THE EXPLORERS CLUB FLAG 99 REPORT

Petén Archaeological Expedition, Guatemala

31 January, 2014 – 14 February, 2014

Alistair Calvert contemplating his options on the Petén Archaeological Expedition. Image: Toby Savage©

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Project Overview:

This report describes the results of the Petén Archaeological Expedition (PAE), a multidisciplinary project involving 23 scientists, engineers, archaeologists, journalists, EC Members, and support staff. Our objective was to complete a series of field tests of experimental LiDAR UAV platform prototypes in the jungles of Guatemala. The expedition also collected archaeological and conservation data including a series of highly precise recordings of fragile and deteriorating limestone iconography, large scale recordings of pyramid and plaza complexes as well as highly accurate 3D LiDAR data sets of a previously unrecorded Maya tomb (AD 300-600). AIRSAR radar was used to successfully predict the location of two previously unrecorded Maya settlement sites (circa AD 300–900) which were documented via ground reconnaissance.

Figure 1: Flag #99 and EC members in Flores Guatemala at the end of the Expedition: Robert J. Atwater, LF, Dr Albert Lin, FN, Douglas Inglis, TM and Jason Paterniti, FN

Project Explanation:

The Petén in northern Guatemala covers approximately 36,000 square kilometers.   This area was once the home of the ancient Maya, a civilization which flourished from the Pre-classic period circa 1,500 B.C., and then abruptly collapsed starting around AD 900. (William Saturno, 2007).

For the last 200 years, non indigenous explorers have battled heat, humidity, insects and disease in their efforts to penetrate the dense jungles of the Petén in search of Maya ruins. More often than not, the objective of these efforts was to loot these sites for profit, not to learn from or preserve them.

While many monumental Maya sites have been discovered and recorded in the last century,   Maya scholars believe that much of the physical remains of the ancient Maya civilization may still be buried deep in the jungle (Barnhart). Today, advances in remote sensing technologies can help researchers and scholars to level the playing field against looters before these precious unrecorded cultural heritage sites are lost forever.

History of Remote Sensing Exploration in the Petén:

The use of remote sensing techniques in the Petén can be traced back to 1929. During a survey to identify airmail routes for Pan American Airways, Charles A. Lindbergh saw what appeared to be ancient ruins rising above the jungle canopy. Later that year, Lindbergh returned with archaeologists Alfred V. Kidder and Oliver Ricketson Jr. to explore the northeastern Yucatan Peninsula in search of ancient ruins in a twin motor Sikorsky Amphibian aircraft. During this expedition, Kidder recorded distinct vegetation patterns he associated with ancient sites though he did not record the locations.   While these early exploratory efforts did not produce scientific results, aerial technology enabled archaeologists to rise above the jungle canopy and obtain a bird's eye perspective of the sites and their contexts (William Saturno, 2007).

Figure 2: Charles Lindbergh in Cozumel Mexico, 1929. Image courtesy: (tem)

In the following decades, aerial photography was used at Tikal and Copan in any effort to identify the extent of these monumental settlements. The resultant stereoscopic imagery was useful in generating better contour maps. (Garrison D. T., 2011)

In the 1970's, Radar[1] was first used in the Petén as part of environmental studies of soil analyses and to identify vegetation types in the satellite imagery near Tikal. While early satellite technology could not match the resolution of aerial based image collects, satellite remote sensing provided two critical advantages over aerial photography. First landscapes could be viewed in different resolutions to provide different perspectives and second, satellites can collect data across a wider range of the electromagnetic (EM) spectrum. This later feature would prove to have a significant impact on the development of Maya research. A key breakthrough came as researchers began to recognize that the archaeological sites themselves were impacting their environments in ways that could not be seen in visible part of the electromagnetic spectrum. Through remote sensing technology, changes which were only observable outside of the visible EM spectrum could be detected and used as a proxy to predict the existence of other archaeological sites (Parcak, 2009).

In the 1980's, Thomas Sever from NASA began looking for vegetation signatures in multispectral imagery as an indicator of potential presence of archaeological material (Saturno, 2007). While the resolution of this technology was not sufficient to identify structures, Sever was successful in identifying canals and roads.

In the 1990's Sever conducted further surveys using the new STAR3i system which was able to identify islands in the bajo areas. These islands coincided with the location of modest bajo communities. Sever next experimented with satellite imagery using the 30m resolution per pixel images generated from the LANDSAT satellite. (Garrison, 2011)

In 1999, the IKONOS satellite was launched which provided much higher resolution data collects than previous satellites. In the early 2000's Sever proposed to Dr. William Saturno to conduct a survey of the recently re-discovered San Bartolo site in the northeast Petén. In 2003 Saturno was successful in predicting archaeological sites and features around San Bartolo. By manipulating different bands of the visible EM spectrum Saturno was able to amplify variations in vegetation signatures using these differences as a proxy for possible features located below. In this case it is believed concentrations of limestone used in Maya architecture may have leeched into the soil which is absorbed by and affects the overlying vegetation. (Garrison, 2007).

Figure 3: The Ikonos satellite, at left, offered high-resolution imagery at 1 meter resolution. On right the GeoEye-1 satellite, which boasts 0.4 meter resolution capabilities. Image courtesy of GeoEye.

[1] Radar reconstructs surfaces by sending and recording the amount of time it takes for pulses of energy to reach an object and return to the sensor. Radar is an "active" system versus other types of "passive" satellites which collect radiation emitted from objects such as the earth (Parcak)

Saturno identified a specific spectral signature in IKONOS satellite imagery that he believed indicated the presence of Maya Settlements[2]. Survey work was conducted to confirm the signature and later the signature was used to discover new settlements at new locations around San Bartolo. (Garrison , 2007)

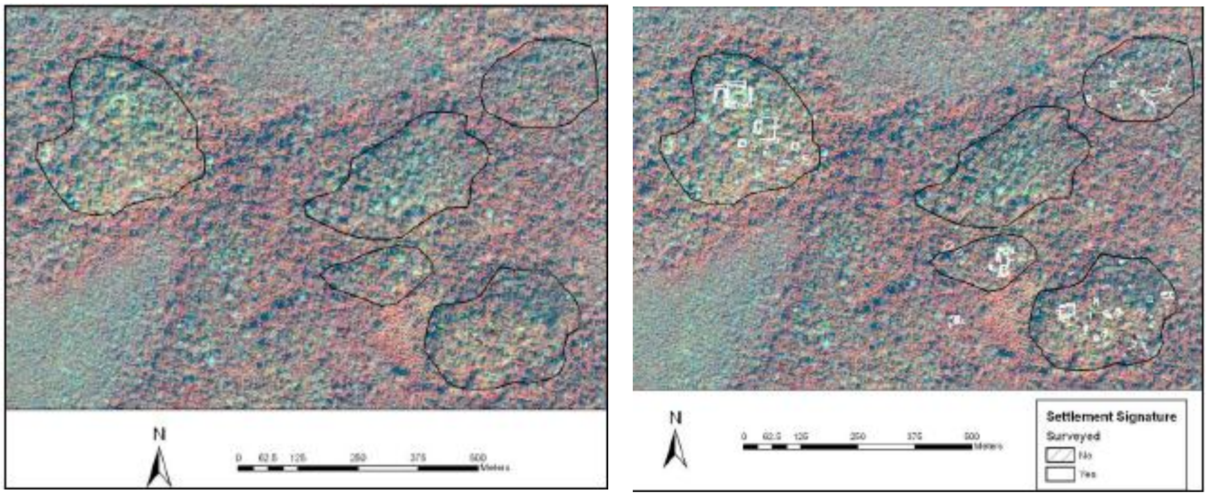

Figure 4 & 5: Example of identification of a settlement signature using the infrared (IR) part of the EM spectrum to accentuate differences in vegetation at a site near San Bartolo. Note: ancient settlements structures were identified in the textured "yellowish" areas surveyed in the imagery. Images courtesy Dr. T Garrison (Garrison T. , 2007)

Starting in 2005, Dr Thomas Garrison, who had worked with Saturno at San Bartolo, continued research of the Maya using remote sensing technologies. Using the same methodological approach as Saturno, Garrison conducted regional reconnaissance around a site known as El Zotz. However, Garrison was unable to replicate Saturno's results [3].

From a review of data collected across different sites, Garrison concluded that the effectiveness of this remote sensing technique may be influenced and possibly limited by:

1. The geomorphology of the area being analyzed, and
2. The spectral band combination being used to manipulate the satellite imagery, and
3. The climate conditions when the imagery is collected (Garrison T. , 2013)

Undoubtedly the use of high resolution satellite imagery to search for cultural material in subtropical environments has become far more useful and cost effective in recent years. However, it remains unclear, if this approach can be systematically replicated to predict and map the extent of archaeological sites in the jungle.

