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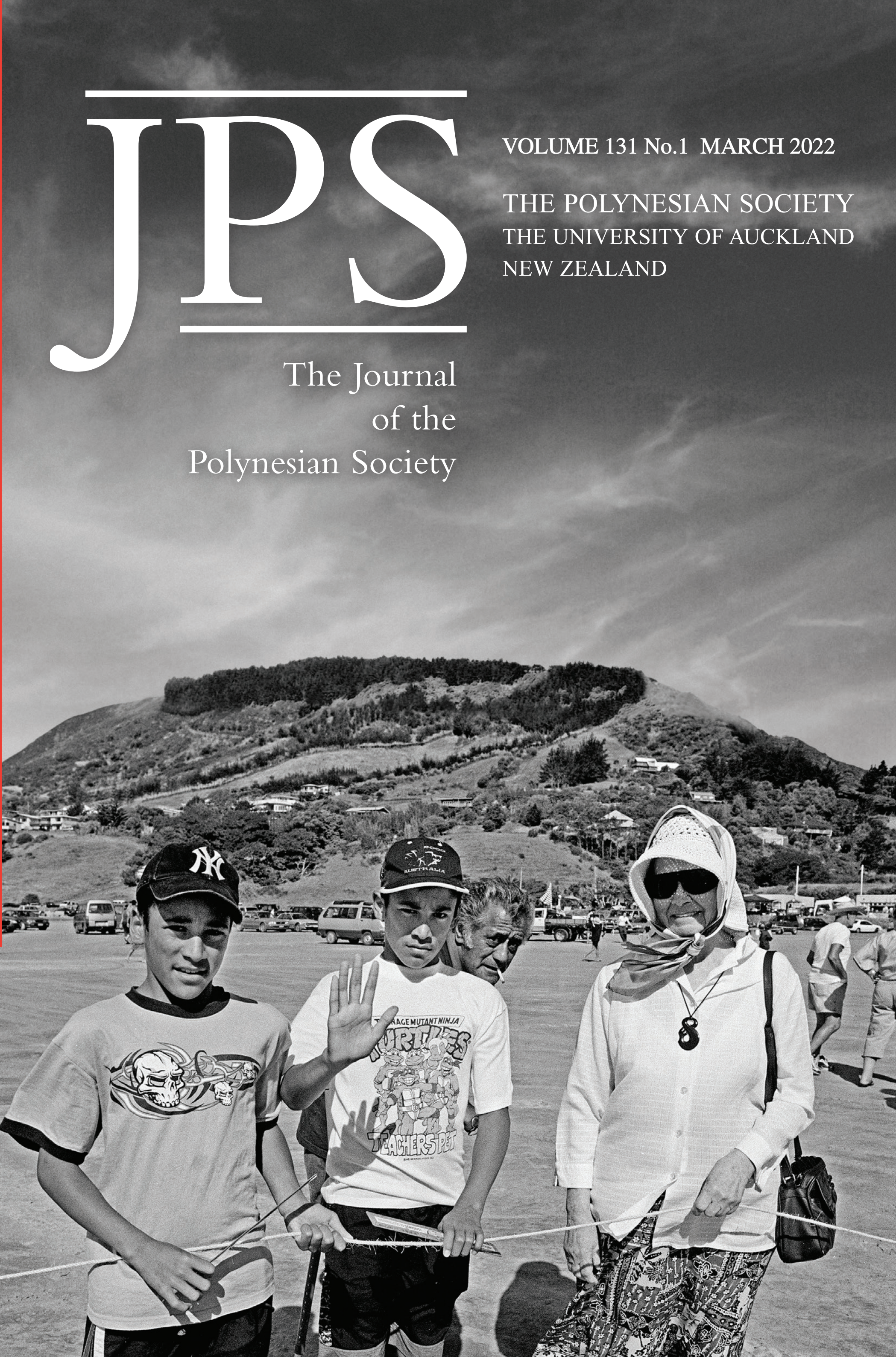

MAPPING ANCIENT ARCHITECTURE VIA UNPILOTED AERIAL VEHICLE–ACQUIRED LIDAR: A CASE STUDY OF HŌLUALOA ROYAL CENTRE, KONA DISTRICT, HAWAI‘I ISLAND

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ABSTRACT: At present there is no systematic record of the size, form or density of architecture at Hawaiian royal centres. We report on the results of a UAV LiDAR survey of one of the best-preserved examples of a royal centre in the archipelago: Hōlualoa Royal Centre, Kona District, Hawai‘i Island. The resolution of our data (0.3–0.1 m) is far superior to previous airborne LiDAR surveys (1.0 m); however, several factors, including thick understory vegetation, made resolving archaeological targets challenging. We nonetheless were able measure the volume of building material of the largest features, which allows us to compare structures in this royal centre with other monuments in the region. This study highlights the advantages, and limitations, of UAV LiDAR as well as the need for more high-quality quantitative data on architecture at royal centres.

