waka kuaka

The Journal of the Polynesian Society

VOLUME 133 No. 4, DECEMBER 2024

The Polynesian Society
Waipapa Taumata Rau
The University of Auckland, New Zealand

SCIENTIFIC ASPECTS OF HĀPAIALIʻI HEIAU

ALBERT S. KIM
University of Hawaiʻi at Mānoa

BRENTON SASAOKA
University of Hawaiʻi at Mānoa

ABSTRACT: A heiau is a Hawaiian pre-Christian place of worship composed of rocks and holding historical and cultural significance, with a variety of uses ranging from worship to rituals. The scientific origins of Hawaiian heiau have yet to be fully inspected in the literature. This paper covers Hāpaialiʻi heiau on the island of Hawaiʻi and its main function as a seasonal calendar through continuous observation of the sunrise and sunset locations over the sea horizon. Understanding the calendar functionality of the heiau contributes an essential step towards understanding Hawaiians' use of indigenous science. This study mathematically investigates the sacred structure's functionality with numerical accuracy and scientific rigour. A brief overview of the history of the Kahaluʻu area and the surrounding heiau provides important context for the heiau's significance. This study reports and analyses the heiau's relevant history, cultural significance and reconstruction by Kamehameha Schools. The importance of the calendar lies in the determination of the responsibilities for the current season, indicating which crops are to be harvested and which fish are in the mating season. In the mathematical analysis, the coordinates of the stones within the heiau are independently measured using Google Earth and Google Maps. The relative distances and angles between the internal stones are calculated using Google Sheets and Matlab to discover the underlying sciences possibly used by ancient native Hawaiians.

Keywords: sunset, haversine, calendar, Makahiki, season

Heiau, regarded as sacred in Hawaiian history, were structures constructed of rocks and used as places of worship, typically restricted to high-ranking officials (Nuuhiwa n.d.). The ancient Hawaiians constructed heiau in good harmony with the surrounding environment, using culturally significant natural materials. The architecture of heiau served distinct purposes, encompassing sacrificial ceremonies, bathing ponds, housing and god veneration. The latter ceased in 1819 following the abolishment of the Hawaiian kapu (taboo, special privilege) system by Queen Kaʻahumanu, due mainly to foreign influence and pressure (Kamehameha Schools n.d.).

Kim, Albert S. and Brenton Sasaoka, 2024. Scientific aspects of Hāpaialiʻi heiau.
Waka Kuaka: The Journal of the Polynesian Society 133 (4): 465–478.
https://doi.org/10.15286/jps.133.4.465-478

Hāpaiali'i heiau (Fig. 1) is one of at least 50 individual heiau that were present near Hāpaiali'i (Kamehameha Schools n.d.). The carbon dating conducted on the heiau indicates it was originally constructed on a smooth lava flow during the period between 1411 and 1465 (The Kohala Center n.d.). Kalaninui'īamamao, an ali'i (chief) of Hawai'i, is believed to have been responsible for the initial construction of Hāpaiali'i. Later, it was rededicated during the era of Kalaunuiohua and the kahuna nui wahine (female high priest) Wa'ahia. The heiau's reconstruction was undertaken by an unidentified Maui kahuna kuhikuhipu'uone (priest who provides guidance on the construction of sacred edifices). Once used as a residence for King Kamehameha during the Makahiki (religious sports festival) season, it was later repurposed by Lānai'i, a kahuna (priest), for religious practices in the 1800s.

