



## Airborne LiDAR, archaeology, and the ancient Maya landscape at Caracol, Belize

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### ABSTRACT

Advances in remote sensing and space-based imaging have led to an increased understanding of past settlements and landscape use, but – until now – the images in tropical regions have not been detailed enough to provide datasets that permitted the computation of digital elevation models for heavily forested and hilly terrain. The application of airborne LiDAR (light detection and ranging) remote sensing provides a detailed raster image that mimics a 3-D view (technically, it is 2.5-D) of a 200 sq km area covering the settlement of Caracol, a long-term occupied (600 BC–A.D. 250–900) Maya archaeological site in Belize, literally “seeing” through gaps in the rainforest canopy. Penetrating the encompassing jungle, LiDAR-derived images accurately portray not only the topography of the landscape, but also, structures, causeways, and agricultural terraces – even those with relatively low relief of 5–30 cm. These data demonstrate the ability of the ancient Maya to modify, radically, their landscape in order to create a sustainable urban environment. Given the time and intensive effort involved in producing traditional large-scale maps, swath mapping LiDAR is a powerful cost-efficient tool to analyze past settlement and landscape modifications in tropical regions as it covers large study areas in a relatively short time. The use of LiDAR technology, as illustrated here, will ultimately replace traditional settlement mapping in tropical rainforest environments, such as the Maya region, although ground verification will continue to be necessary to test its efficacy.

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### 1. Introducing LiDAR technology to Maya landscape archaeology

Classic Period Maya civilization (A.D. 250–900) evolved within and eventually returned to a jungle-enshrouded tropical environment, making it exceedingly difficult to see the full extent of their settlement and centers. Documentation of settlement is both arduous and incomplete, with virtually all researchers reduced to recording a sample of remains, even within a single site or region. How the ancient Maya distributed and organized themselves over the landscape and how they supported large populations continue to be debated (Becker, 1979; Fox et al., 1996; Iannone, 2002). These issues are made more difficult because the documentation of ancient settlement has been – of necessity – partial. The ability to map an ancient settlement within a dense jungle is hindered not

only by the covering foliage but also by the amount of funding and time required to undertake the effort. Thus, even the best surveyed sites in the Maya area are only represented by a limited portion of the landscape, meaning that broader interpretations are derived from incomplete samples. The result is continued disagreements over the nature and composition of ancient Maya social structure (Chase et al., 2002), over their political organization (Grube, 2000), and even over the causes behind the Classic Maya collapse (e.g., Webster, 2002).

In studying the Maya, researchers have focused mainly on the impressive public architecture that exists within most site epicenters and interpreted their social fabric through hieroglyphic texts located in these areas (Martin and Grube, 2000), leading to a somewhat myopic view of Classic Period society. Settlement archaeology at many of these Maya centers has supplemented these interpretations (Sabloff and Ashmore, 2007), but has generally not succeeded in defining the full spatial layout of sites, in explaining their variable social composition, or in demonstrating how sustainable systems were promulgated.

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After 25 years of research and mapping, the archaeological ruins of Caracol, Belize (Chase and Chase, 1987, 2001a; Chase and Chase, 1994b), can be described as the largest known site in the Southern Maya lowlands. As currently understood, Caracol covers almost 200 sq km, spanning most of the Vaca Plateau (Fig. 1); its various parts are linked by a dendritic causeway system embedded in continuous settlement. While agricultural terracing has been documented for Caracol (Healy et al., 1983; Chase and Chase, 1998), the full extent of the modified landscape has been difficult to demonstrate, let alone conceptualize. Yet, several days of airborne light detection and ranging (LiDAR) flyovers of the site, combined with three weeks of post-field processing, yielded results that far surpassed over two and a half decades of on-the-ground mapping by revealing images of a massive, modified landscape that ties settlement, roadways, and agricultural terraces together into a complete settlement system.

## 2. Landscape challenges in building the Maya site of Caracol

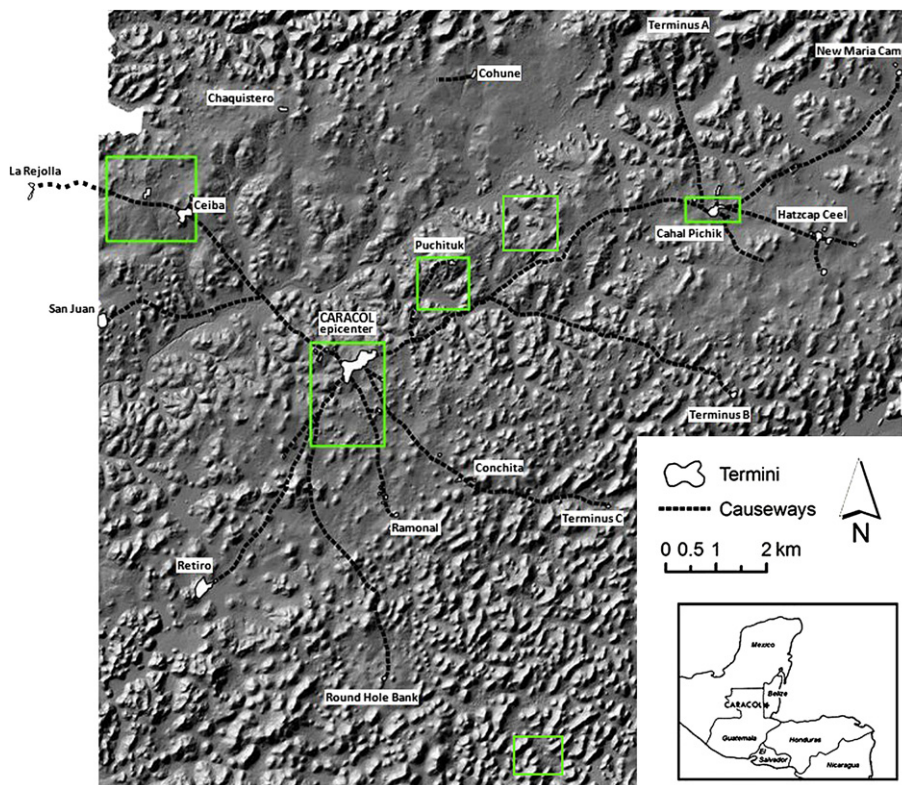
The LiDAR survey reported here covered the majority of the Vaca Plateau, a level plain located amidst the karst topography of western Belize, where the site of Caracol was built. Caracol and the Vaca Plateau are located at an elevation ranging from 450 to 600 m above sea level (Chase and Chase, 1987). No running water can be found within the 200 sq km constituting the site, despite the Macal and Chiquibul Rivers being located a short distance to the west and east of the plateau. To solve this challenge, the ancient Maya inhabitants of Caracol constructed a plethora of reservoirs for drinking water (averaging approximately 5 per 1 sq km) and also managed the landscape hydrology through the construction of terraces. The Vaca Plateau receives between 2000 and 2400 mm of rain per year. Temperature ranges from 5.6 to 38.9° Celsius (Johnson and Chaffey,

1973: 11), sometimes within the same 24 h period of time. Sub-tropical moist rainforest covers the entire area with a canopy that reaches approximately 25 m in height. In antiquity, the entire Vaca Plateau was heavily occupied by the ancient Maya and integrated into the single urban center of Caracol, characterized by public architecture and thousands of residential groups.

### 2.1. Earlier mapping techniques at Caracol

Mapping the site of Caracol has been a long and protracted effort that has spanned almost 60 years. By looking at the history of the various mapping efforts at the site, the full potential of airborne LiDAR as a technique for recording ancient Maya sites becomes glaringly evident. The earlier mapping techniques used at Caracol were labor-intensive, tedious, and partial – providing nowhere near the amount of information contained in the digital elevation model gained from LiDAR. Knowledge of pre-LiDAR research is important to contextualize and to fully utilize the results of this new technique.

