Progression and Issues in the Mesoamerican Geospatial Revolution

An Introduction

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Mesoamerican archaeology has a long history of conducting research on the spatial patterning that can be derived from Maya settlements. For almost 100 years, the majority of this research involved using a transit or alidade to map the visible structures that could be seen in a Maya site. Because of the time that was needed to undertake this exercise and the relative lack of interest in

ABSTRACT

The use of airborne mapping lidar (Light Detection and Ranging), a.k.a airborne laser scanning (ALS), has had a major impact on archaeological research being carried out in Mesoamerica. Since being introduced in 2009, mapping lidar has revolutionized the spatial parameters of Mesoamerican, and especially Maya, archaeology by permitting the recovery of a complete landscape and settlement pattern for further analysis. However, like any new technology, there are learning curves to be overcome, resulting in a feedback relationship between the on-the-ground archaeologists, the virtually grounded computer analysts, and the instrument designers. Archaeologists have been able to identify problems and issues with data production and visualization for the determination of archaeological remains caused by vegetation, special terrain conditions, and modern disturbance. The identification of these concerns helps the technician to develop new techniques, especially when working in conjunction with the field researcher. As seen through the papers in this volume, this symbiotic relationship promises to yield both new breakthroughs in landscape and settlement analysis for Mesoamerican archaeology and enhanced analytic and visualization techniques for lidar with the potential for applicability in other contexts. In many regards, the development of lidar has parallels to the development of radiocarbon dating as a revolutionary technology.

El uso de lidar de mapeo aéreo-trasportado ha tenido un impacto muy significativo en la investigación arqueológica que se lleva a cabo en Mesoamérica. Desde su introducción a la practica en el 2009, el lidar de mapeo ha revolucionado los parámetros espaciales de la arqueología Mesoamericana, en especial la de los Mayas, permitiendo capturar completamente la topografía y los patrones de asentamiento para análisis posteriores. Sin embargo, como con cualquier otra tecnología, hay curvas de aprendizaje que tiene que superarse, lo que resulta en una relación de retroalimentación entre los arqueólogos en el campo y los analistas y técnicos informáticos en el campo virtual, así como también con los diseñadores de instrumentos. Los arqueólogos han sido capaces de identificar problemas en la producción y visualización de los datos para la identificación de remanentes arqueológicos, problemas que son causados por la vegetación, condiciones particulares del terreno y perturbaciones modernas. La identificación de estos aspectos ayudan a los técnicos a desarrollar nuevas técnicas, en especial cuando se trabaja en conjunción con el investigador de campo. Como se verá en los artículos publicados en este volumen, esta relación simbiótica promete producir nuevos desarrollos en el análisis de los asentamientos y la topografía aplicado a la arqueología mesoamericana así como también desarrollos de técnicas mejoradas para el análisis y la visualización de datos de lidar con potencial para ser aplicados en otros contextos. En múltiples maneras, la evolución del lidar tiene muchos paralelos con la evolución del fechado por radiocarbono como una tecnología revolucionaria.

Advances in Archaeological Practice 4(3), 2016, pp. 219–231

DOI: 10.7183/2326-3768.4.3.219

non-elite residential architecture until the 1950s, usually only the larger architecture in the centers of sites was ever recorded, and few researchers took the time to undertake topographic mapping of the landscape upon which a Maya site was situated. Until the publication of the Tikal, Guatemala, map in 1961 (Carr and Hazard 1961), most large central architecture in a Maya site was not fully conjoined with the surrounding residential architecture. The Tikal map covered the central 16 km^2 of the site and was later augmented by cardinal-direction transit mapping to look for settlement fall-off that added an additional 7 km^2 to the map (Puleston 1983), but the full extent of Tikal has yet to be defined—although it is suspected to be bounded by a system of walls (Webster et al. 2007). Since the central Tikal site plan was completed, other large-scale mapping has been accomplished at Calakmul (30 km^2; Folan et al. 2001), Caracol (23 km^2; A. Chase and D. Chase 2001), and a series of sites in the northern lowlands (e.g., Hutson et al. 2008 for Chunchucmil; Stuart 1979 for Dzibilchaltun). The northern lowlands have also been covered by aerial survey (Garza Tarazona de Gonzalez and Kurjack 1980), which provides detailed visualizations for areas not covered by foliage.

Lidar has significantly moved the field of Mesoamerican archaeology forward by finally providing information on the scale and organization of Maya sites (A. Chase, D. Chase, Awe, Weishampel, Iannone, Moyes, Yaeger, and Brown 2014; A. Chase, D. Chase, Awe, Weishampel, Iannone, Moyes, Yaeger, Brown, et al. 2014). While it is true that traditional mapping could record much of the site data collected in lidar, it would take significantly more time on several orders of magnitude and would still not contextualize a Maya site in the ways that lidar does. Lidar not only permits the visualization of the site structures, but also presents detailed information on the topography and landscape; the details available in these kinds of data have almost never been collected by on-the-ground mapping projects, at least at any significant scale. While it is true that lidar needs to be ground-truthed, because of the amount of research that has been undertaken in the Maya area it is possible to use already mapped data to understand what is being seen in the lidar visualizations (e.g., A. Chase et al. 2011). Yet there are multiple areas in which the interface between archaeology and lidar can be improved. Several of these areas are addressed by the papers in this issue of *Advances in Archaeological Practice* with regard to ground-truthing man-made features, attempting to better define less-elevated structures, looking at the way that anthropogenic features modify water flow over the landscape, examining ways of penetrating different kinds of vegetation cover, and developing new computer algorithms that can aid in the identification of archaeological features. While the initial use of lidar focused on the simple visualization of the landscape, as can be seen in the following papers, researchers are now examining ways to use the lidar data for other kinds of archaeological interpretations. In this evolutionary step, the use of lidar in archaeology can be likened to the use of radiocarbon dating in archaeology; the interplay between archaeological data and technology was significant in advancing both archaeological collection methods and technological parameters.