The interior of the heiau was mapped in 1906 by J.F.G. Stokes, an archaeologist of Australian origin. In 1953, Henry Kekahuna and Mitchell Fujisaka undertook a comprehensive mapping effort to document the surrounding area and ascertain the heiau's exterior dimensions and distances to the neighbouring heiau, as shown in Figure 2. Based on its unique coastal location, Hāpaiali'i at Kahalu'u, Hawai'i, it appears to possess several additional

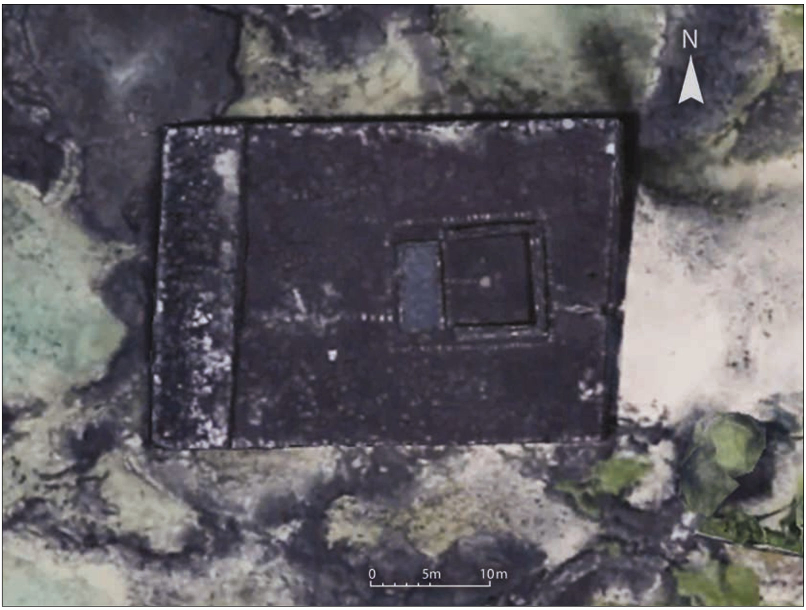

Figure 1. Top view of Hāpaiali'i heiau, taken using Google Earth.

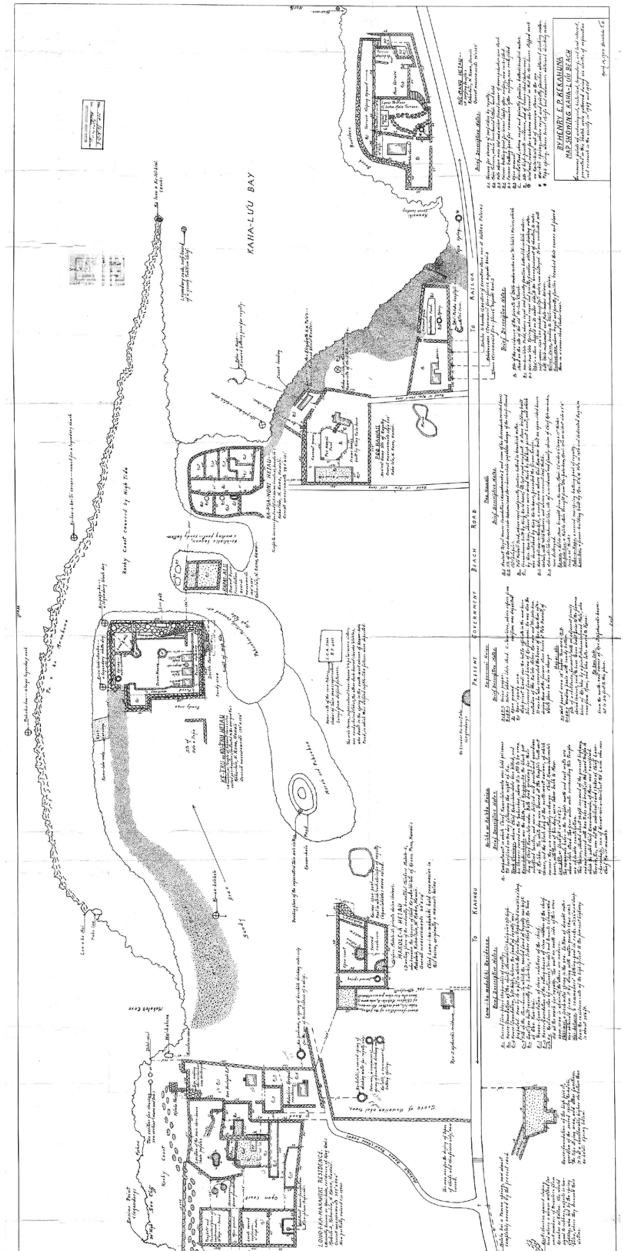

Figure 2. Map made by Henry E.P. Kekahuna in 1952.
(http://data.bishopmuseum.org/Kekahuna/kekahuna.php?b=closeup&ID=19)

functions not documented in the existing literature. The heiau seems strategically positioned near an estuary to cater to fish that could thrive in brackish water and kōlea (Pacific golden plover) that rely on freshwater for drinking (Kamehameha Schools n.d.).

