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Locating Aguadas in Northern Guatemala Using Remote Sensing

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Locating Aguadas in Northern Guatemala Using Remote Sensing

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Abstract

Water management is critical in the Maya Lowlands due to the karst landscape and seasonal wet-dry climate. To ensure that a reliable source of water was available year-round, the ancient Maya constructed aguadas, which are reservoirs of varying dimensions capable of holding water throughout the dry season. The goal of this research was to develop a method of detecting aguadas using remote sensing in the vicinity of Tikal National Park in northern Guatemala. While it is known that many aguadas exist, their distribution is poorly documented. In this study, high resolution satellite remote sensing data are used to determine aguada locations using a tasseled cap image transformation developed specifically for IKONOS images, a laplacian edge enhancement filter to detect their circular shape, a target detection algorithm and a high resolution digital elevation model.

Key words: Maya, aguadas, remote sensing
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Chapter 1

Introduction

The Central Petén plateau of Guatemala is a karst environment, and as a consequence, the landscape absorbs surface water quickly through sinkholes (cenotes) and fractures in the surface (Dunning et al. 1998). Northward on the Yucatan Peninsula, aquifers lie close to the ground surface and the Maya used cenotes as water sources. Further south, in what is now northern Guatemala and Belize, the Maya modified plugged sinkholes or constructed artificial reservoirs of various sizes, known locally as aguadas, to store rainwater that fell during the wet season. These reservoirs allowed the Maya to thrive during the peak of their civilization during the Classic period (AD 250 – 850). Localized intensive agriculture may have been possible because of these reservoirs, which may also have been used as a form of political and economic control (Scarborough and Gallopin 1991.) The inability to store sufficient quantities of water may have contributed to the downfall of many ancient Maya communities. (Beach and Dunning 1997; Dunning et al. 2002).

The locations of some aguadas are known; however, many others remain hidden within the forest canopy that covers large parts of the Petén. Aguadas were a vital component of ancient Maya communities and discerning the distribution of these features is critical to understanding the nature of Maya environmental adaptation. The study reported in this paper sought to answer one question about water supplies in the vicinity of the ancient urban center of Tikal: can aguadas be detected through remote sensing? If aguadas can be found using remote sensing, it will allow archaeologists to tie the spatial distribution of these features to the distribution of settlement remains – known both from ground surveys and, increasingly, also detectable on high
resolution satellite imagery (Garrison et al. 2008; Saturno et al. 2007) Finding aguadas has proven to be important because core samples collected from these features contain proxy data about past climatic and environmental conditions. Aguadas may also hold the key to the mystery surrounding what environmental changes that took place during the course of Maya civilization (Akipnar et al. 2008; Dunning et al. 2003).

The research reported here is an exploration of the ways in which remotely sensed imagery might be used to detect aguadas over broad areas in the Maya Lowlands. The study was carried out on the eastern side of the large ancient Maya center of Tikal (Figure 1).

(Figure 1) A map of physiographic regions in the Maya Lowlands. 1) Three rivers region. 2a) El Mirador Basin. 2b) Southern Plateau. 3) Rio de la Pasion. 4) Lancandon Fold. Adapted from Garrison et al. (2008).

Remote sensing is an important tool in this area because the dense tropical forest cover around Tikal makes ground access to many areas extremely difficult. The goal of this research
was not the classification of aguadas using traditional remote sensing methods, but target
detection of aguadas using vegetation and topography as a proxy. The aim was to find vegetative
“signatures” using image transformation techniques that will enable researchers to indentify
ancient reservoirs or aguadas in satellite imagery. Image transformations are necessary because
aguadas may not be visible in true color imagery or could be mistaken for tree crowns or other
natural features. The variability in vegetation surrounding Tikal required the development of
multiple methods. After suitable candidates were identified, field verification was attempted.