Like movement forward in any discipline, change sometimes comes from unforeseen directions, involving the interactions of different research areas and methodologies. This is certainly true for archaeology, which utilizes both methods and theories from a broad range of disciplines, ranging from geology and chemistry to history, anthropology, and sociology. The practice of archaeology, however, always incorporates two cross-cutting dimensions: time and space. While the relative temporal dimension of archaeology can be established because of stratigraphy and cross-dating associated artifacts and styles in the archaeological record, the absolute scale of the temporal units that are identified through archaeology is difficult to establish without scientific dating techniques. Until the advent of radiocarbon dating (Anderson et al. 1947; Libby 1946, 1952), which provided absolute dates within a calendric framework, the assignation of time to the archaeological record was largely a matter of "experienced guesswork" (the American Southwest and dendrochronology were an early exception). J. Desmond Clark (1979:7) noted that, without radiocarbon dating, researchers "would still be foundering in a sea of imprecisions sometime bred of inspired guesswork, but more often of imaginative speculation."

Similar to the temporal dimension of archaeology prior to the 1946 development of radiocarbon dating, the precise spatial dimensions and full extent of the units that comprised many ancient civilizations were largely unknown for many parts of the world until relatively recently. In particular, the spatial extent of ancient complex societies in tropical regions were often incompletely documented (A. Chase et al. 2012). This was due to any number of reasons, including dense canopy overgrowth in difficult terrain; lack of funding for extensive large-scale research; and archaeological sampling strategies based on an unknown universe. However, our understanding of the spatial dimensions of these ancient societies and cities is currently being revolutionized through the application of airborne mapping lidar (A. Chase et al. 2010, 2011; Evans et al. 2013). This is particularly the case in the tropics, where mapping jungle-enshrouded sites was exceedingly challenging and time-consuming, resulting in a patchwork of data, which because of its incompleteness, could be interpreted in multiple ways. Lidar has permitted large-scale visualization of landscapes that could only be dreamed about before its application and is permitting new cross-cultural comparisons to be made of ancient tropical civilizations (Lucero et al. 2015).

Having lauded the ability of these two technologies to help establish the dimensions of time and space in archaeology, however, it should be noted that these technologies at their best are not static, but also develop in conjunction with the research questions being asked. Both radiocarbon dating and lidar have been and are being refined through the interplay of researchers, often coming from different disciplinary backgrounds. The application of radiocarbon dating in archaeology has a considerable history that features frequent enhancements to methodology in order to gain improved results and to answer new questions. Similarly, lidar as a technology is also evolving not only with enhanced technical capabilities but also as newer and different research questions impact the kinds of visualizations and analyses that are produced and interpreted (Fernandez-Diaz, Carter, Shrestha, and Glennie 2014; White 2013). In essence, the applications of both technologies have had a significant impact on their eventual refinement. Moreover, this interplay between technology and research is key to the scientific process. While radiocarbon dating has a longer track record, the current focus on data interpretation among practitioners of lidar in Mesoamerican archaeology (e.g., Hare et al. 2014; Hutson 2015; Prufer et al. 2015; Rosenswig et al. 2015) is driving enhanced lidar technology and better interpretive results and visualizations.

RADIOCARBON DATING

Examination of the history of radiocarbon demonstrates the continuous improvement of this dating technique in conjunction with new research inquiries. In a brief history of radiocarbon dating, Currie (2004:186) has noted that Libby first focused on simply demonstrating that ^{14}C existed in nature by developing a technique of counting ^{14}C decay:

> subsequent metrological and scientific advances have included: a major improvement in ^{14}C decay counting precision leading to the discovery of natural ^{14}C variations; the global tracer experiment following the "pulse" of excess ^{14}C from atmospheric nuclear testing; the growing importance of quantifying sources of biomass and fossil carbonaceous contaminants in the environment; the revolutionary change from decay counting to atom counting (AMS: accelerator mass spectrometry) plus its famous application to artifact dating; and the demand for and possibility of ^{14}C speciation (molecular dating) of carbonaceous substances in reference to materials, historical artifacts, and in the natural environment.

All of this forward movement was in turn accompanied by other technical advances often brought about because of the application of radiocarbon dating in other disciplinary fields.

Libby's (1946) initial decay counting yielded a half-life of 5,568 years for ^{14}C; this half-life was corrected to 5,730 years in 1962 (Godwin 1962). Libby (1952; see also Arnold and Libby 1949) had tested his method of projecting dates back into the past to validate that it worked through using known-age ancient tree rings and also independently dated Egyptian artifacts. Ancient tree-ring testing continued as a way of refining radiocarbon dating and resulted in the recognition that at least one of the fundamental expectations of radiocarbon dating—that ^{14}C was constant in the atmosphere—was incorrect. The first indication of this was found when more modern materials yielded anomalous dates for ^{14}C samples, which eventually was linked to the testing and use of atomic weapons that added additional radioactive carbon into the atmosphere (Suess 1955). However, the tree ring dating and calibration curves also demonstrated that the actual amount of ^{14}C varied over time (Klein et al. 1982; Suess 1965; Stuiver 1965; Stuiver and Suess 1966); this variance has been related to potential sunspot activity (Suess 1965) but may also correlate with volcanic activity and/or climatic conditions. The calibration correlations resulted in a recognition that some past time periods were difficult to date (Bayliss 2009), as possible dates crossed several potential curves. There were also dating differences in the organic material being dated, particularly from Arctic latitudes (Stuckenrath 1965) and variation in atmospheric pooling depending on latitude (Olsson 1970; Stuiver 1971), again demonstrating that some of the basic assumptions of immediate mixing for ^{14}C in the atmosphere were incorrect.