Researchers have uncovered multiple carvings resembling bowls near the periphery of the heiau. These carvings are thought to have served as bait cupules for fishing during high tides (Tuggle and Tomonari-Tuggle 1999). Apart from these functions, the primary purpose of Hāpaialiʻi was to function as a natural calendar, carefully monitoring the designated sunrise and sunset positions on prearranged structures parallel to the sea horizon. Hawaiians in ancient times would ascend to the pinnacle of the heiau to observe meticulously the shadows created by the five pillar stones in front of them, facing toward the ocean. The months and seasons of observation time throughout the year could be determined by the relative position of the setting sun in relation to the pillar stones. The winter solstice was recognised when the sun set directly above or close to the leftmost pillar. If the sunset happened near the rightmost stone, the date corresponded to the summer solstice. Once reaching one of the pillar locations, the sun would stay there for two to three days before moving back towards the middle pillar.

The heiau's most recent restoration, conducted between 2003 and 2007, employed two survey maps as points of reference to establish the historical placement and measurements (Kekahuna 1950, 1952). Once the reconstruction was finished, the crew discovered that the general time of year could be ascertained by observing the sun behind the pillar stones during the solstices (Nuuhiwa n.d.). The restoration process was conducted with the utmost care to maintain the heiau's original form. Contemporary materials and construction methods were employed sparingly to supplement the structures as a substitute for scarce traditional materials. The initial phase comprised creating a 1∶100 scale plane table map that meticulously depicted the plans and cross-sections of the heiau. The scaled plane maps were compared to those produced by J.F.G. Stokes in 1906 and Henry Kekahuna in 1952 and used to study the natural changes in the area over the course of a century. Archaeological excavations were performed within demarcated sections of the original heiau to expose buried foundation stones and other artefacts of historical significance (Mahealani Pai, pers. comm., 2007). The stonework was accomplished under the careful guidance of a licensed contractor with extensive expertise in traditional Hawaiian dry stone masonry construction. The involvement of an archaeologist was crucial in documenting any traces of former structures that could have existed within the boundaries of the heiau. In the end, the Bishop Holdings corporation, with input from Hawaiian organisations, evaluated the cultural significance of the heiau, with oversight from cultural resource specialist Mahealani Pai.

METHODS

All measurements and calculations in this study are based on images of the newly reconstructed heiau, which were created by twenty-first-century scientific and technical experts. Unfortunately, physically visiting the heiau was challenging to accomplish, particularly for entering the sacred structure for civil survey work. There needed to be a standard civil survey within the heiau; therefore, various methodologies and software applications were employed in this study to guarantee precise data collection. The average distances were estimated using Google Earth by acquiring absolute coordinates, in degree format, from each corner of the heiau. Subsequently, the coordinates, with the centre stone's location, were transformed into a decimal degree–minute format. The distance between two designated points and the corresponding line heading was computed using the measure tool integrated into the Google Earth application. In addition, Google Maps was employed independently to calculate distances accurately based on Google Earth or to measure other distances on a two-dimensional map.