[2] The best results for sat imagery around San Bartolo were in images from transitional months (late Jan-early Feb, mid May-early June) when the moisture levels were changing. The best band combo for analysis that we used was Near Infrared, Red, Blue (4,3,1) (Garrison T. , 2013)

[3] Garrison used slightly different spectral bands as well as satellite imagery which was collected during the dry and the transitional rainy to dry season period (Jan/Feb) when differences in healthy versus stressed vegetation signatures might be expected to be amplified.

LiDAR

Maya researchers have also recently begun experimenting with other remote sensing technologies. *Light Detection and Ranging (LiDAR),* uses an infrared laser to create three dimensional images of complex environments. LiDAR has given Maya researchers the ability to effectively search for and visualize the full extent of a Maya settlement and its surrounding landscape in an efficient and non invasive manner. Even in sub tropical environments where thick canopy obscures terrain and or archaeological features from view, LiDAR has proven to be an effective survey tool. LiDAR is extremely effective for survey work because even if only a small percentage of the

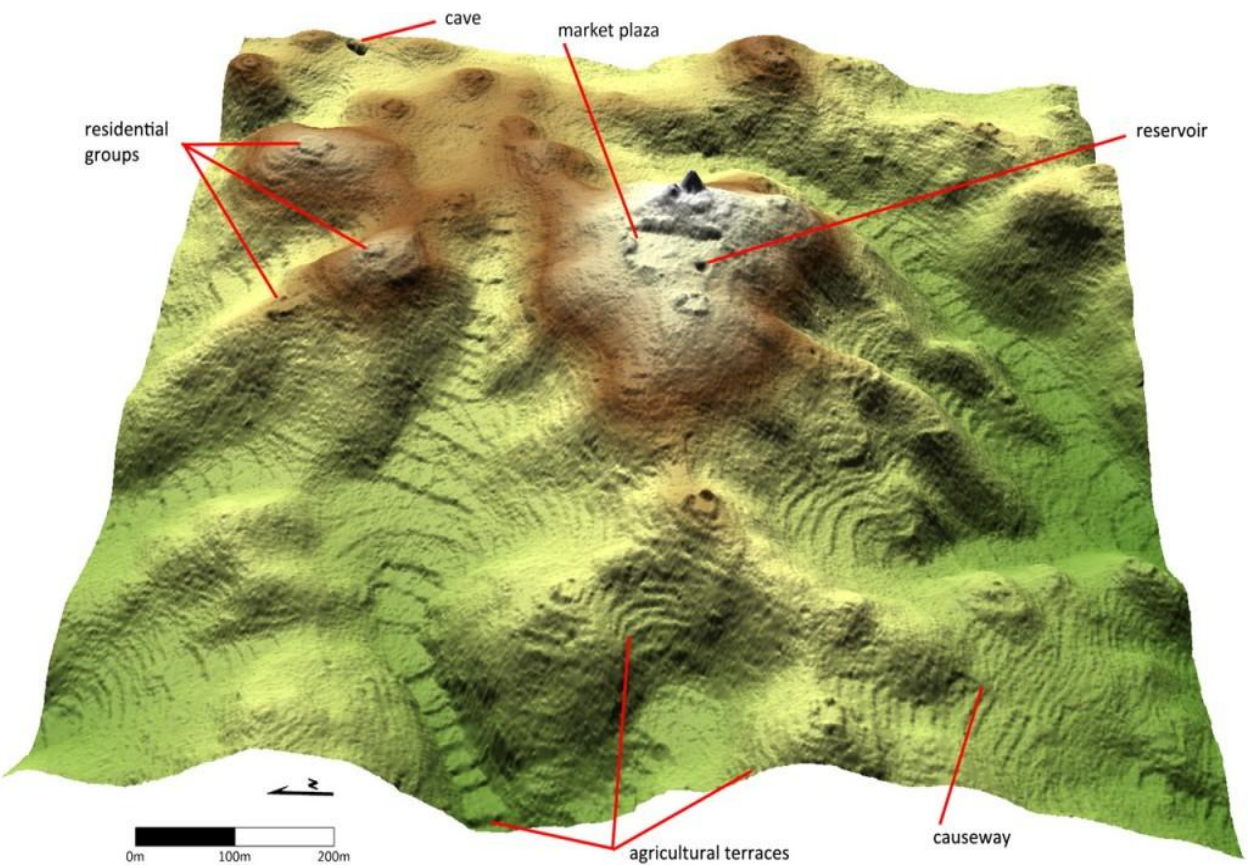

Figure 6: Example Results of LiDAR visualization model at Caracol. Image courtesy: (Arlen F. Chase, 2013, p. 186)

hundreds of millions of points collected from a laser manage to penetrate through the jungle canopy, this can be sufficient to identify and "map" the terrain and any archaeological features below. In Belize the first successful deployment of a LiDAR was used in Central America by the Chases to map the Maya site known as Caracol (see above). This data was used to validate/correct mapping done by the field researchers over the last 20 years.

Beyond validation of prior work, some Maya scholars believe LiDAR can deliver substantially greater benefits to archaeologists.

"LiDAR holds the greatest promise for finding every last major (and minor) site in the jungles of Northern Guatemala. This is the purest, most authentic exploration, of course, and momentous scientifically.

-Dr Stephen Houston, Brown University

As of the writing of this report, LIDAR technology has been used at archaeological sites where survey and excavation work has already been conducted. While this has proven useful to identify archaeological features not identified through traditional survey methods or to correct locational errors in surveys, it has not been used as the basis to visualize a previously un-surveyed landscape and direct a more efficient and effective field survey and research program (Garrison , 2013).

Recent successes of manned LiDAR surveys over portions of Central America and Southeast Asia have highlighted the revolutionary utility of this sensor to identify and visualize archaeological remains from above. However, LiDAR has not been used extensively to search for, identify or map archaeological sites to date in large part because of cost LiDAR mapping deployed from fixed wing manned aircraft remains prohibitively expensive for most projects.

Research Aims:

Maya sites remain undocumented in the Jungles of Central America. Artifacts are constantly being unearthed and distributed on the black market. Searching for and scientifically documenting sites requires an enormous amount of time and labor. At present, looters are identifying sites faster than Archaeologists can record them. Manned aerial LIDAR surveys allow archaeologists to rapidly identify and precisely map archaeological sites. However this technology is very expensive to deploy. Our team believes they we have revolutionary answer to this problem: compact LIDAR arrays mounted on portable UAVs that can be launched from within the jungle itself. We believe this technology will change the landscape of Maya archaeology by reducing the cost of aerial LIDAR surveys, and place the controls of the survey equipment in the hands of archaeologists. The aim of the Petén Archaeological Expedition is to conduct the preliminary field tests in order to develop a cost effective UAV based LIDAR prototype to assist archaeologists in their efforts to understand the ancient Maya. Building on the remote sensing work of Dr William Saturno and other Maya researchers, our team intends to construct a robust and economic UAV based LiDAR system for remote sensing data capture. Successfully field testing our prototype equipment on this Flag expedition was the first stage in an effort to build a UAV based LiDAR prototype which will allow future archaeologists to capture a comprehensive survey data of targeted Maya Landscapes at a fraction of the cost required to deploy LiDAR via fixed wing manned aircraft.

Project Objectives:

- Demonstration of unmanned aerial vehicle (UAV) survey capacity in sub tropical jungle environment including full path plan, data capture, data processing (stitching, geo-referencing, ortho-rectification), and LiDAR and SFM workflow
- Capture images of temple complexes from above jungle canopy
- UAV reconnaissance to explore cliffs at El Zotz for cave entrances
- Collect high resolution LiDAR and SfM recordings of monumental cultural material for conservation
- Collect large scale SFM of Plaza complexes and pyramid of context visualization and archaeological recording purposes
- Collect high resolution LiDAR data of tomb for recording
- Test research hypothesis that the Maya built on geographically favored topography to take advantage of view sheds by ground truthing targets predicted from high orbit remote sensing Radar data

Orientation:

Our team arrived by various small planes to Flores Guatemala, our *rendezvous* location and the traditional jumping off point for many expeditions heading into the Petén. From Flores our introduction to this intense environment was much like early explorers descriptions of their own incidents of travel: mud, insects, and more mud which resulted in our failure to reach our first objective- the Maya site today known as Nakum. Wary of our tight schedule and running low on fuel, we reluctantly turned back after 18 hours of winching and digging, having covered only 30 kms. At our next target site-Naranjo we found more favorable driving conditions and mostly undocumented temple ruins. Many of the ruins at Naranjo are obscured by thick jungle and covered by a millennium of earth and organic material. Much like explorers must have done almost two centuries ago, we could only wonder about the size and context of these ruins and of the people who built these cities.

Figure 7: PAE Route, Inset: Petén, Guatemala Inset Central America

As we climbed to the top of one of larger unexcavated mounds at the Maya site today known as "Naranjo", the obvious problem of working in the jungle became clear: How does an archaeologist make sense of such a large site? Where does one start? Naranjo showed us the problem. Now it was up to our team to see if we could deliver the solution.