Over time, there have been significant improvements to both the counting methods and the ways in which chronological dates are approximated. When Libby began working with ^{14}C, it was with solid carbon. In the 1950s, both a gas counting method and a liquid scintillation counting method were developed; these enhancements were followed in the late 1970s by an accelerator mass spectrometry (AMS) method of counting (Theodorsson 1991). AMS dating measures the ^{14}C isotope and permits the counting and analysis of very small carbon samples, leading to high-precision temporal resolution. In archaeology, statistical methods have also been applied to radiocarbon dates in order to gain better chronological control (Bayliss 2015; Ramsey 1995). Thus, what the history of radiocarbon dating shows is ever increasing attention to more accurate results through an interplay with the different fields that use the methods.

Radiocarbon dating has been applied to a series of archaeological problems, some of which still remain unanswered both in the Old World and the New World. One of the more perplexing issues is a 200-year discrepancy between independently dated remains and radiocarbon dates associated with the eastern Mediterranean (Renfrew 1973), showing that not all factors influencing the carbon cycle are completely understood. For the Maya area in particular, radiocarbon dating has had a significant impact on the correlation that is being used to date the Maya hieroglyphic calendar (A. Chase 1986). The interpretation of radiocarbon dates has proved to be crucial for positioning the beginning and end of the Maya "collapse," as well for positioning the Maya Classic period calendar in terms of our own time scales. Each new advance in radiocarbon methodology brings forward new considerations of dating factors (see Satterthwaite and Ralph 1960 and Ralph 1965 for an earlier interpretation of the correlation and, then, Aldana 2015 and Kennett et al. 2013 for recent arguments).

MAPPING LIDAR

Similar to radiocarbon dating, lidar also has a history of evolving technology and methodologies, much of which has been fostered by interdisciplinary collaborations and applications. Although fairly new in terms of its archaeological applications, lidar has been in use for more than half a century in other fields. It experienced parallel development with applications in two distinct fields: atmospheric science research and as a distance measuring technique for land surveying (see Fernandez-Diaz et al. 2013 for a detailed historical overview). In its crudest form, using search lights, the technology was employed in the first half of the 1930s to study atmospheric scattering layers (Synge 1930; Tuve et al. 1935). It was later adopted by meteorologists for remote sensing of clouds (Goyer and Watson 1963). The use of visible light in a fashion similar to the use of radio waves in radar resulted in this kind of research being referred to as "light radar" or lidar (Ring 1963), meaning "Light Detection and Ranging." In 1971, as part of the Apollo 15 mission, lidar was utilized to map transects of the moon's topography (Robertson and Kaula 1972); later, the technology was used to map Mars (Zuber et al. 1998). Much of the early development of lidar was correlated with space research; NASA developed two airborne laser technologies that are ancestral to current airborne mapping lidar systems: Airborne Oceanographic Lidar (AOL) and Airborne Topographic Mapper (ATM) (Anderson et al. 2010:875).

Currently, research projects have a choice of multiple kinds of mapping lidar technologies, which can be classified in different ways. For instance, based on the type of surface to be mapped, it can be classified as topographic (land surface) or bathymetric (underwater surface) lidar. Based on the platform that is used to carry the mapping lidar instrument, it can be classified as airborne, mobile (using moving ground or water vehicles), or terrestrial (or tripod-based lidar); there are also spaceborne and handheld lidar systems. Based on the system design architecture and the nature of the ranging/scanning systems, there are numerous families of lidar, which include high signal-to-noise-ratio (SNR) or linear lidars, Flash lidars, and Geiger-mode or photon-counter lidars (for a more detailed classification and description of lidar taxonomies and working principles, see Fernandez-Diaz et al. 2013 and Fernandez-Diaz, Carter, Shrestha, and Glennie 2014).

As an active laser scanning technology, lidar produces point clouds—a series of point measurements recorded in three dimensions (x, y, and z), plus some ancillary attributes such as laser intensity and color—that can be further manipulated and analyzed by researchers. Most of the technological advances made so far in lidar have been aimed at improving the fidelity, resolution, and accuracy of the resultant datasets. Fidelity refers to the ability of a dataset to accurately represent the "reality" that is being mapped, while resolution gives an idea of how detailed the mapping is. To achieve higher levels of fidelity and resolution improvements in lidar technology, there have been attempts to increase the data "throughput" (measurement density) and the range resolution. For airborne mapping lidar, which usually works from a bird's-eye geometry, the resolution is broken down into vertical and horizontal resolutions. The horizontal resolution is highly dependent on measurement density (e.g., as point density or return density), but it also is dependent on factors such as the laser footprint and the percentage of surface area that is illuminated. The vertical resolution is proportional to the system range resolution, and it determines the ability of a lidar system to produce distinct returns from multiple targets separated along the line of sight and within the footprint illuminated with the laser. For example, these two factors determine the ability of lidar to separate returns coming from the ground and the vegetation that is located just above the ground (provided that there are enough gaps in the vegetation to allow for a two-way travel of the laser energy). The range resolution is a function of fixed system parameters, such as laser pulse and detector dead-time.

To achieve improved fidelity and resolution, multiple approaches have been taken in designing and implementing lidar systems, including traditional linear-mode lidar systems and alternative systems such as waveform lidar, Flash lidar, and Geiger-mode lidar. For linear-mode lidar (a.k.a. conventional, high SNR, discrete lidar), which uses a single laser in short, rapid pulses that returns multiple points per pulse, improvements have included the increase of the effective pulse repetition frequency (PRF) by using faster pulsing lasers and/or using multiple lasers (channels) to increase the return density, as well as the use of shorter laser pulse widths for the improvement of the range resolution. Full-waveform lidar is an alternative to increase the range resolution of conventional lidar systems by recording a continuous vertical summation of the return signal from each outgoing laser pulse. Flash-lidar is an a alternative approach to produce high-density datasets by employing a multi-pixel 2D detector array to simultaneously record hundreds of returns from a single laser burst (or flash) that is spread over a wide footprint but with a very short duration. Geiger-mode or photon-counting lidar is aimed at producing very high return densities with extremely high-range resolutions, which usually works by using a low PRF with an extremely short pulse laser source in which single beam output is split into multiple beamlets that illuminate a large footprint. The return signal is detected by an extremely sensitive sensor that can detect the signal of one or more photons from targets that are separated by as little as a few centimeters along the range direction.