Haversine Distance and Azimuthal Angles

The software Matlab was employed to import data from Google Earth and Google Maps, as well as to calculate the decimal distance and azimuth between the two coordinates. Google Maps uses the Mercator projection for its browser-based maps. Google Earth uses the WGS84 geographic projection with an EPSG code of 4326, which represents the Earth as a three-dimensional ellipsoid instead of a flat map like Google Maps. WGS84 is a global standard for geographic coordinates that allows for accurate positioning, but it requires a projection method for visualisation on flat maps. The azimuthal angles were transformed into distances in metres, and the bearings were computed based on two sets of coordinate points. The haversine formula was used in Google Sheets to calculate the distance between two coordinates without reliance on other methods (Movable Type Scripts n.d.), with an accuracy considered 0.3% to 0.5% error. These numerical results were compared to estimate the specific dimensions of the heiau, with the aim of closely resembling its original state.

Latitude and Longitude

One can employ the haversine formula to calculate the shortest distance, denoted as d, over the earth's surface between points on a sphere based on longitude and latitude. The latitude and longitude values obtained through Google Earth were used to calculate the distance d, such as

$$d = 2R \text{ atan}^2 \left(\sqrt{a}, \sqrt{1-a}\right)$$

using

$$a = \sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right) + \cos(\lambda_1)\cos(\lambda_1)\sin^2\left(\frac{\phi_2 - \phi_1}{2}\right)$$

where λ is the latitude, ϕ is the longitude, and R is the earth's radius of about 6,371 km.

AUTOCAD-Measured Distances

Our observation of the sunset pillars at the western edge of the heiau used pictures from Kalei Nu'uhiwa's Hāpaiali'i presentation, as shown in Figure 3, because Google Earth does not offer "street views" at all locations and angles near the heiau. The Google Earth measuring tool was used to determine the distance across the westward wall of the heiau. The image from Kalei Nu'uhiwa's presentation on Hāpaiali'i was subsequently adjusted to align with the measured length on Google Earth.

Figure 4 depicts the angles between each sunset pillar, as determined through AUTOCAD. The precise line from the initial measurement was identified on the topside view of Google Earth and marked with distinct

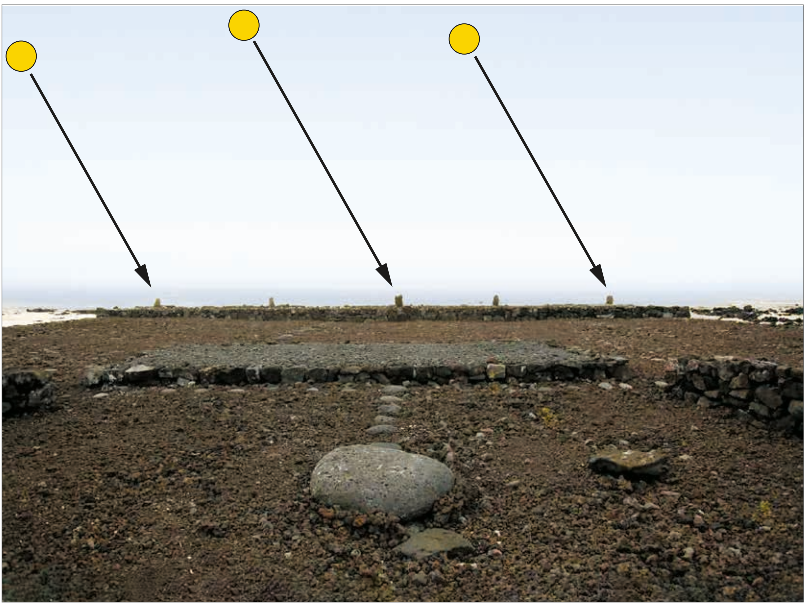

Figure 3. Westward view behind the observation stone (from Nuuhiwa n.d.).

colours between the pillars. The angle of the summer solstice on 19 June 2021 was determined by using the sun calculator at SunEarthTools (https://www.sunearthtools.com/tools/distance.php) and comparing it with corresponding angles obtained from AUTOCAD. The angles in Figure 4 are derived from the first digital measurement. We repeated this measurement five times to provide the statistical values, such as ∠A5C = 26.2 ± 0.2°, ∠B5C = 14.7 ± 0.1°, ∠C5D = 11.6 ± 0.2° and ∠C5E = 24.2 ± 0.3°. Standard deviations of these angles are small.