Figure 8: Driving deeper into the ruins at Naranjo we encountered a strange and fascinating landscape of large conical mounds which covering unexcavated Maya structures. (Fltr: Doug Inglis, Alistair Calvert, Jason Paterniti, Toby Savage)

Geography

The Maya Lowlands is generally composed of a karst topography with *bajos* (seasonal wetlands) comprising 40% or more of the land surface (Garrison D. T., 2011). The porous limestone bedrock acts as a sponge. Instead of flowing into streams and rivers, rainwater flows down through sinkholes to underground drainage systems far below the surface.

Site Selection

For this project we identified four potential locations for study based on three criteria: accessibility, canopy density and site excavation status. For practical reasons, logistics required we have at least marginally passable roads to reach the sites in the time available for the field study. In order to deploy and recover the UAV system, canopy density was an additional constraint for the project. We needed at least 3 meter gaps to deploy and recover the UAV.

SITE	Location	Accesibility	Canopy	Site status
Nakum	17° 10.570'N 89° 24.278'W	Very Muddy Track. 10 hours to cover 16kms. Trucks had to turn back 10 kms short of target as we were running low on fuel and time.	Partially open	Partially excavated
Yaxha	17° 4.508'N 89° 24.125'W	Dirt road, maintained.	Open	Excavated
Naranjo	17° 7.537'N 89° 15.359'W	dirt road/ muddy track 8 hours to go 19kms	Dense coverage	Un Recorded
El Zotz	17° 14.491'N	Dirt road/ muddy track: 4 hours to go 21 kms	Dense/small openings	Partially excavated

The state of excavation of a site was also factored into our decision. Mostly cleared and excavated sites like Nakum and Yaxha offered comparatively little for scholars to learn from our results. From a research perspective, El Zotz and Naranjo offered an excellent location to field test our equipment while also potentially allowing us to collect useful data as part of the effort to conduct a complete inventory of cultural sites. Based on road and canopy accessibility we selected the archaeological site at El Zotz located in the San Miguel la Palotada Biotope for our field study[4].

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[4] We are extremely grateful to the Instituto de Antropologia e Historia de Guatemala for authorizing this project and to CECON and the Universidad de San Carlos San Miguel Biotopo which runs the reserve.

History of El Zotz

El Zotz is located 14 miles west of the more famous major center of Tikal. The site contains many unexcavated mounds and tombs and is so named for the hundreds of thousands of bats that fly out from under nearby cliffs at sunset. El Zotz is also known for its well preserved Early Classic (AD 300-600) architecture, with elaborately decorated stucco surfaces. The Maya most likely referred to El Zotz as *Pa' Chan*, or "fortified-sky," and the site was occupied for over nine centuries between (AD 300–1250) (Garrison D. T., 2013). The earliest royal palace at the site is located on a hilltop overlooking the area where the major ruins are located. This palace, known as the El Diablo Group, would have housed the royal family for about two centuries and included a 13–meter-tall funerary pyramid.

Modern History of El Zotz

It is unclear when El Zotz was first rediscovered, but we do know that the site was heavily looted in the 1960's and 1970's. During this period, academic study of the site was limited to a handful of survey and mapping efforts undertaken first by Marco Antonio Bailey followed by George Andrews in 1977 and Ian Graham in 1978.

In the 1980's the Proyecto Nacional Tikal and the Departmento de Monumentos Prehispanicos (DEMOPRE) of the Guatemalan Institute of Anthropology and History (IDAEH) conducted mapping and limited test pits excavations with some removal of artifacts in 1987, 1995, 1999 and 2000. In 2006 a team led by Dr. Stephen Houston of Brown University and Héctor Escobedo (Ministerio de Cultura y Deportes de Guatemala) began a five year project to map El Zotz. (Houston D. S., 2008)

In 2009 Dr Tom Garrison joined the project as the director of regional investigations. As of 2012, Garrison became Project Director (based at the University of Southern California) in collaboration with Edwin Román (University of Texas at Austin) who served as Guatemalan project co-director.

Expedition Members & Areas of Responsibility:

The Petén Archaeological Expedition brought together two groups of highly talented scientists and researchers. Dr Thomas Garrison and his team of Maya Archaeologists partnered with Dr Albert Lin, Prof Ryan Kastner and Dr Curt Schurgers and their team from University of California San Diego's Institute for Telecommunications and Information Technology or (Calit2). Dr. Lin, a Lowell Thomas award recipient, describes the Engineers for Exploration (E4E) program at Calit2, which is also known as the Qualcomm Institute, as "a student-powered innovation incubator for exploration. By the end of this expedition the UCSD team had more than lived up to this description.

Figure 9: The Petén Archaeological Expedition team

NAME	EC	NATIONALITY	ROLE	AFFLIATION
Albert Yu-Min Lin, Ph.D.	FN	USA	Lead Engineer	California Institute for Telecommunications and Information Technology @ UC San Diego
Alistair Calvert		UK	Equipment	Royal Geographical Society
Anatolio Lopez		Guatemala	Lead Guide	El Zotz Project
Angela Brown		USA	Logistics	NLX
Curt Schurgers Ph.D		Belgium	Lead Engineer UAV based aerial survey	California Institute for Telecommunications and Information Technology @ UC San Diego
Dominique Ernest Meyer		Switzerland	UAV Platforms	California Institute for Telecommunications and Information Technology @ UC San Diego
Doug Inglis	TM	USA	Archaeologist	Texas A&M University
Edwin Roman, Lic		Guatemala	Archaeological Co-Project Director Proyecto Arqueologico El Zotz	University of Texas at Austin
Eric Kwok-Cheung Lo		USA	UAV Platforms	California Institute for Telecommunications and Information Technology @ UC San Diego
Gramham Jackson		UK	Logistics	NLX
Hector Ac		Guatemala	Guide	El Zotz Project
James Brown		USA	Logistics	NLX
Jason Paterniti	FN	USA	Expedition Leader	GEOS Foundation
Joel		Guatemala	Support Vehicle Driver	El Zotz Project
Jorge		Guatemala	Support Vehicle Driver	El Zotz Project
Luis		Guatemala	Support Vehicle Driver	El Zotz Project
Oscar Cac Pan		Guatemala	Guide	El Zotz Project
Perry Winstead Naughton		USA	Data processing/ SFM	California Institute for Telecommunications and Information Technology @ UC San Diego
Robert J. Atwater	EC LF	USA	Project Health & Safety Officer	Explorers Club
Ryan Kastner, Prof.		USA	Lead Engineer ground SFM and Stereo data capture	California Institute for Telecommunications and Information Technology @ UC San Diego
Sarah Newman		USA	Faunal Analyst Proyecto Arqueologico El Zotz	Brown University
Toby Savage		UK	Project Photographer/Journalist	Toby Savage Photography
Tom Garrison Ph. D		USA	Archaeological Co-Project Director Proyecto Arqueologico El Zotz	University of Southern California

Logistics:

In Flores, we met up with our local logistics team who provided transportation, food and meals for the project. Due to late season rains, we encountered far more difficult terrain than we had expected.

Figure 10: Late season rains meant deep mud and lots of winching. Image courtesy Douglas Inglis.

Figure 11: Graham Jackson from our logistics support team in the middle of a bush repair of a HD rear spring that had broken in half on the trail out of Nakum. The spring was reset on its mount using a block of wood; later a metal block was fabricated to better seat the broken spring. Image: Doug Inglis

Figure 12: Camp for the night- rarely used logging roads allowed us to stop right on the trail and hang our hammocks for the night.

On Day 6, after a four hour drive through muddy tracks we reached our target site at El Zotz. One of our drivers volunteered to return to Flores for the 8 plus hour return trip to pick up one of our undergrad students as well as four pelican cases which contained 4 helicopter platforms which had not made the fight from Los Angeles to Guatemala City. This fellow made the trip back to El Zotz this time solo without a winch and in the dark.

Figure 13: Base camp at El Zotz: Image Courtesy Albert Lin

Project Methods:

In order to build a robust UAV based LiDAR sensor capable of operating in sub tropical environments, the components of our prototype would need to be tested in the field under actual conditions. The main objective of these experiments was to determine if the equipment could operate beyond normal engineering tolerances. As we could not risk destroying our borrowed LiDAR sensor, the engineering team broke up the field tests into a series of discreet controlled experiments including LiDAR data capture, UAV deployment, flight path and recovery and finally UAV deployment with a photo recording payload package.

Laser sensor

A laser scanner works by emitting a beam of infrared laser light and reading the energy reflected back to the scanner to place a point in a three dimensional context. This light beam is sent from the scanner onto a rotating mirror that then sends a beam laser light out of the unit. The rotating scanner sends a light beam out and over a target area. When the beam encounters the surface of an object or terrain feature the laser will “bounce” back to the scanning unit and this information is recorded as a data “point” (Faro, 2012). The latitude, longitude and height from the ground of each of these points can then be aggregated into what is known as a “point cloud”. Point clouds can then be used to generate Digital Elevation Models (DEM) which are computer generated simulations of the LiDAR data. Airborne LIDAR typically consists of a laser, a scanner, an integrated GPS receiver and some type of flying platform. Airplanes and helicopters are the most commonly used platforms for acquiring LIDAR data over broad areas. (NOAA) .