The epicenter of Caracol was first reported to Belizean authorities in 1936 because of the discovery of carved stone monuments with hieroglyphs. Archaeological research was initially undertaken at the center in the early 1950s, primarily to uncover and record the site's historic monuments, many of which were shipped to The University Museum in Philadelphia for display. Initial work at the site produced a description of the hieroglyphs and images on these monuments along with a map of 78 structures that documented their location in the site epicenter (Beetz and Satterthwaite, 1981). In the late 1980s, investigations documented the existence of terraces and settlement within an area located 2 km from the site center (Healy et al., 1983) and later demonstrated that maize had been one of the crops grown on these constructed terraces (Webb et al., 2004).



**Fig. 1.** Hillshaded two hundred sq km LiDAR Digital Elevation Model with an overlay of the dendritic Caracol causeway system and the major architectural nodes; the highlighted boxes are areas shown in more detail in subsequent figures (lower box = Fig. 10; upper boxes from left to right: Figs. 8, 6, 3, 9 and 4; the terrain in the northern part of the figure that is not hilly is referred to as the “Vaca Plateau.”).

After preliminary seasons in 1983 and 1984, the first formal field season of the University of Central Florida Caracol Archaeological Project took place in 1985. Over the course of subsequent years of investigation, the focus of research has varied extensively, but has always contained elements of archaeological excavation and mapping. As a result of this research (see field reports and publications at <http://www.caracol.org>), most of the site epicenter has been excavated and stabilized for tourism under the auspices of the project, the Belize Institute of Archaeology, or some combination of the two. Besides the larger architecture in the site epicenter, some 118 residential groups have been investigated by a combination of testing, trenching, and areal excavation. Mapping efforts have resulted in the detailed recording of some 23 sq km of settlement by transit. Additionally, over 75 km of causeways have been documented and approximately 350 ha of agricultural terraces have been intensively mapped. These combined data have led to projected population densities in some parts of the site on the order of 1000 people/sq km (Healy et al., 1983; Chase and Chase, 1998), with an overall population estimate of approximately 100,000 people within a projected area of 177 sq km (Chase and Chase, 1994a:5), making it one of the most populated sites in the Maya lowlands at A.D. 650.

This long-term research has led to a detailed view of this ancient city that combines multiple classes of archaeological data with the site's hieroglyphic texts (Chase and Chase, 2008). Monuments recovered from Caracol provide a history of the site's dynastic rulers from A.D. 330 through A.D. 859, albeit with some gaps. Archaeological data show that the site was first settled by B.C. 600 and continued to be occupied until at least A.D. 900. The site is perhaps best known for the epigraphically recorded defeat of Tikal, Guatemala in A.D. 562 (Chase, 1991), but it also engaged in warfare with a number of other sites during its 500 years of written history (Chase and Chase, 1989; Chase and Chase, 2003b). As a result of successful warfare, Caracol increased in population and expanded over its landscape at the beginning of the Late Classic Period (ca. A.D. 550), integrating its population by means of an extensive road system that radiated out from the epicenter to distances of up to 10 km (Chase and Chase, 2007). These roads directly connected both pre-existing and purposefully established public space and monumental architecture with the epicenter. The intensity of the agricultural fields that accompanied these expansions was capable of supporting an increased population. The agricultural fields imbedded within the Caracol settlement clearly showed the site to be a "garden city," concerned with long-term sustainability (Chase and Chase, 1996).

## 2.2. How survey was undertaken during the Last 25 years of research at Caracol

At Caracol, settlement research was initiated by the current project in 1983. The tropical rainforest and undulating karst terrain made it difficult to map ancient settlement and almost impossible to view the immense amount of landscape modification without extensive removal of the jungle vegetation. Particularly problematic were low-lying "vacant terrain" constructions, some of which are difficult to locate even when vegetation has been completely removed (Ashmore, 1981). Traditional mapping techniques involved the cutting of pathways, called "brechas," through the rainforest, usually at 50 m intervals, and then making systematic survey sweeps along the sides of these brechas (Chase, 1988). At Caracol, the mapping of all structural remains used a traditional transit, an EDM (electronic distance meter), or a total station. However, even the most careful mapping in the rainforest misses ancient settlement that is obfuscated by foliage.

While a rectangular area measuring 3 km by 3.5 km (and comprising a "block map" of 42 quads each measuring 500 sq m) around the site epicenter has been surveyed, the early discovery of causeways at Caracol led to the adoption of a sector approach to mapping, which was designed to provide a better sampling of the range of settlement, including modifications located deeper in the surrounding landscape (Fig. 2). The sector between the Conchita and Pajaro-Ramonal Causeways was recorded between 1987 and 1990 (Chase and Chase, 1989; Liepins, 1994); it was subsequently engulfed in an expanded block map. A second mapped sector located to the northeast of the epicenter was recorded between 1994 and 1996 (Chase and Chase, 2003b). Subsequently, north-south transects were added to these sampled areas in an attempt to define settlement limits, resulting in the addition of the architectural nodes called "Cohune" and "Round Hole Bank" to the settlement map.

Causeway mapping added the "Ceiba" and "Retiro" Termini. A 12 m wide causeway was also followed to the terminus known as "Cahal Pichik" and, then, further linked to the "Hatzcap Ceel" terminus; both loci were venues of archaeological work in the 1920s by the Chicago Field Museum (Thompson, 1931). Two dissertation projects resulted, first, in the recording of settlement and terraces between Cohune and Chaquistero (Murtha, 2009) and, second, in the mapping of the causeway between Hatzcap Ceel and Cahal Pichik, as well as both termini (Morris, 2004). The mapping of other terraces was undertaken as part of this settlement research, particularly in the southeast and northeast site sectors, but given the extensive nature of the occupation, the recording of these features proved too difficult and time-consuming to be completed for more than a sample of the settlement area (Chase and Chase, 1998); these initial efforts did not do justice to the magnitude of the landscape modification that comprised ancient Caracol.

## 2.3. Historic remote sensing

Researchers in the Maya area have long attempted to move beyond traditional mapping and surveying through the use of remote sensing (e.g., Adams et al., 1981; Sheets and Sever, 1988; Saturno et al., 2007; Garrison et al., 2008). The earliest remote sensing involved flyovers of the Yucatan Peninsula by Charles Lindbergh in the 1920s, resulting in the discovery of new sites and the aerial confirmation of ancient causeways (Madeira, 1931). In the 1960s, plane flyovers of the Mexican lowlands led to the identification of ridged fields (Siemens and Puleston, 1972), which ultimately revolutionized our understanding of ancient Maya subsistence (Harrison and Turner, 1978). Synthetic aperture radar was subsequently used to better define canals and intensive cultivation in wetland areas of the Southern lowlands (Adams et al., 1981). Early use of profiling LiDAR technology in Central America (Sheets and Sever, 1988) were not as successful as the current application reported here, causing the majority of the remote sensing focus in the Maya area to gravitate toward satellite imagery, such as LANDSAT (Chase and Chase, 2001a,b) and IKONOS (Saturno et al., 2007). With the advent of the space program in the 1960s, researchers worked to adapt satellite imagery to the interpretation of Maya sites, hoping to first identify and then to map these remains. Most of the innovative work relating to mapping and surveying, however, has attempted to build on new technologies pioneered by the space industry, such as passive optical satellite systems. While these efforts sometimes permitted the identification of previously unknown occupation areas, they did not result in the ability to locate and map individually constructed archaeological features. Until airborne swath mapping LiDAR none of these technologies permitted us to successfully "see through the trees." Early tests of LiDAR in Central America used only a single beam profiling system and were deemed unsatisfactory (McKee and Sever, 1994) for

