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High-resolution documentation, 3-D modeling and analysis of “desert kites”

Reuma Arav [a,*], Sagi Filin [a], Uzi Avner [b], Guy Bar-Oz [c], Amnon Nachmias [c], Dan Malkinson [d], Dani Nadel [c]

[a] Mapping and Geo-Information Engineering, Technion — Israel Institute of Technology, Haifa 32000, Israel
[b] Arava Institute and the Dead Sea-Arava Science Center, Israel
[c] The Zinman Institute of Archaeology, Haifa University, Mt. Carmel 3498898, Israel
[d] Department of Geography and Environmental Studies, Haifa University, Mt. Carmel 3498898, Israel

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ABSTRACT

Using terrestrial laser scanning technology we create high-resolution 3-D models of wild ungulates' archeological large-game drives (desert kites) and demonstrate how the collected data can be utilized to conduct spatial and architectural analyses. Visual reconstructions show in great detail how kites were constructed according to geographic and topographic settings and how they were set to maximize prey capture. The models are used to simulate how a kite was operated and especially how it appeared from the hunted animal's perspective. The models also serve as a useful tool for detecting macro and micro construction details, and as a platform for an array of intra- and inter-kite comparisons in different geographic landscapes. Finally, they provide the basis for future documentation of archaeological structures in arid environments.

1. Introduction

“Desert kites” is a term coined in Near Eastern archaeology for describing large game drives solely found in arid and semi-arid environments. Most kites can be grouped into two major types with many varieties: small triangular, V-shaped structures, and large enclosure-like (Betts and Helms, 1986; Helms and Betts, 1987; Echallier and Braemer, 1995; Betts et al., 1998; Betts and Yagodin, 2000; Kempe and Al-Malabeh, 2010; Kennedy, 2012; Bar-Oz and Nadel, 2013; Barge et al., 2013; Brochier et al., 2014; Crassard et al., 2014). In the Negev and Sinai deserts, only the small triangular kites are present, each built of two long converging stone walls (arms) with a more-or-less circular enclosure at the apex, commonly termed the ‘head’. The arms are constructed of local stones and may extend for hundreds of meters, while vary in width and height.

Desert kites are commonly interpreted as game traps of wild ungulates. This observation is based on both the size and shape of the structures and on historical accounts and rock engravings (Hershkovitz et al., 1987; Van Berg et al., 2004; Bar-Oz and Nadel, 2013 and references therein). Radiometric dates are available for a very few kites, mostly indicating abandonment by the mid 3rd millennium BC (e.g., Holzer et al., 2010; Nadel et al., 2010, 2013; Zeder et al., 2013). In excavated kites in the southern Levant, in situ material remains and animal bones are very rare.

The geographic and topographic settings of some kites in the Negev and Sinai suggest that animals were approached while crossing the landscape along their daily/annual routes or while grazing near pasture areas. Then, they were driven into the funnel-shaped arms of a kite, and frightened over a cliff or into a small enclosure (Meshel, 1974, 2000; Avner, 1987; Perevolotsky and Baharav, 1991; Rosen and Perevolotsky, 1998).

The kites construction materials are local un-dressed stones, currently covered by dust, patinas and lichen, similar to the surrounding stones. Hence, in many cases the kites are hardly distinguishable on the landscape. The rugged topography and problematic differentiation between constructed in situ stone walls, collapsed stones, and naturally scattered stones on the surface, hamper high-resolution documentation. Accordingly, the use of traditional archaeological documentation techniques, which include detailed measurements, drawing, and photography of the various features in each kite, provides only limited results while

* Corresponding author. Tel.: +972 4 829 2774.
E-mail address: reumaa@technion.ac.il (R. Arav).

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being time consuming. Furthermore, topographic details are hard to obtain using these traditional techniques. These are particularly important for understanding the kites' settings and the parameters that were considered by their builders when selecting the exact location and orientation of each kite.

Although kites have recently been the focus of remote sensing documentation, such efforts are usually based on aerial photography or Google Earth images, and less on detailed high-resolution documentation of the kites and their surrounding topography (Kennedy, 2011; Kempe and Al-Malabeh, 2013; Brochier et al., 2014). It therefore follows that such documentation level is a leap forward. In our Negev kites survey we utilized terrestrial laser scanning (LiDAR) as a documentation protocol to study three kites located on plains and five in hilly areas (Fig. 1). Noteworthy, the topographic constraints and the local challenges differ dramatically between the two areas. In the first, no cliffs or topographic vertical features exist, while in the latter there are steep slopes and deep gorges. The settings of each area as well as animal behavior, dictated particular solutions regarding the location of the head and arms, and also the construction details.

In this paper we utilize the 3-D point clouds of two plain kites (*Samar West* kites, SWA and SWB) and two kites in the hills (*Pitam* and *Achshuv*, Fig. 1) for high-resolution documentation, characterization, and for comparison of the two distinct topographic settings. The acquired point clouds are incorporated with field observations and general photography. Detailed three-dimensional models provide also an efficient platform for a range of geometrical and quantitative analyses, as discussed below. To the best of our knowledge, such work and some of the analyses presented have never been carried out for desert kites, though the use of laser scanners in archaeological sites becomes commonplace (e.g. Alkheder et al., 2009; Lerma et al., 2010; Gidding et al., 2013; Olson et al., 2013).

2. Materials and methods

2.1. Scanning the kites and 3-D modeling

Terrestrial laser scanners use collimated and coherent energy pulse to measure directly the range to an object. Adding a longitudinal and latitudinal beam-deflection mechanism yields a panoramic range-data coverage of the surveyed scene (Pfeifer and Berise, 2007; Petrie and Toth, 2008). Since ranging is based on a line-of-sight principle, securing complete coverage and obtaining sufficient level of detail was achieved by scanning from several posts. Registration of the individual scans into a common reference frame was carried out by enlisting designated reflector targets (Fig. 2) which act as tie elements that can be automatically recognized. Geo-referencing to the national reference grid was performed by using real-time kinematic GPS (RTK-GPS) receivers, using the national virtual reference station (VRS) control network.

Scanning of all four sites was performed using the Leica ScanStation C10 terrestrial scanner with an accuracy of ±4 mm in range measurements and ±12″ in angle measurements. Vertical and horizontal angular resolution was approximately 0.057°, with each scan consisting of ~5.5 million points, spanning 360° horizontally and 90° vertically. On average, the point density was 7000 pts/m^2, which was satisfactory for the goals of this study.

Generally, the scanner was stationed around and along the arms of each kite. The head (apex) is the most important feature, and accordingly one post was set inside of it and two more outside, on both its sides. Considering the arms documentation, flat topography facilitated large distances between scan posts without loss of coverage. Mountainous setting dictated, sometimes, shorter distances between posts. In both, the arms morphology and the topographical details were targeted. On average, complete coverage of the arms was achieved by setting consecutive scanning posts approx. 30–40 m apart. This setup has led to 20%–30% overlap

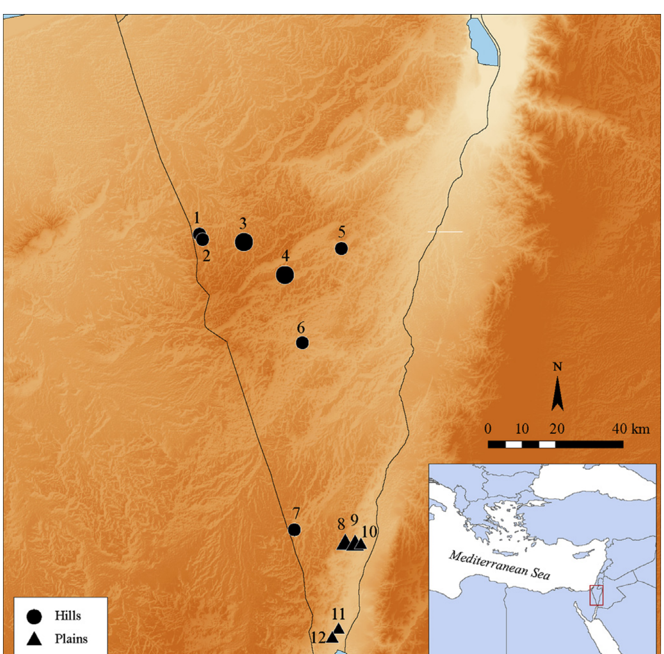

Fig. 1. Map of the Negev kites differentiating between plain and hill examples. 1, 2: Nahal Horsha, north and south, respectively; 3: Achshuv; 4: Pitam; 5: Harut; 6: Eshel; 7: Sayarim; 8, 9: Samar West B and A; 10: Samar East; 11: Giv'at Shehoret; 12: Har Shahmon.