Keywords: archaeology, ancient architecture, royal centres, UAV LiDAR, Hawaiian Islands

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At the time of initial European contact, in AD 1778–1779, "royal centres" were hubs of social, political and religious life in the four independent kingdoms of the Hawaiian Islands (Kaua‘i, O‘ahu, Maui and Hawai‘i) (Fig. 1). These centres are described by Kirch (2018: 383) as "clusters of temples, houses for the king, his wives, and retainers, dwelling compounds of other high-ranking chiefs, storehouses, canoe sheds, and other specialized facilities". While the

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royal court and retainers had no fixed location, and would move with the ruling family, centres were located within heavily populated areas, and some had resident priests who lived in special precincts. They were the location of large ceremonies, such as during the makahiki ‘harvest celebration’ season, and were also used as places to assemble military forces ahead of a major campaign. In the nineteenth century, the archipelago was consolidated under a single kingdom (AD 1810), traditional religious practices were abolished by royal decree (AD 1819) and a new palace was dedicated on O‘ahu (‘Iolani Palace, AD 1882). Naturally, the role of royal centres changed over that time and many have been transformed by modern development and restoration (on restoration and care for sites of religious ritual see Kawelu and Pakele 2014).

Nearly everything we know about royal centres—including basic information like their location, function and history—comes from oral histories written down in the nineteenth century (Ii 1959; Kamakau 1961; Malo 1951) or from early European accounts (Beaglehole 1967; Vancouver 1798). Archaeology began to contribute to our understanding of royal centres beginning with maps made by early surveyors Henry Kekahuna (Kawelu 2015: 96; Tengan and Roy 2014) and John Stokes (Flexner *et al.* 2017). Their schematic maps, while only focused on a handful of centres, were often annotated with traditional knowledge specific to that location. Each royal centre had a unique layout with a dense and complex combination of different types of architecture. These include some of the largest stone platforms ever constructed for temples (*heiau*) and massive free-standing walls, also called Great Walls, that enclosed areas reserved for special purposes. Other smaller stone walls were commonly used to enclose spaces, and early maps also show small features that may have served as building foundations. In some cases, features had a specialised function specified in tradition, such as bleachers for viewing sports or rituals. Some centres had artificial ponds and tracks created for *hōlua*, the sledding game, including the largest track ever created (see McCoy 2018 for more details on the layout of royal centres).

Except for early excavations (e.g., Ladd 1969a, 1969b), archaeological research focused on royal centres has been surprisingly rare (Kirch *et al.* 2009; Kolb 1991; McCoy *et al.* 2021; Rieth *et al.* 2013). Much of the focus of sustained academic research in the Hawaiian Islands has focused on how changes in the economy, society and religion affected people living far from royal centres where these changes are thought to have been easier to unpack from the archaeological record (e.g., Kirch 2014; Ladefoged *et al.* 2020). Consequently, they are often sidelined in broader discussions of ancient Hawaiian society. For example, Bayman *et al.* (2021: 48) include “royal residences and palaces” in a list of things that they see as “equivocal or altogether lacking in the Hawaiian archaeological record”. While other claims they made have been challenged (Hommon 2021; Kirch 2021; McCoy and Ladefoged 2021), this point has not been specifically disputed.

Jennings and Earle (2016: 478) see royal centres as “modest in comparison to central places” elsewhere in the world when it comes to “spatial scale and monumental construction” (see also Bayman and Dye 2013: 97). To support this claim, they reference the area of two royal centres (in hectares) but provide no quantitative data on monuments. Again, the absence of supporting quantitative evidence was largely undisputed. Beginning in the 1990s, the volume of building material (m^3) was used by Kolb (1991) to estimate the amount of labour put into Hawaiian monumental architecture. For example, for Pihana Heiau (Kolb 1991, Table 5.5), after considering transport and construction costs, a single labour day would have been required for every 4.5 m^3 of building material. However, concerns about the conversion of building material to labour days (Mulrooney *et al.* 2005: 26) and about calculating the volume of building material at certain sites and construction periods (Kirch 2010: 233) has had the unintended consequence of discouraging further quantitative study of architecture.

We believe that at present almost all archaeological generalisations about royal centres are disputable, and unwarranted (i.e., without empirical support), in the absence of a systematic record of the size, density and form of architecture at royal centres. To begin to create such a database we turned to remote sensing. Remote sensing, and especially via airborne LiDAR, has been central to the geospatial revolution in archaeology (McCoy 2020a, 2021) since technical advances now give us maps of ancient architecture at a resolution that mimics traditional field survey in challenging environments like tropical forests (e.g., Chase *et al.* 2012). We have argued that unpiloted aerial vehicle (UAV)–acquired LiDAR is specifically valuable in that it can allow archaeologists to rapidly collect data at a consistent resolution on the order of hectares (Casana *et al.* 2021; McCoy *et al.* 2021). While we are not alone in our enthusiasm for UAV LiDAR in archaeology (Barbour *et al.* 2019; Opitz and Herrmann 2018; Poirier *et al.* 2020; Risbøl and Gustavsen 2018; VanValkenburgh *et al.* 2020), the relative novelty of the technology means for most regions we lack systematic studies that deal with the challenges of mapping ancient architecture via LiDAR. As more archaeologists turn to LiDAR to augment traditional field survey, or in some cases as a replacement, it is important to know both the technique’s strengths and weaknesses.