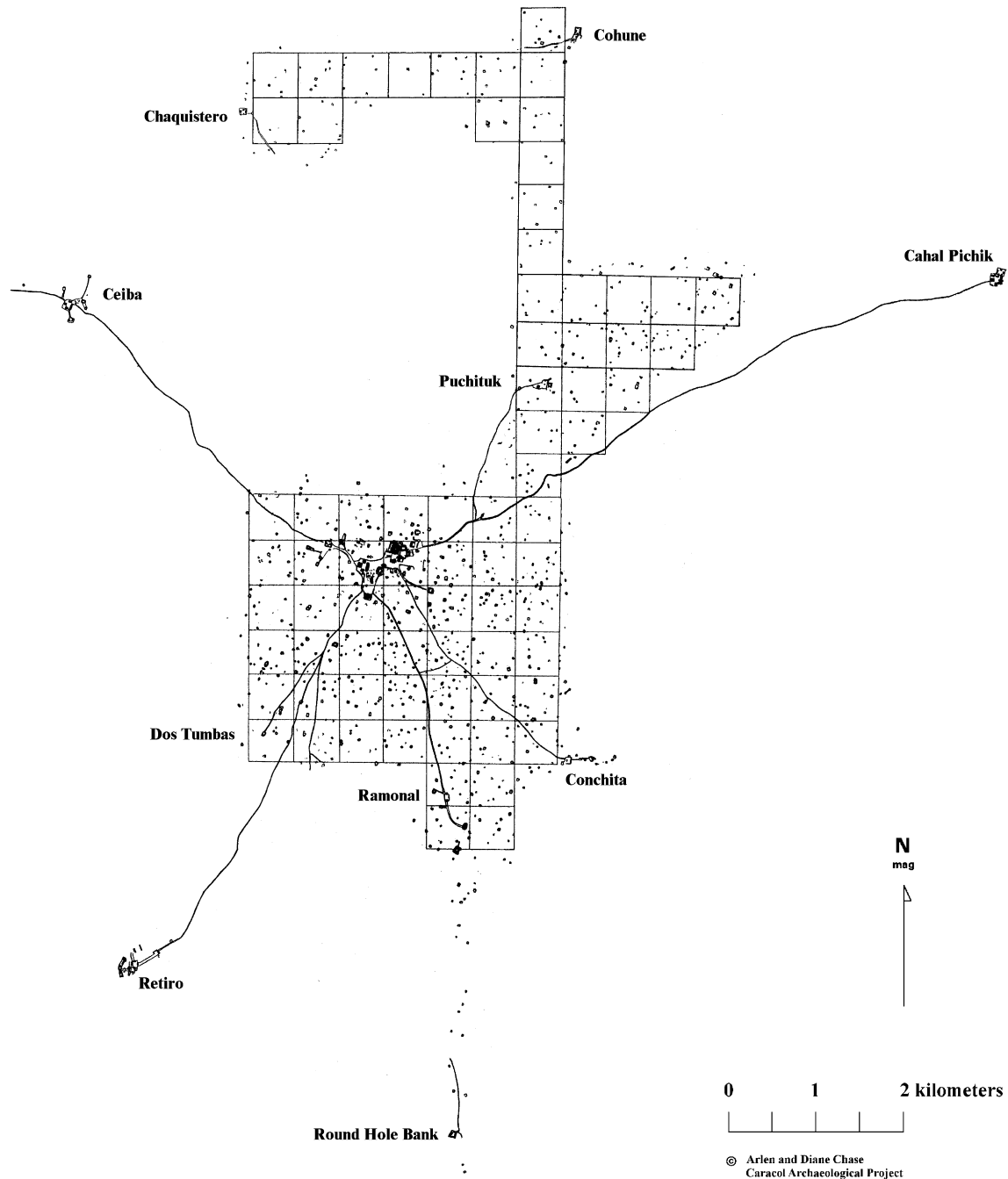


Fig. 2. Transit map of 23 sq km of Caracol (after Chase and Chase, 2001a).

recording surface remains, although the usefulness of LiDAR for interpreting tree canopies was recognized (e.g., Drake et al., 2002; Weishampel et al., 2000, 2007). In spite of the successful use of LiDAR imaging to record the Copan epicenter (Gutierrez et al. 2001), this technology was not applied to other Maya sites or regions. The potential for LiDAR applications to forested areas (Carter et al., 2007) has only recently been touted in the archaeological literature (Devereux et al., 2005; Doneus et al., 2008), but with examples that were spatially limited. However, a recent book on remote sensing predicted that, “Lidar imagery will have much to offer the archaeology of rainforest regions, especially with its ability to see beneath dense canopy at high resolutions” (Parcak, 2009:119). The LiDAR application reported here fulfills this prediction.

### 3. Revealing Caracol settlement through airborne LiDAR

The success of a large-footprint waveform LiDAR to penetrate the tall complex rainforest canopies of Costa Rica to record ground topography, such as previously unknown hydrological drainage networks (Hofton et al., 2002), suggested that a small-footprint LiDAR might provide the horizontal and vertical resolution needed to detect below-canopy archaeological features.

The LiDAR over-flights of Caracol were undertaken by the National Science Foundation’s National Center for Airborne Laser Mapping (NCALM), jointly operated by the University of California, Berkeley and formerly by the University of Florida (now by the University of Houston). The survey used an Optech GEMINI



Airborne Laser Terrain Mapper (ALTM) mounted in a twin-engine Cessna Skymaster and was flown between April 26 and April 30, 2009, requiring a total of 9.24 h of laser-on time during 23 h total flying time. In order to optimize penetration through the rainforest canopy, the over-flights were made at the end of the dry season to maximize the number of leaves that would be off. There were 62 north-south flight lines and 60 east-west flight lines, at nominal spacings of 260 m, from a flying height of 800 m.

The aircraft had a nominal ground speed of approximately 80 m per second and the laser was operated at a pulse rate of 100 KHz. The oscillating mirror scanner was set to a frequency of 40 HZ, and a scan angle of  $\pm 21^\circ$ , resulting in 5–6 laser shots per sq meter in each swath. With the planned swath overlap of 200 percent, approximately 20 laser shots per square meter were collected. The Gemini unit recorded up to 4 discreet returns per shot; range vectors and signal strength (intensity) were also recorded for each return. For the entire survey, 2.38 billion shots were fired, yielding 4.28 billion measurements. On average, 1.35 laser shots per square meter were able to reach the ground. Point cloud coordinates were processed with respect to ITRF2005 and referenced to the international CORS network; heights are ellipsoidal (no GEOID model was used). The end results were point-cloud data in LAS format, classified as “ground” or “non-ground,” a 1-m Digital Elevation Model (DEM) for bare earth, and a 1-m Canopy Surface Model (CSM) for canopy top points. The 1-m grid node spacing or “resolution” permits features that are just a few meters across to be easily resolved. This survey covered a total area of 199.7 sq km with a vertical accuracy of 5–30 cm.

From the DEM<sup>1</sup>, a hillshade model was applied to the 2-D raster that represents the surface. This simulates the solar and azimuth angles and permits shading and illumination across the landscape to readily depict topographic relief. This was done using ArcGIS v. 9.3 (ESRI Inc. 2009) and Surfer v. 9.9 (Golden Software, Inc. 2010) software packages in combination with Perl and Arc Macro Language (AML) scripts. Different light angles bring out different features. Thus, it is often necessary to view a piece of the landscape with several light and shade conditions to record and map the surface features (e.g., [Devereux et al., 2008](#)). The software programs permitted the rescaling of the data in the z-dimension and the application of a color gradient based on elevation above sea level. Once rendered, the user is able to view or fly through the karst hills, traversing up and down terraces or along the ancient causeways from the epicenter to the various termini.

#### 4. Results

As a result of the LiDAR imaging, the entire landscape of Caracol can be viewed in 2-D or 2.5-D (“3-D”)<sup>2</sup> ([Chase et al., 2010](#)). This imaging effectively reveals topography and built features

throughout the entire 200 sq km area; it reveals both previously mapped and previously undiscovered structural groups, agricultural fields, and causeways. Whereas before only 23 sq km of settlement and 3.5 sq km of terracing were archaeological recorded ([Chase and Chase, 1998, 2001a](#)), it is now possible to identify features throughout the entire 200 sq km area and to demonstrate that the Vaca Plateau was organized into a single urban system ([Fig. 1](#)).