Fig. 2. The Leica ScanStation C10 set to work at the Samar West sites. An arm wall is visible behind, with two reflector targets positioned behind the wall on both sides of the photograph (marked).

between scans. Important features, such as the head or well-preserved wall sections, were scanned from closer distances and with higher overlap (approx. 50%), yielding higher level of detail. Supplemental images were acquired using the scanner's camera to enrich the data of features of archaeological importance.

High-resolution models, which were derived from point cloud, enabled characterizing each kite and its topography, and retrieving plans, sections, inclinations and a variety of measurements (see below).

2.2. Kite characterization

Characterization of each kite includes general parameters and particular details of the head and arms. The general data pertain to the entrapped area and the opening angle between the arms and for the topography. The characterizations and computations are listed below.

Entrapped area between the arms – Defined by a polygon between the arms and head, and computed by:

$$\mathbf{A} = \frac{1}{2}\left|\sum_{i=1}^{n-1} x_i y_{i+1} + x_n y_1 - \sum_{i=1}^{n-1} x_{i+1} y_i - x_1 y_n\right| \tag{1}$$

where x_i, y_i are the coordinates of the polygon i-th vertex.

Opening angle – The angle between the arms is computed by the head as the dot product of vectors $\vec{a}$, $\vec{b}$,

$$\alpha = \cos^{-1}\left(\frac{\vec{a}\cdot\vec{b}}{\|\vec{a}\|\cdot\left\|\vec{b}\right\|}\right) \tag{2}$$

which are measured from the head to a point 10 m away from it on each arm, and *again* from the head to the arms' endpoints; α is the opening angle, and $\|\vec{a}\|$ is the vector's norm.

Topography characterization – The immediate topography is characterized by the general *slope* of the surrounding and its *aspect*. The slope provides a measure for the steepness of the topography, whereas the aspect measures the orientation. Slope and aspect are general topographical characterizations. They were computed by re-sampling the point cloud into a 25 × 25 cm grid and using:

$$\|\nabla f\| = \sqrt{Z_x^2 + Z_y^2} \tag{3}$$

$$\psi = 45{*}round\left(\frac{\operatorname{atan2}(Z_y, Z_x)}{45}\right) \tag{4}$$

where Z_x, Z_y are the first order derivatives along the x and y axes, respectively; $\|\nabla f\|$ the gradient magnitude; and Ψ is the aspect angle, rounded to the direction towards the cell it points to.

2.3. Head characterization

The kite's head features a round wall, sometimes surrounding a manmade pit; thus, it is characterized by the wall's dimensions (height, width and volume) and, when present, the pit's dimensions (depth, width and area). Cross sections were generated to study in detail the construction of the head.

Pit dimensions and area – In most cases, dimensions and area were defined by the enclosing wall that surrounds the pit. In cases where parts of the wall were missing or modified at later periods, the pit outline was completed to the expected original form. Following the outline delineation, the depth and width were measured while the area was computed by Eq. (1) with the coordinates of the delineated polygon.

Cross-sections of the head – Were used for generating dimensions such as width and height, as well as for calculating the amount and size of stones used for construction.

Wall height and width – The height was measured outside, from ground level to the topmost in situ stone. However, in most cases the heads were excavated prior to the scan and thus height was also measured from the walls' exposed foundations to the topmost in situ stone. The width was measured at the top and the bottom of the wall.

Volume – was computed using a cut and fill computation (Brinker and Minnick, 1995):

$$V = \left(\frac{\Delta H_1 + \Delta H_2 + \Delta H_3 + \Delta H_4}{4}\right)(a \cdot b) \tag{5}$$

where a, b are the horizontal cell dimensions, and ΔH_i, the change in elevation between each cell corner and the wall base.

2.4. Arms characterization

The arm details provide insights into the complexity of the construction and the layout on the landscape. We characterize each arm by its length, course, volume, and structural variability.

Arms profile and lengths – a longitudinal profile along the entire arm characterizes the underlying natural topography on which the arm is built and how it utilizes it. Lengths were measured once as the actual length along the arm, and then as the direct distance (straight line) from the head to the endpoint of the arm.

Cross-sections along the arms – These are sections perpendicular to the arms and crossing both. They provide characterization of the arm and measures of the wall at its base and at the preserved top,

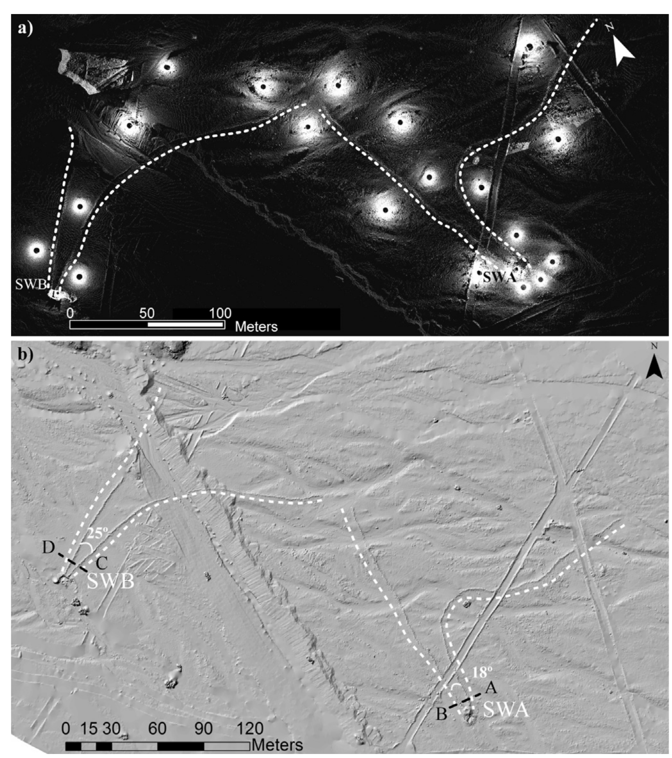

Fig. 3. The Samar West A and B kites; a) locations of 21 scanning posts and, b) the model of the kites (arms marked in dashed lines) with topography, shallow wadis, modern dirt roads and a modern canal. The locations of transects A–B and C–D are marked (see Figs. 12 and 13).