To test how a laser sensor would react to an intense humid environment a Faro Focus 3D laser scanner™ was utilized. Our goal was to determine whether LiDAR can be used to collect and record useful data in the intense jungle environment. The Focus 3D unit is a laser Class 1 sensor providing a ranging error accuracy of +/-2mm and can collect up to 970,000 points/sec. Typical scans ranged from five to ten minutes resulting in hundreds of millions of points of data (Naughton, 2014). The 240 x 200 x 100mm unit weighs 5kg, beyond the payload capacity of our existing UAV but useful for testing how the equipment would function in an intensely humid environment.

A secondary mission for the LiDAR team was to record high resolution recordings monumental cultural material for conservation.

Figure 14: Faro 3D Laser scanner™

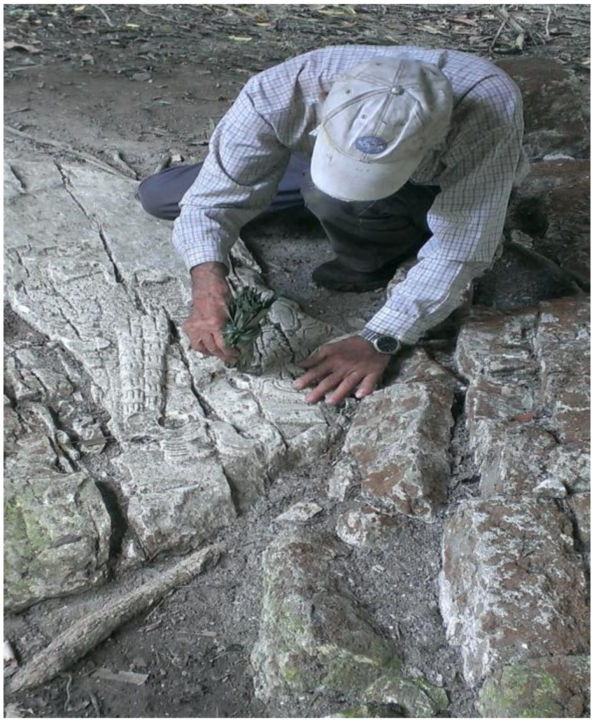

Figure15: Stella 2 The legendary Don Anatolio López cleaning a Stella for our LiDAR data collects in the same manner he used to clean and prepare iconography for Ian Graham's sketches during the 1980's. Right Figure 16: Lidar senor recording Stella no 1. Image courtsey Doug Inglis

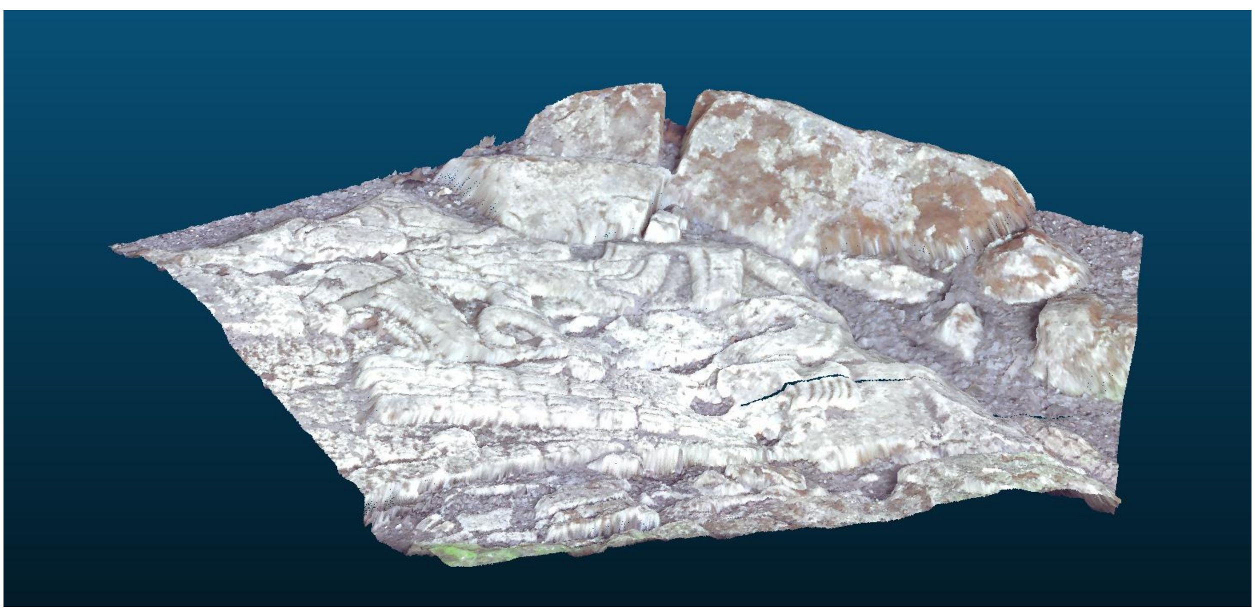

Figure 17: Digital elevation model of Stella no1. El Zotz. Image courtesy of UCSD E4E

Beyond recording of individual objects the lidar sensor was used to record large scale environments in precise detail such as the looter tunnel of Structure M-71: **Click here for a link to LiDAR Scan results of M71 Courtesy of UCSD Calit2**

Structure from Motion

While LiDAR technology undoubtedly represents the cutting edge in remote sensing research tools, Structure from Motion (SfM) provided us with a cost effective proxy for LiDAR for our field tests. SfM is a process which combines a series of two dimensional image sequences into a three dimensional visualization model. The process entails taking two-dimensional photographs of an object or site from multiple angles and then tracking and aligning features in the photos (such as corner points) to 'stitch together' and reconstruct the object digitally in 3D (Kastner D. R., 2014) For our tests, SfM recording equipment was also used as a proxy to deploying a highly sensitive (and expensive) LiDAR sensor on our prototype UAV system.

For SfM image collection we used Canon DSLR cameras. SfM data input into a commercially available Agisoft software program **http://www.agisoft.ru/**. However in order to process and view the resultant models, UCSD's CISA3 group developed custom software to process the data sets (Naughton, 2014).

For our tests, we selected several plaza and pyramid complexes at El Zotz. These tests would also represent the initial trials of SfM recording at El Zotz in advance of deploying a team in June 2014 to record a series of monumental masks found by Garrison's team in 2010 at Diablo Complex at El Zotz.

Figure 18: Calit2 professor Dr. Ryan Kastner and PhD student Perry Naughton preparing to gather stereoscopic images using the "CaveCam" at El Zotz

Figure 19: Looter trench leading into the tomb of the "dead frog"