RESULTS AND DISCUSSIONS

Coordinates and Directions

Distances calculated using the four methods described above are included in tables 1–4. Table 1 shows the latitude and longitude values of the heiau's corner and central observation stones, and these coordinates were used as input data for the haversine formula. Table 2 demonstrates the distances determined from Google Earth and Google Maps, as compared with those obtained using the haversine formula. Table 3 includes the azimuthal angles calculated using the coordinates of cornerstones included in Table 1. Finally, Table 4 shows distances to each sunset pillar and angles from the observation stone calculated using AUTOCAD.

As shown in Figure 4, the line extending from the central stone to the top-left corner (5 → *E*)) points directly toward the island of Niʻihau but does not intersect with any beaches. If this corner were used as a directional guide for sailing to Niʻihau, the sailors would have had to navigate the island to find a suitable beach for docking and unloading. In Hawaiian legend, this island was considered Pele's original home before she moved to other islands (Niʻihau Cultural Heritage Foundation 2020). The line leading to the top-right corner from the centre stone (5 → 2) runs parallel to Mauna Loa and Mauna Kea, crossing numerous farms and lava flows before ending near Hauola Forest Reserve. This corner may have been a directional guide for those searching for fertile land. Similarly, the line leading to the bottom-right corner from the centre stone (5 → 4)) traverses many coffee farms before terminating between Punaluʻu Pond and Nīnole Cove. The coffee farms along the line to the bottom-right corner from the centre stone do not have any particular significance besides indicating fertile land. On the other hand, the line to the bottom-left corner (5 → *A*) leads straight to the ocean and towards Papua New Guinea, passing through some of the Marshall Islands. It is conceivable that this corner was used as a directional guide to other Polynesian islands, given the belief that all Polynesians trace their origins to a familiar location.

Figure 5 shows the numbered line segments from 2 to 7 as distances between two adjacent sunset pillars, determined using AUTOCAD software. Table 4 shows, along with Figure 5, mean distance values with standard deviations obtained with five repeated digital measurements. The indigenous

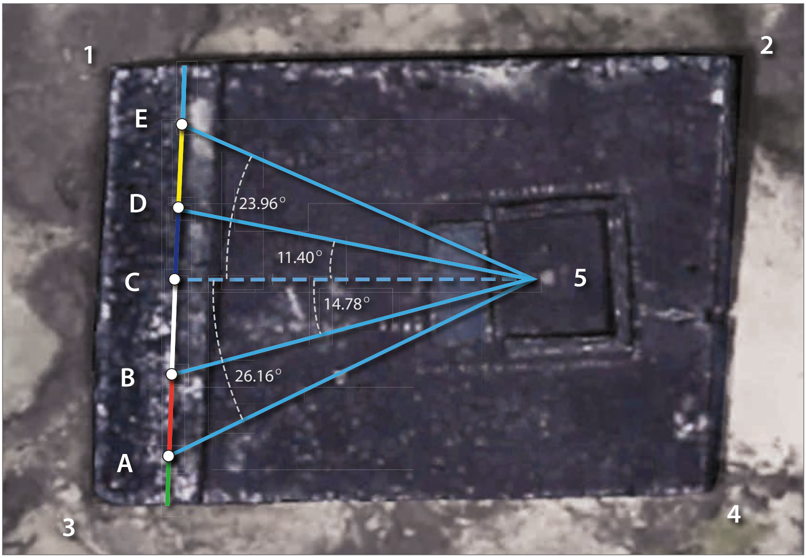

Figure 4. Top view with corner numbers and sunset pillars.