1.1) Background

This research follows from previous remote sensing analysis using high resolution
satellite imagery to identify objects of interest in the Maya Lowlands. Remote sensing surveys in
the Maya Lowlands began with Kidder (1930). Kidder and his associates, including Charles
Lindbergh, spoke about the difficulties of aerial surveys: “the sea of jungle proved to be
unbroken. Hour after hour the green floor of the tree-tops flowed back under the speeding plane
(p. 197).” Nevertheless, the aerial survey did reveal several unmapped Maya temples which
poked out of the dense tree canopy. While Lindbergh and Kidder’s aerial surveys appear crude
compared to modern remote sensing, it laid the foundation for future Maya Lowland remote
sensing research for others, for example, in Adams et al. (1981). Here synthetic aperture radar
(SAR) was used to scan the topography of the Maya Lowlands for canals and other evidence of
environmental modification. Many canals were thought to have been discovered but were
misidentified as anomalies caused by the radar instrument and post processing of the data
(Garrison 2007). With SAR, Pope and Dahlin (1989) also attempted to map canal systems in
western and northern Guatemala and the Yucatan Peninsula, but concluded that smaller canal
systems did not exist in many areas identified by Adams et al. The absence of hypothesized canal systems inside swamps was “not due to forest cover and reflects a true absence of canals (Pope and Dahlin 1989, p. 101).”

One of the first applications of high resolution satellite imagery in this area was detailed by Sever and Irwin (2003). IKONOS high resolution satellite imagery, along with other high resolution data sets, was used to analyze linear features hypothesized to be canals or causeways in bajos (seasonal swamps) near Tikal and elsewhere. The features were conspicuous in Landsat medium resolution imagery and are still being analyzed to determine their nature. Saturno et al. (2007) developed a “settlement signature” using IKONOS imagery with the aid of several image transformations to enhance the discoloration of vegetation over archaeological sites resulting from limestone and plaster decay which affects overlying vegetation. Subsequent fieldwork verified that the signature was indicative of large-scale Maya settlements. Garrison et al. 2008 applied this technique to other areas in the Maya Lowlands with varying degrees of success. They concluded that differing levels of vegetation moisture along with other topographic factors affected the analysis in such a way that the success rate found for identifying sites achieved by Saturno et al. could not be replicated. Linear features were also detected on IKONOS imagery in the Bajo de Azucar north of San Bartolo (Garrison 2007; Garrison and Dunning 2009), along with many dark spots that were interpreted as probable aguadas (Garrison 2007). However, later ground reconnaissance in the bajo revealed that the two dark spots visited on the ground were not aguadas and that two very large aguadas visited on the ground had not been detected in the IKONOS imagery (Dunning and Griffin 2009).

These past research projects were focused on locating large features in high resolution imagery. In some cases, aguadas were incidentally identified but were never the focus of the
research. In this research, we will examine the effectiveness of several remote sensing techniques specifically for detecting potential aguadas. Explanations are then offered as to why some methods work well and why others were not as effective.

**Chapter 2**

**Study area**

The ruins of the ancient Maya city of Tikal are located in the Department of Petén in northern Guatemala, about 30 kilometers north of Lake Petén Itza, the nearest significant body of permanent surface water. The region contains roughly 800 species of trees along with 500 species of birds and large numbers of mammal species of various sizes from herbivores such as tapirs to carnivores such as jaguars (Sever 1998). Despite its great distance from any perennial water source, Tikal once boasted a population of possibly 25 – 50,000 or more (Harrison 1999). The national park today covers more than 574 square kilometers (Nations 2006). Tikal is situated in a region underlain by carbonate rock the dissolution of which manifests itself in three distinct types of karst terrain such as dolines, polygonal networks, and mogotes (Bundschuh and Alvarado, 2007). The climate can be characterized as humid subtropical with average annual rainfall ranging from 1000 mm to over 3000 mm, 90% of which arrives during the June - November wet season. The inhabitants of the ancient city relied on an innovative system of reservoirs with an estimated storage capacity of 900,000 m³ to meet their needs, especially during the dry season (Scarborough and Gallopin 1991). While the occupation of Tikal is known to extend back at least to 800 BC, the major periods of occupation and construction of monumental architecture were the Late Preclassic through the Late Classic periods (ca 300 BC to 800 AD) (Harrison 1999).
During the 1950’s, researchers from the University of Pennsylvania Museum initiated an excavation project to document, analyze, and eventually restore sections of the site of Tikal. Between the years of 1958 and 1960, J.E. Hazard and R.F. Carr began a mapping project of the city of Tikal. The final product was a topographic map of nine square kilometers with major temples, plazas, and house mounds. Also included in the map were the locations of reservoirs that formerly stored water during the dry season. The larger reservoirs were located next to major temples and plazas on higher elevation, while smaller reservoirs were located next to residential groups. It was also noted in their final report that there is considerable evidence to suggest that quarries were turned into reservoirs.