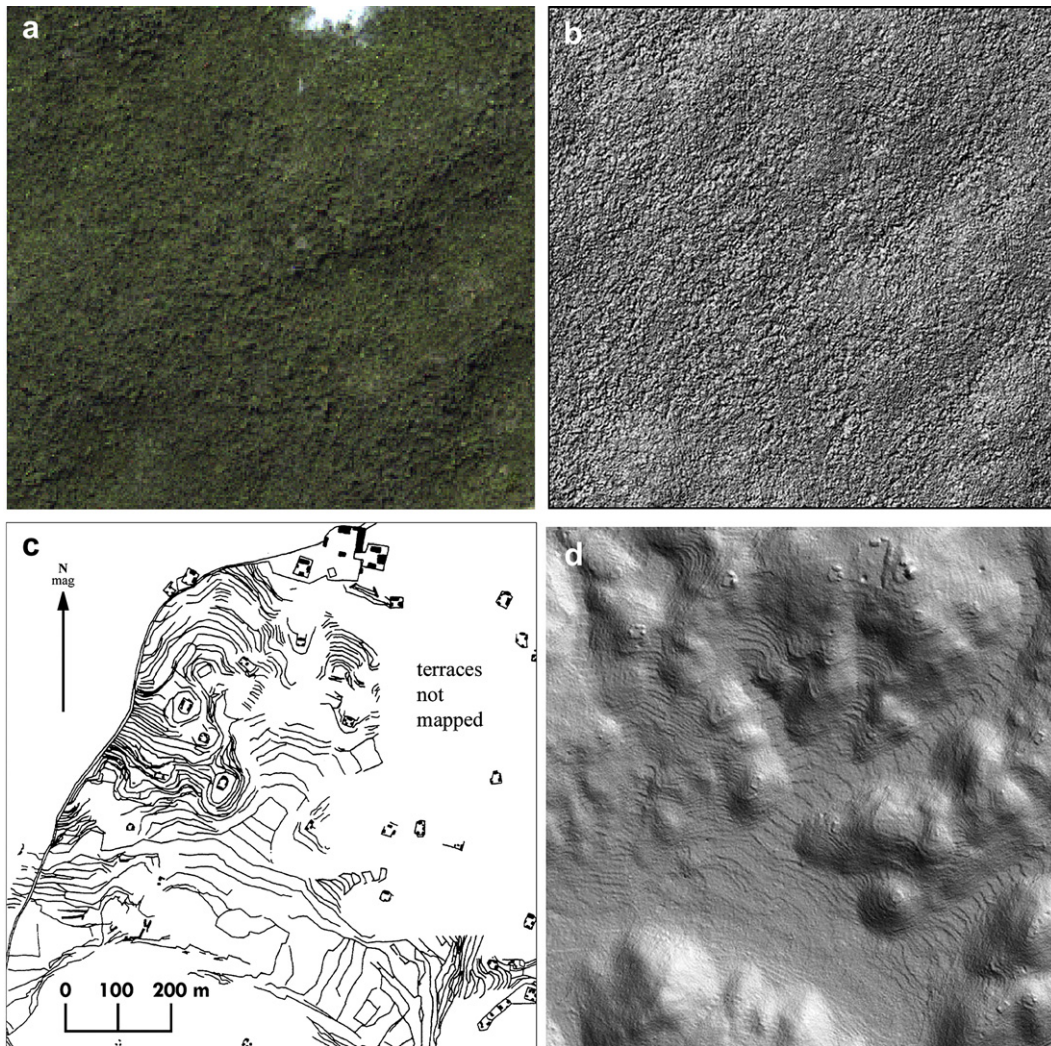
##### 4.1. Detection of new surface features at Caracol

The initial phase of the Caracol remote sensing project has two goals: first, to analyze IKONOS (1- and 4-m resolution) satellite imagery and airborne LiDAR data relative to tree canopy structure ([Weishampel et al., 2000](#)); and, second, to determine if previously mapped features, as well as undocumented remains, could be discerned from the IKONOS and LiDAR imagery. While the IKONOS imagery did not result in any definitive detection of ancient construction, in accord with a recent critique of this method ([Garrison et al., 2008](#)), the LiDAR-derived imagery provided far more useful detail than initially hoped ([Fig. 3](#)). 2-D LiDAR hillshaded DEM images clearly depict terraces, settlement, and causeways, in some cases documenting previously known features and in other cases showing previously unreported ones. The 2.5-D imagery is just as productive, revealing full topographic data, the forms and elevations of constructed features, and the height and density of the overlying tree canopy ([Fig. 4](#)). Examination of the Caracol epicenter allows effective contrast between IKONOS and LiDAR imagery, showcasing the detail evident in the LiDAR images. The largest constructed feature in the epicenter is the architectural complex known as Caana ([Fig. 5](#)), which rises to a height of 43.5 m above the plaza to its south and supports three constructions on pyramidal bases at its summit ([Ballay, 1994](#)). While Caana is visible on IKONOS imagery because the enveloping canopy has been removed, the majority of the site epicenter is not. In contrast, the hillshade model from the DEM displays the full extent of the epicenter – not only portraying the monumental architecture, but also showing causeways, walls, other settlement, and terracing ([Figs. 6 and 7](#); compare with [Fig. 2](#)).

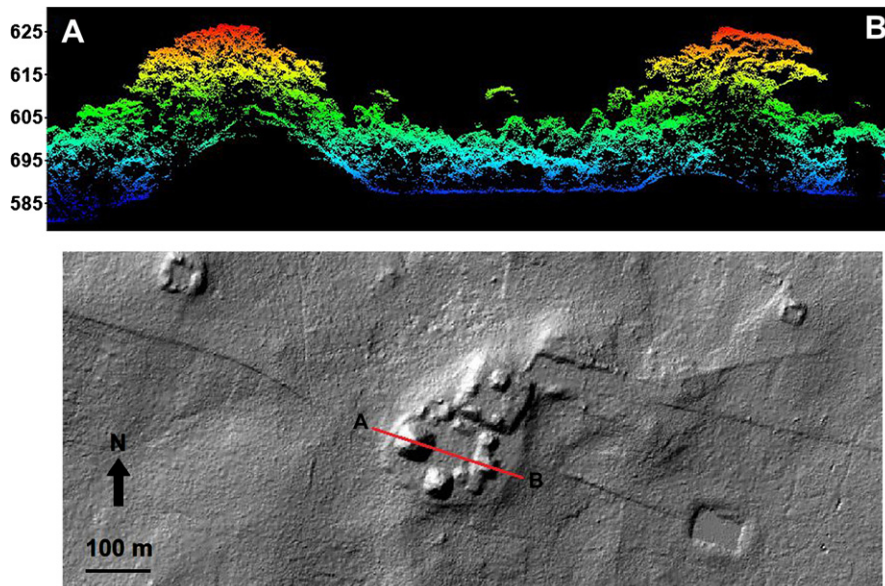
The LiDAR DEM reveals the extensiveness and density of agricultural terraces at Caracol (e.g., [Figs. 8 and 9](#)). The LiDAR DEM also portrays the anthropogenic landscape with better accuracy than can be obtained through traditional archaeological mapping and it is certainly far more comprehensive in its coverage. LiDAR shows the vast majority (nearly 90%) of the Caracol landscape to have been completely modified; terraces cover entire valleys and hills, indicating the degree to which agricultural production and sustainability was a driving force for the Maya living here. This imaging can be directly compared with existing archaeological settlement maps ([Fig. 9](#), see also [Chase and Chase, 1998](#)). Juxtaposing the earlier mapping of settlement and terraces in the vicinity of the Puchituk Terminus ([Fig. 3c](#)) with the LiDAR imagery ([Fig. 3d](#)) reveals both the accuracy of this type of remote sensing and its ability to fill in areas not completely mapped in the field. Perhaps most surprising is the fact that in both hilly and flat terrain, the LiDAR accurately accounts for both the terracing and the settlement. Even in areas that were intensively surveyed, LiDAR imaging reveals additional ancient land modification beyond that recorded through traditional archaeological techniques. In addition to terraces, visual inspection of previously mapped areas has revealed approximately 15% more elevated plazuela groups in the LiDAR images than were recorded through intensive on-the-ground mapping. These features were missed in the ground surveys because they were obscured by the rainforest growth – the same growth that the LiDAR successfully penetrates. While the airborne LiDAR may not record extremely low “vacant terrain” constructions, in most cases resolution was