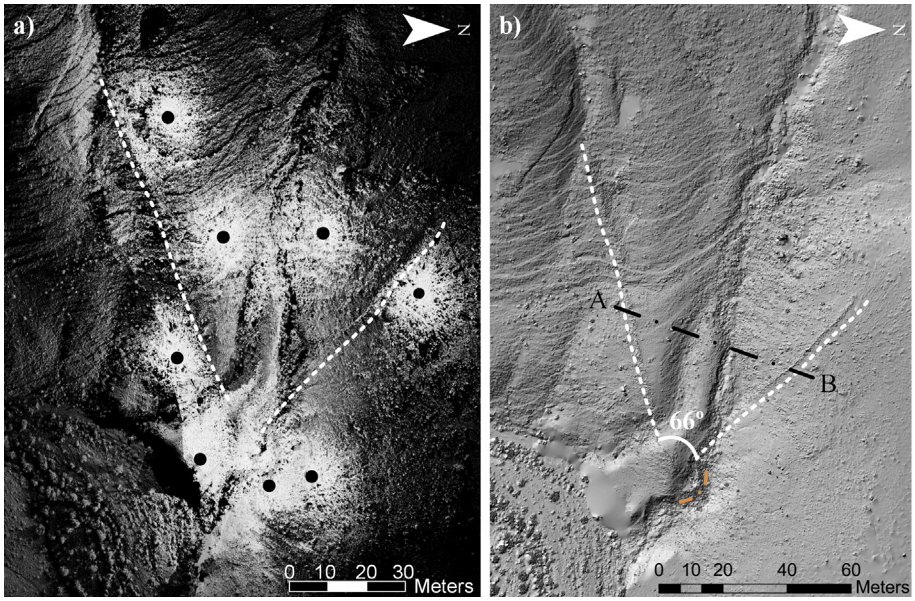

Fig. 4. The Pitam kite; a) locations of eight scanning posts; b) a model of the kite (head is marked by a dashed orange line). Note the steep wadi running through the middle of the kite. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

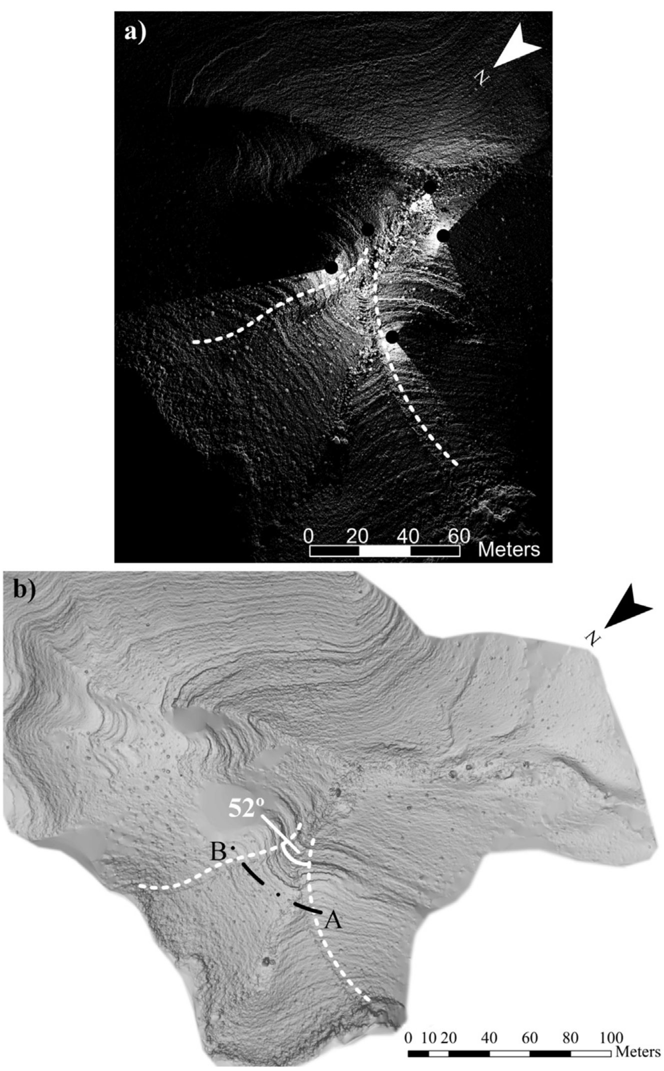

Fig. 5. The Achshuv kite; a) location of five scanning posts; b) a model of the Achshuv kite. The top section of the left arm was not scanned.

including widths, heights and number of construction stones. For construction studies, the dimensions of larger stones (wider than 30 cm) were measured at selected sections and statistically analyzed.

Additionally, the arm's *volume* was computed from the head interface along the walls (Eq. (5)).

2.5. Study sites

2.5.1. Samar West

There are three kites at Samar, the southern 'Araba Valley, Israel (Avner, 1984, 2002, 2006; Bar-Oz et al., 2009, 2011; Holzer et al., 2010; Meshel, 1974, 2000). Two are adjacent to each other and are viewed as one complex (*Samar West* A and B, SWA and SWB, respectively) while a third is located about 1 km to the east. The first two are the focus of this study. Following an archaeological survey of the site, an excavation of a trench in each of the heads, as well as several test pits along their arms was carried out (Nadel et al., 2010).

All three *Samar* kites were disturbed or altered during the Early Bronze Age. SWA has a burial cairn built on top (*tumulus*), blocking the passage from the arms into the head. Human and cattle bones were found inside, and charred fragments were dated to ca. 2500 Cal BC (Nadel et al., 2010), which is a minimum age for the kite. One side of the SWB head was robbed of its stones for building a wide enclosure.

Twenty-one posts around and along the two kites, including one station within each head, were needed to scan the two *Samar West* kites complex (Fig. 3). The covered area is approx. 600 $\times$ 400 m^2. The point cloud consists of ~100,000,000 points, with point density of 4000–10,000 pts/m^2.

2.5.2. Pitam

Located within the Ramon crater, the *Pitam* kite is laid in hard limestone hilly terrain (Fig. 4). It was set across many animal trails, in a topographic bottleneck. The right arm (as one descends towards the head) descends along a steep slope, while the left begins on a plateau, crosses a narrow rugged wadi channel and then turns sharply (~90°) into the head (Nadel et al., 2013). We excavated a trench through the head, exposing a rampart (rather than a vertical wall) around it. Charred fragments found 0.5–0.8 m below surface, in the trench, yielded a ^{14}C date of 1560–1390 Cal BC (#RTT 5868).

Table 1
General kite characterizations as derived from the 3-D models.

Site	Head		Between arms			Actual arm length		End-to-end arm distance	
	Inner area	Wall's volume	Opening angle		Entrapped area	Right	Left	Right	Left
			Close to head	Between endpoints					
	(m^2)	(m^3)	(deg.)	(deg.)	(m^2)	(m)	(m)	(m)	(m)
Achshuv	32.4	19 (est.)	52°	54°	2697.5	90.6	84.7	86.2	81.2
Pitam	15.9	14.5	68°	66°	3339.5	97.6	77.0	97.1	74.1
Samar West A	21.5	32.5	18°	66°	7465.8	151.6	201.6	149.9	155.8
Samar West B	22.1	45.9	25°	44°	4876.2	140.8	188.5	140.0	175.2