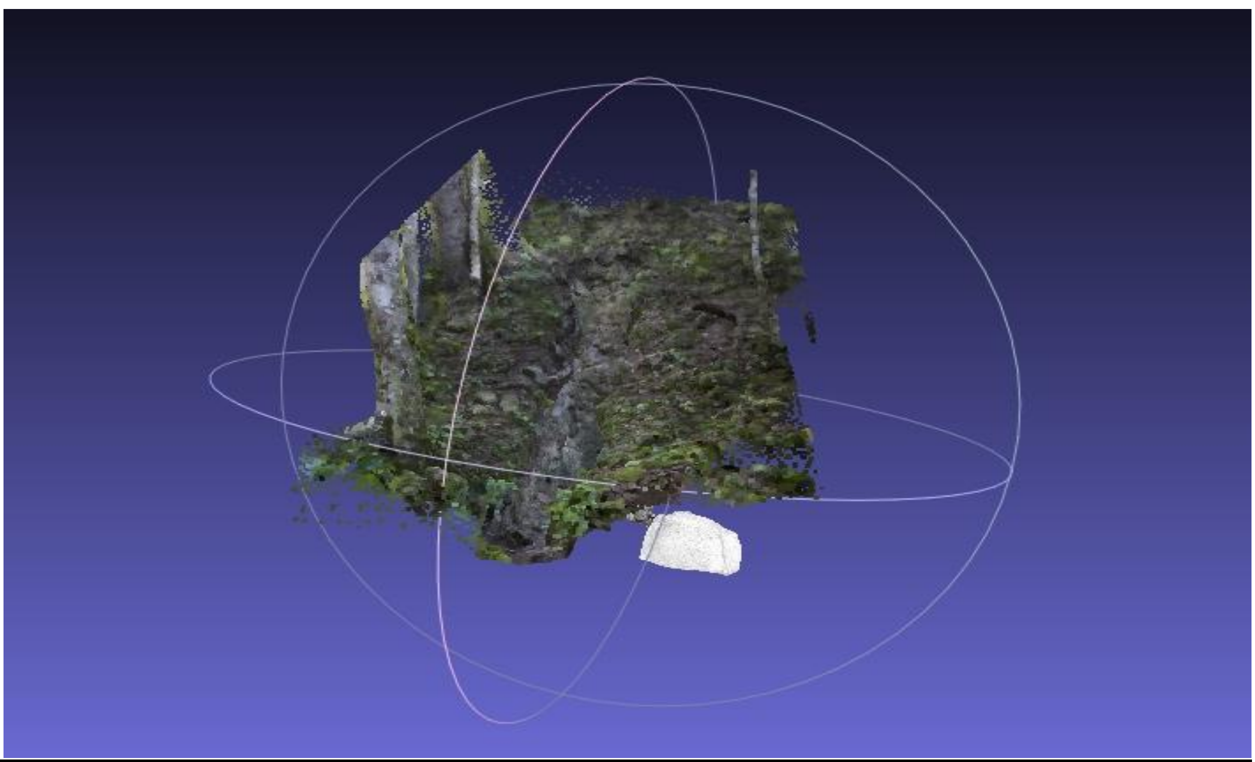

Figure 20: SFM model of Tomb of the "dead Frog" Image UCSD E4E Calit2

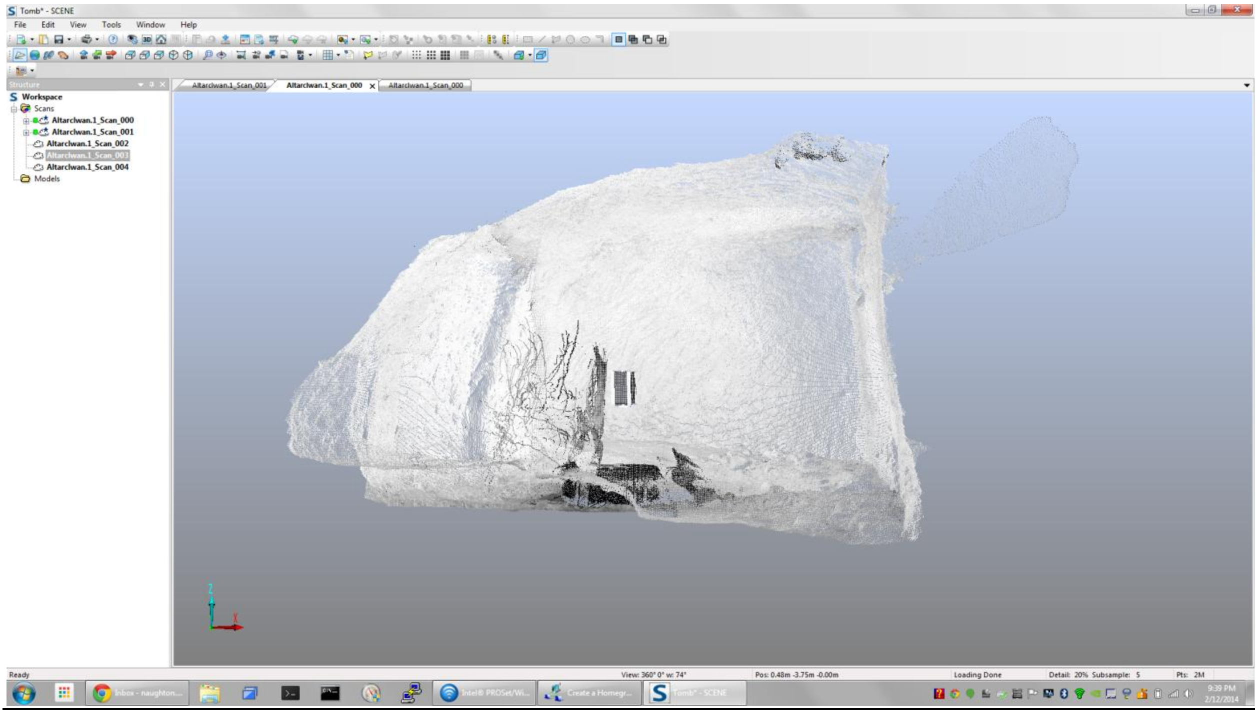

Figure 21: Lidar recording of the Tomb of the "Dead Frog". Courtesy UCSD E4E Calit2

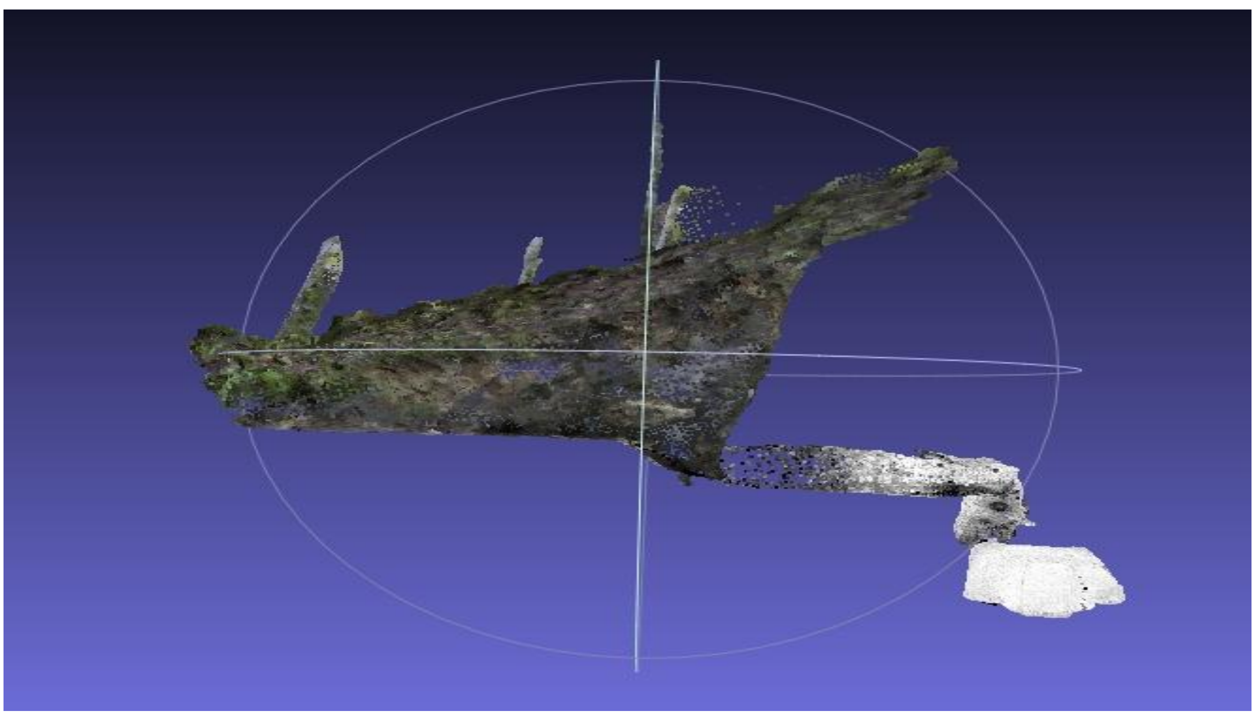

Figure 22: SfM and LiDAR construct of Looter trench and tomb Courtesy UCSD E4E

3D model of Maya Mask uncovered at El Zotz created using SfM: Click here for link to SfM model of Maya Mask. Model courtesy of Calit2

Long range UAV based aerial survey:

The final set of engineering experiments at El Zotz involved demonstration of multiple path plans, data capture, data processing (stitching, geo-referencing, ortho-rectification[5] and SfM workflow) in order to demonstrate UAV platform validation.

UAV:

Our experimental copters were equipped with fully integrated flight and position systems. The larger “hexacopter” was based on an RC Timer F800 airframe with a brushless gimbal to support various sensors. Flight time for the hexacopter was approximately 10 minutes, moving at 5 meters per second. Payload capacity for this UAV including gimbal is approximately 1kg. The quadcopter "crawler" is an entirely custom built in the UCSD machine shop, and carries the QX100 mounted directly on the copter. Flight time is for the crawler is approximately 15 minutes with a payload of 0.5kg. The third hexacopter used was a DJI F550 with a Zenmuse GoPro gimbal. Flight time for this UAV is approximately 10 minutes. We used this UAV with the GoPro Hero 3 Black to conduct aerial filming. Payload including gimbal is approximately 0.5kg sensor. For our field trials we used a Sony QX100, a 20MP camera with a 1" sensor, and weighs ~200g, at 28mm focal length in 35mm equivalent. (Lo, 2014)

Figure 23: Local guide Moises and UCSD Student Dom Meyer carrying a UAV system to the test site.

[55] Variations in the surface being recorded and or the angle of the sensor and or the platform doing the recording distorts how terrain data is displayed in an image. Digital Elevation models are used to remove these distortions in a process known as Orthorectification (SatImagingCorporation)

Successfully deploying and recovering these UAV's would be critical to justify the development of a more extensive sensor platform which would carry a LiDAR sensor payload.