In addition to this survey, Dennis Puleston (1983) undertook a survey using a transect starting between Temple 1 and Temple 2 heading east to the eastern boundary of the park - as well as transects to the north, south, and west. He reported the presence of many aguadas, along the course of the East Transect, both within the densely settled uplands and along the margins of bajos. The presence of these aguadas distributed within the mosaic of land surface and forest types led us to select the East Transect and contiguous areas as a proving ground for aguada detection.

2.1) 2009 field season

In 2009, a University of Cincinnati project began work examining ancient Maya water, land, and forest management at Tikal (Lentz et al. 2009). This work included investigations of reservoirs and aguadas in the site center and hinterlands. Some of these aguadas were previously known from the excavations and survey projects conducted by the University of Pennsylvania in the 1950’s and 1960’s and detailed later in the “Tikal Reports,” as well as from later studies. Our
investigations included the Aguada Pucte and Aguada de Terminos situated in a sprawling seasonal wetland known as Bajo de Santa Fe on the east side of Tikal. The two aguadas help illustrate the variable nature of vegetative cover in aguadas today.

Aguada Pucte lies within an arm of the Bajo de Santa Fe stretching into exurban Tikal. Although it is roughly 25 x 20 m the aguada is almost completely canopy covered and cannot be seen on satellite imagery except as an indistinct cluster of pucte trees (*Bucida buceras*). A 50-cm sediment core was obtained from the Aguada Pucte and a calibrated basal radiocarbon date of AD 900 – 1030 indicates that the core only sampled sediments from the Terminal Classic onward, likely a byproduct of the periodic dredging of this and other aguadas during the Classic Period (Dunning et al. 2009).

Aguada de Terminos lies on the southern flank of the same large arm of the Bajo de Santa Fe. Access to the aguada is relatively easy as it lies along the east arm of the Tikal Park cruciform brecha which formed the baselines for Dennis Puleston’s settlement survey (Puleston 1983). The aguada also lies along an older informal access road and evidently long served as a camp spot for chicleros and other modern users of the forest. In April 2009, much of the aguada was filled with a meter or more of water (Figure 2). Reportedly the aguada retains some water through the dry season during all but the driest years. The open interior area of the aguada is roughly 50 x 60 m, large portions of which are usually vegetated with “lechuga de agua” (*Pistia stratiotes*) which is distinctive in high resolution satellite imagery as a bright lime green color.
Aguada de Terminos also stands out in satellite imagery because it lies on an ecotonal boundary. The area to the west and north of the aguada is Tintal bajo, dominated by Palo de Tinto \textit{(Haematoxylon campechianum)} and other vegetation adapted to edaphic moisture extremes. South and east of the aguada are low-lying mixed palm forests; on the east, the terrain rises onto a peninsula of well drained upland forest that projects northward into the bajo. Coring and excavations in and around the aguada indicate that it likely originated as a Preclassic chert quarry before being modified into a reservoir, and which was used intensively until at least 800 AD (Dunning et al. 2009).
Investigations were also undertaken in several of the reservoirs within the central precinct of Tikal (Carr and Hazard 1961; Lentz et al. 2009). However, these reservoirs were not included in the aguada prospection study because these high elevation features are intimately linked with central monumental architecture and are physically very different than most aguadas.