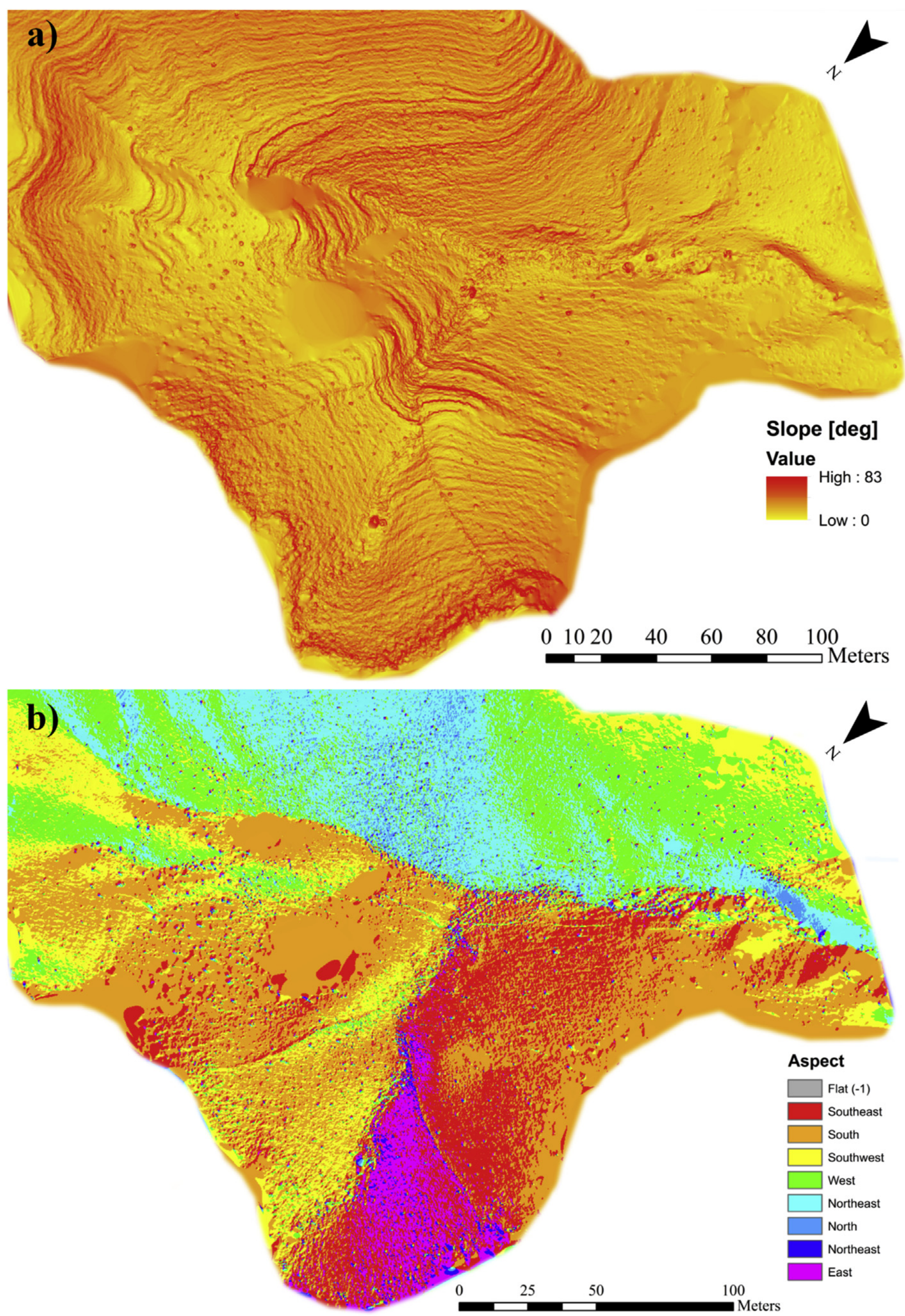

Fig. 6. Slope (a) and aspect (b) characterization of the Achshuv kite, bottom half of both figures. Note that the arms were built along the "ridges" between two slopes; this is especially apparent at the distal end of the left arm (north) and along the right arm.

The site was scanned from eight posts, covering an area of 500 × 300 m^2 (Fig. 4), yielding ~40,000,000 points and a 2000–8000 pts/m^2 density.

2.5.3. *Achshuv*

Located in the Negev Mountains, the *Achshuv* kite is laid in hard limestone hilly terrain (Fig. 5). Like the *Pitam* settings, the right arm descends on a steep slope, while the left arm begins on a plateau and then descends steeply, crossing a rugged wadi channel before connecting to the head. The kite was scanned from five posts, covering an area of 250 × 315 m^2 (Fig. 4), yielding ~66,000,000 points and a 5000–15,000 pts/m^2 density. The distal top part of the left arm was left un-scanned.

3. Results

The two *Samar* and *Pitam* kites have been published in previous reports, where we addressed construction details and general settings regarding animal trails and topography (Bar-Oz et al., 2009, 2011; Nadel et al., 2010, 2013). However, by scanning the sites and using the high-resolution 3-D models we can now provide new results and analyses for those sites as well as for the *Achshuv* kite whose construction details were never published, pertaining to both architecture and topography.

3.1. General characterization

The entrapped area (between the arms) of the two *Samar West* kites are 7465.8 m^2 and 4867.2 m^2 (SWA and SWB, respectively, Table 1). The opening angle between the arms, near the heads, is 18° (SWA) and 25° (SWB), and when measured to the endpoints grows to 66° and 44°, respectively. The average inclination along each of the *Samar West* arms is 3°–5°, reflecting a generally flat topography. The *Pitam* kite covers an area of 3339.5 m^2. The opening angle near the head is 68°, and 66° towards the endpoints. The arms are relatively straight, and the slight decrease is due to adaptation to the topography near the head. The inclination varies between 10° and 20°, about four times steeper than the *Samar* kites. The *Achshuv* kite covers an area of 2697.5 m^2. The opening angle near the head is 52°, and increases slightly, to 54°, when measured to endpoints. The inclination varies between 11° and 20° (Fig. 6). Slope and aspect computations for the underlying topography clearly show that both walls were constructed along specific topographic "ridges", where the aspect (orientation) of the slope changes (Fig. 6).

3.2. The heads

Cross sections along the main axis of each head show the vertical topographic differences between the bottom of the pit and the surrounding topography (Figs. 7–10). They show that in the *Samar West* kites, with their settings on flat topography, this difference was enhanced by the digging and the construction of a ramp (Figs. 7 and 8; Nadel et al., 2010). In the hilly *Pitam* kite, some digging was carried out (Fig. 9b), but there was no need for ramp construction. Notwithstanding, a rampart and not a wall was built around the head pit to capture the target animals (Fig. 9). The inner dimensions of the pits are similar for all three excavated sites (Table 1).

In addition to measuring the heads' perimeter and the width of their walls, volume computations were carried out according to their preserved height, which may not necessarily be the original. Therefore, we conclude that the presented volume is the minimal value for the original wall.

The heads of the two *Samar West* kites are similar in some respects, regardless of the different shapes and dimensions of the two kites (Figs. 7 and 8). The area of both heads is similar – 21.5 m^2 and 22.1 m^2 (SWA, SWB, respectively, Table 1), and while the walls widths are not constant and not the same, 2.2–4.0 m in SWA and 0.5–3 m in SWB, there is a high resemblance between them. The preserved heights are also similar, 1.4 m and 1.2–1.4 m respectively.

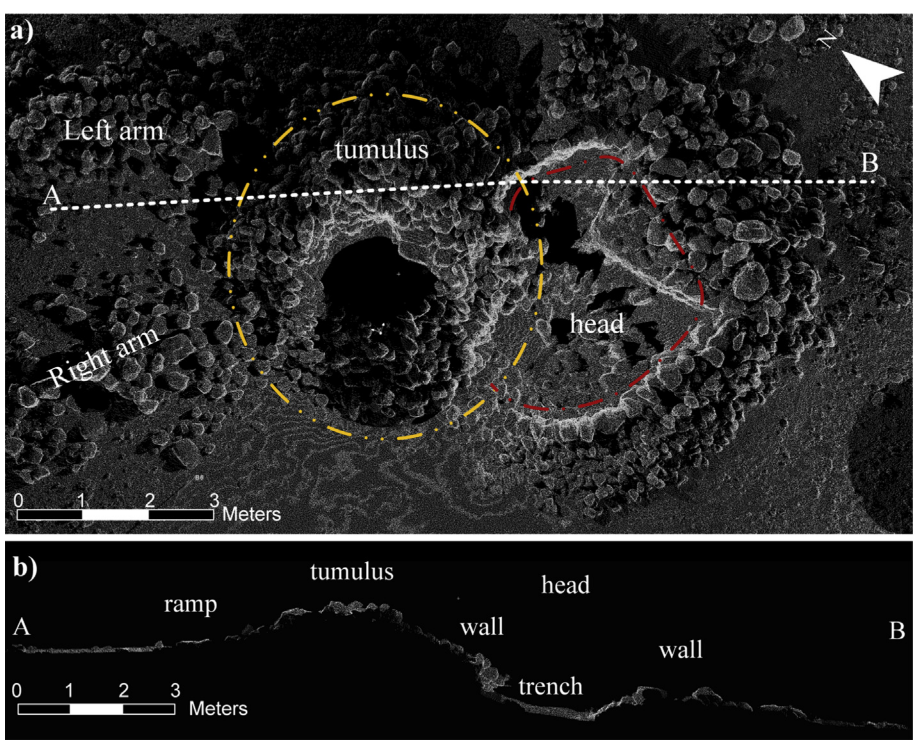

Fig. 7. SWA head point cloud. a) Top view, *tumulus* (yellow) and inner contour of the head wall (red) are marked; b) a cross-section along the ramp, tumulus and head. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