For this study we focused on a royal centre located in Hōlualoa (Kona District, Hawaiʻi Island) (Fig. 2). It was one the first places listed on the National Register of Historic Places in the Hawaiian Islands (Yent 2003), having been given legal protection as an “archaeological district” (Hōlualoa 4 Archaeological District, State Site No. 50-10-37-23661). It includes two complexes, one that traditions tell us was used for religious rituals, celebrations and sport (Keolonāhihi Complex) and the other a rare example of royal residence, or what elsewhere would be designated as a palace (Flannery 1998), built by Queen Keākealaniwahine. In these complexes,

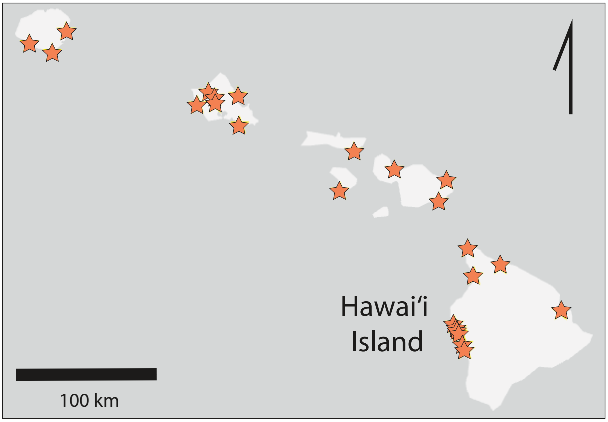


Figure 1. Locations of royal centres. The Hawaiian Islands has two dozen locations that were designed as royal centres.

and the area immediately around them, more than 50 "sites" have been reported on field surveys constituting a landscape that includes six temples, 26 household compounds, agriculture fields and historic-era stone boundary walls. However, this research has been sporadic, stretched over a century of surveys (see review in Yent 2003), and excavations have been extremely rare, with most structures lacking basic chronometric information. And so, while it is hard to imagine another location in the Hawaiian Islands with the same range of forms and functions of architecture, at present we lack a coherent picture of the archaeological landscape.

We chose to focus on the royal centre at Hōlualoa because we suspect it may be among the best preserved of known royal centres. We also saw it as a strong candidate for low-altitude UAV-acquired LiDAR survey given that even though there is thick vegetation across the study area it is possible to resolve some features on previous high-altitude, fixed-wing, airborne LiDAR. Unfortunately, our results, when viewed from the perspective of LiDAR as providing an alternative to pedestrian survey, were disappointing. Due to thick vegetation only the largest of the many remnants of architecture were detectable (Fig. 3). We see our work as contributing to "an emerging arena of research [that] is beginning to employ remote sensing as an independent and complementary means of interrogating the archaeological record and, in so doing, is providing insights into the human past that could not be achieved through conventional fieldwork" (Casana 2021: 168). From this perspective, our results succeeded in that they allowed us to compare

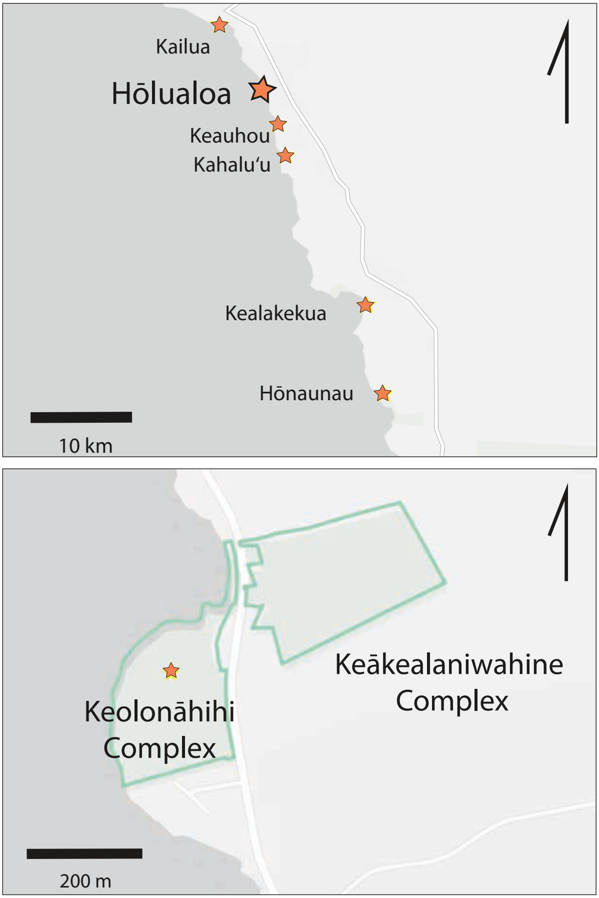


Figure 2. Location of Hōlualoa Royal Centre, Kona District, Hawai'i Island. Within the Kona District there are six royal centres within a 30 km stretch of coastline (top). Our study area focused on two complexes within the Hōlualoa Royal Centre (bottom).

architecture between two royal centres (Hōlualoa and another Kona centre at Kealakekua), specifically in terms of the volume of building material used (m^3) (McCoy *et al.* 2021). These limited results go a small way toward creating a systematic record of the size, density and form of architecture at royal centres, but leave a great deal yet to be done.