Independently of the lidar technology employed, the first available data product is the point cloud, which is an irregularly spaced, full-density dataset. While the point cloud is relatively easy to visualize, its manipulation for analysis is a bit complicated and, for this reason, archeologists have preferred to work with different types of DEMs. The DEMs are regularly spaced 2.5D datasets that are the result of resampling and interpolating the point cloud. The use of a DEM permits an archaeologist to undertake a series of analyses with much better spatial resolution than is generally available from traditional technologies. The DEM can also be used to provide contour lines, slope and aspect, hillshade and shaded relief, hydrological models and networks, viewsheds and line-of-sight, least-cost routes and networks, and change detection in temporally different sets of point clouds (see White 2013). Developing algorithms for visualizing features within lidar data is also a very productive research area in archaeology (e.g., Hanus and Evans 2015).

Finally, visualization techniques that are applied to the acquired lidar data will result in different kinds of renderings and interpretations (e.g, Challis et al. 2011; see also Comer and Harrower 2013 and Opitz and Crowley 2013). While standard programs may be utilized to produce a variety of basic visualizations (e.g., Figure 1, Figure 2), it is also possible for researchers to write new algorithms that result in the ability to reconfigure the lidar point clouds to produce visualizations that apply to specific questions and problems (e.g., Fernandez-Diaz, Carter, Shrestha, and Glennie 2014; Pingel et al. 2015; Renslow 2012; White 2013). This is one area where the interface between provider and user is most productive—and it is the position in which Mesoamerican archaeology now finds itself. Problems that are being encountered in lidar visualizations are being innovatively addressed in order to get at results (as seen below and in the papers accumulated in this issue).

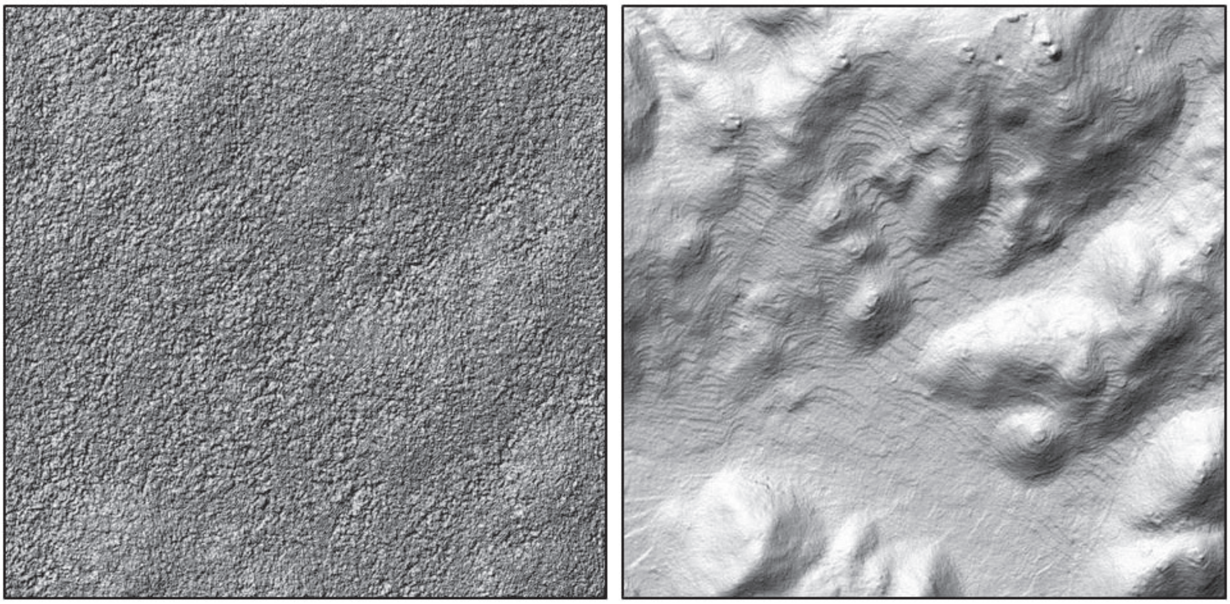

FIGURE 1. Examples of two DEMs: (a) Digital Surface Model (DSM) of tree canopy overlying the Caracol's Puchituk Terminus; (b) Digital Terrain Model (DTM) showing the bare earth visualization of Caracol's Puchituk Terminus.