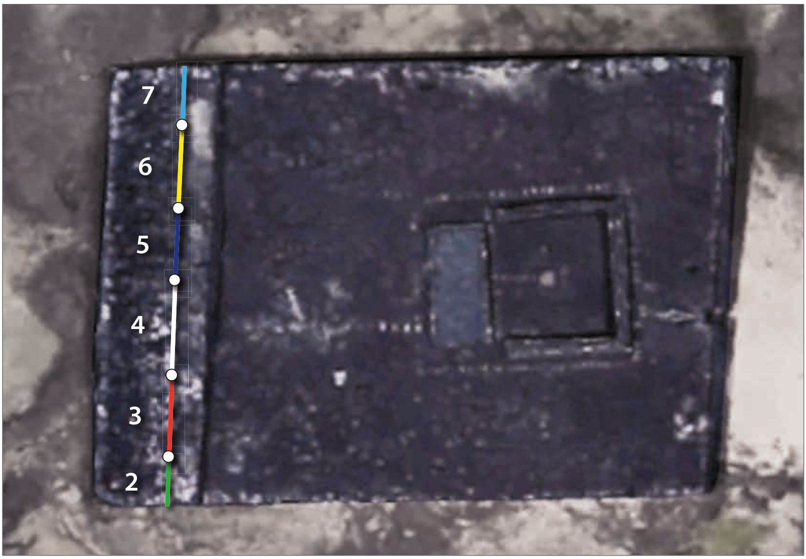

Figure 5. Sunset pillar distance lines.

Table 1. Coordinates of corner positions in Figure 4.

Corner number	Latitude (λ)	Longitude (ϕ)
1	19.577014	−155.968639
2	19.577019	−155.968219
3	19.576742	−155.968628
4	19.576747	−155.968233
5	19.576881	−155.968336

Table 2. Relative distances in metres between the positions shown in Figure 4, calculated using data of Table 1.

Points	Google Earth	Google Maps	Haversine
1–2	42.27	41.46	44.01
1–3	30.27	30.52	30.27
4–2	30.56	30.23	30.28
4–3	41.40	41.24	41.39
1–5	32.56	32.55	35.02
2–5	19.78	19.80	19.64
3–5	35.67	34.21	34.27
4–5	18.17	18.50	18.40

Table 3. Azimuth values.

Points	Azimuth (degrees)
1–2	89.280
1–3	177.800
4–2	2.776
4–3	269.200
1–5	295.000
2–5	38.620
3–5	243.200
4–5	144.090

Table 4. Distances to each sunset pillar and angles from the observation stone (values calculated using AUTOCAD).

Line number	Length (m)	Angle (degrees) from the observation stone
2	3.32 ± 0.05	26.2 ± 0.2
3	5.9 ± 0.1	14.7 ± 0.1
4	6.79 ± 0.08	0.00
5	5.01 ± 0.09	11.7 ± 0.2
6	5.96 ± 0.06	24.3 ± 0.2
7	4.27 ± 0.06	n/a

Hawaiian star compass was placed atop the heiau to delve deeper into the precision of the heiau's calendar. Aligning the centre of the compass with the observation stone, the sunset pillars corresponded accurately with the solstice locations displayed on the star compass, specifically the central sunset pillar aligned with the compass's Komohana "west" marker. Similar results were obtained while overlapping Mau Piailug's Micronesian voyaging compass, which is identical to the traditional Hawaiian compass that uses constellations as markers. The sunset positions on the heiau align with these constellations. Murn and Marigaht, representing the constellations Vega and Makaliʻi (Pleiades), are situated on the compass at the point where the sun sets during the northmost summer solstice pillar. Both constellations are symbols of the new year, correlating with the Hawaiian calendar. Mesario (Shaula and Antares) serves as a representation of the brightest stars in the Scorpius constellation (Thompson n.d.).

By scrutinising the natural periodic phenomena of sunrise and sunset, the Hawaiians could distinguish distinctive patterns of shadows cast by the pillar stones. Furthermore, they determined how to leverage these natural observations for agricultural ends.

Heiau as a Temporary Freshwater Source

The existence of brackish water near the heiau was assimilated into the design of loko iʻa (fishponds). The tendency of fish to be attracted to brackish water has been observed throughout the islands wherever such water was present. Native Hawaiians could skilfully employ this phenomenon by constructing permeable walls that spanned from the shoreline to the ocean. Within these walls were apertures through which smaller fish could access the brackish water. Freshwater from upland areas would flow through farmland, gathering nutrients and dispersing them into the ponds. This abundant source of sustenance allowed the fish to thrive, leading to their growth, while the structure prevented their escape.