Chapter 3

Methodology

Our investigations included examination of existing maps and imagery to inventory known aguadas, ground investigations at several aguadas in 2009, subsequent analyses of satellite imagery with the goal of creating a signature or signatures for aguadas, and ground truthing of detected aguadas in 2010. Four processing techniques were applied to the remote sensed imagery: three to the IKONOS image and one to the AirSAR DEM.

Past research by Lundell (1937) and many others revealed that aguadas can be as small as 10 meters across while other can be more than 100 meters. As a result of this variability, high resolution satellite data is needed to find aguadas of all sizes. For this research, IKONOS images, distributed by the GeoEye Corporation were used because of high spatial resolution and its successful application in archaeological research (Campana 2002; De Laet et al. 2006; Garrison 2007; Garrison et al. 2008; Sever and Irwin 2003). The IKONOS remote sensing data, purchased and provided by the NASA Marshall Space Flight Center, in Huntsville, Alabama is equipped with four spectral bands with 4 meter resolution – blue, green, red, near infrared. In addition, the IKONOS dataset comes with a grey scale panchromatic band with 1 meter resolution. The multispectral bands can be pan – sharpened with the panchromatic band to produce a 1 meter
resolution color dataset. The IKONOS image used in this study was acquired in March of 2001, the peak of the dry season (Figure 3).

(Figure 3) False color IKONOS view of Tikal. The runway used during the University of Pennsylvania excavations is seen as a straight line near the center image going from the southwest to the northeast. The dark expansive feature on the right side of the image and extending into the middle of the scene is the Bajo de Santa Fe

Many aguadas and reservoirs began as quarries or small dolines and are manifested as sharply defined depressions. Hence, we hypothesized that it might be possible to detect them topographically by using remote sensing data that is able to see localized circular or oval features on the surface. In 2004, NASA Jet Propulsion Laboratory (JPL) conducted a radar mapping mission of several archaeological sites in the Maya Biosphere Reserve (MBR). The radar
instrument, known as the airborne synthetic aperture radar (AirSAR), has the ability to penetrate
the forest canopy because of its longer wavelengths that passes through vegetation without
significant loss of its return signal known as backscatter. The JPL radar instrument operates in
three bands C, L, and P. The C band is more or less “first return” – the wavelengths are not long
enough to penetrate the dense forest canopy thus are reflected back once they strike an object.
From this band, a 5 meter spatial resolution digital topographic map or digital elevation model
(DEM) was produced (Figure 4). The L band does penetrate the forest canopy but is scattered by
branches at the mid-level. The P band has wavelengths long enough to penetrate the canopy and
the mid-level branches (Jensen 2007). We hypothesized that aguadas with open canopies should
appear in the DEM as roughly circular depressions.
3.1) Data processing

For this research, we used ENVI 4.7 image processing software to perform image transformations, as discussed below. The resulting transformations were then exported in a geotiff file format and displayed in ArcGIS software for easier viewing. The IKONOS image used in this study was pan-sharpened for better detailed viewing using the Gram-Schmidt method since this method preserves color and texture (Jensen 2005). Three transformations were applied to the IKONOS image in an attempt to create aguada signatures.
After pan-sharpening was accomplished, a tasseled cap transformation was applied to the IKONOS image. The tasseled cap was originally developed for Landsat MSS satellite images and is an orthogonal rotation of the image similar to a principal components transformation (Crist and Cicone 1984; Crist 1985). This orthogonal rotation results in the creation of several new bands based on brightness, greenness and wetness factors (Turner et al. 2004). A tasseled cap transformation for IKONOS images was developed by Horne (2003) by sampling over 195 IKONOS images and applying principal component transformations to each image to derive the eigenvalues which explain the variance in each image band. Using a least squares regression to fit the results, four new tasseled cap coefficients were derived for each original band in the IKONOS dataset:

\[ TC1 = 0.326 \times \text{blue} + 0.509 \times \text{green} + 0.560 \times \text{red} + 0.567 \times \text{nir} \]

\[ TC2 = -0.311 \times \text{blue} - 0.356 \times \text{green} - 0.325 \times \text{red} + 0.819 \times \text{nir} \]

\[ TC3 = -0.612 \times \text{blue} - 0.312 \times \text{green} + 0.722 \times \text{red} - 0.081 \times \text{nir} \]

\[ TC4 = -0.650 \times \text{blue} + 0.719 \times \text{green} - 0.243 \times \text{red} - 0.031 \times \text{nir} \]

