could identify Popolá as an important site would be to ground-truth all elevation anomalies in the area.

The Yaxuná-Popolá & Yaxuná-Joya-Tzacauil-X-aul Transsects

The next two areas we will discuss briefly are areas of lower occupational density and generally smaller structures. The
Yaxuná-Popolá transect (.2 km x 4 km) is very sparsely populated. This transect was mapped after the lidar data was collected. Jessica Wheeler fully surveyed the .2-km wide, 4-km long transect from Yaxuná to Popola, ground-truthing the DEM and mapping all archaeological features with tape and compass (given the small size and scarcity of features, no total station was used to map along this transect). Heading away from the northern part of Yaxuná (the first kilometer or so still includes large residential platforms that belong to Yaxuná), it crosses rural areas with few isolated residential groups or small isolated foundation braces, before reaching Popolá 4 km to the northeast. In the rural portion of the transect, the majority of structures mapped on the ground were semi-circular or quadrangular foundation braces elevated less than 50 cm from ground level. These features are often difficult to distinguish even at ground level by trained archaeologists, so it is no surprise that they hardly show up in the lidar imagery. In Table 1, the relatively high detection rate (33 percent) for the rural hinterland portion of the Yaxuná Popola transect is due to the fact that only six large platforms were included in the count, since the majority of structures were smaller than 25 m$^2$ (and completely undetected in lidar imagery). In this area, we also had the largest amount of false positives (7), more than the actual number of structures included in the count (6).

The transect mapped from Yaxuná heading east to the Tzcauail Acropolis and past it to X-auii goes through two secondary sites (Joya and Tzcauail) and a tertiary site (X-auii). This area was mapped with total station, pace, and compass in 2007. At these sites where the residential structures are small and low-lying, the detection was low, ranging from 20 to 23 percent (Table 1). As this transect continues west into Yaxuná in the less dense areas of the urban settlement, the detection rate goes up to 28 percent.

**FINAL COMMENTS**

In this article, we have discussed the challenges of using lidar data in central Yucatán, Mexico, particularly as local conditions such as underlying topographic features, vegetation types, and archaeological features can negatively impact the detection thresholds. In our area, only 20–41 percent of non-monumental structures can be identified in the lidar imagery. There is no doubt that lidar is a tremendous tool for archaeologists. We can locate and map sites at a rate unparalleled in the field's history. The data are georeferenced and easily managed in GIS software to help us understand the spatial distribution of human activity across landscapes. In sum, lidar represents a giant step forward for Willey’s (1953) vision of settlement patterns in archaeology. Yet it is clear that lidar technology does not pick up all ground features, since it samples—but does not continuously map—the surface. Thus, under vegetation, lidar can detect only significant elevation anomalies (in open areas, lidar intensity could also be used to visualize differences in textures and materials to aid in the identification of structures). For instance, with low-lying platforms (< 1 m above natural terrain), we could have some returns from the top of the platforms, but unless we have returns on the platforms edges, when the DEM is generated, the gridding algorithm will most likely smooth or fill in the edges. Without a clearly recognizable edge, we are not able to identify the platform, even though lidar detected the correct elevation of the feature. Lidar’s utility to identify height anomalies is dependent upon the density and system configuration of lidar data collected (directly correlated to its cost), as well as local conditions including the range or morphologies of archaeological remains (including preservation and surface visibility; deeply buried sites such as Cerén would not be visible, for example), vegetation...
cover (which could include seasonal variations), and underlying topography. Central Yucatán, with low, rolling topography with numerous small bedrock hummocks, presents a challenge for the identification of residential structures which tend to be located on the natural bedrock outcrops. Where these challenges can be anticipated, the most effective strategy to ensure that a high-resolution bare-earth DEM can be produced is designing an airborne lidar survey with system parameters that maximize the probability of canopy penetration and utilizing double or triple overlap of survey swaths (e.g., Fernandez-Diaz, Lee, et al. 2014; Langridge et al. 2014; Lin et al. 2013; Zielke et al. 2015). There is a limit to what can be accomplished through post-processing and manipulation of low-quality data as we present, which demands careful planning and acquisition.

Another important lesson learned in our study and already mentioned in other studies (e.g., Bennett et al. 2012; Hare et al. 2014; Štular et al. 2012) is that there is no single visualization technique that is best for archaeological interpretation. Since each visualization method has something to contribute, it is best to utilize a wide range of techniques. Moreover, we have also highlighted the challenges of the removal of modern buildings or reconstructed/consolidated ancient architecture when using standard ground classification algorithms, which isolates returns coming from features with tall vertical walls. Our experience—where several prominent pre Columbian features at Chichén Itzá and one historic site in Yaxuná were eliminated from the DEM—serves as a cautionary tale that additional processing steps beyond the standard processing must be taken to ensure that all potentially useful data are considered during the DEM generation. We suggest that modern construction should be manually removed from the dataset to avoid the loss of pertinent archaeological through the close collaboration of archaeologist and the provider of lidar data.

The ~48 km² of lidar that was flown by the PIPCY/INAH project in central Yucatán was able to pick up only large and taller > 1-m structures with a well-defined square/rectangular shape in the centers of Yaxuná, Chichén Itzá, Popolá, Joya, Tzacaual, and X-aul. As Table 1 clearly illustrates, our detection rate ranges from a low 20 percent in less dense settlement to a high 41 percent in the central part of Yaxuná. Given the “linearity” or “rectangularity” of causeways and broader platforms, we were able to clearly identify some of these features at Yaxuná and Chichén Itzá without great need for ground reconnaissance. Yet even near the centers of both these large cities, there were numerous smaller structures that were not as clear in the lidar imagery and would have been missed if interpreted solely from the lidar imagery. Further, while we know that there is substantial rural occupation between Yaxuná and Chichén Itzá, we were not able to clearly recognize most structures in rural areas, including a substantial secondary site like Popolá. We were able to identify some areas that are worthwhile to check on the ground, but even many of the known structures did not appear as promising in the lidar data. This is extremely worrisome, as a reliance on lidar mapping without a program of ground reconnaissance would lead to the complete omission of rural settlements in central Yucatán, quite the opposite of the empty ceremonial center model utilized by earlier generations of archaeologists (e.g., Thompson 1954). Yet, like such outdated archaeological practice in the Maya area, it would also lead to a myopic focus on the big elite architecture (see Chase et al. 2011:387), undoing the advances in settlement research over the past 50 to 60 years. We argue that lidar is an invaluable tool, but one that cannot be used in isolation. It is a tool that complements traditional techniques of ground reconnaissance, survey, and mapping in places like the northern Maya lowlands, but by no means replaces them (cf. Doneus et al. 2008).

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Data Availability Statement
The lidar data used in this study are permanently stored at the Eastern Information Center (EIC) at the University of California Riverside. Access to these data (accession number EIC2016-TS01) can be arranged by contacting Dr. Matthew Hall (EIC Coordinator), Eastern Information Center, University of California Riverside, 900 University Ave., Riverside, CA 92521, 951-827-5745; matthew.hall@ucr.edu.

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NOTES

1. By averaging the results of the three separate exercises, we hope to have taken out the personal biases.

2. Maler is a set of drawing conventions used to represent architectural features, with particular emphasis on representing the height, length, and width of architectural features. This style of drawing is commonly used in the maps of prehispanic Maya sites.
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