Journal of Archaeological Science 69 (2016) 64–74

Contents lists available at ScienceDirect

Journal of Archaeological Science

journal homepage: http://www.elsevier.com/locate/jas

Automated feature extraction for prospection and analysis of monumental earthworks from aerial LiDAR in the Kingdom of Tonga

Travis Freeland [a, *], Brandon Heung [b], David V. Burley [a], Geoffrey Clark [c], Anders Knudby [d]

[a] Department of Archaeology, Simon Fraser University, Education Building 9635, 8888 University Drive, Burnaby, BC, V5A 1S6, Canada
[b] Department of Geography, Simon Fraser University, 8888 University Drive, Burnaby, BC, V5A 1S6, Canada
[c] Department of Archaeology and Natural History, The Australian National University, 5205 H C Coombs Building, Canberra, ACT, 0200, Australia
[d] Department of Geography, Environment, and Geomatics, University of Ottawa, Simard Hall 047, 60 University, Ottawa, ON, K1N 6N5, Canada

ARTICLE INFO

Article history:
Received 10 December 2015
Received in revised form
18 March 2016
Accepted 7 April 2016
Available online 19 April 2016

Keywords:
Settlement patterns
Monumental architecture
LiDAR remote sensing
Automated featured extraction
Kingdom of Tonga
Grave mounds
Landscape archaeology

ABSTRACT

Recent LiDAR (Light Detection and Ranging) survey in Tonga has documented a dense and complex archaeological landscape, particularly on the principal island of Tongatapu. Among the features revealed by the LiDAR are a profusion of earthen mounds, most of which are associated with residence, sporting, or burial in the period 1000–1850 CE. For identification and mapping of the mounds we use and evaluate two automated feature extraction (AFE) techniques, object-based image analysis and an inverted pit-filling algorithm ("*iMound*"). Accuracy of these methods was measured using an F1-score (harmonic mean of precision and recall). Variable AFE results indicate that continual and iterative fine-tuning is required. Successful mapping of some 10,000 mounds on Tongatapu reveals a distinct spatial structure that relates to traditional land division and tenure.

1. Introduction

Aerial LiDAR technology is fundamentally changing the way archaeological survey is conducted around the world (Chase et al., 2012). Survey using LiDAR provides more extensive ground coverage than is possible with pedestrian survey methods; it also gives archaeologists the ability to peer beneath dense forest canopy, sometimes revealing spectacular anthropogenic landscapes. Detection of architecture and microtopographic alterations over wide swaths of land can have a profound effect on our understanding of the "spatial element" of human societies. It allows us to shift focus from a local scale to a regional scale, providing archaeologists with unprecedented geospatial contextualization for individual features in a cultural landscape.

The island of Tongatapu in the Kingdom of Tonga (Fig. 1) had a densely populated landscape and a politically complex dynastic chiefdom beginning no less than 1000 CE (Burley, 1998; Clark and Reepmeyer, 2014). Political complexity is marked on the land by large chiefly tombs as well as a widespread distribution of chiefly sitting mounds, earthwork fortifications and various-sized burial mounds in which non-élites are interred. While some mounds are monumental in scale (>10 m high), many of these mounds are low-lying features (<50 cm) and are often concealed by vegetative ground cover. Traditional methods of pedestrian and aerial survey are thus time-consuming to implement and leave substantial questions on survey accuracy. Employing recently acquired LiDAR for Tongatapu, we apply, evaluate and compare two automated feature extraction (AFE) techniques for mound identification, characterization and mapping. The spatial patterning of monuments on Tongatapu extracted from the LiDAR data can then be examined as a politically structured landscape reflecting internal complexities and organization of the dynastic Tongan chiefdom.

2. Background

2.1. LiDAR in archaeological practice

In aerial LiDAR, laser pulses are fired downward from an aircraft and reflect from the ground surface as well as objects on the ground

* Corresponding author. Present address: 6408 34 Ave NW, Calgary, AB, T3B 1N1, Canada.
E-mail address: tfreelan@sfu.ca (T. Freeland).