<sup>1</sup> There appears to be some confusion over what a DEM and a DTM are; the two terms are often used interchangeably by researchers. A DEM, or Digital Elevation Model, has a precise meaning as an xyz elevation raster; DEM data files are digital representations of cartographic information in raster form and is the term used by the United States Geological Survey (USGS). A DTM, or Digital Terrain Model, is less precisely defined and can refer to anything from the irregularly spaced point cloud of the ground-classed points to models containing other types of information in addition to elevation rasters, such as break-lines and textures. DTED, or Digital Terrain Elevation Model, is a term used by the military for similar data. For the purposes of this research, the term DEM is used.

<sup>2</sup> Though commonly referred to as 3-dimensional or 3-D, a topographic surface is fractal in nature meaning its dimension is a fraction between 2 and 3. When such “3-dimensional” data are projected onto a 2-dimensional space such as a computer screen or piece of paper giving the illusion of depth, it is considered to be 2.5-D or pseudo-3-D. Here, we use the 2.5-D terminology which is not to be confused with a fractal dimension.



**Fig. 3.** Comparison of 4 different images of the Puchituk Terminus of Caracol: a. IKONOS imagery; b. LiDAR Canopy Digital Surface Model (DSM); c. Rectified on-the-ground map; d. Hillshaded bare earth DEM.



**Fig. 4.** LiDAR Cross-Section of the tree canopy and mounds at the Cahal Pichik Terminus. The colors from the point cloud correspond to different elevations above sea level.



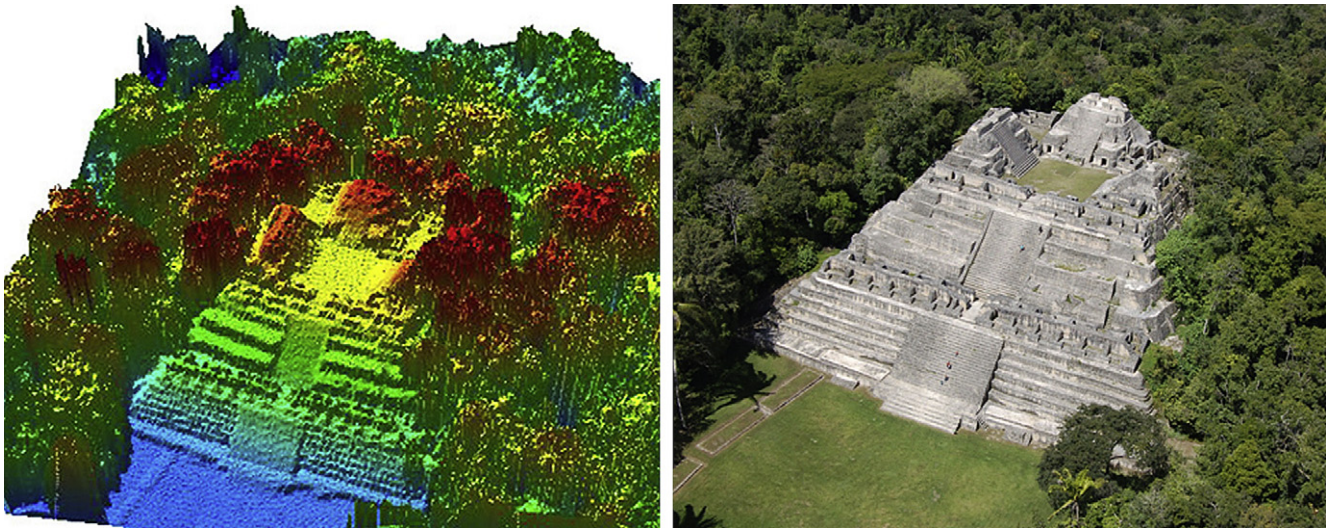


Fig. 5. Photograph and LiDAR imagery of “Caana,” Caracol’s main architectural complex; varying colors in the LiDAR data represent different elevations.

fine enough to record structures that are no more than 25 cm in height. Ground checks, traditional mapping, and excavation add details, functional information, and dating to what can be seen through the remote sensing. Equally important, the hillshaded DEM produced from LiDAR also clearly shows what non-modified hills and valleys look like in the Caracol area (Fig. 10), indicating the

limits of the urban site and permitting insight into settlement preferences and expansion.

#### 4.2. Settlement organization

Archaeological investigations at Caracol carried out over the past 25 years permit the application of temporality to the 2-D and 2.5-D images, not only providing a detailed history of occupation of the site (<http://www.caracol.org>), but also demonstrating that the majority of surface features were contemporaneously in use during the Late Classic Period. Population at Caracol peaked at approximately A.D. 650 (Chase and Chase, 1994a:5) and almost all residential groups provide archaeological evidence of occupation that brackets this date. Although having antecedents in the Late Preclassic (B.C. 300–A.D. 250), the central architectural node referred to as “Caana” (Fig. 5) became of primary importance to the site between A.D. 533 and A.D. 634, with a final rebuilding effort after A.D. 790 (Chase and Chase, 2001b). LiDAR images confirm that Caana clearly forms the central node for the entire urban system (Fig. 1); this dominance is physically expressed by the complex’s height, by its positioning in the heart of the Caracol epicenter (Figs. 6 and 7), and by the fact that it is a unique construction that is not replicated elsewhere within the Caracol landscape. Residential settlement also is the most concentrated in the vicinity of the Caracol epicenter (Fig. 11), again emphasizing the importance of this spatial location. Earlier architectural concentrations that were once independent centers were subsumed within the Caracol metropolitan area during the Late Classic Period (Chase and Chase, 2007). These include the Cahal Pichik, Hatzcap Ceel, Retiro, and Ceiba Termini in Belize, and probably the La Rejolla and San Juan Termini in Guatemala (see Fig. 1). The incorporation of these architectural nodes into the Caracol metropolitan area was physically expressed through the causeway connections and reinforced by continuous settlement and terracing that exists between the epicenter and the termini.

