A UAS lidar case study in the archaeological landscape of ancient Halos, Greece

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Introduction

This paper presents the technical, methodological, and preliminary archaeological results of the Unmanned Aerial System (UAS) lidar experiments at the archaeological landscape of ancient Halos, executed as part of the Halos Archaeological Project of the Amsterdam Center for Ancient Studies and Archaeology, in cooperation with the Ephorate of Magnesia, the University of Groningen (till 2023) and the University of Thessaly.[1] The main elements of this archaeological landscape consist of various archaeological remains related to human burial, habitation, fortification, and related infrastructure, spanning all periods from the Neolithic onwards (Figure 1).

Recent fieldwork at the University of Amsterdam has prioritized the examination of the 10th to 3rd centuries BC, while not overlooking/disregarding other historical periods. There remain notable gaps in the understanding of developments in this region during antiquity, which in turn has generated a series of pertinent research inquiries. For example, the 10th-6th century BC funerary area at Voulokaliva – covering an area close to 2km x 2km and including *c.* 30 burial mounds – is one of the largest known from the Greek world.[2] Despite an extensive program of archaeological field surveys in the area, it cannot yet be clearly connected to a landscape of the living.

At Magoula Plataniotiki, the presumed location of ancient Halos, the current excavation focuses on the ancient urban centre. At *c.* 7ha, this tell site, with a yet unclear date range (certainly including the 7th-3rd centuries BC) is surprisingly small to be the centre of an ancient city state, as Halos is supposed to have been. Furthermore, it has an unusual location in the middle of marine marshlands and next to an ancient lagoon. This provokes questions such as how does the size of the tell site compare to other known central places of small ancient Greek city states? The relationship of the

[1] Reinders 1988; Stissi *et al.* 2015a; 2020.
[2] Stissi *et al.* 2004.

Figure 1. Location in Greece, overview of the archaeological landscape of ancient Halos (Illustration by J. Waagen, UvA)

urban center at Magoula Plataniotiki to a much larger, but very short-lived, heavily fortified city of 42ha, located further inland and dating to the early 3rd century BC, also needs clarification.[3] Additionally, there is evidence for early habitation at the bottom of the slope of the Acropolis, directly west of the early 3rd century city. Remains of a Protogeometric (10th century) house have been excavated there;[4] a little to the north, survey suggests Early Iron Age habitation.[5] Despite the insights gained from the various archaeological and geological field surveys, coring campaigns, excavations, geophysical investigations, and analyses of aerial photography at Magoula Plataniotiki and parts of the Voulokaliva, much of the ancient (human and natural) landscape and topography remains to be explored.

The dimensions, preservation, diversity, richness, and connectedness of archaeological features in the area make Unmanned Aerial Systems (UAS) remote sensing an important complement for studying the archaeological landscape.[6] The way the town at Magoula Plataniotiki was connected to dry land and its possible funerary area at Voulokaliva, for example, remains unclear; likewise, our archaeological survey seems to offer only a very partial image of presumable scattered habitation outside the centre at Magoula Plataniotiki and several fortified subcenters in the surrounding hills, which were inhabited in some periods, but perhaps not continuously or permanently. The possible roles of agriculture and animal husbandry, especially in the low-lying areas, also remain a subject to explore, in relation to both excavation and survey results. At a different level, Herodotus (7.197) mentions a sanctuary at Halos that has not yet been identified and the combination of built structures on the acropolis of the 3rd century BC city is also badly understood.

[3] Stissi *et al*. 2015a; 2020.
[4] Malakasioti and Mousioni 2004.
[5] Stissi 2016.
[6] E.g., Attema *et al.* 2020; Casana 2021.

These examples/research questions show that the application of an integrative approach to the archaeological landscape of ancient Halos that combines remote sensing at the feature, site, and landscape level, with the already abundant research data collected in the past century of archaeological fieldwork and study can help to develop new insights regarding standing questions.

In order to address these inquiries, we conducted a series of data collection campaigns utilizing UAS. These campaigns employed both conventional methodologies and widely used sensors, and also engaged in experimental research, incorporating less established technologies in the context of archaeological prospection, such as beyond-visible-light spectrometry.[7] The focus of this paper is specifically on the collection of lidar data across various parts of the research area. For the region in Greece under investigation, lidar data are not publicly available, if they exist at all. Therefore, acquiring lidar data through UAS offers a valuable opportunity to obtain high-resolution measurements of the local landscape, as well as the ability to penetrate its vegetation cover.[8] In this paper, we evaluate the application of a relatively low-budget approach, the development of effective data collection strategies and data processing workflows, the management of extremely high point densities, and the ubiquitous problem of low vegetation. In addition, we share and discuss several preliminary observations and their impact on the archaeological historical understanding of the area.