Figure 24: USCD students Eric Lo and Dom Meyer recording a start image to mark the beginning of a data gathering run

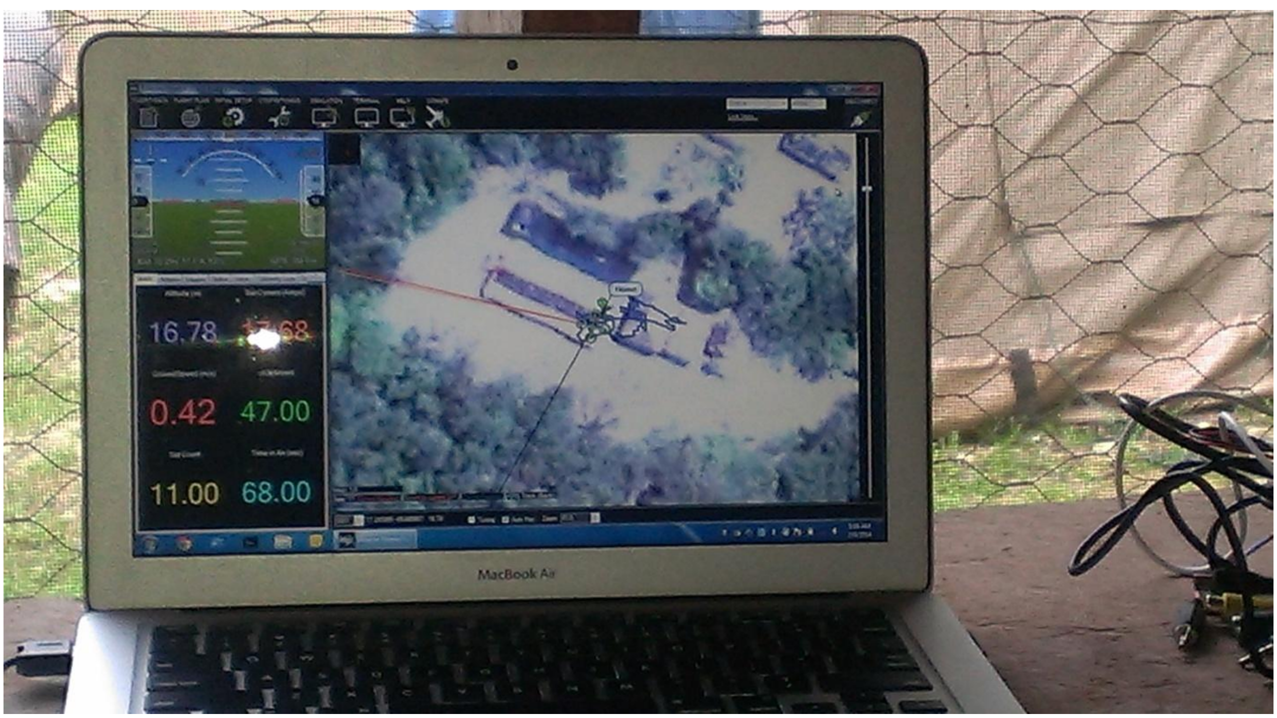

Figure 25: UAV Flight Path planning

In order to obtain detailed image captures of temple complexes above the jungle canopy we had to identify clearings in the canopy a minimum of 3 meters in diameter. This resulted at times in the team being forced to deploy the UAV from the tops of Maya temples.

Figure 26: UCSD Engineers in first flight test of UAV over El Zotz atop temple M-71. Image courtesy Dr Albert Lin

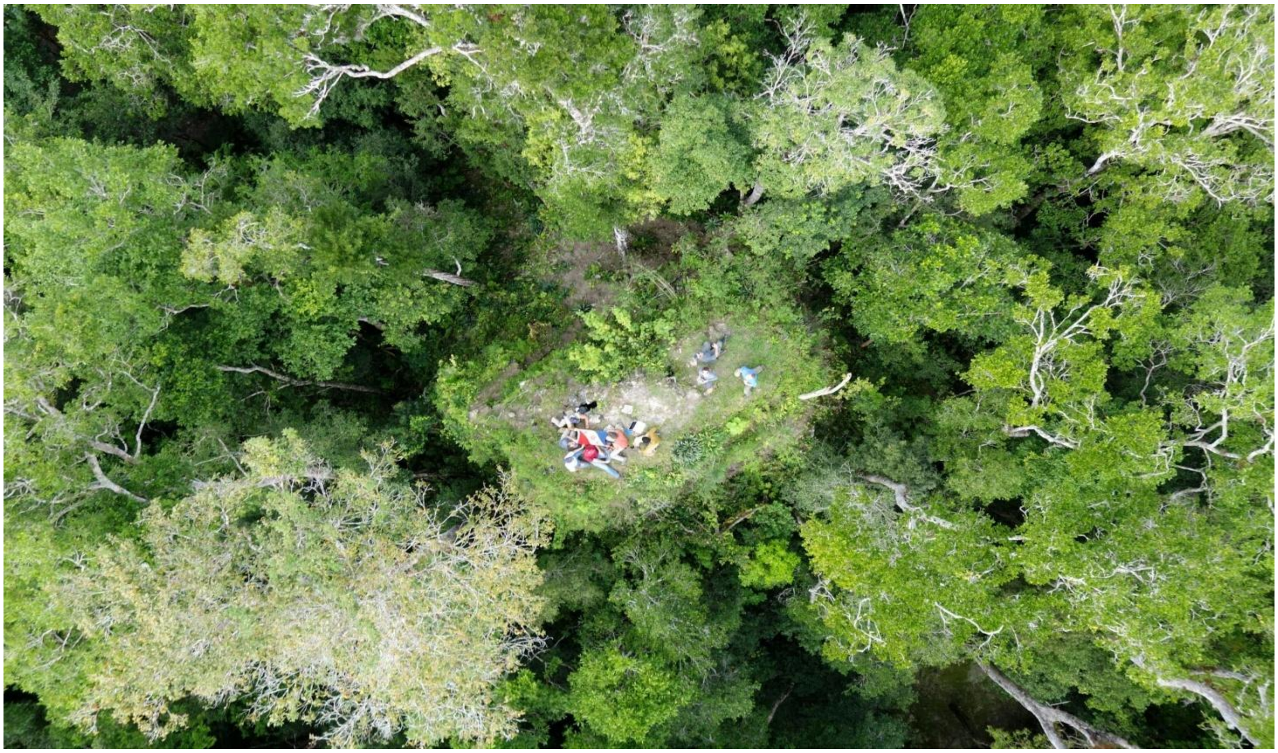

Figure 27: Flag 99 photographed from the UCSD UAV from 30M above M-71 Temple of the "Wooden Lintel" Image Dr Lin

Figure 28: ***Flag #99 on top of M71 Pyramid of the Wooden Lintel at El Zotz, The UCSD UAV critically low on batteries is about to make an exciting landing. Image Douglas Inglis TM'13***

Figure 29: UAV reconnaissance flights also demonstrated their versatility as they allowed us to explore cliff faces in search of hidden cave entrances in toxic and dangerous environments

Click here for a video demonstration of the UAV SfM flight at El Zotz: http://vimeo.com/88212266

Inter regional study: Site prediction using remote sensing technologies:

Some of the most spectacular discoveries in the El Zotz region have occurred on hilltops with elite architecture on them. The site known as "Bejucal" on the map below is an example, but also some of the outlying groups at El Zotz itself (El Diablo, Las Palmitas) (Garrison T. , 2013). As part of the PAE project we also conducted investigations to test the research hypothesis that the Maya in this region built on geographically favored topography to take advantage of viewsheds. In order to test this theory, our team employed radar data to test whether remote sensing technologies can be used to predict the potential location of archaeological sites.