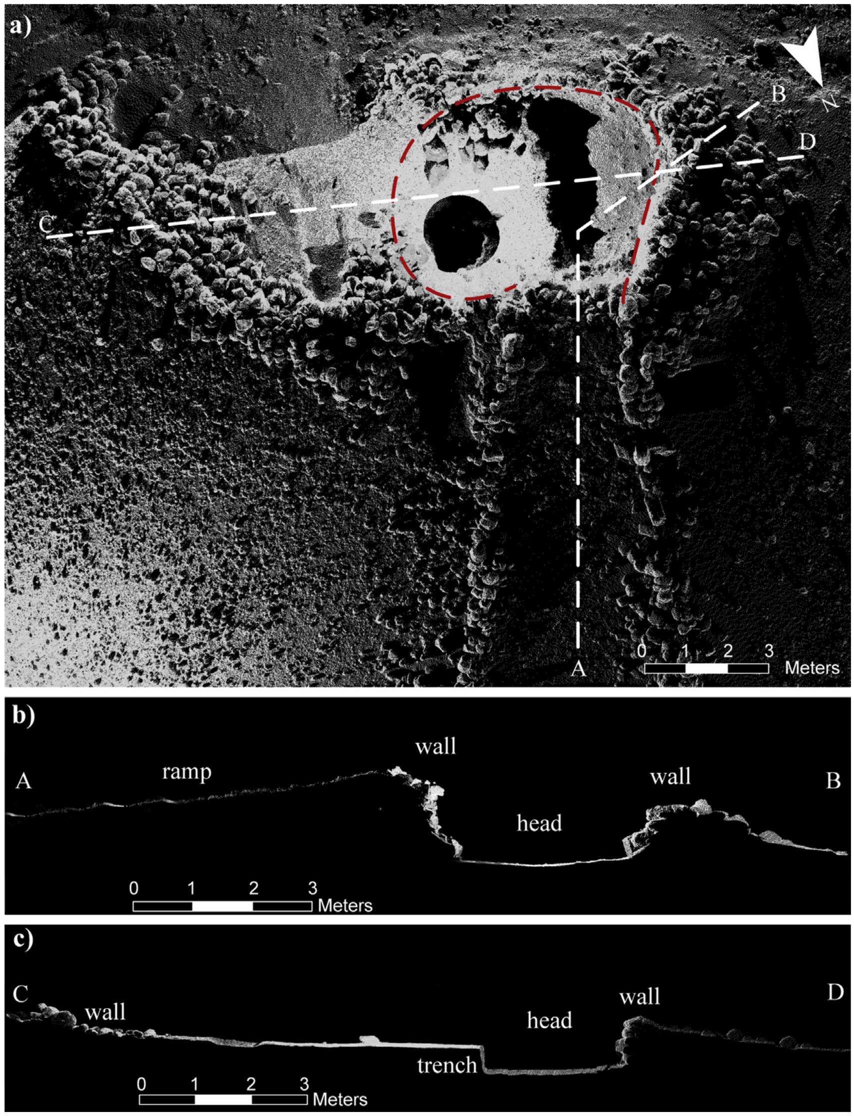

Fig. 8. SWB head point cloud. a) Top view, inner contour of the head wall is marked in red; b, c) cross-sections along the ramp and the head. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

The volume of the walls is however different, 15 m^3 and 32 m^3 (SWA and SWB, respectively, Table 1).

The head of the *Pitam* kite covers 15.9 m^2 (Fig. 9), but as noted, instead of a wall, a massive rampart was built around its lower side, towards the wadi – up to 3 m wide and 1.2 m high. As there are no nearby post-kite constructions, there is no indication that stones have been robbed. Thus, except for natural, gradual processes that removed occasional stones down the slope/wadi, the structural remains represent the original volume of the rampart, which was calculated to be 67 m^3.

The *Achshuv* head was not excavated. According to field observations and the acquired model its inner diameter was approx. 5 m and its area is 32.4 m^2. The wall is 2 m wide and possibly 1.5 m high, on the wadi side (Fig. 10). Its estimated volume is 19 m^3 (Table 1).

3.3. The arms

The arms are not necessarily straight. Those of SWB, for example, are almost so, while the left ones of SWA and *Pitam* turn right by ~90° either right before the head (*Pitam*, Fig. 4) or a few meters from it (SWA, Fig. 3). All arms cross water courses: in the plain these are very shallow, mostly shallower than 0.5 m, while in hilly terrain they are deeper than 1.5 m.

All arms have been built in a similar fashion, where local undressed stones and boulders of various dimensions were taken from the immediate vicinity and used for construction. The absence of many collapsed stones along any of the walls indicates that the walls suffered very little damage, and their original widths and heights have basically been preserved.

The lengths of the arms vary considerably (Table 1). The arms of the SWA and SWB kites are much longer than the hilly ones. The total length of the two SWA arms is 353.2 m and that of SWB is 329.3 m. In contrast, the total length of the two *Achshuv* arms is 175.3 m and that of *Pitam* is 174.6 m. Note that the total length of the two hilly kites is literally identical, with less than 1 m difference. The *Samar West* arms are double in length, compared to the two hilly kites. Furthermore, while adjacent and situated in identical settings, they are about 33 m different in their total arm length. Noteworthy, the kites are asymmetrical, and the arms lengths of each kite, differ considerably, between ~6 m (*Achshuv*) and 50 m (SWA). Apparently, the kite's shape and arm lengths were dictated by the local topography and the position of the trap