Based on archaeological excavation, three termini – Puchtuk, Conchita, and Ramonal – were all purposefully constructed after A.D. 550 as part of a 3 km ring of market complexes embedded in the landscape around epicentral Caracol (Chase and Chase, 2004a,b). At the same time, Ceiba, Cahal Pichik, Hatzcap Ceel, and Retiro also appear to have witnessed the addition of market plazas to their already extant monumental architecture. Based on the new hillshaded DEM for Caracol, other architectural groups were also directly linked into this system, including New Maria Camp at the

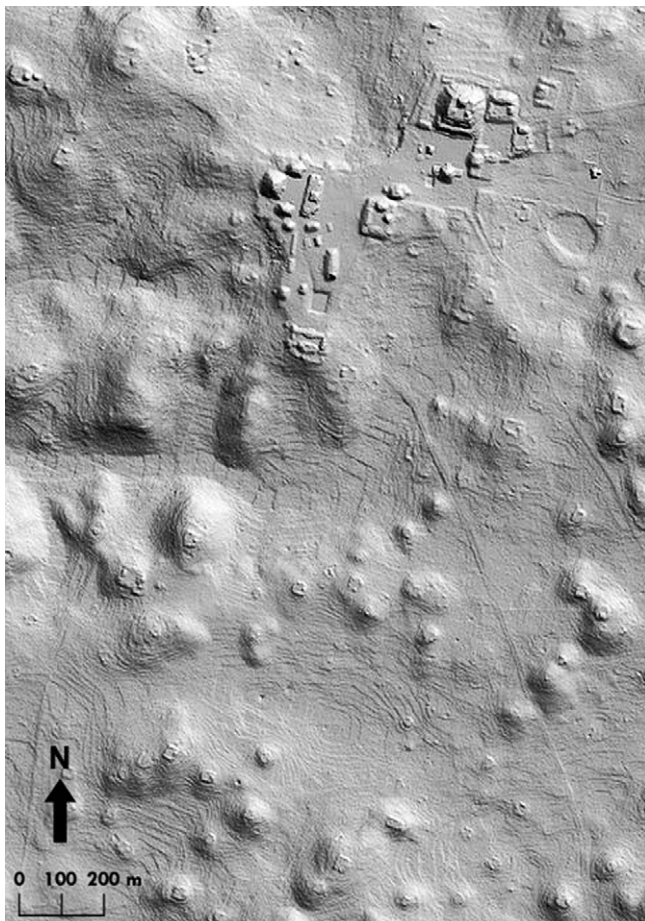


Fig. 6. LiDAR 2-D image of the Caracol epicenter.



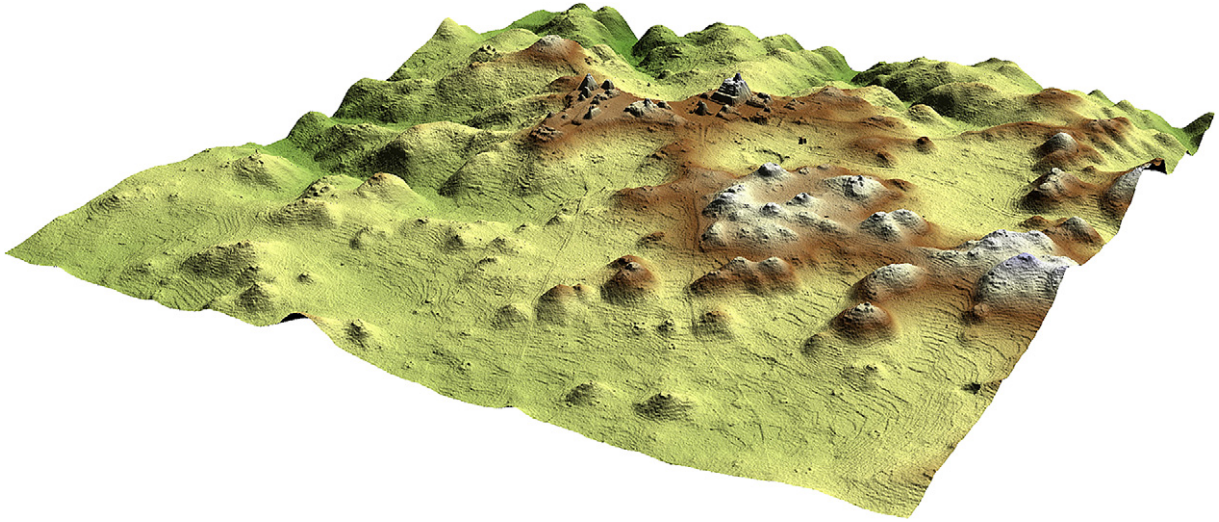


Fig. 7. LiDAR 2.5-D image of Caracol epicenter.

extreme northeast of Fig. 1 and Round Hole Bank in the southern part of this same figure. Three smaller unnamed termini, all discovered by visual inspection of the DEMs, connect to the Caracol system and likely represent purposefully placed expansion complexes: one is located in the far northern reaches of the metropolitan area and runs back to Cahal Pichik (Fig. 1: new terminus “A”); another is located in the southeastern portion of the site and connects to the Caracol – Cahal Pichik Causeway (Fig. 1: new terminus “B”); the third was placed even farther to the southeast and connects to the Conchita Terminus (Fig. 1: new terminus “C”). Cohune, Chaquistero, and another newly found architectural concentration east of Cohune (referred to as “Vaca”) do not directly tie into the system, unless the causeways are so low as to be invisible to LiDAR – suggesting that a different developmental trajectory may have occurred in this part of the site.

The initial results from the Caracol LiDAR fully indicate the relevance of this technique for documenting and interpreting landscape modification in densely forested areas. Airborne LiDAR is

more effective than previously used remote sensing techniques in that it penetrates gaps in the canopy cover to provide point data for the ground surface. Based on the Caracol DEM, LiDAR appears to be more efficient in locating ancient land modifications than traditional surveying techniques – even those of relatively low elevation contrast. It can also cover larger areas than can normally be accommodated by on-the-ground traditional mapping programs. When combined with survey and excavation, it provides an extremely powerful tool for reconstructing the ancient past.

## 5. Discussion

Interpretations made about the ancient Maya have been conditioned by modern conceptions of scale in past civilizations and by the opportunistic sampling that has been undertaken in settlement archaeology. Despite their intricate system of writing

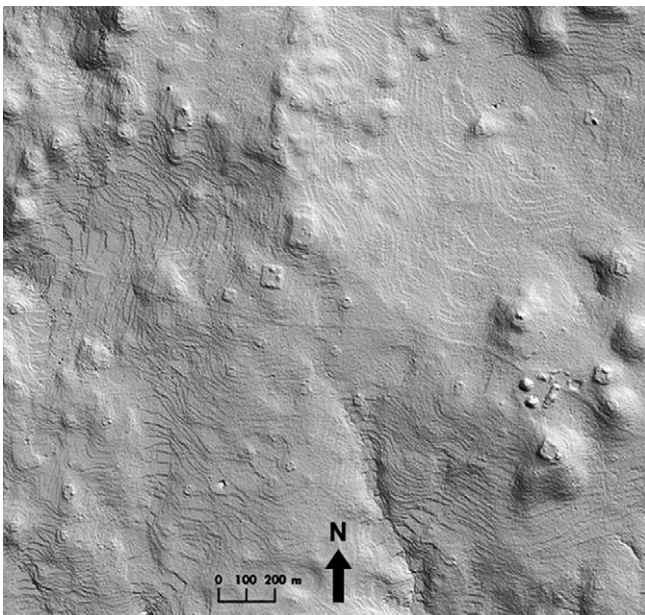


Fig. 8. LiDAR 2-D image of Ceiba Terminus showing an anthropomorphic landscape filled with constructed terraces.

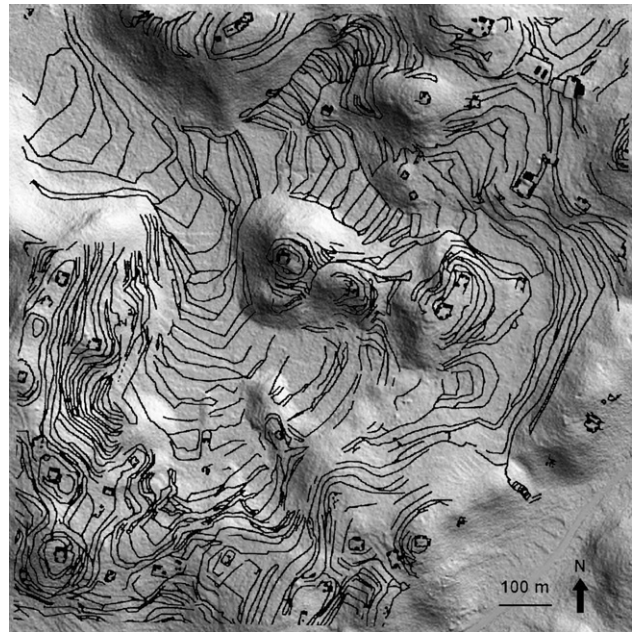


Fig. 9. LiDAR 2-D image of an area between the site epicenter and Cahal Pichik with an overlay of the archaeologically mapped settlement and terraces (after Chase and Chase 1998).