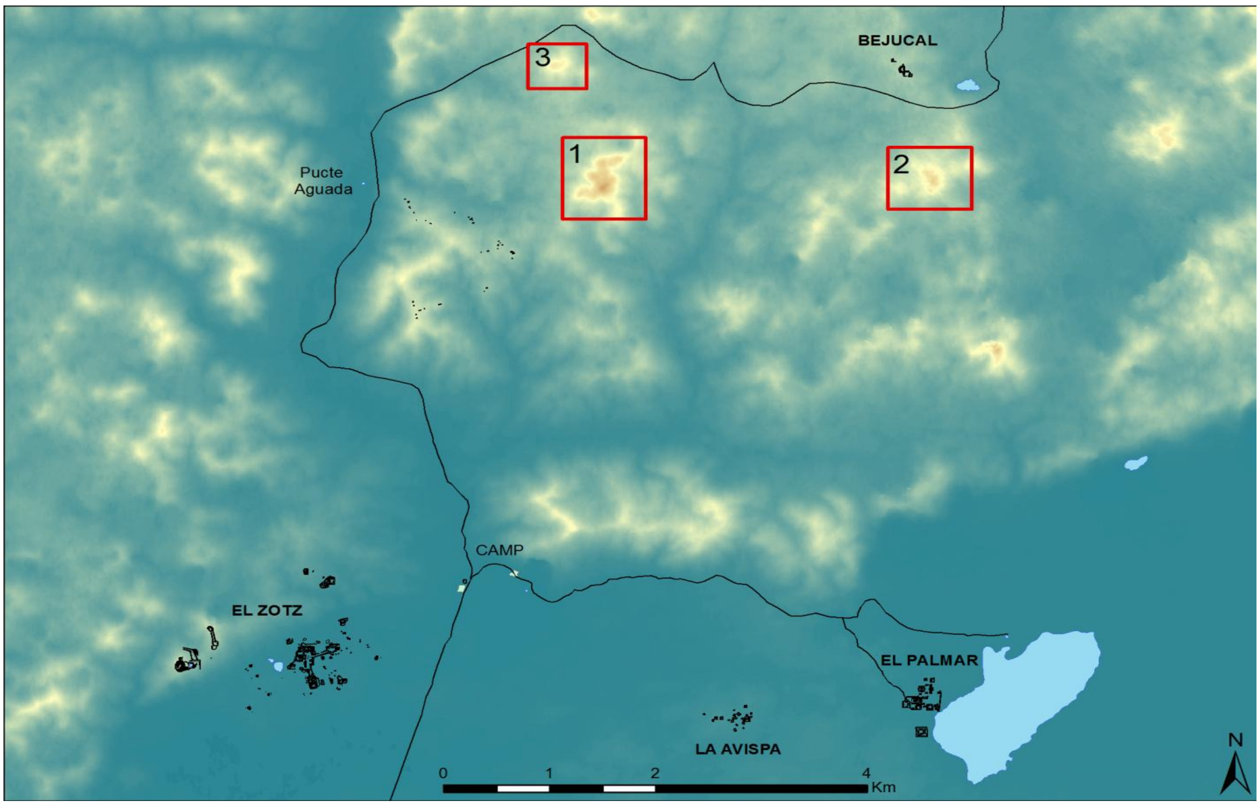

Figure 30: AIRSAR radar data that has been stretched to accentuate and highlight hilltops. Image courtesy of Dr. Tom Garrison.

Using high orbit remote sensing Radar data obtained from NASA, three targets were identified for ground truthing reconnaissance by our team. The areas in question are located between El Zotz and Bejucal[6] and had not previously been explored or documented by researchers.

[6] The word Bejucal translates to "Big snarl of vines" and it lived up to its name.

Figure 31: GIS overlay of AIRSAR radar data, GPS path and Google Earth

Figure 32: Left: Don Anatolio López (at right) ***with his local crew at the entrance of IR STr 2 a previously undocumented (but looted) Maya Site. Figure 33: Right: Dr Tom Garrison, Jason Paterniti FN and Doug Inglis TM with Flag 99 at the entrance of IR STR 2***

At the site Dr Garrison named IR Str 2 we discovered what appears to be an "elite" Maya structure. Elite structures tend to be sites which are well built using high quality materials such as the use of a thick layer of plaster exterior coating. Its hill top location is unusual for the Inter-regional findings at El Zotz to date. Typically elite settlement or ceremonial complexes are clustered and arranged around a plaza.

One possible theory is that the structures we found were watch towers positioned in geographically favored locations (highest points in the area).

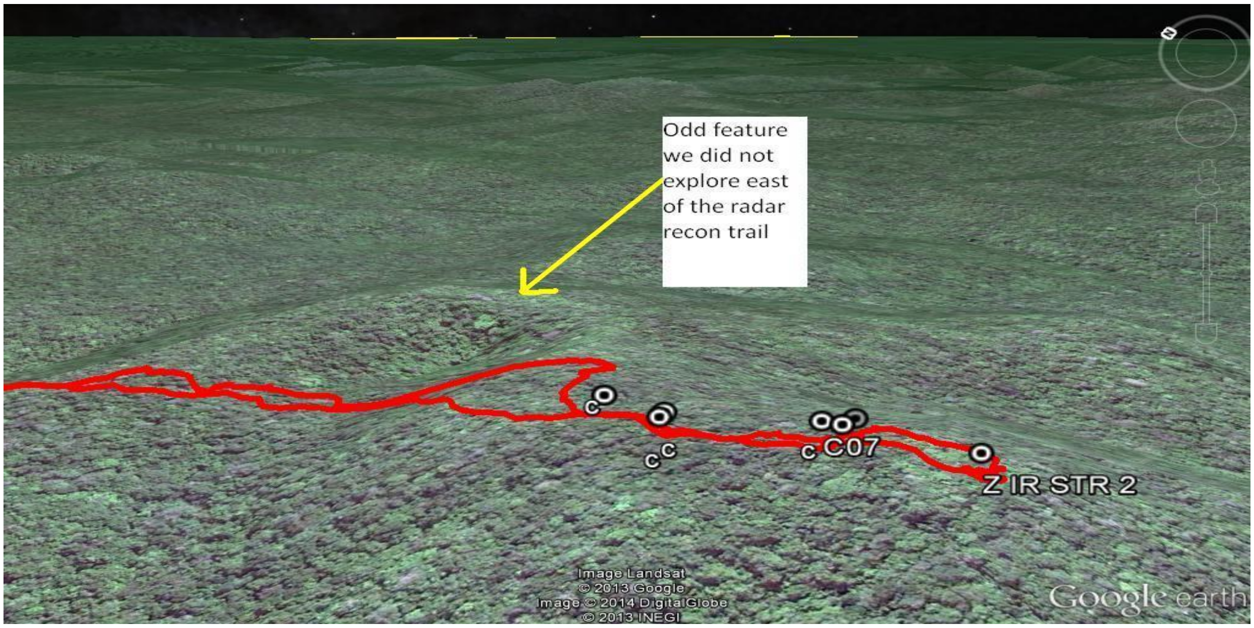

Figure 34: Inter regional study between Bejucal and El ZOTZ Image: Google Earth (Coordinates redacted)

This theory is based in part on the remote locations of these sites relative to other Maya centers combined with the comparatively high concentration of *chultunob* (underground storage chambers typically used to store water and or maize) which were observed in and around the structures.

Site	Zotz IR Str 1	Zotz IR Str 2
Quarry	1	1
Mound	1	1
Chultunob	2	5
Terrace	1	0

While it is possible to see the city of Tikal from El Zotz, it is not clear from our preliminary analysis of view sheds if Tikal was visible from IR Str 1 or IR Str 2. The El Zotz Archaeological team will need to conduct a full inter-visibility study using GIS data to determine view-sheds from these newly located sites.

Project Results & Outcomes:

Figure 35: Doug Inglis, TM and UCSD student Dom Meyer working late into the night to process data collected from the day's trials. Image Dr Albert Lin

Some experts believe that looting, resource extraction and human development will destroy most of the world's remaining undiscovered cultural heritage sites in the next 20 to 25 years (Parcak, 2009). Advances in remote sensing technologies offer researchers the potential to level the playing field to locate and record these precious cultural heritage sites before this information is lost forever. As part of this effort, the development of an economic UAV LiDAR platform can bring the significant benefits of LiDAR data collection to archaeologists working in dense sub tropical environments where traditional survey methodologies remain both expensive and inefficient.

During the Petén expedition, we obtained positive outcomes across a wide range of trials. From our field test results our engineering team has a clear understanding of the potential and current limitations of UAV systems. Our challenge will be to develop a UAV which can handle a larger payload capacity without loss of battery life and to integrate a small lightweight LiDAR into the system.

From an archaeological and conservation perspective, useful data was collected including a series of highly precise recordings of fragile and deteriorating limestone monumental cultural material, large scale recordings of pyramid and plaza complexes as well as highly accurate 3D LiDAR data sets of a previously unrecorded Maya tomb (AD 300-600). AIRSAR radar and HRSI was used to successfully predict the location of two previously unrecorded elite Maya settlement sites (AD 300–1250) which were documented via ground reconnaissance. Study of this newly discovered Maya site and its geographical context is currently being investigated by archaeologists from USC and may form the basis for a future MA thesis.