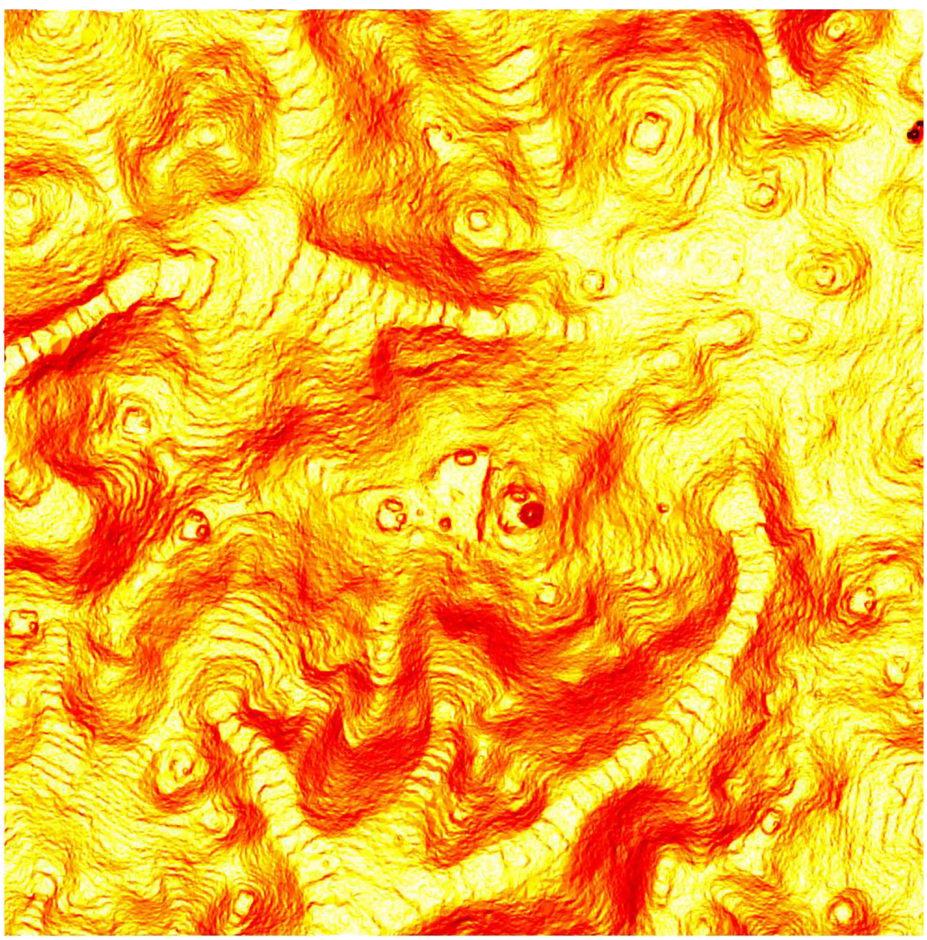

FIGURE 2. Example of a 2D visualization of Caracol's Puchituk Terminus, illustrating 1-m derived slope.

TABLE 1.

Site/Region	Year Flown	Area Covered (square kilometers)	Density (points per square meter)
Copan, Honduras (UT-BEG/USGS)	2000	unknown	unknown
Caracol, Belize	2009	200	20
Izapa, Mexico (Airborne 1)	2010	42.2	3.1
Angamuco, Mexico (not NCALM)	2011	9	15
Uxbenka, Belize	2011	103	12
El Pilar, Belize (Mayaniquel)	2012	20	20
Mosquita, Honduras	2012	122	15-25
El Tajin, Mexico (INAH/ PEMEX)	2012	unknown	unknown
Western Belize	2013	1057	15
Mayapan, Mexico	2013	55	40-42
Copan, Honduras (WSI)	2013	25	15
Tres Zapotes, Mexico	2014	72	12-13
Chichen Itza/Yaxuna, Mexico	2014	50	15
Cansahcab, Mexico	2014	26	15
Yaxnohcah, Mexico	2014	90	15
Izapa, Mexico (Airborne 1)	2014	47.5	3.2
El Ceibal, Guatemala	2015	400	15
Teotihuacan, Mexico	2015	120	20
Angamuco, Mexico	2015	40	20
Zacapu, Mexico	2015	40	20

PARADIGM SHIFTS, ADAPTING LIDAR TECHNOLOGY, AND OTHER ISSUES IN MESOAMERICA

Just as archaeologists were in the vanguard of the radiocarbon revolution, archaeologists in the Maya area and Mesoamerica have been at the forefront of using airborne lidar for settlement pattern work because of the ability of this technology both to penetrate foliage and to provide detailed topographic renderings of surface features that can be used to highlight anthropogenic modifications. The use of lidar is revolutionizing our understanding of ancient settlement and landscape use (A. Chase et al. 2012) by showcasing the fact that ancient tropical cities were in fact large urban places. The spatial area of lidar coverage in this part of the world continues to grow by hundreds of square kilometers annually—with much of the recording being undertaken by NCALM, the National Center for Airborne Laser Mapping (see Table 1; Carter et al. 2016; Fernandez-Diaz, Carter, Shrestha, and Glennie 2014).

The formal lidar campaigns carried out in Mesoamerica (Table 1) started in 2009 with a 200-km^2 survey of the site of Caracol, Belize (A. Chase et al. 2010, 2011, 2012, 2013; A.S.Z. Chase and Weishampel, this issue; D. Chase et al. 2011; Hightower et al. 2014; Weishampel et al. 2010, 2013). Because of the pristine forest cover for this region, the survey was an unqualified success and produced imagery and results that more than justified the cost of using lidar and also justified its use in other tropical areas (Evans et al. 2013). While NCALM had carried out the successful Caracol survey, several other early surveys at Izapa (Mexico; Rosenswig et al. 2013, 2015), Angamuco (Mexico; Fisher et al. 2011), El Tajin (Mexico; Zetina Gutierrez 2016), El Pilar (Belize; Ford 2014), and Copan (Honduras; Gutierrez et al. 2001 and Schwerin et al. 2016) were carried out by independent contractors, covered smaller areas, and produced processed lidar of variable quality. However, all of these uses again demonstrated the utility of the technology even when varying methodological parameters were utilized. Subsequent to Caracol, NCALM has carried out high-quality lidar surveys of Uxbenka (Belize; Prufer and Thompson, this issue; Prufer et al. 2015; Thompson and Prufer 2015), Mosquita (Honduras; Preston 2013 and Fernandez-Diaz, Carter, Shrestha, Leisz, et al. 2014), western Belize (A. Chase, D. Chase, Awe, Weishampel, Iannone, Moyes, Yaeger, and Brown 2014; A. Chase, D. Chase, Awe, Weishampel, Iannone, Moyes, Yaeger, Brown, et al. 2014; various, this issue), Mayapan (Mexico; Hare et al. 2014; this issue), Tres Zapotes (Mexico; this issue), Chichen Itza/Yaxuna (Mexico; this issue), Cansahcab (Mexico; Hutson 2015; this issue), Yaxnohcah (Mexico; this issue), El Ceibal (Guatemala), Teotihacan (Mexico), Angamuco (Mexico), and Zacapu (Mexico).