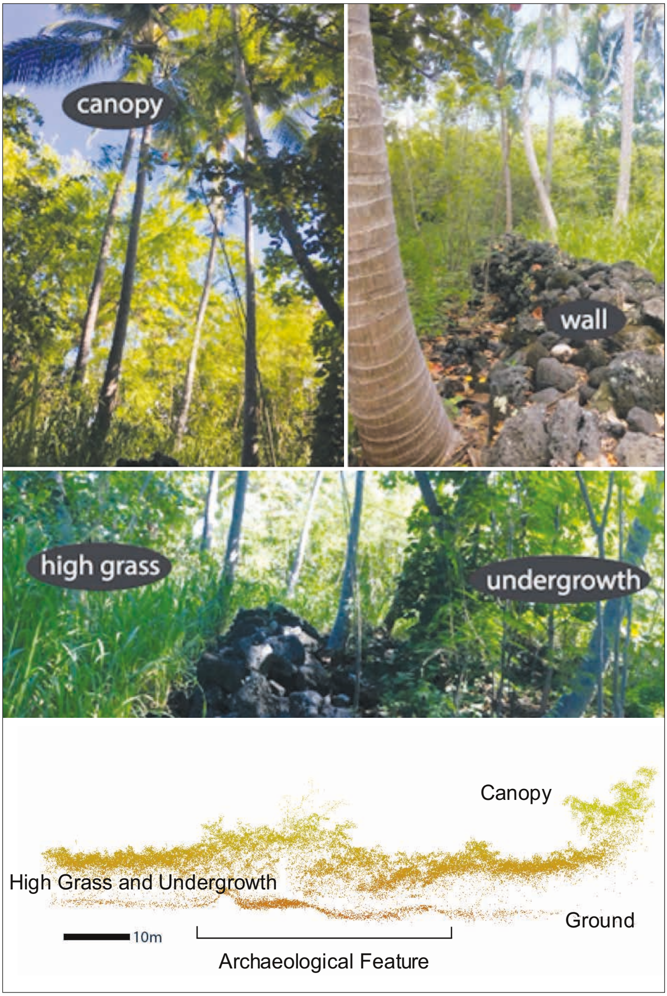


Figure 3. Examples of vegetation in the Hōlualoa Royal Centre. Our UAV LiDAR survey faced several challenges including high palm canopy (upper left), numerous low stone walls and platforms (upper right) and a thick undergrowth of brush and high grass (lower). We also show a representative cross-section profile of a raw point cloud from LiDAR collected via UAV. The point cloud includes the top of the canopy (first return, top of image) and ground (last return, bottom of image), as well as points representing vegetation in between the canopy and the ground.

STUDY AREA

Culture History of the Hawaiian Islands

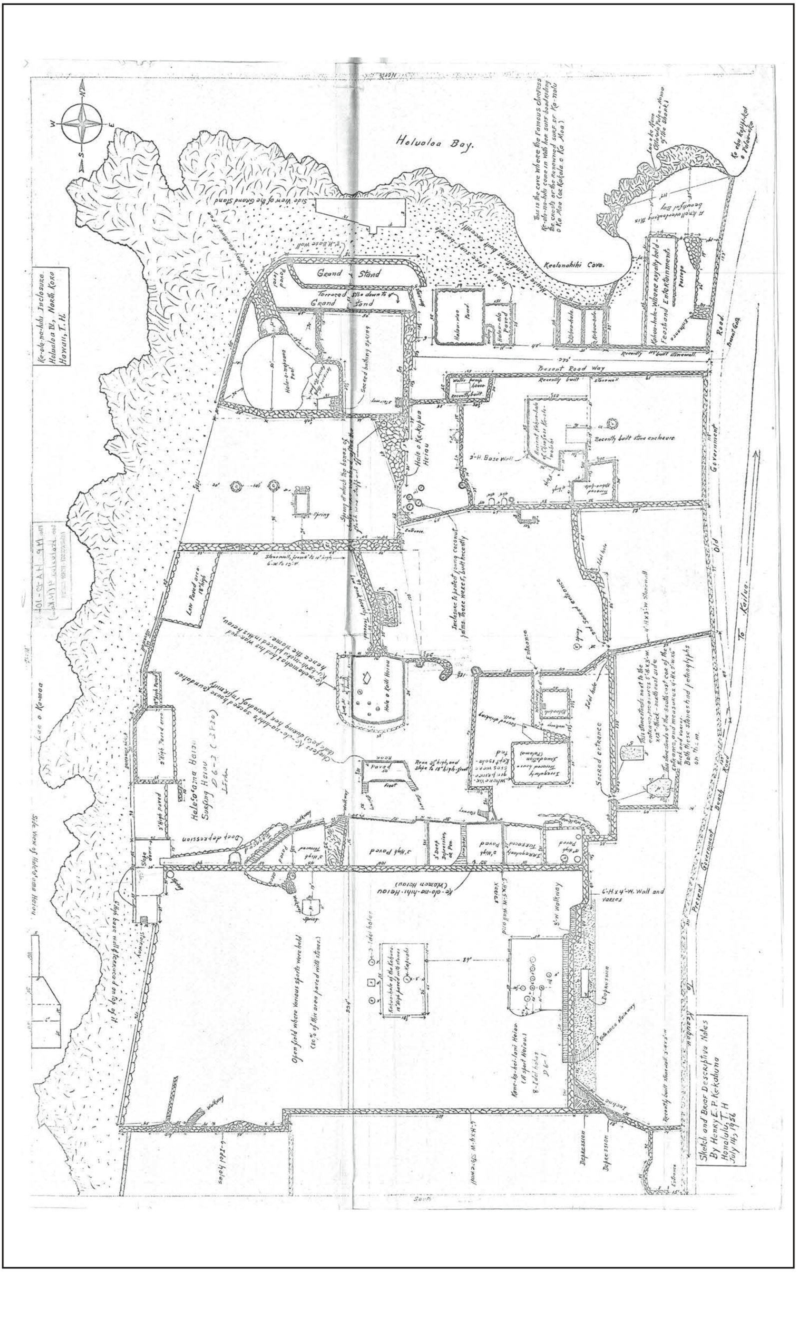
The Hawaiian Islands were first settled from Central Eastern Polynesia, likely the Marquesas Islands, around AD 1000, with subsequent voyages from the Society Islands described in oral histories in the following centuries (Athens *et al.* 2014; Kirch 2011). Later voyages are closely associated with the historical figure of Pa‘ao, a Tahitian priest who introduced a number of traditions around AD 1200–1400. Initially classified as a “chiefdom” (Cordy 1981; Kirch 1984, 1985; Sahlins 1958; Service 1962), we now believe that there was a fundamental shift around AD 1550–1700 to an archaic state society (Hommon 2013; Kirch 2010). The material record of this change can be seen in the increase in population, the increase in scale and intensification of agricultural production, the construction of monumental architecture (especially heiau) and the establishment of royal centres.