http://dx.doi.org/10.1016/j.jas.2016.04.011
0305-4403/

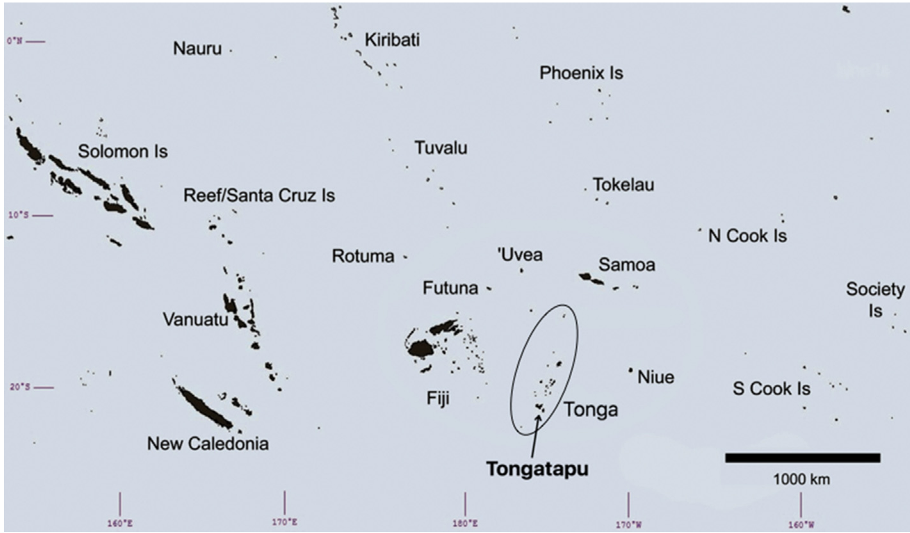

Fig. 1. Map of Tonga in West Polynesian context.

(trees, buildings). Reflected pulses are detected and the location of the reflected surface is established (Glennie et al., 2013). These datasets are processed to generate digital elevation models (DEM), which can be visualized to reveal different topographic features (Fernandez-Diaz et al., 2014). In archaeology, LiDAR is now frequently used for visualization of known sites, and for prospection of landscapes for previously unrecorded sites. A series of recent high profile discoveries have brought this technique to the attention of archaeologists and a captivated public. Examples include the discovery of the totality of the Caracol urban landscape by Chase et al. (2012); the detection of previously unrecorded urban centres in Cambodia (Evans et al., 2014); and the continued use of aerial LiDAR to reveal the full context of Stonehenge within a local monumental landscape (e.g., Bewley et al., 2005).

Survey using LiDAR can be particularly helpful in areas that are otherwise inaccessible for logistical, environmental, or political reasons. Rochelo et al. (2015) used LiDAR to document earthworks in Florida's challenging everglades environment. Recent studies employing LiDAR have also brought the "geospatial revolution" to South Pacific archaeology. Ladefoged et al. (2011) employed LiDAR in their analysis of the leeward Kohala field system in Hawai'i. Field alignments and trails were manually digitized in order to document the development of agricultural infrastructure in relation to agricultural potential productivity. McCoy et al. (2011) additionally mapped field systems in the northern Kohala district using LiDAR. Recently, Quintus et al. (2015) used LiDAR and semi-automated feature extraction to document artificial terraces in the hilly terrain of Ofu and Olosega in Samoa, combining their GIS analysis with systematic "ground truthing".

2.2. Automated feature extraction

For general usage of LiDAR in archaeological prospection, individuals with expert regional knowledge visually inspect DEMs to locate features of archaeological interest. Increasingly, however, automated GIS-based analyses are being developed to make digital prospection as effective as possible. These include the suite of techniques referred to as automated feature extraction (AFE), which are well developed in the field of computer-based image processing, but are relatively new for archaeological purposes (e.g., Luo et al., 2014). In large spatial datasets, AFE can be advantageous in that it applies objective criteria (e.g., roundness, relative elevation, etc.) for features of interest over vast survey areas.

Automated feature extraction algorithms can be developed for any type of remote sensing data. In the case of LiDAR, the 3-dimensional "point cloud" data acquired using LiDAR devices are processed and used to create high-resolution bare-earth DEMs. The AFE algorithms themselves consist of a series of classification rules, employing subjective contextual and geometric criteria to distinguish features of interest from other features on the landscape (the DEM "image"). In cases where features of interest in a survey area are relatively uniform in their shape and dimensions, and where the geology of the underlying landscape is neutral relative to the targeted features, AFE programs can be used to "extract" all cases of landforms that fit the set criteria. This study employs two AFE techniques that differ in their approach but share this fundamental definition.

Detection of anthropogenic relief in LiDAR-derived datasets has been achieved using a variety of techniques, most of which involve a form of template matching (e.g., Luo et al., 2014; Schneider et al., 2014; Trier and Pilø, 2012). The success of these and other related approaches centres on the fact that regular geometric shapes (squares, circles, straight lines) rarely occur in nature (Kvamme, 2013:55). For example, Trier et al. (2009) and Trier and Pilø (2012) detected circular features in Norwegian satellite imagery and LiDAR data by constructing circular templates of various sizes. Riley (2009) similarly developed a conical mound detection model, achieving nearly 90% success rate in detecting prehistoric burial features in the US Midwest.

The trend toward automation is a result of larger and more complex datasets becoming available, but their application to archaeological problems has been met equally with enthusiasm and skepticism as their results are of variable quality (Cowley, 2012). With continual and iterative development, however, AFE can be a powerful tool where automated techniques have been employed with increasing success in archaeological research (e.g., De Laet et al., 2007; Luo et al., 2014; Riley, 2009; Schneider et al., 2014; Trier et al., 2009; Trier and Pilø, 2012).

Like other "coarse" research methods, the value of AFE lies in its ability to reveal broad and otherwise undetectable patterns. Automated detection benefits prospection in large datasets where manual/visual inspection is considered to be too subjective, cumbersome, or time-consuming. In studying the Tongan archaeological landscape, we considered AFE a worthwhile endeavour