The first tasseled cap band is capable of detecting very bright objects similar to the panchromatic band and could be considered a summation of the original four band dataset. The second is useful in distinguishing surface types such as vegetation and man-made features. The third and fourth tasseled cap bands are useful in distinguishing different types of vegetation and soil and represent 1.5% and 2% of the total variance respectively (Cheng et al. 2008). These coefficients were applied to the IKONOS image of Tikal. If aguadas with *Pistia* or any other surface vegetation are present, they should be visible based on brightness factors.

Sever and Irwin (2003) used a laplacian filter to isolate linear features within bajos. Filters have also been used in archaeological studies to enhance targets which were thought to be
ancient structures (Parcak 2009). A laplacian filter is a special type of filter which enhances edges regardless of direction. This filter uses a processing window block with a high central value or kernel surrounded by negative weights. It centers on one pixel and analyzes its neighboring pixels to determine if the center pixel is distinct or similar from the neighboring pixels. If a pixel is distinct from its neighboring pixels, it will be enhanced then the processing window moves to the next processing window block. Our goal was to use this filter to enhance the abrupt edges of aguadas with open canopies. For this research, a laplacian filter with a window size of 13x13 was applied to the original pan-sharpened data set and the tasseled cap transformation. A 13x13 window was deemed optimal after experimenting with smaller and larger window sizes. Smaller window sizes tended to reveal less textural information while larger window sizes resulted in too much textural information, which was impractical to analyze.

The last image transformation technique used on the IKONOS image was the Reed-Xiaoli Detector algorithm (RXD). This algorithm was originally developed for hyperspectral imagery but is also used in multispectral datasets. This algorithm detects spectral differences between a test region and the image background. The filter is implemented using the following equation –

\[
\delta_{RXD}(r) = (r - \mu)^T K_{LXL}^{-1} (r - \mu)
\]

In this equation, \( r \) is the pixel vector; \( \mu \) refers to the sample mean and \( K_{LXL} \) is the sample covariance of the image (Chang and Chiang, 2002). In this way, it highlights anomalies based on either a global scale, which takes into account the whole image, or a local scale for which a local kernel size must be selected (Chang and Chiang, 2002). Based on the 2009 aguada visits, we hypothesized that aguadas with surface vegetation would be spectrally distinct in comparison to the surrounding tree canopy. Similar to the laplacian edge enhancement filter, this algorithm also
uses a processing window to analyze pixels to determine spectral differences. For this study, a
local window size of 300 was applied to the original pan-sharpened dataset and the tasseled cap
image after experimenting with different window sizes.

The AirSAR derived DEM was converted into a hillshade. A hillshade is a surface which
has been given an artificial illumination based on sun azimuth and angle. In this research, the
DEM was imported into ArcGIS 9.3 software and turned into a hillshade with a default sun
azimuth angle of 315 and altitude of 45 degrees. By varying the azimuth and altitude, it is
possible to highlight features based on line of sight of a hypothetical light source. For our
analysis, the default settings were sufficient to highlight features that were suspected to be
aguadas.

Chapter 4

Results/Discussion

Using the tasseled cap method, four potential aguadas of various sizes were detected in
the area east of central Tikal and which were not mapped by the University of Pennsylvania
excavation team, and are a considerable walking distance from the center of Tikal and from the
East Transect (Figure 5).
(Figure 5) IKONOS tasseled cap transformation. All the aguadas, with the exception of aguada #2 are located on uplands and all are more than 4 kilometers from the center of Tikal.