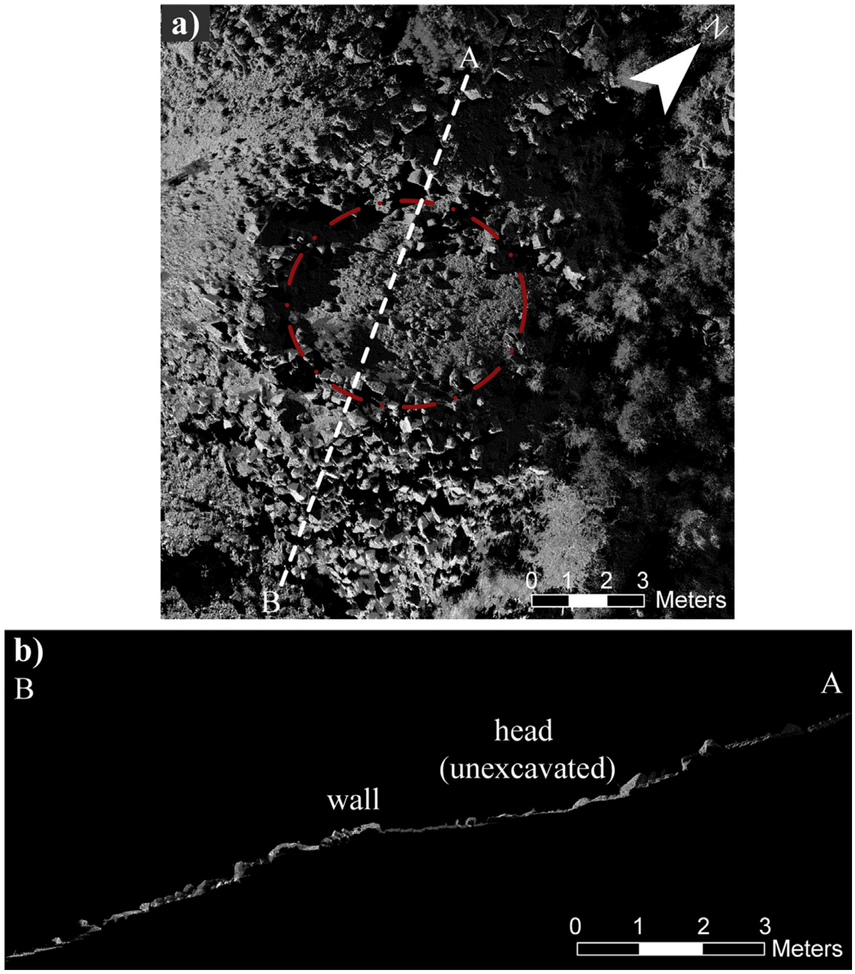

Fig. 9. Pitam head point cloud. a) Top view, inner contour of the head wall is marked in red; b) a cross-section along the hilly kite and the head. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

in relation to the targeted animals' locations, such as pasture areas, trail passing, or a bottlenecks, and not by an independent geometrical planning.

3.4. Stone size

One of the questions regarding the kites' architecture addresses the size of the stones: are the arms and heads constructed of similar stones in terms of size? Are there any significant differences within each kite (e.g., arms vs. head) and between kites?

As an example of a size-analysis of the construction stones, we sampled each arm at one place at the distal end, along a well preserved section of 5 m, and along a 3 m long preserved section of the head's wall (Fig. 11). In each marked section, all visible stones longer than 0.3 m and still incorporated within the wall were measured on the model for their length, width and area (Fig. 11). In all four sites we maintained the same length criteria of the studied wall section, and thus the relevant results are also comparable in terms of densities. Noteworthy, the data herein form only a small sample (8–20 stones per arm or head) and thus the results and ensuing discussion are but an example for the potential of such analyses.

The arms of the two hilly kites were constructed of stones very similar in their dimensions, with an average length of 0.44 m and 0.43 m (each arm) for the *Achshuv* kite, and 0.38 m and 0.40 m for the *Pitam* kite (Table 2). The *Samar* kites are built of stone whose lengths are 0.36 m and 0.35 m (SWA) and 0.37 m and 0.33 m (SWB); a little smaller than the hilly kites. The average stone area (length $\times$ width) is 0.09 m^2 and 0.08 m^2 for the *Achshuv* arms, and 0.10 m^2 for both of the *Pitam* arms. Areas for the plain kites stones are similar, with 0.09 m^2 and 0.07 m^2 for the SWA arms, and 0.08 m^2 for both SWB arms. While the average (arms) stone length is a little longer for the hilly kites, the average stone area is similar in both settings. Area, rather than length, may be a better measure of overall size and weight, when seeking to establish construction efforts (see Discussion).

Turning to the heads, in *Achshuv*, the average area of the stones composing the head is 0.08 m^2, similar to the average area of the ones constructing the arms. The average head stone area in *Pitam* is the largest, 0.15 m^2, compared to 0.10 m^2 for the arms. For the *Samar* kites, the SWA average head-stones area is 0.07 m^2, which is smaller than that of the SWB head, 0.11 m^2. Note that the average SWA head stones area is similar to that of the arms, whereas in SWB the average arm stones area is much smaller, 0.08 m^2. The large disparity may reflect the size of available local stones at the time of construction; however, this is partially negated by similarities in arm stones. It should also be noted that *Achshuv* is the only site that was not excavated (namely no stone was moved), and thus the larger head stones are probably still covered by the collapsed top stones which are usually smaller. In SWA a *tumulus* was built on the kite, and likely some of the larger head stones were used for its construction.

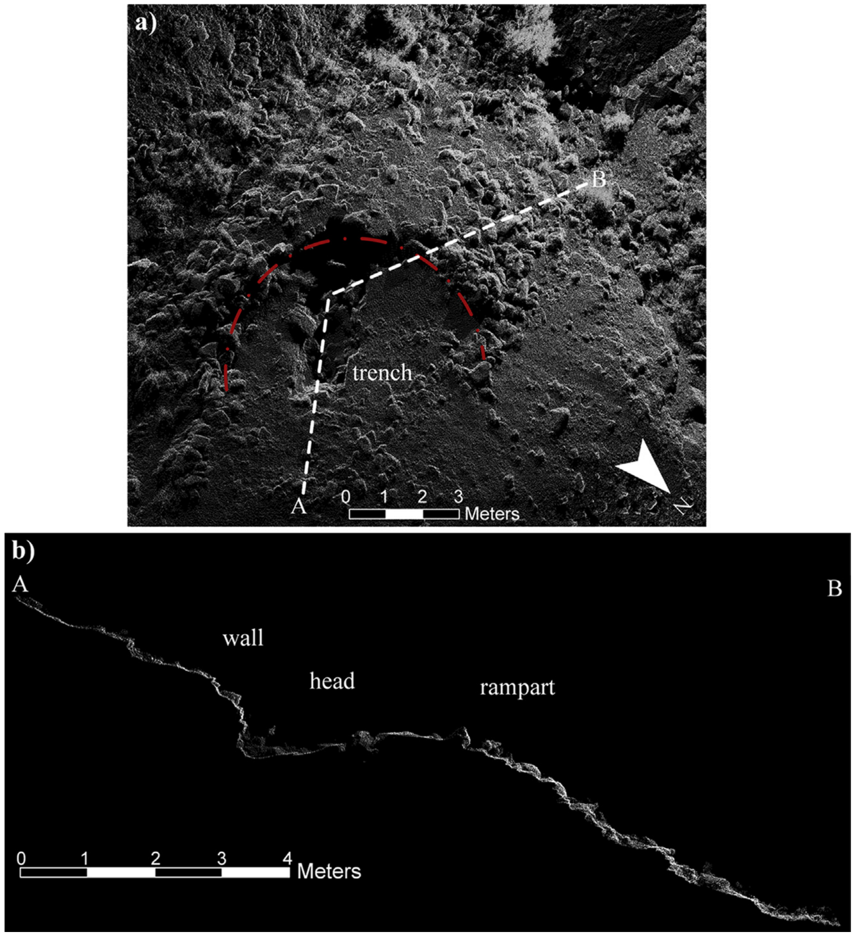

Fig. 10. Achshuv head point cloud. a) Top view, inner contour of the head wall is marked in red; b) a cross-section along the head, not excavated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

Densities were calculated as the number of stones larger than 0.3 m per wall length, and presented as stones/m (Table 2). The analysis shows that the arms' stone-density exhibits some variations. In *Pitam* it is the lowest with 1.6 stones/m and 1.8 stones/m. In *Achshuv*, the density is 2.0 stones/m and 2.3 stones/m, while the *Samar* kites' arms are characterized by 2.0 stones/m and 2.2 stones m (SWA), and 2.8 stones/m and 2.6 stones/m (SWB). Note that the arms' stone density is more or less similar per site. The heads' density is higher. In order to provide comparative measures to the arms, density was normalized to the arms' height. In *Pitam*, it rises to 3.0 stones/m and in *Samar* to 3.0 and 4.7 stones/m (SWA and SWB, respectively). In *Achshuv* the head density is similar to that of the arms (2.3 stones/m), but as the site was not excavated, larger stones might be buried under rockfall. Considering these results cautiously, they show a trend for higher densities of larger stones in head construction. This may reflect higher investment in the head wall construction, and since the massive head wall is significantly higher and wider than the arms, a larger number of large stones may be required.