The function of the royal centre within the broader political, economic, religious and social spheres is something that remains poorly understood (McCoy 2018). Oral histories, combined with the presence of a variety of monumental structures, make it clear that royal centres were used for religious ceremonies and major gatherings (Ii 1959; Kamakau 1961; Malo 1951). The court of island kingdoms, unlike other pre-modern states, was mobile (Hommon 2020). There were times when the court would settle within royal centres, but it was always temporary. There were, nonetheless, full-time residents in and around royal centres, including some precincts set aside for priests and others for the local community.

In part due to a lack of excavations and a revision in the chronometric techniques we use (Rieth and Athens 2013), there are no direct dates on the construction or use of royal centres except for Kealakekua Royal Centre in the Kona District of Hawai‘i Island. New radiocarbon dates suggest the Great Wall, a massive free-standing stone wall that enclosed the religious precinct of Kealakekua Royal Centre, was likely built around AD 1640 (McCoy *et al.* 2021). This is consistent with oral histories that describe the shift of the island’s capital to Kona initially around AD 1600 by King ‘Umi-a-Līloa and carried on by his successors. By the time of initial European contact in AD 1778–1779 there were six royal centres, including one at Hōlualoa, spread across a 30 km section of the island’s west coast.

Previous Research

The oral history of Hōlualoa provides us with a broad framework for the development of the royal centre. The coastal complex is associated with Keolonāhihi, a chiefess and daughter of Tahitian voyaging priest Pa‘ao (Pinehaka 1974); therefore it is likely this was an important location centuries before the island’s capital was moved by King ‘Umi-a-Līloa in AD 1600.


Heluoloa Bay.
Grand Stand
Present Road Way
Keolonahihi Cove.

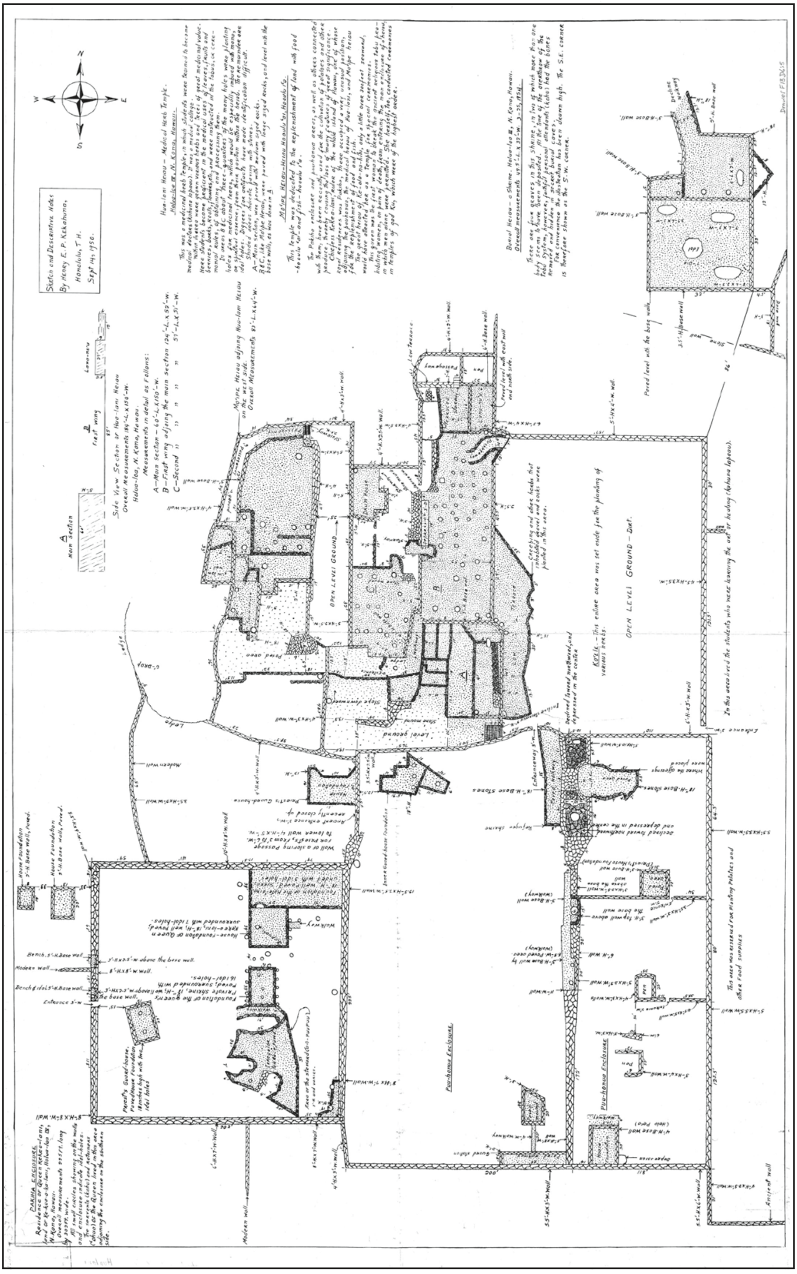


Figure 4. Detailed maps of Hōlualoa Royal Centre. Sources: Kekahuna (1950, 1956).