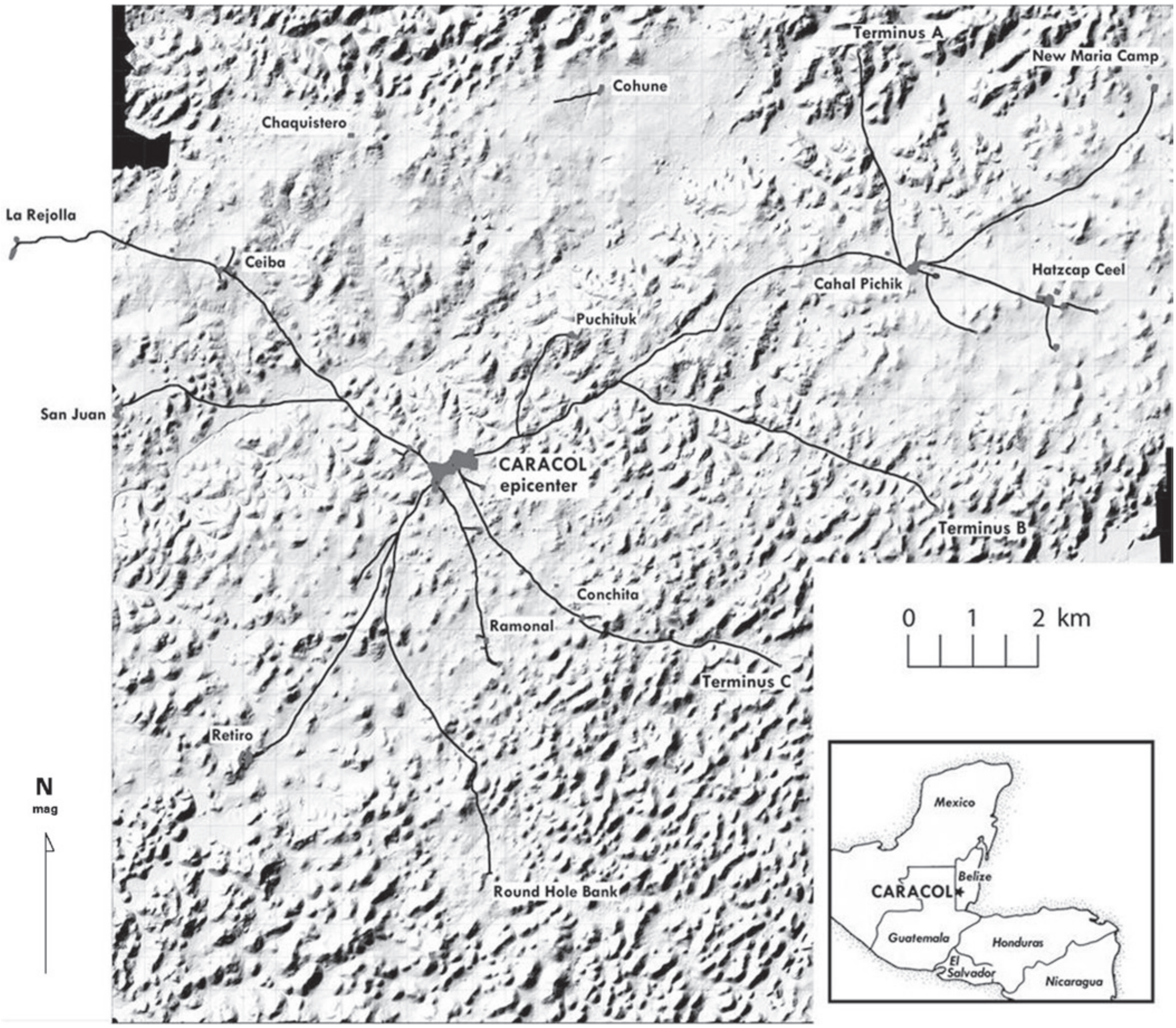

FIGURE 3. Example of complete DEM of the 2009 Caracol LiDAR campaign with the site's causeways and termini positioned.

While the lidar campaign carried out at Caracol produced data and images that revolutionized our understanding of ancient Maya settlement and landscape modification (Figure 3, Figure 4), part of the success was due to the lack of modern population in the region and the high canopy that obscured the ground remains. Subsequent lidar campaigns were done in areas that had modern human disturbance, and it became clear that the kind of vegetation that was on the ground had a profound effect on the clarity of bare-earth images that used standard processing procedures and visualization techniques (see Fernandez-Diaz, Carter, Shrestha, and Glennie 2014:9967). This issue had been raised previously in other parts of the world (Crow et al. 2007; Devereux et al. 2005), but in the Maya area it was compounded by both natural and human-made vegetation disturbances. Hurricanes significantly affected ground cover (Gutierrez et al. 2001), as did standard Maya farming practices that focused on milpa or slash-and-burn agriculture. Because of the way that the Maya site of Uxbenka had been mapped—by following milpa clearance over more than a decade—it was possible to use the lidar coverage of that site to demonstrate the disastrous long-term effects that vegetation regrowth after clearing had in affecting bare-earth visibility (Prufer et al. 2015:9).