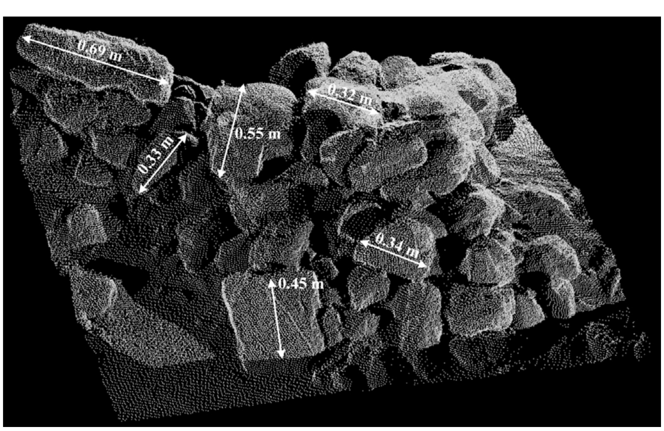

Fig. 11. Stones extracted and measured at the head of Samar West B kite.

The particular details regarding the way each head and arm was constructed on the landscape are important when seeking to understand the parameters and considerations of the builders. The 3-D models provide the accurate relevant data, showing how each kite deviates from all others in a variety of details. For example, by combining the model with field observations it becomes clear that the arms of SWA were mostly constructed on the highest available grounds, though the topographic differences may not be greater than 0.5 m (Fig. 12). The arms of the nearby SWB kite were built on a flat area (Fig. 13). In both cases large boulders are hardly present between the arms, or adjacent to them on the outside. Clearly, the builders used local boulders and stones for construction, leaving the ground between the arms clear. This may indicate their desire to provide a clear driving area to facilitate the frightened run of the target game.

The arms of the hilly kites were constructed on slopes of similar inclinations (Fig. 14b and 15 a, b). However, when a section

Table 2
Average dimensions and densities of construction stones of the heads and the distal ends of the arms. These include only stones visible in the models (>0.3 m) incorporated in the walls. Measurements were carried out on the models of each kite at the heads and the distal sections of the arms. See text for details.

	Left arm				Right arm				Head			
Site	Length (m)	Width (m)	Area (m^2)	Stone density (stones/m)	Length (m)	Width (m)	Area (m^2)	Stone density (stones/m)	Length (m)	Width (m)	Area (m^2)	Stone density (stones/m)
Achshuv				2.0				2.3				2.3
AVG	0.44	0.22	0.09		0.43	0.19	0.08		0.35	0.24	0.08	
STD	0.08	0.07	0.04		0.09	0.08	0.04		0.04	0.08	0.03	
Pitam				1.6				1.8				3.0
AVG	0.38	0.26	0.10		0.40	0.25	0.10		0.50	0.31	0.15	
STD	0.06	0.07	0.02		0.09	0.08	0.04		0.10	0.14	0.05	
SWA				2.2				2.0				3.0
AVG	0.36	0.25	0.09		0.35	0.22	0.07		0.34	0.22	0.07	
STD	0.06	0.10	0.05		0.05	0.06	0.03		0.06	0.06	0.03	
SWB				2.8				2.6				4.7
AVG	0.37	0.21	0.08		0.33	0.23	0.08		0.42	0.27	0.11	
STD	0.05	0.04	0.01		0.03	0.07	0.03		0.11	0.07	0.06	

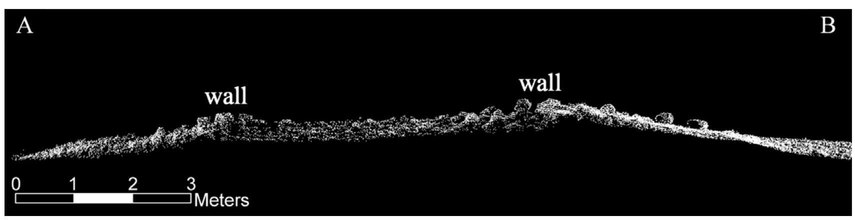

Fig. 12. A northeast–southwest cross-section through the arms of Samar West A, 10 m from the head (see Fig. 3b). Note the topographic elevated setting of the walls.

perpendicular to the general axis of the kites is generated, the slopes are much more moderate (Fig. 14a and 15c). These results, supported by field observations, indicate that in the hilly terrain examples the arms were constructed in chosen locales where the trap would be long and steep, topographically leading the animals downwards towards the head.

4. Discussion

Until now, kites were usually described cursorily: mainly by using 2-D plans in relatively low accuracy and resolution, very limited topographic details, and commonly only with partial information regarding the construction methods. In recent years, many kites were described using Google Earth satellite imagery. These may provide general data, as seen from the air, but they are also limited in resolution and topographic details, and construction methods are beyond the capacity of these means. In that respect, the laser scanning data provide a powerful tool for documenting the macro- and micro-topography of the landscape, as well as the ability to create a precise and high-resolution digital model for each kite.

The detailed documentation and 3-D model provide empirical data that can be used to conduct spatial and architectural analyses of kites. As the kites were not randomly constructed on the landscape, and their general location and specific details, such as where exactly will the head be and what exactly will be the course, height and width of each arm, were carefully and sophisticatedly planned and executed, such data are imperative for an accurate characterization of each kite. By studying the kites' architecture via visual reconstruction we are able to provide significant information regarding the construction methods and the landscape exploitation patterns around it. The data also serve as a platform to estimate the amount of labor invested in the construction of each kite. All of these add new ways to understand the profound knowledge of past hunters and their decisions regarding the choice of the best location for kite construction, and the location of the hidden enclosure in particular.

The close relationship between the desert hunters and their prey is further supported by simulating how the kite was operated and how the kite looks from the hunted animal's perspective (cf. online animation in the supplementary data, http://dx.doi.org/10.1016/j.jas.2015.02.040.). This simulation can be used as an analytical tool to explore the ways kites were operated, used, and incorporate ethological reconstruction to create a more discriminating model of how hunting was operated and which hunting decisions should have been considered.

In addition, the 3-D models and their analyses clearly show how symmetry was not important; in most cases, the left and right arms are set on distinct topographies and have very different shapes, lengths, widths and heights. Apparently, the factors dictating

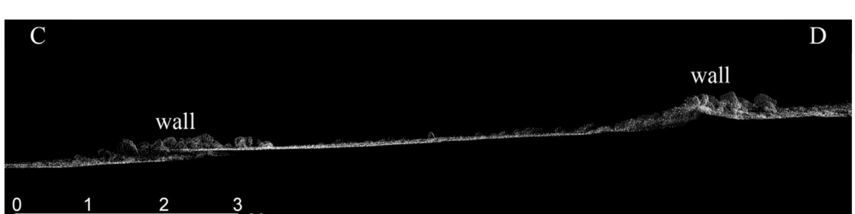

Fig. 13. A southeast–northwest cross-section through the arms of kite Samar West B, 15 m from the head (see Fig. 3b). Note the inner area clean of stones, taken for construction.