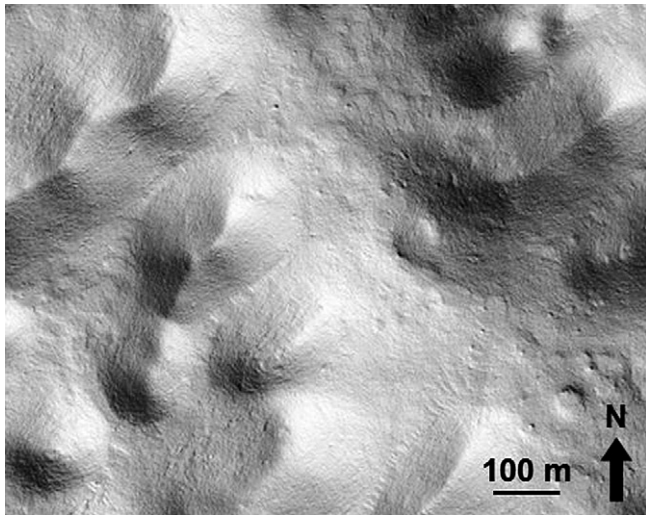


Fig. 10. A largely unmodified landscape from the southern part of the Caracol DEM.

and calendrics, Classic Period Maya cities and states have often been viewed as being smaller and less complex than contemporary societies in highland South America or central Mexico (Chase et al., 2009). To a large extent, this viewpoint has been driven both by the inability of archaeologists to fully situate Maya sites within their landscapes and by hieroglyphic interpretation that has tended to partition the landscape into individual site centers, royal courts, and hegemonic alliances (Inomata and Houston, 2001; Martin and Grube, 2000) without fully considering the potential for larger intra- and inter-regional systems of integration.

### 5.1. Scale of ancient Maya landscapes

Interpretation of Maya site scale has been constrained by the ability of researchers to fully map settlement areas. Karst topography and dense forest growth has made the complete mapping of Maya sites time-consuming and difficult – if not impossible. Even though LiDAR does not physically produce a rectified map of ancient constructions, it does enable archaeologists to view the landscape and to interpret how it was modified. Thus, LiDAR can provide a relatively complete sample of past settlement, something not hitherto possible in the Maya area. Long-term, multi-year projects have increased mapped settlement areas, but these usually have been center-focused efforts that do not fully situate these sites relative to their landscape. The difficulties of conducting survey and mapping in the tropical Maya lowlands has meant that many researchers focused on intensively recording relatively small settlement areas in the vicinity of larger architecture (e.g., Sayil, Mexico (Tourtellot et al., 1988), Dos Pilas/Aguateca, Guatemala (Demarest, 1997), and Piedras Negras, Guatemala (Houston et al., 2000)) and that other databases, such as hieroglyphic records, have often been relied upon to make socio-political interpretations. This has resulted in an inability by researchers to successfully conceptualize and communicate both the scale of Maya centers and the massive landscape modifications that could take place within their boundaries (Chase and Chase, 2003a; Chase et al., 2010).

In spite of the difficulties involved in recording the extent of Maya sites, changes in our view of ancient Maya civilization has been driven by advances in settlement studies (Sabloff and Ashmore, 2007). Once thought to be unoccupied ceremonial centers with sparsely occupied settlement areas in which populations practiced non-intensive slash-and-burn (*milpa*) agriculture (e.g., Willey, 1956), settlement mapping at the site of Tikal, Guatemala completely

changed this view by showing that slash-and-burn agriculture would have been insufficient to support the estimated population (Harrison and Turner, 1978). Subsequent research elsewhere on Maya settlement and subsistence revealed the existence not only of large populations but also of intensive agricultural systems focused on raised fields and terracing (e.g., Turner and Harrison, 1981). However, even with an increase in settlement pattern archaeology, time, funding, and rainforest growth impeded the complete documentation of most Maya landscapes.

Work at several sites – particularly, Tikal, Guatemala (Puleston, 1983), Dzibilchaltun, Mexico (Kurjack, 1979), Coba, Mexico (Folan et al., 1983), Calakmul, Mexico (Folan et al., 2001), Chichen Itza, Mexico (Cobos, 2004), and Caracol, Belize (Chase and Chase, 1987, 2001a,b) – has greatly expanded our knowledge of ancient Maya settlement. Traditional survey efforts have resulted in size estimates for many of these sites that range from 50 to 200 sq km (Chase and Chase, 2003a; Webster et al., 2007). However, in spite of years of research, the full documentation of settlement and landscape modification has generally not been possible. In some cases, popular views of these sites have been largely dependent on – and conditioned by – initial, rather than subsequent, mapping efforts and research. For instance, survey of Caracol in the 1950s produced a map of 78 buildings within its epicenter, leading the site to be viewed as small and peripheral (e.g., Adams and Jones, 1981) – a stigma that has been difficult to replace in the literature despite 25 years of continuous archaeological research.

### 5.2. Population size of Caracol

As with the spatial extent of ancient Maya settlements, population estimates for Maya sites have remained problematic (Culbert and Rice, 1990). However, image classification has the potential to discover spatial arrangement patterns that can be contrasted with available literature to create dynamic occupation models suitable for subsequent testing through excavation. Archaeological investigations in the Southern Lowlands demonstrate that many sites were fully occupied during the Late Classic Period (Haviland, 1970). Excavations in 118 residential groups at Caracol establish that minimally 95%, if not 100%, of them were in use between A.D. 650–700, at the height of the site's power and influence. Caracol's peak population has been estimated as being 115,000 people in A.D. 650, distributed over a 177 sq km area (Chase and Chase, 1994a:5). Initial cursory counts based on a visual inspection of a limited number of LiDAR light and shade combinations of the same areas indicate a minimum of 4732 elevated residential or “plazuela” groups – raised quadrilateral platforms supporting multiple structures – within the LiDAR DEM (Fig. 11). Examination of other selected areas of this DEM suggests that non-elevated residential groups – those directly on the ground surface or embedded within the terrace systems – will double the final plazuela counts. Thus, the original estimate of 115,000 people for Caracol at A.D. 650 is viable. The scale of the landscape modification and terracing visible at Caracol provides a visible demonstration as to how this population sustained itself. While it cannot yet be fully demonstrated, it is suspected that other primate Maya sites also had similarly large Late Classic Period populations embedded within an extensively modified landscape.