In other parts of the Maya area, there are topographic issues that, when combined with disturbed vegetation, severely complicate the interpretation of bare-earth imagery. Small natural hills in the Maya Northern Lowlands resemble constructed mounds, and the scrub vegetation that covers them makes it extremely hard to discern these hillocks from the actual ruins (e.g., Hutson 2015; various, this issue). Discerning less-elevated structures is a general issue that needs further resolution, especially in areas of secondary growth. Yet the continued interac-

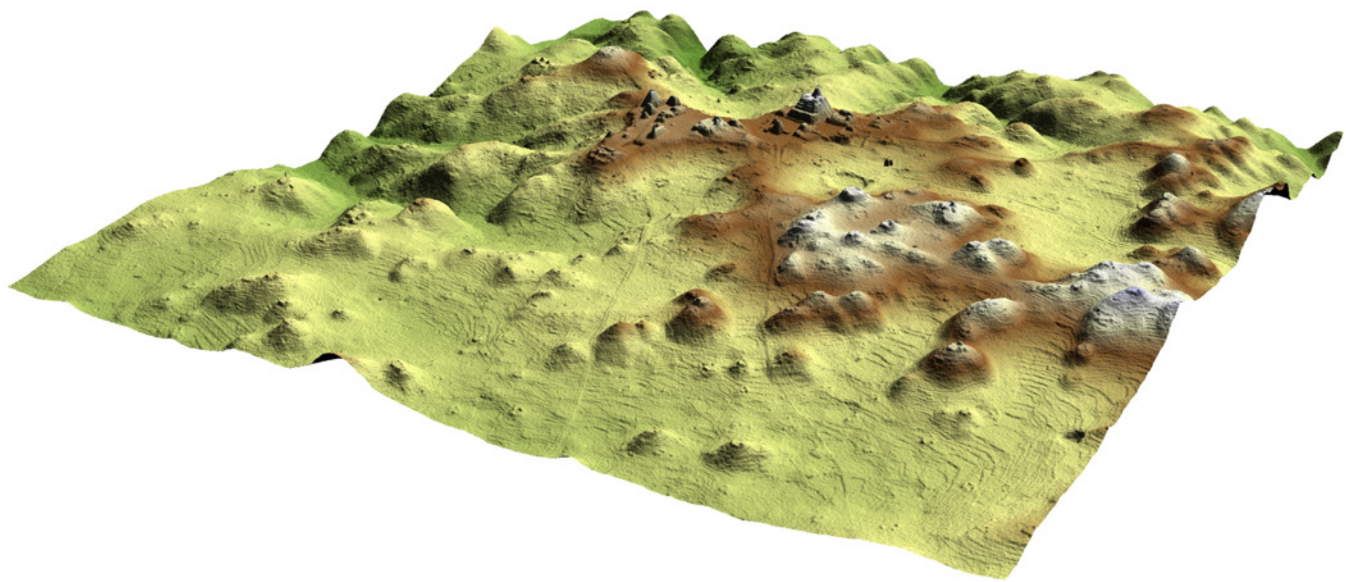

FIGURE 4. 2.5D lidar visualization of central Caracol derived from the 2009 point cloud (after A. Chase et al. 2011:Figure 7).

tion between the users and producers of lidar should eventually result in better computer algorithms and visualizations.

The technology of lidar also continues to improve, especially with regard to point density and range resolution (see Geiger-mode lidar, above). Point density has a significant effect on the bare earth visualizations and analyses that are possible. Digital Elevation Models (DEMs) are affected by both the vegetation that is present and the size of the features being recorded. (As used here, DEM encompasses Digital Surface Model [DSM], which is usually the tree canopy, and Digital Terrain Model [DTM], which is usually "bare earth.") Any DEM cell that lacks a ground return is usually assigned one during processing through spline interpolation, inverse distance weighting, or kriging. This is done by mimicking surrounding ground returns. Built archaeological features usually do not mimic their surrounding landscape topography. Thus, an increased point density will enhance the likelihood that all terrain cells will have a ground return, making for better, more accurate, and higher-fidelity visualizations and 3D modeling.

With the creation of such large datasets, questions of data sharing arise. Because the visualizations that result from lidar are so good, they not only have a multitude of uses in different fields, but they also have raised ethical issues with regard to how publically available these data should be. Federal agencies, like the National Science Foundation, and even some publications, like *Advances in Archaeological Practice*, call for open and accessible data. However, lidar surveys often collect sensitive data, such as the specific location of archaeological sites, roads near borders, military installations, and other data that governments often restrict in terms of sharing with the public. Some countries, such as Mexico, Guatemala, Honduras, and El Salvador have not established policies regarding fair use of sensitive data collected though lidar survey; moreover, in these same countries, the permits necessary to conduct large-scale lidar survey bypass regulatory agencies responsible for the protection of environmental and archaeological resources. Most Mesoamerican countries also have significant problems with the looting of their ancient ruins and, given that lidar visualizations can be used as road maps, these countries do not want the full release of geo-referenced lidar data. The country of Belize has a policy in place that prohibits the public distribution of lidar data covering archaeological remains and also of geo-referencing any published images (A. Chase, D. Chase, Awe, Weishampel, Iannone, Moyes, Yaeger, and Brown 2014:218). Thus, there are existing tensions between data sharing and accessibility standards in various fields and data responsibilities. While some may see only the positive aspects of openly posting all data for distribution, archaeologists note the damage that this can cause in terms of site destruction and looting, especially as many images provide sufficient spatial clarity to easily lead to long-hidden archaeological remains. Given that most lidar collection to date in Mesoamerica has been undertaken with funding raised by archaeologists who are interested in the datasets, these same archaeological researchers have an ethical responsibility for the preservation of cultural heritage that must take precedence over the uninformed release of datasets that can be easily misused (even unintentionally) by the non-archaeological community.