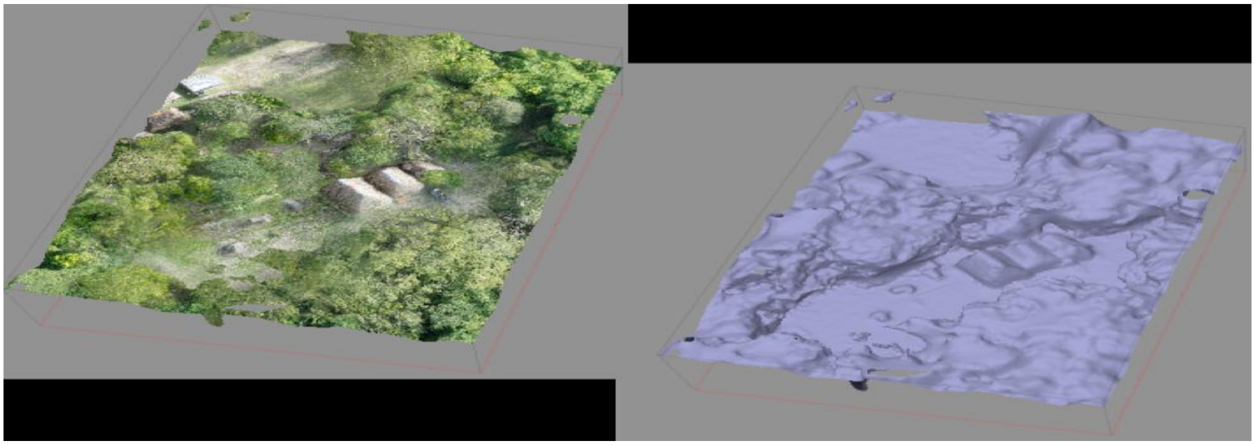

Figure 36: SfM data processing Image Courtesy Albert Lin, UCSD E4E Calit2

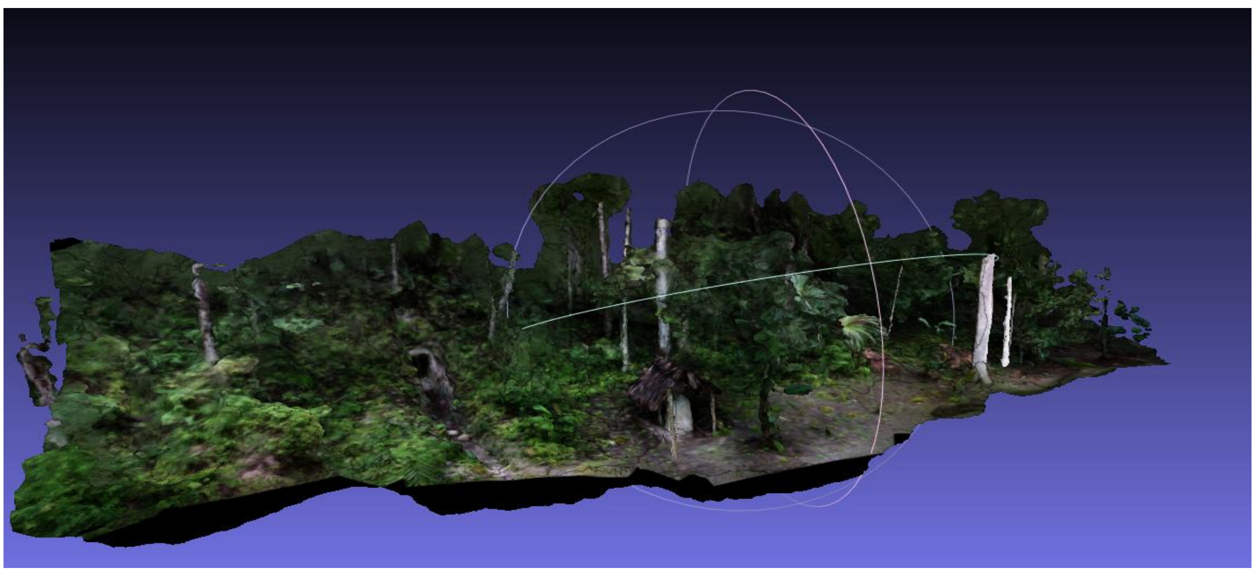

Figure 37: Image Courtesy UCSD E4E Calit2

Figure 38: Back at UCSD, Dr Lin presents results of SfM UAV trials to the team on the "visualization wall"

Beyond these technical accomplishments, the Petén Archaeological Expedition provided an opportunity to share in the pure joy of exploration for its own sake- the rare thrill of seeking and finding previously undocumented ancient ruins, and as was once said: *"to break away from civilization, to face the elements at close quarters as did our savage ancestors, returning temporarily to their life of primitive simplicity and physical vigour; being short of water, to be obliged to go unwashed; having no kit, to live in rags, and sleep in the open without a bed"* (Bagnold, 1935).

For our youngest members from UCSD, being a part of the expedition provided other intangibles:

> *"The students are working hard on these (engineering) applications over the course of the year. This (expedition) is a motivator for the students -- not just the ones who go on the expedition, but those who work with them -- to take all the engineering work they've done and skills they're learning and use them for something in the field. It becomes something more than just an academic problem."* (Kastner R. , 2014)

At a broader level it is also our hope that our efforts can make a contribution to science and to our host nation of Guatemala through the refinement of new technologies which are enabling archaeologists to more quickly, economically and accurately capture data of critically endangered cultural heritage sites before they are lost forever.

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Lessons learned:

- Clarify image/article rights issues in writing in advance
- Take deposits early for Expedition cost sharing and be transparent upfront with regards to cancellation /refund policy
- If using local logistics company establish roles and responsibilities in advance in writing:
    - Provisions list
    - Damage to equipment terms
    - Expected Fuel & water consumption rates for intended route and conditions (V8 used fuel tank of petrol to go 11kms in deep mud)
    - Fuel & Water reserves
    - Establish daily start /end times and communicate to entire team in advance (lost ½ day of recording due to logistics team requiring we leave at first light on last day
    - Review key equipment condition and spares (spare Winches, spare tires) and contingency plans

APPENDIX

Terrain	Sum of kms	HOURS
DIRT	50.15	14.2
DIRT ROAD	60.52	2.9
DIRT ROAD SHOCK REPAIR	12.06	3.5
JUNGLE	5.63	4.1
MUD	72.22	25.7
SEALED ROAD	200.55	4.1
Grand Total	401.13	54.4

	Data	
Terrain	Average of OA kph	Average of MA kph
DIRT	4.42	8.12
DIRT ROAD	20.63	22.70
DIRT ROAD SHOCK REPAIR	3.10	24.10
MUD	4.03	7.80
SEALED ROAD	48.63	56.35
Grand Total	16.71	21.50

Start	End	DATE	kms	Cummulative	Terrain	OA k	MA kph	MT mins	T otal time mins	mode	diesel
flores	Dirt road	3-Feb-14	60.8	60.8	SEALED ROAD	40.0	58.0	64	92	truck	76
CA 13 to dirt road	nakum track	3-Feb-14	11.1	71.9	DIRT ROAD	16.0	19.0	35	43	truck	
nakum track	Nakum jungle camp	3-Feb-14	16.57	88.47	MUD	1.6	6.0	168	625	truck	
Nakum jungle camp	yahxa	4-Feb-14	15.28	103.75	MUD	1.6	7.1	129	428	truck	
yaxha	CA 13	6-Feb-14	12.06	115.81	DIRT ROAD SPRIN	3.1	24.1	30	207	truck	
CA 13	Melchor de menos	6-Feb-14	27.99	143.8	SEALED ROAD	54.7	54.7	30	30	truck	
Melchor de menos	Naranjo dirt	6-Feb-14	3.37	147.17	DIRT ROAD	19.3	19.3	10	10	truck	
Naranjo dirt	Naranjo Camp	6-Feb-14	15.90	163.07	DIRT	1.8	11.3	77	453	truck	
Naranjo Camp	Naranjo dirt	7-Feb-14	16.40	179.47	DIRT	5.8	7.2	138	171	truck	
Naranjo dirt	CA 13	7-Feb-14	1.50	180.97	DIRT ROAD	22.5	22.5	4	4	truck	
CA 13	Flores	7-Feb-14	82.00	262.97	SEALED ROAD	61.2	61.2	81	81	truck	
flores	San Andres	8-Feb-14	29.76	292.73	SEALED ROAD	38.6	51.5	34	45	truck	
San Andres	Cruces Dos Aguadas	8-Feb-14	18.50	311.23	DIRT ROAD	30.6	30.6	36	36	truck	
Cruces Dos Aguadas	El Zotz Park entrance	8-Feb-14	5.95	317.18	DIRT	6.8	12.9	29	53	truck	
El Zotz Park entrance	El Zotz	8-Feb-14	14.64	331.82	MUD	5.0	8.0	99	173	truck	
El Zotz	Bujcal Road	9-Feb-14	5.14	336.96	MUD	5.3	8.0	39	57	truck	
Bujcal Road	jungle	9-Feb-14	3.70	340.66	DIRT	3.4	3.9	58	67	foot	
jungle	Bujcal Road	9-Feb-14	5.63	346.29	JUNGLE	1.4	2.1	157	245	foot	
Bujcal Road	El Zotz	9-Feb-14	8.20	354.49	DIRT	4.3	5.3	92	105	foot	
El Zotz	El Zotz Park entrance	11-Feb-14	14.48	368.97	MUD	4.3	8.0	118	200	truck	
El Zotz Park entrance	Cruces Dos Aguadas	11-Feb-14	6.11	375.08	MUD	6.4	9.7	36	58	truck	
Cruces Dos Aguadas	San Andres	11-Feb-14	20.10	395.18	DIRT ROAD	24.1	27.1	45	49	truck	
San Andres	lake hotel	11-Feb-14	5.95	401.13	DIRT ROAD	11.3	17.7	20	29	truck	19
			401.13			**16.05**	**20.66**	**25.48**	**54.35**		**94.625**

Average of H20 Consumption(litres)	
Conditions	Total
dirt	2.3
hiking	4.3
mud	4.1
Grand Total	3.78

Figure 39: UCSD UAV in flight over El Zotz. Image Dr Albert Lin