A meaningful thought experiment can be conducted to explore a potential physicochemical phenomenon within the heiau. During the rainy season, precipitation on Hawaiʻi leads to runoff flow on the land surface and infiltration into the ground. The freshwater flow, which has a negligible salt concentration, enters the stationary water body enclosed within the heiau's structure, encompassed by permeable walls composed of systematically arranged rocks. The rain descends onto the surface of the seawater within the heiau, creating a mild fusion with the seawater and infiltrating the groundwater. In contrast to the standard salt concentration of 35 grams per tonne in seawater, both rain and groundwater have a salinity level of zero. Because of the difference in density gradient, which is approximately equivalent to the seawater concentration, the freshwater remains on the surface of the stable seawater in the heiau. As this density profile is established along the water depth, it is essential to note that the settling of particulate materials can occur, leading to the natural removal of turbidity-causing materials. Further literature surveys of historical documents and rigorous scientific simulations are imperative to substantiate the postulated scenarios.

Methodological Limitations

Our current study used Google Maps and Google Earth for remote measurement. However, it is essential to exercise caution, as these tools have limitations that are qualitatively described as follows.

Google Maps calculates straight-line distances, which may differ from actual travelling distances. The road and path network data used for Google Maps may be incomplete or outdated and, therefore, could underestimate a distance, especially if measured at a higher altitude. The accuracy of the distance also depends on the level of detail in the map data. It is also crucial to be mindful of the limited accuracy of Google Earth that uses a simplified spherical model of the Earth for distance measurements, which is less accurate than an ellipsoidal model. It measures short distances using a flat surface assumption and relies on satellite imagery, which may only sometimes be perfectly aligned with the actual terrain, especially in remote or less-mapped areas. Although Google Earth uses a three-dimensional globe model to reduce projection distortion, it can still exhibit distortions, especially near the poles or over large distances and in the vertical direction of terrain data and 3D views. These intrinsic limitations become serious when measuring distances of several kilometres or more. However, the lateral lengths of the heiau are approximately 30 m. This size is optimal because it is small enough not to be affected by the differences between the spherical and ellipsoidal approximations of the Earth's surface and large enough to provide approximate but reliable measurements with consistent error ranges. The distances between pillars are on the order of metres, beyond the submetre measurements known to be inaccurate in Google Maps and Google Earth.

Further Interpretation

The appearance of the setting sun on the far-left pillar symbolised the beginning of the wet season and a period of more lenient governance associated with Lono, the deity of peace and fertility. Simultaneously, maintenance work on tools and houses occurred in tandem with the rationing of food and other supplies, further signifying the initiation of the Makahiki season, a period marked by tranquillity, recreational activities and ample resources. Moreover, the wet season brought about the arrival of migrating animals and winter surf swells. The initiation of planting activities would occur in the arid regions of the islands, while the inhabitants of the humid regions would concentrate on restoring their equipment and tools in anticipation of the upcoming season (Nuuhiwa n.d.).

The setting of the sun on the pillar on the far-right showed the commencement of the dry season for the islands and signalled the initiation of more stringent governance under Kū, the deity responsible for overseeing warfare and political matters. In this particular time frame, the community prioritised accumulating resources and enhancing their overall health. The prioritisation of fishing and spiritual activities was also emphasised during this time, given the abundant and flourishing state of the earth. Planting would occur in the wet regions of the islands, whereas the dry regions would focus on harvesting the previously sown crops (Nuuhiwa n.d.).