By providing broad-scale information on landscape modification, these new data should finally permit a more fruitful discussion of Maya urbanism; such data will aid in the modeling of Maya settlement and cities through the ability to discover and categorize spatial arrangement patterns that can be conjoined with excavation data to examine change over time. The nature of ancient Maya cities and whether or not they were truly urban has been a topic of some contention (Becker, 1979; Chase et al., 1990; Graham, 1999; Marcus

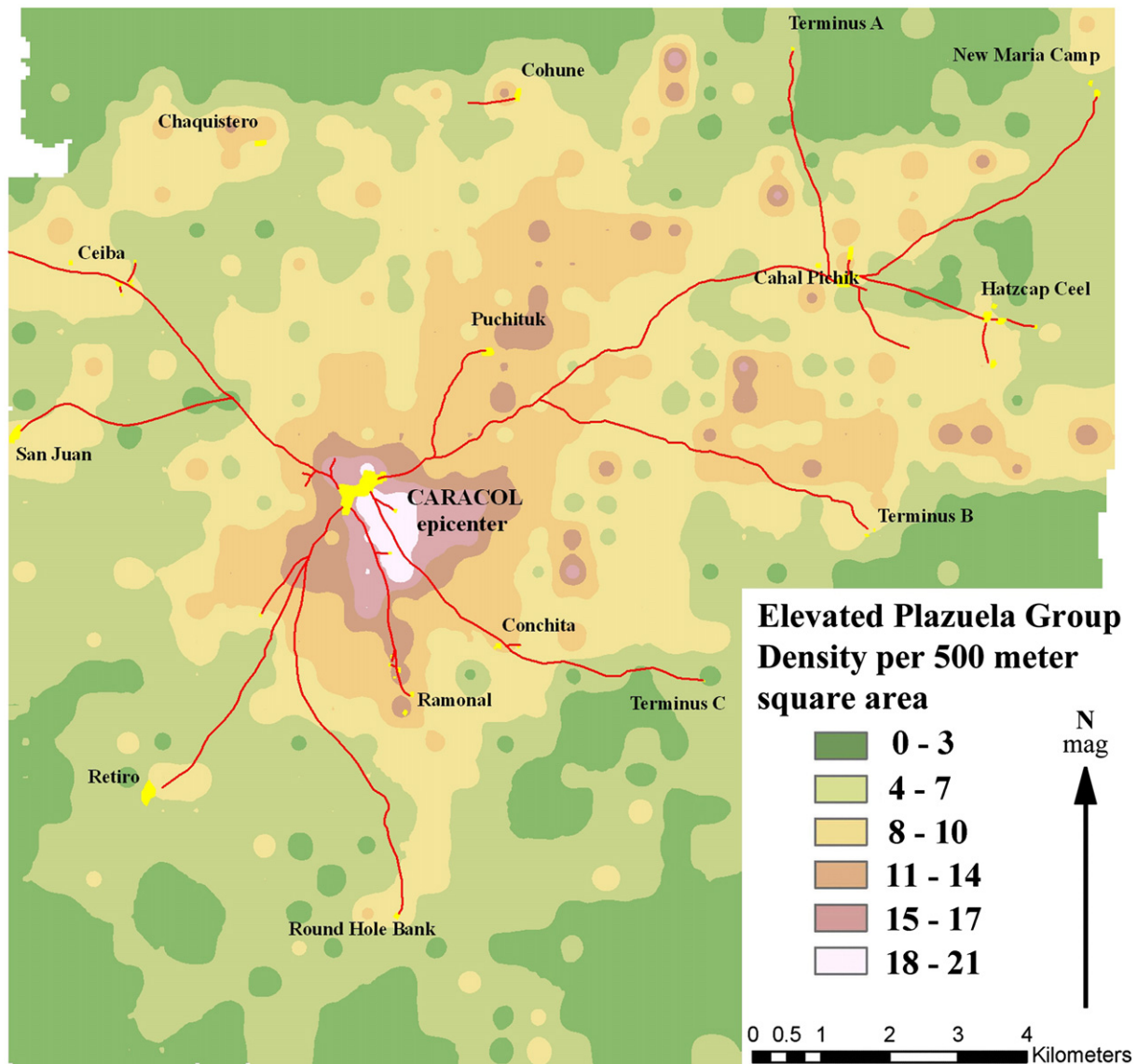


Fig. 11. Spatial distribution of elevated plazuela groups in the Caracol DEM.

and Sabloff, 2008; Rice, 2006). It has also been an issue that has been examined without recourse to full landscape information because of the difficulties involved in undertaking large-scale settlement research in a tropical environment and the inability of most remote sensing techniques to adequately penetrate dense leaf cover. Some researchers have noted that urbanism in the tropics differs from traditional Western forms (Chase and Chase, 2007; Graham, 1999), which tend to focus on dense compact settlements often arranged in a grid-like lattice (Smith, 2007). Recent synthetic writings on urbanism and city planning have led to the recognition of greater variety in past urban developments (Smith, 2007, 2009). Remote sensing has also helped to define tropical cities on the ground, particularly in Southeast Asia. Based on work using AIRSAR radar at Angkor Wat, Cambodia (Evans et al., 2007; Lustig et al., 2008; Moore et al., 2007), Fletcher (2009) has defined the ancient existence of a form of urbanism that is both low-density and agrarian-based for tropical Cambodia, Myanmar, Java, and Sri Lanka. Angkor Wat, for example, is argued to encompass almost 1000 sq km. As noted by Fletcher (2009:6), Caracol,

Belize could also be considered as a Classic Maya example of this low-density agrarian-based urbanism.

The Caracol LiDAR data presented here demonstrate the integrated form of Maya urbanism at this city and the concern with sustainability that is manifest in the immensely terraced landscape. Models of how the ancient Maya distributed themselves over their landscapes frequently focused on the relationship between monumental architecture and residential group dispersion or concentration (e.g., Willey, 1956). An integrated landscape, like the one seen at Caracol (Figs. 1 and 11), was not a consideration because of a mistaken belief in the small scale of Maya socio-political units. However, the LiDAR data for Caracol, Belize conclusively demonstrate: (1) the large-scale integration of a Maya metropolis; (2) the high density of its dispersed ancient inhabitants; and, (3) the intensive development of the Maya landscape for a sustainable base. This also constitutes the first time that an entire ancient Maya urban landscape can be viewed and analyzed, providing needed time-depth to the modern debate on massive industrial low-density urbanism (Lang and LeFurgy, 2003).



### 5.3. Ethical issues

One concern raised by the LiDAR data relates to the ethics involved in revealing such detailed imagery of an archaeological site. It is possible that the open sharing of such detailed information could lead looters directly to new targets of opportunity. These kinds of archaeological data need to be presented with caution and used responsibly. In order to protect cultural heritage, it may be necessary to place restrictions on the access and use of such high definition remote sensing data. Unless readily available already as a more traditional archaeological map, large segments of a DEM should not be openly displayed on websites like Google-Earth because of the clarity provided by the point data – and the likelihood that the hillshaded DEM could be utilized by unscrupulous individuals for looting. For the Caracol LiDAR data, different levels of access are being established through the Caracol Archaeological Project and the Belize Institute of Archaeology.

### 6. Conclusions

The imaging provided by the Caracol airborne LiDAR data squarely establishes this city as a highly-integrated, large-scale settlement located within an anthropogenic modified landscape. Archaeological investigations can reveal the fine points behind this integration by providing contextual information on dating and function. The intensity of landscape modification and the construction of agricultural terracing reveal an abiding concern with sustainability by the ancient Maya who occupied this environment. Given that the Maya had neither beasts of burden nor the use of wheeled transportation, large Maya centers may have needed to embed agriculture amidst their urban settlements. Two-hundred sq km of LiDAR data confirm the original size estimate for Caracol of 177 sq km, placing the city well within the size range of other low-density urban developments elsewhere in the ancient world. It is important to note that this 200 sq km area only constitutes the extent of the city of Caracol; archaeological investigations indicate that the Caracol polity was much larger, extending well beyond the LiDAR surveyed area and, presumably, incorporating other smaller centers.

Further application of LiDAR in the Maya lowlands will add to our understanding of Maya settlement patterns and landscape use, effectively rendering obsolete traditional methods of surveying. This technology will help dispel preconceived notions about the nature and scale of Maya sites by finally permitting the accurate and extensive recording of ancient Maya landscape alteration. While not all Maya sites will reveal the terracing so evident at Caracol, other modifications – such as boundary walls in the Northern Lowlands or hydraulic features in the bajos of the Southern Lowlands – should be identifiable in future work. LiDAR also has the capability to help researchers identify not only settlement configurations and limits but also potential political boundaries, eventually permitting accurate reconstructions of the size and make-up of ancient Maya states. For now, however, it is enough to be able to see the entire urban landscape for one ancient Maya city. These same data show that the ancient Maya designed and maintained sustainable cities long before such terminology became popularized in present-day development and “green” literature.

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