Lidar use in archaeology also has several other issues that need to be overcome. The technology produces massive datasets that require a lot of computing power and storage space, as well as specialized software and knowledge. There is also a need for accuracy improvements in the collection and processing of the data. Accuracy is extremely important, both in terms of relative (point-to-point) and absolute (points-to-real-world locations). The use of a lidar system does not mean that it is particularly accurate. Common points of failure include the algorithm being used, the scanner being used, and the person doing the interpretation. Another area that will see increasingly normal use in the future is working across points collected at multiple scales (e.g., high-altitude aerial, low-altitude aerial, mobile, and terrestrial) for the same site as well as conjoining the data with other modalities (e.g., multispectral, hyperspectral, thermal, and synthetic aperture radar). This will especially become the case as

FIGURE 5. The deployment of a tripod lidar scanner was able to accurately map a deposit of partially buried stone artifacts in the Honduras Mosquitia; compare photograph to scan.

lidar is encoded in common devices like phones (e.g., Google Project Tango) that will easily permit interdigitation with other LAS files. A final area of challenge is in the creation of bare earth models. Various disciplines see "bare earth" differently. Archaeologists are looking for low-elevation anthropogenic features and seek to filter out vegetation and random rocks from their models. However, many other scientists working with lidar do not care about anthropogenic features and are fine with models that strip everything away. Thus, identifying and keeping man-made features in bare earth algorithms is a specific archaeological issue that will force the field to continue to work with system designers, geospatial scientists, and software developers to solve this problem.

It is important to point out that, while the papers presented in this issue of *Advances in Archaeological Practice* focus on the use of airborne mapping lidar and how lidar is revolutionizing archeological practice in Mesoamerica, the argument is not only based on the potential of airborne lidar to improve our understanding of past civilization but also on the potential of other lidar-based applications and technologies to provide geospatial information at scales that range from the regional landscape level through the settlement, site, building, and artifact level that allow us to answer anthropological questions in ways that were not possible before. As argued throughout this paper (and as illustrated through Figures 1 and 4), airborne mapping lidar provides visual evidence at the landscape level on the impact of humans of their environment and how the terrain was modified,

FIGURE 6. A close-range handheld lidar scanner provides a detailed image of an artifact and can be used in a variety of settings (in this case, an artifact in a museum setting).

evidence that it is not possible to obtain with other technologies on areas covered by dense vegetation. However, other types of lidar technologies also have the potential to provide valuable 3D spatial information at site, building, and artifact levels at extremely high resolutions, complementing the larger-scale information provided by airborne lidar. It is by integrating information from multiple sources at multiple scales and resolutions that lidar will continue to revolutionize archaeology.

Terrestrial laser scanning (TLS) or tripod mounted lidar (as illustrated in Figure 5) can provide high-resolution, high-fidelity 3D models of entire sites (at a significant effort), buildings, structures, and large-to-medium-sized artifacts. With this type of technology, field archaeologists can produce highly detailed and accurate 3D maps of excavation sites sequentially, as the excavation takes place, at a fraction of the time needed for conventional methods. The lidar method can provide a virtual record of the entire operation, allowing researchers to make measurements, analysis, and reconstructions after the excavation, something that would be very hard or impossible to accomplish with traditional methods. At an even smaller scale, handheld lidar scanners operate at very short ranges to the target, usually less than 5 m, and can provide 3D models with millimeter- and even micrometer-level resolution (Figure 6) in both field and laboratory settings. The 3D textured data produced by this kind of scanner technique can be applied not only for artifact reconstructions and archiving, but also for analysis regarding the form and function of artifacts. Creating 3D libraries of thousands of artifacts and applying big data techniques for pattern recognition and machine learning can yield breakthroughs, such as developing cultural and temporal diagnostic markers based on an artifact's spatial properties or potentially new insights into the interpretation of iconography and epigraphy.

CONCLUSION

Progression in any scientific enterprise results from continued research, testing, and reassessment. Examining the history of radiocarbon dating shows that this is how the methodology associated with the technology moved forward. After the initial dating breakthroughs in ^{14}C dating, new techniques of counting were developed, new issues were discovered and resolved with regard to calibrations, smaller samples were more accurately dated, and Bayesian statistics were applied in conjunction with archaeological stratigraphy for even further refinement. Research in airborne lidar is paralleling this scientific path. Like ^{14}C dating, research in lidar is undergoing a similar progression involving both enhanced technologies and more innovative ways of rendering point cloud data in order to obtain ever better visualizations and analyses. On-the-ground research in Mesoamerican archaeology has shown the value of lidar data for basic interpretation. As more lidar data have been collected and rendered, they have revealed a wide variety of both direct and indirect issues that need to be assessed and overcome. Thus, the interplay between researchers using the collected lidar point clouds in conjunction with known topographic and archaeological features is moving the methodologies of both fields forward and highlighting a true scientific process.

Acknowledgments

Portions of this paper were originally discussed at a lidar session held at the 47th Annual Chacmool Conference in Calgary, Canada, in November 2014. Additional conversations about lidar were held with a series of individuals representing ICOMOS at the 80th Annual Meetings of the Society for American Archaeology in San Francisco in April 2015. The impetus for this paper derives from both a NASA grant to John F. Weishampel, Arlen F. Chase, and Diane Z. Chase in 2009 and an Alphawood Foundation grant to Arlen F. Chase, Diane Z. Chase, Jaime J. Awe, John F. Weishampel, Gyles Iannone, Holley Moyes, Jason Yaeger, and M. Kathryn Brown in 2013. In both cases, NCALM was the chosen lidar subcontractor; subsequent field projects in Mesoamerica have also generally used NCALM. One of the goals of the 2013 grant was to help the recipients become proficient in the use of lidar by having them publish their data; this was also a goal of the 2014 Calgary session. Without the guidance of Christopher Dore, at that time the editor for *Advances in Archaeological Practice*, this goal may not have been realized; Christopher encouraged us to make a proposal to undertake a special issue of the journal on the methodology and practice behind using lidar with Mesoamerican settlement data derived from archaeological research; once the proposal was accepted, he mentored us through the editorial process and answered unending questions through email; thus, the success of this issue truly must be credited to him and we sincerely thank him for all that he has done. In terms of this introductory paper, the authors also wish to acknowledge the detailed comments from three reviewers that helped to make this contribution more cohesive.

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