Queen Keākealaniwahine, a descendant of ʻUmi-a-Līloa through her mother, Queen Keakamāhana, is credited with building the inland complex.

Of the early maps of the royal centre the most detailed were those created by Kekahuna (1950, 1956) (Fig. 4). The layout of structures is shown schematically with annotations as to traditional uses of different features. Features include walls of varying sizes and platforms as well as a number of other forms, such as depressions where wooden carved statues (*kiʻi*) once stood. These maps formed the basis of the first overall map created when Hōlualoa was nominated for and accepted onto the US National Register of Historic Places (Fig. 5). Unlike earlier maps, Figure 5 shows an attempt to give an overview of both major complexes and modern and historic-era features, including roads and stone boundary walls created to control livestock, as well as neighbouring sites and locations where features had been disturbed. It also includes information from cultural resource management archaeology surveys in the area (see Yent 2003).

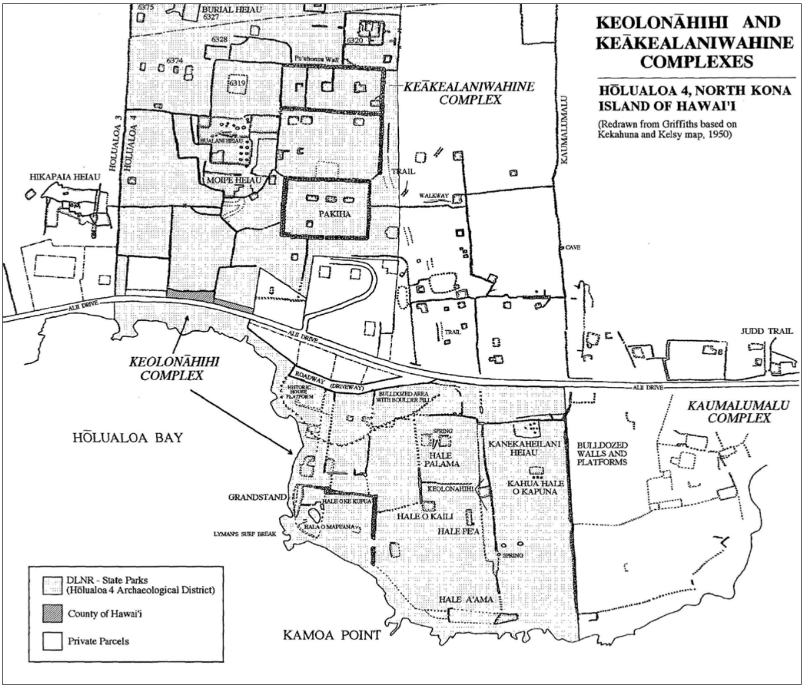


Figure 5. National Register map, Hōlualoa Royal Centre. Source: Yent (2003).

Figure 6. Sites currently recorded in the Hawai'i Cultural Resource Information System (HICRIS) for Hōlualoa Royal Centre. Features are recorded as polygons, lines and points.

One of the challenges in recording field observations here, and elsewhere in Hawai'i, is the inconsistent use of complex, site and feature identification systems (McCoy 2017, 2020b). The first surveys adopted local place and site names (i.e., Kanekaheilani Heiau). By the 1970s, the State of Hawaii's Historic Preservation Division began compiling site records, and last year launched a GIS database called HICRIS (Hawai'i Cultural Resource Information System) (https://shpd.hawaii.gov/hicris/). At present, only a third of the total site records have been migrated into HICRIS (Fig. 6). We have used the current database to compile a list of previously recorded sites to use in our remote sensing study.

MATERIAL AND METHODS

UAV Visible Light

In 2019, our team flew a visible-light survey over Hōlualoa (Fig. 7). We used a DJI Phantom 4 Pro, flown at 40 m above ground level, with flight planning and autonomous mission control executed using the third-party

Figure 7. UAV survey: visible light, Hōlualoa Royal Centre.

Pix4Dcapture application. Aerial images collected with at least 80 percent overlap in all directions were processed using Agisoft Metashape to produce a digital surface model and orthoimage of the site with a ground sampling distance (resolution) of 4 cm^2. The survey covered an area of 0.4 km^2 georeferenced using ground control points to UTM NAD 1983, Zone 4N. While dense vegetation makes it unlikely that visible-light surveys will reveal any archaeological features, these data provide a good perspective on the nature and density of vegetative cover.