When viewed up close, aguada #1 and #4 have similar texture and perhaps contain similar vegetation (Figure 6).
Aguada #2 is situated inside a bajo and Aguada #3 appears to contain surface vegetation that is different from the other aguadas (Figure 7).
The laplacian edge enhancement filter was able to discern three out of the four possible aguadas seen in the tasseled cap transformations. The edge enhancements below are from the original pan – sharpened dataset. There was no discernable difference between the edge enhancement of this dataset and the tasseled cap dataset. One disadvantage to using this filter in heavily forested areas is the height of vegetation. If an aguada is located next to Tintal bajo where the vegetation is short, such as aguada #2, the edge enhancement filter may have difficulty delineating distinct edges (Figure 8).
The RX algorithm, applied to the original pan-sharpened, was successful in locating two out of the four potential aguadas seen in the tasseled cap image (Figures 9 and 10). There was also no discernable difference when this algorithm was applied to the tasseled cap dataset. It should be noted that using a high kernel size resulted in the image displaying dozens of potential targets many of which are undoubtedly false targets. This is possibly due to the IKONOS image having only four bands in particular, the near-infrared band which is not very useful in differentiating vegetation species (Estrada-Belli and Koch, 2007).
In March of 2010, the field team was given coordinates for these potential aguadas and those mapped by Puleston along the East transect for ground truthing. The team confirmed that Aguada #2 is a previously undocumented aguada (now called Aguada Vaca del Monte). Unfortunately, the other potential aguadas (1, 3, and 4) seen in the tasseled cap image could not
be reached on the ground. However, several other aguadas along the East Transect were successfully ground-truthed against the IKONOS image or DEM hillshade map (Table 1 and Figure 11).

(Table 1) Aguadas studied in this research

<table>
<thead>
<tr>
<th>Aguada</th>
<th>Coordinates (UTM 16N) WGS 84</th>
<th>Dimensions</th>
<th>Canopy</th>
<th>Visible in IKONOS</th>
<th>Visible in hillshade</th>
<th>Ground truthed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pucte</td>
<td>225802.46E 1906203.03N</td>
<td>25 x 20 m</td>
<td>Closed</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Terminos*</td>
<td>226254.46E 1905604.03N</td>
<td>50 x 60 m</td>
<td>Open</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Benito</td>
<td>227976.46E 1905851.03N</td>
<td>40 x 50 m</td>
<td>Closed</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Elmer*</td>
<td>228567.46E 1905512.03N</td>
<td>20 x 30 m</td>
<td>Closed</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Carlos</td>
<td>229530.46E 1906847.03N</td>
<td>30 x 40 m</td>
<td>Partially open</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Vaca Del Monte</td>
<td>230209.46E 1907436.03N</td>
<td>40 x 50 m</td>
<td>Open</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Aguada #1</td>
<td>227336.46E 1910159.03N</td>
<td>30 x 30 m</td>
<td>Open</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Aguada #3</td>
<td>228892.46E 1903261.03N</td>
<td>60 x 70 m</td>
<td>Open</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Aguada #4</td>
<td>225797.46E 1901602.03N</td>
<td>20 x 20 m</td>
<td>Open</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Sarteneja*</td>
<td>231561.51E 1905409.06N</td>
<td>50 x 50 m</td>
<td>Open</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>La Presa*</td>
<td>231919.51E 1905155.06N</td>
<td>20 x 30 m</td>
<td>Closed</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

*Aguadas mapped by Puleston*
(Figure 11) Hillshade map of aguadas visited in 2010 and false positives
Aguada de Terminos in March 2010. The aguada was completely dry and its floor was covered with vining ground cover and sedges.
Chapter 5

Conclusions

Based on the aguadas discovered or confirmed, it is clear that remote sensing is an effective tool to locate aguadas when using high resolution remote sensing datasets. Although the team could only visit one of the aguadas seen in the tasseled cap transformations, its confirmation as an aguada proved that a tasseled cap transformation can be used to detect and