CONCLUSIONS

This research provides evidence supporting the claim that observation stones can allow people to ascertain the time of year by examining the positioning of the stones in relation to the sunset. The winter solstice was shown by the sun setting on the left-most pillar, while the summer solstice was indicated by the sun setting on the right-most pillar. By observing the sunset locations, one can acquire a profound understanding and note the predictability of the yearly seasonal patterns. The winter solstice resulted in a season more conducive to precipitation, highlighting the importance of peace and recovery. This contrasts with the right pillar, which suggests the potential for gathering and preparing for war. Through meaningful and continuous observations, the Hawaiians could discover the optimal periods throughout the year to fulfil their cultural obligations and uphold a sustainable way of life. The current study focuses on specific scientific aspects of the sacred heiau and their potential cultural analysis, necessitating further examination for a comprehensive understanding of the heiau system.

ACKNOWLEDGMENTS

The authors express extreme gratitude to Māhealani Pai for his generous sharing of historical and cultural materials, as well as his guidance on the construction, maintenance and treatment of heiau, the sacred structures of Native Hawaiians. This work was partially supported by the U.S. National Science Foundation (grant no. 2034824).

GLOSSARY

The terms in this glossary are Hawaiian unless otherwise stated.

aliʻi	chief
heiau	pre-Christian place of worship
kahuna	priest

kahuna kuhikuhipu‘uone	priest who provides guidance on the construction of sacred edifices
kahuna nui wahine	female high priest
kapu	taboo, special privilege
kōlea	Pacific golden plover (*Pluvialis dominica*)
loko i‘a	fishpond

REFERENCES

Kamehameha Schools, n.d. Virtual Huaka‘i Resource Site. https://sites.google.com/view/vft

Kekahuna, Henry E.P., 1950. Image SP 201871: Sketch of Pa-o-Umi Heiau and Keekuiki Heiau; the heiaus are situated between the Old Helani Church and the Kahaluu-Keauhou I boundary; Kahaluu, North Kona, Hawaii. The Maps of Henry E.P. Kekahuna. Bishop Museum, Honolulu.

——1952. Image SP 201869: Sketch of Kahaluu Beach; Kona, Hawaii; including the residence of Lonoikamakahiki (Umi-Hale), Makole-a-Heiau (formerly a women's heiau), Keeku or Kueku Heiau, Hapai Alii, Kapuanoni Heiau, Poo Hawaii, and Kuemanu Heiau. The Maps of Henry E.P. Kekahuna. Bishop Museum, Honolulu. http://data.bishopmuseum.org/Kekahuna/kekahuna.php?b=closeup&ID=19

Movable Type Scripts, n.d. Calculate distance, bearing and more between latitude/longitude points. https://www.movable-type.co.uk/scripts/latlong.html

Niihau Cultural Heritage Foundation, 2020 (November 16). Ni‘ihau history. https://niihauheritage.org/niihau_history/

Nuuhiwa, Noi‘ī ‘ia e Kalei, n.d. Hāpaiali‘i: Tracking Time. Presentation slides. Kamehameha Schools. https://blogs.ksbe.edu/clalexan/files/2016/08/Hapaialii-Heiau.pdf

The Kohala Center, n.d. Ho‘iho‘i kūlana wahi pana | Restoring Sacred Places (Keauhou and Kahalu‘u). https://kohalacenter.org/docs/resources/kbec/kic_brochure.pdf

Thompson, Charles Nainoa, n.d. Star compasses. Hawaiian compasses. http://archive.hokulea.com/ike/hookele/star_compasses.html

Tuggle, D. and M. Tomonari-Tuggle, 1999. The petroglyphs of Kahalu‘u, Kona, Hawai‘i. *Rapa Nui Journal* 13 (1): 3–13. http://hdl.handle.net/10524/64393

AUTHOR CONTACT DETAILS

Corresponding Author: Albert S. Kim, Department of Civil, Environmental, and Construction Engineering, The University of Hawai‘i at Mānoa, Holmes Hall 383, Honolulu, Hawai‘i 96822, USA. albertsk@hawaii.edu | https://orcid.org/0000-0002-9027-4616

Brenton Sasaoka, Department of Civil and Environmental Engineering, The University of Hawai‘i at Mānoa, Holmes Hall 383, Honolulu, Hawai‘i 96822, USA. bsasaoka@hawaii.edu