UAV LiDAR

At the same time we conducted a UAV LiDAR survey over Hōlualoa, using a Geodetics Geo-MMS LiDAR system deployed on a DJI M600 drone (Fig. 8). The Geo-MMS system utilises a Velodyne VLP-16 sensor integrated with a proprietary IMU and two dual-frequency GNSS receivers. Three flights were undertaken using a methodology described by Casana *et al.* (2021), at an altitude of 40 m above ground level with a transect spacing of 50 m. Two flights were completed over the western half of the study area to try to ensure significant penetration of the canopy, and one flight over the eastern area producing an average of 330 points per m^2. Flight planning and autonomous

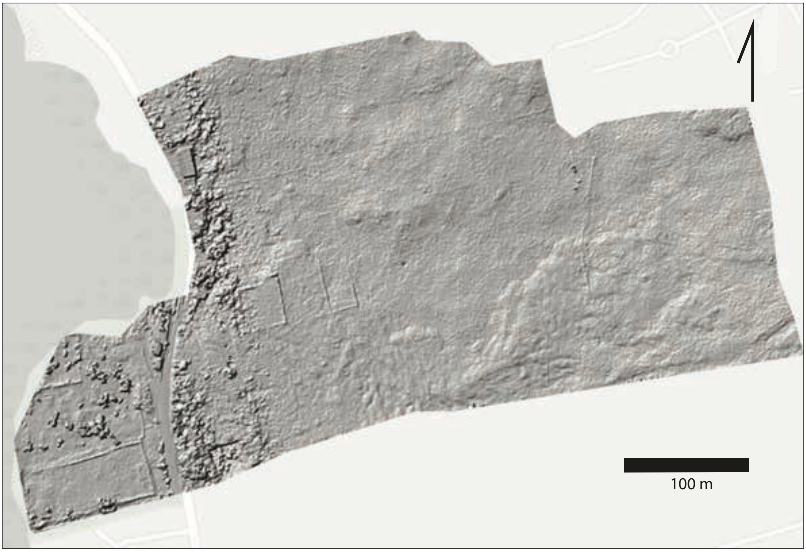


Figure 8. UAV survey: LiDAR, Hōlualoa Royal Centre.

mission control was accomplished with UgCS Pro. Raw LiDAR data were then processed to integrate post-processed kinematic GNSS data and generate a georeferenced point cloud output (134 million points) using the Geodetics LidarTool software. The resulting point cloud was further processed to generate a bare-earth digital terrain model (DTM) through a combination of SAGA GIS and LASTools. Hillshades were generated from the DTM using SAGA GIS to best visualise the surface for analysis. The resulting point-cloud data covered 0.4 km^2 and 30 ground points per m^2. Elevation above sea level was corrected using bare-earth airborne LiDAR flown by FEMA in 2006 (UTM NAD 1983, Zone 4N; vertical datum: NAVD 88, vertical units: metres).

RESULTS

The analysis of the LiDAR data reported here improves significantly on the resolution of existing free and accessible LiDAR data (Fig. 9). Data sets recorded by NOAA in 2006 and 2013 are available for part but not all of the study area. Derived bare-earth DTM have relatively low resolution for archaeological site mapping, and most obvious features revealed by the resulting DEMs (digital elevation models) are only reported at 1 m grid

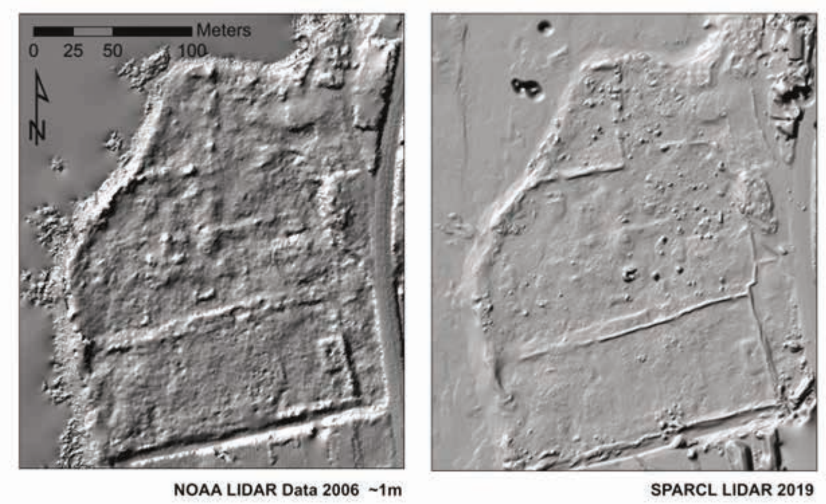


Figure 9. Comparing previous airborne LiDAR with UAV survey LiDAR, Hōlualoa Royal Centre.

resolution (OCM Partners 2021: 2013 USACE NCMP Topobathy Lidar: Big Island (HI), https://www.fisheries.noaa.gov/inport/item/49745). The data set reported here, in contrast, provides significantly more ground points per metre, to produce a finer DEM (10–30 cm resolution) over the entire site.

However, even though this data is better quality than what was otherwise available, most of the previously recorded architectural features could not be resolved in the LiDAR data, likely due to the dense vegetation that covers many of them. Not only was there significant tree cover, which blocks many points from penetrating to the ground, there was also significant vegetation near the ground and considerable dead vegetation build-up on the ground and features, which are all difficult to filter from points that are actually ground. Combined with the inherent noise of "lower-cost" LiDAR sensors like the Velodyne VLP-16, it proved difficult to resolve subtle archaeological features. In fact, even the large enclosure walls can only be mapped incompletely.

We nonetheless selected 16 sections of walls that can be resolved in the LiDAR data to examine the volume of building material using the image mensuration technique (ArcGIS Pro 2.4.1) (Fig. 10, Table 1). There are four categories of walls visible on UAV LiDAR: very large (7–5 m^3 per linear metre, LM), large (5–2 m^3 per LM), medium (2–1 m^3 per LM) and small (less than 1 m^3 per LM) walls (Table 1).