(Figure 13) Aguada Vaca del Monte. The interior was still moist in many areas and the floor was covered in 3 different types of saw sedge (*Scleria bracteata*) and cattails (*Typha domingensis*).
distinguish aguada surface vegetation from the surrounding canopy vegetation though this will
depend on conditions such as water and vegetation type. Thus our goal of finding aguada
“signatures” based on vegetation was somewhat successful. The laplacian edge enhancement
filter performed sufficiently well but appeared to have problems detecting aguadas that are
surrounding with short vegetation. The implementation of the RXD algorithm had similar results
when compared to the tasseled cap transformation although it took several permutations to
determine the correct local kernel size to display anomalous entities within the image and only
two aguadas of the four aguadas seen in the tasseled cap image were visible. The hillshade could
be considered as successful as the tasseled cap image in locating aguadas; however, we
encountered false positives while using the hillshade. Three potential targets turned out to be
areas of fallen trees which appeared in the DEM as depressions.

Based on their distribution in the image, most of these aguadas are located on uplands
next to bajos. This appears logical: aguadas would not be constructed in seasonal swamplands
which dry up every year with the exception of Vaca del Monte. They would be located in areas
near settlements or where topography was favorable to facilitate the construction of an aguada.
In this study, potential aguadas were discovered without the expense of spending weeks in a
dense forested area looking for objects of interest, which is often inefficient and unnecessary.
While remote sensing is a very powerful tool, we must also be aware of the fact that false
positives are an unavoidable aspect of remote sensing research especially in heavily forested
areas.

As with many remote sensing techniques, there is room for improvement and validation.
Since the remote sensing techniques applied above were successful in one study area, it should
be applied to other areas to validate the techniques. In addition, it would be beneficial to acquire
other high resolution imagery such from platforms such as WorldView – 2 from the Satellite Imaging Corporation. This platform has eight multispectral bands with 1 meter resolution. Eight multispectral bands will allow for more spectral analysis than is possible with IKONOS. Although WorldView – 2 may offer more information, the images are expensive and beyond the means of this project. Therefore, it was prudent to use free or existing datasets to locate suitable study areas.

The humid subtropical forest contains microclimates thus there will be years with localized drought. It is advantageous to acquire high-resolution satellite images with multi-temporal datasets. The ASTER instrument aboard NASA’s Terra satellite provides higher image resolution (15 m per pixel) and more spectral bands than the Landsat series satellites although Landsat has better temporal coverage with medium resolution (30 m per pixel). If some large aguadas dry out because of drought conditions in certain years, multi-temporal datasets would allow us to analyze the localized seasonal cyclicity of drought periods. From this, perhaps we could detect aguadas that were not originally detected by the IKONOS image since it was taken during a particular month and year.

Another option to be considered is LIDAR which can penetrate the forest canopy and can be used to generate a true surface model. The SAR DEM was sufficient in locating potential aguadas which were not clearly visible in the IKONOS images. However, the DEM was not a true elevation model because the radar band in which the DEM was created did not have enough power to penetrate the dense forest canopy thus; accordingly, the elevation model is actually the tops of trees. With the addition of LIDAR, it may be possible to truly detect aguadas topographically as well as other objects of interests such as house mounds which cannot be seen in the IKONOS image.
We have seen in this research the power of remote sensing technology to study a once great civilization. Remote sensing offers us a non-destructive and cost-effective way of analyzing the extent to which the Maya modified their environment. As remote sensing technology evolves, it will allow us to discover and map what has yet to be discovered in the Maya Lowlands and to aid in preserving biodiversity in this small but historic region.
References


Kidder, A.V. 1930. Five days over the Maya country. Scientific Monthly (March) 30 (3), 193–205