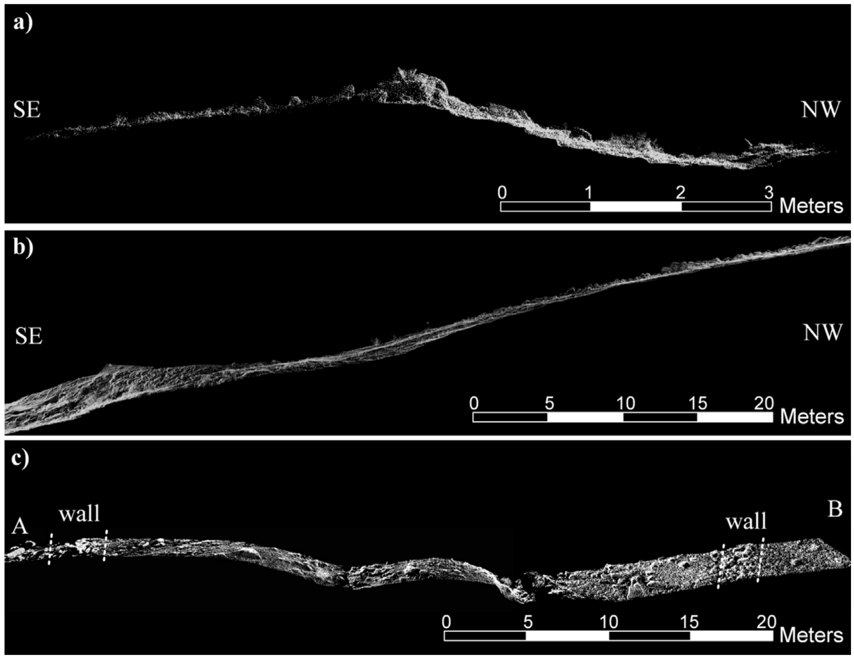

Fig. 14. Pitam kite arms; a) cross-section of the right arm. Left is outside of the kite and right is inside. The section is at the upper part of the arm, near its extreme end; b) a profile along the left arm's topography; c) a cross-section through the arms (see Fig. 4b). Note the two gullies crossing the kite.

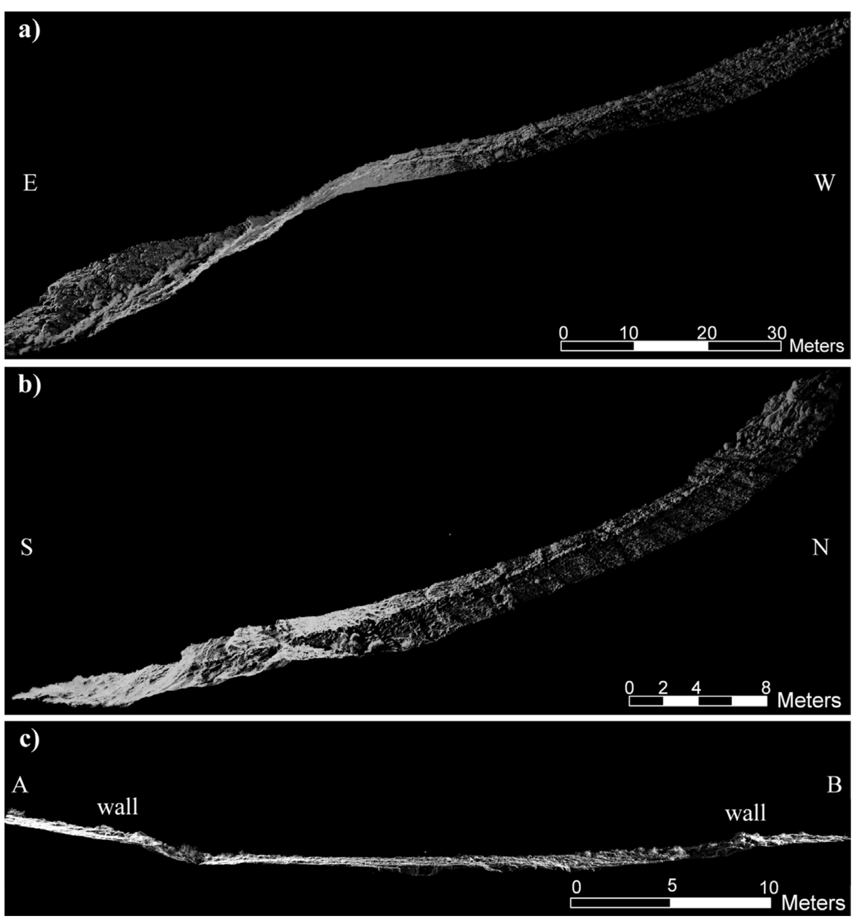

Fig. 15. Achshuv arms; a) a profile along the left arm's topography; b) a profile along the right arm's topography; c) a cross-section through the arms (see Fig. 5b).

Table 3
Estimated wall volumes, weights and working days.

Site	Head wall volume (m^3)	Weight (metric ton)	Head wall work days	Head digging (days)	Wall construction (days)	Total work days
Samar West A	15	40	15	5	70	90
Samar West B	32	88	32	12	50	94
Pitam	67	180	67	6	60	133

specific location and characteristic of each arm were not influenced by the need of a symmetrical hunting feature (though the general funnel shape was always maintained). The main goal of their specific design and settings were to reach maximum capture of prey. In this regard, future cross-regional comparisons using similar 3-D models are expected to be fruitful.

Viewed from another angle, the measurements of the kites' walls (arms and heads) enable the estimation of stone volumes and accordingly construction days (Table 3). Estimates are based on the experimental results described in Hockett et al. (2013) (see also Kempe and Al-Malabeh, 2013). The two *Samar* kites are similar in terms of estimated construction (and head digging) workdays, ca. 90 days per each kite. Constructing the *Pitam* kite likely took longer (ca. 130 days). Though the arms are shorter, the head rampart was very massive and the walls were thicker and higher, too. These numbers are no match to the huge chains in Eastern Jordan (e.g., Betts et al., 1998; Kennedy and Bewley, 2009; Kennedy, 2011; Kempe and Al-Malabeh, 2013) or the large enclosure kites in Jordan, Syria, Armenia and elsewhere (e.g., Echallier and Braemer, 1995; Brochier et al., 2014).

Still, even the smaller kites, such as those in the Negev, are remarkable in terms of the social system behind them. Small societies, either farmers in certain locations, and more likely herders (nomadic?) in most arid environments, invested much planning, time and resources (such as water and food for the builders during construction days) in the construction of the game traps. The exact contribution of the kites to past local economies is yet to be reconstructed and fully comprehended, yet their importance is evident through the remains themselves and the efforts they represent. In many ways, these are the most sophisticated and invested stone-built monuments in terms of time and resources, of otherwise humble societies with simple dwellings and basic mundane utilities.

The 3-D model of each kite shows clearly and in many details, the architecture. These high-resolution models enable not only to reconstruct the kite, but also serve as an excellent basis for the conservation and preservation of these sites. Even if a kite will be damaged by modern activities or earthquakes, its accurate model will still be accessible. Monitoring deterioration is also feasible, based on the models. Furthermore, we can now highlight certain areas within kites, mark stones which are not in situ, or code and digitally record specific stones or features that need to be protected and preserved.

Archaeological sites in the desert are in many respects an open book that can be read with the proper analytical tool. Here we used laser scanning technology to create high-resolution 3-D models of the Negev desert kites. This allowed us to reach better understanding of the construction methods of kites; more accurate assessment of the efforts needed to construct the kites; useful instrument for detecting macro- and micro-construction differences, which are difficult to evaluate using traditional 2-D documentation methods; detailed spatial characterization of shape and extensive record of topographic alteration; and find intra- and inter-kite construction differences on both global and local scale.

Future studies in arid environments should apply more commonly laser scanning technology (or any other 3-D modeling) to document additional desert structures, such as enclosures served as animal pens (Davidovich et al., 2014), open sanctuaries (Avner, 1984; Rosen et al., 2007) and seasonal camps (Rosen, 1993, 2011). This will allow better comparisons of site types, construction methods, social-needs, constraints, etc., and will lead to better understanding of human adaptations to harsh arid environments.

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