Figure 10. Polygons represent large architecture remotely mapped in Hōlualoa Royal Centre. Keolonāhihi Heiau (4 on the map) was found to account for a large proportion of the total volume of the coastal complex. The Pakiha Enclosure (8 on the map) accounts for a large proportion of the building volume measured in the inland complex. See Table 1 for more information on the sizes of features.

Our previous study of UAV-acquired LiDAR from the royal centre at Kealakekua found this technique provided good estimates of building material volume. However, for the Keolonāhihi Complex, maps from the 1950s note a great deal of variability in height and width of walls, problematising a comparison between field survey results and LiDAR-derived DTM data. The Keākealaniwahine Complex, however, shows a good match for the Pakiha Enclosure, specifically the extremely large northeast corner, which Kekahuna reports at 13.6 m^3 per LM and for which the UAV LiDAR gives a value of 12 m^3 per LM. At another structure identified as a *pu'uhonua* 'refuge', Kekahuna gives the volume as 2.55 m^3 per LM, and

UAV LiDAR returned a result of 2.99 m³ per LM. These data suggest that our volume estimates at this site are reliable.

The combined total volume measured at the royal centre is 4,653 m³. The largest single structure by total volume measured on this survey is a massive wall that includes Keolonāhihi Heiau at 796 m³, which accounts for 37 percent of the total volume of walls measured at the Keolonāhihi Complex (2,156 m³). At Keākealaniwahine Complex, the Pakiha Enclosure, at 1,650 m³, accounts for 66 percent of the total volume in that complex (2,497 m³).

Table 1. Estimated volume of each mapped large architecture.

Fe. ID.	Cut m³	Fill m³	Area m²	Total vol. m³	Linear m (LM)	Vol. per LM
0	257	215	635	472	86	5.49
1	58	23	288	81	56	1.45
2	117	13	394	130	28	4.64
3	108	13	304	121	70	1.73
4	726	70	1,407	796	149	5.34
5	55	113	314	168	48	3.50
6	217	103	512	320	83	3.86
7	18	50	197	68	46	1.48
8	685	967	1,932	1,652	240	6.88
9	50	94	600	144	92	1.57
10	3	11	107	14	24	0.58
11	179	95	540	274	86	3.19
12	105	104	431	209	70	2.99
13	37	84	191	121	84	1.44
14	7	15	119	22	38	0.58
15	22	39	245	61	55	1.11

CONCLUDING REMARKS

We are, in our view, still a long way from having the type of systematic quantitative data necessary to warrant the use of monumental scaled construction at Hawaiian royal centres in cross-cultural comparisons (e.g., Jennings and Earle 2016). This is just one of many challenges for archaeology to contribute to our understanding of the Hawaiian past (see also McCoy *et al.*, in press). Our analysis enables us to now compare broadly the amount of building material used at different locations within royal centres or between different centres in the Hawaiian Islands. It is notable, for example, that the total volume of building material used in larger structures we examined at the Hōlualoa Royal Centre (4,653 m^3) is remarkably similar to the amount of material used to build the main temple in the Kealakekua Royal Centre, Hikiau Heiau (4,234 m^3). These results could indicate a broadly parallel degree of effort went into the construction of these monumental complexes, pointing to similarities in elites' ability to mobilise labour, or other normative cultural understandings of the scale of such building enterprises. However, much more empirical data, and strong linking arguments, are necessary to support these or other such claims.

At the Keolonāhihi Complex, on the other hand, we do not see the kinds of investment in large temples or massive enclosing walls that are on display at other royal centres in Kona, but rather a variety of other features within the complex. Keolonāhihi Heiau is noted as a women's heiau, but relatively little is written about it compared with other locations within the complex. The results of this survey highlight the need for further research on this monument.

Our comparative data also reveal that at the Keākealaniwahine Complex, the Pakiha Enclosure, with its massive wall that traditions tell us enclosed the royal residence, stands out from all other monumental buildings in terms of scale and thus presumed political and cultural significance. Historical sources make it clear that the presence of the island's ruler, which required people to prostrate themselves, was disruptive to daily life. If we assume these kinds of cultural protocols were necessary when in the presence of the ruling family these high walls may have both provided security but also helped facilitate daily life in the royal centre.

With these results, our surveys show some of the current limitations of aerial LiDAR surveys in densely vegetated areas like those in this study. In many cases, our UAV-derived LiDAR data failed to resolve previously recorded architectural features, largely due to the fact that they are obscured by vegetation. Far from being a panacea, in several instances our LiDAR data could only resolve the largest monumental features, and even these only in the best-preserved sections, showing that the current technology is not a replacement for more traditional ground-based investigations in environments like those in this study.

We speculate that the relatively disappointing results from some sites in our study are likely a product of the relatively low-cost UAV LiDAR system we employed. The Velodyne VLP-16 sensor collects only two returns per pulse, as opposed to an unlimited number of returns collected by more costly systems, and also collects only 300,000 points per second, while other systems collect more than 1 million. These fundamental limitations restrict the ability of the sensor to penetrate very dense vegetation, and thus remain a stumbling block for surveys of this kind in similar environments. However, as UAV-deployed LiDAR technology continues to improve, we can expect better results with systems that offer higher point density and full-waveform returns, both of which will significantly increase the potential to penetrate tree canopy and ground vegetation. Researchers interested in conducting UAV LiDAR surveys of archaeological sites in densely vegetated areas should take these issues into account when planning what instrumentation is most suitable, as well as the time of year for surveys in environments with seasonal differences in vegetation cover.

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