Appendix

IKONOS Metadata

Product Order Metadata

Product Order Number: 65219
Customer Project Name: 799 Intl Standard Original
Product Order Area (Geographic Coordinates)
  Number of Coordinates: 4
  Coordinate: 1
    Latitude: 17.27717625 degrees
    Longitude: -89.63864517 degrees
  Coordinate: 2
    Latitude: 17.27850867 degrees
    Longitude: -89.53529346 degrees
  Coordinate: 3
    Latitude: 17.17924574 degrees
    Longitude: -89.53393924 degrees
  Coordinate: 4
    Latitude: 17.17792144 degrees
    Longitude: -89.63723589 degrees
Product Order Area (Map Coordinates)
  Coordinate: 1
    Map X (Easting): 230463.99 meters
    Map Y (Northing): 1912137.53 meters
  Coordinate: 2
    Map X (Easting): 230463.98 meters
    Map Y (Northing): 1901145.51 meters
  Coordinate: 3
    Map X (Easting): 219467.96 meters
    Map Y (Northing): 1901145.51 meters
  Coordinate: 4
    Map X (Easting): 219467.97 meters
    Map Y (Northing): 1912137.53 meters
Sensor Type: Satellite
Processing Level: Standard Geometrically Corrected
Image Type: PAN/MSI
Interpolator Method: Bicubic
Multispectral Algorithm: None
Stereo: Mono
Mosaic: No
Map Projection: Universal Transverse Mercator
  UTM Specific Parameters
Hemisphere: N
Zone Number: 16
Datum: WGS84
Product Order Pixel Size: 1.00 meters
MTFC Applied: Yes
DRA Applied: No
Media: CD
File Format: GeoTIFF
   TIFF Tiled: No
   Bits per Pixel per Band: 11 bits per pixel
Multispectral Files: Separate Files
Special Instructions: NA

Source Image Metadata

Number of Source Images: 1
Source Image ID: 2001031316191760000011628207
Product Image ID: 000
Sensor: IKONOS-2
Acquired Nominal GSD
   Cross Scan: 1.04 meters
   Along Scan: 0.92 meters
Scan Direction: 0 degrees
Nominal Collection Azimuth: 97.9205 degrees
Nominal Collection Elevation: 61.56447 degrees
Sun Angle Azimuth: 123.8964 degrees
Sun Angle Elevation: 56.63217 degrees
Acquisition Date/Time: 2001-03-13 16:19

Product Space Metadata

Number of Image Tiles: 1
   X Tiles: 1
   Y Tiles: 1
Product MBR Geographic Coordinates
   Number of Coordinates: 4
   Coordinate: 1
      Latitude: 17.27717625 degrees
      Longitude: -89.63864523 degrees
   Coordinate: 2
      Latitude: 17.27850908 degrees
      Longitude: -89.53526553 degrees
Coordinate: 3  
   Latitude: 17.17921926 degrees  
   Longitude: -89.53391090 degrees  
Coordinate: 4  
   Latitude: 17.17789455 degrees  
   Longitude: -89.63723551 degrees  

Product Map Coordinates  
   UL Map X (Easting): 219467.96 meters  
   UL Map Y (Northing): 1912137.53 meters  

Pixel Size X: 1.00 meters  
Pixel Size Y: 1.00 meters  
Columns: 11000 pixels  
Rows: 10996 pixels

==================================================================================================

Product Component Metadata

Number of Components: 1  
Tile ID: 0000000  
Product Image ID: 000  
Tile File Name: po_65219_pan_0000000.tif po_65219_red_0000000.tif  
   po_65219_grn_0000000.tif po_65219_blu_0000000.tif po_65219_nir_0000000.tif  

Tile Geographic Corner Coordinates  
   Number of Coordinates: 4  
   Coordinate: 1  
      Latitude: 17.27717625 degrees  
      Longitude: -89.63864523 degrees  
   Coordinate: 2  
      Latitude: 17.27850908 degrees  
      Longitude: -89.53526553 degrees  
   Coordinate: 3  
      Latitude: 17.17921926 degrees  
      Longitude: -89.53391090 degrees  
   Coordinate: 4  
      Latitude: 17.17789455 degrees  
      Longitude: -89.63723551 degrees

Tile Map Coordinates  
   UL Map X (Easting): 219467.96 meters  
   UL Map Y (Northing): 1912137.53 meters  

Pixel Size X: 1.00 meters  
Pixel Size Y: 1.00 meters  
Columns: 11000 pixels  
Rows: 10996 pixels