The point deluge – equipment, data collection, and workflow explorations

The efforts with UAS-based lidar data collection and analysis in the context of the Halos Archaeological Project focused on both methodological as well as archaeological research questions. For an effective integration of the technology, it is important to assess its precision, accuracy, potential for scalability, and performance in different landscapes and vegetation.[9] These questions are especially salient, as the lidar operations in the context of Halos Archaeological Project have been executed with the first issue of a low-cost solution to UAS-based lidar. For the operations, we employed the DJI M300 RTK drone in combination with the Zenmuse L1 lidar sensor, connected to the GNSS RTK network provided by METRICA's HxGN SmartNet. The DJI Zenmuse L1 combines a lidar Livox sensor with a 20MP CMOS RGB mechanical-shutter camera and inertial measurement unit (IMU), with an effective point rate of 480 points per second on a three-return setting and a non-repetitive Field of View of 70.4 degrees horizontal, and 77.2 degrees vertical. Clearly, a relatively affordable and flexible lidar solution is of potentially great value for archaeological projects which usually run on strict budgets, but the limitations of the technology must also be critically evaluated.[10] In this case it is important to assess reasonable concerns on the absolute geometrical accuracy of the collected measurements, and furthermore, the L1 only captures three discrete returns per pulse as opposed to >10 returns for higher grade solutions, which likely only amplifies the common challenge of penetrating low vegetation effectively.[11]

Data acquisition parameters

The first tests in data acquisition were done at Magoula Plataniotiki (Figure 2). Here, two flight operations were executed, the first one using the default DJI Pilot 2 settings for L1 data capture, and the second one with settings adapted for maximum vegetation penetration capabilities (Figure 3). This involved setting the maximum number of returns, lowering the flight speed from 6m/s to 5m/s, and increasing sideways overlap from 20% to 50% (Figure 3). The effect of the lower speed is obviously to collect more points as a result of the continuous scanning mode, and the effect of the

[7] E.g.. Casana 2023; Waagen 2023.
[8] Vinci *et al.* 2024; Opitz 2013. For other drone-based lidar applications, see: Levine *et al.* this volume; Pike *et al.* this volume.
[9] Štular *et al*. 2021.
[10] Costs of DJI M300 equipped with the Zenmuse L1 approximately 25k at the time of writing.
[11] Diara and Roggero 2022.

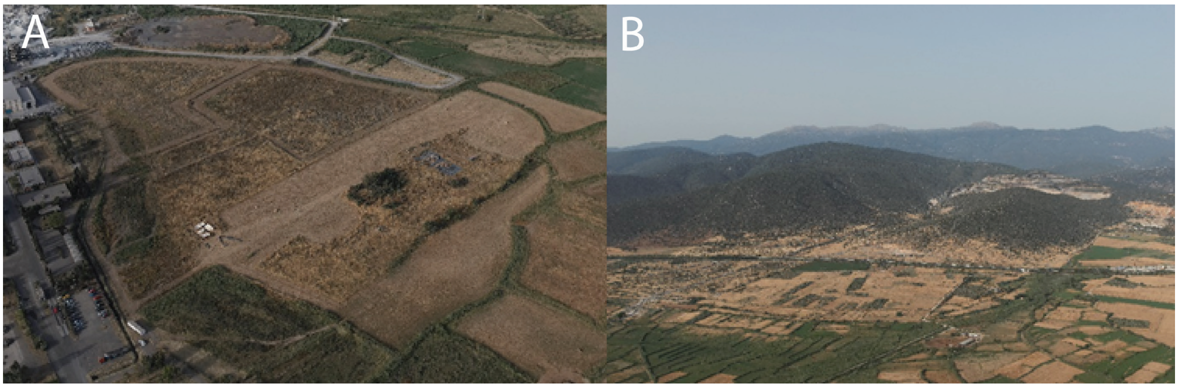

Figure 2. A: Magoula Plataniotiki from the northeast; B: overview of the Hellenistic city (foreground) and the acropolis (lower hill on the right). (Photos by J. Waagen, UvA)

Area	Coverage (ha)	Altitude (m)	Duration (min)	Speed (m/s)	Returns	Overlap	Points (million)	Ground Sample Distance (cm)
Magoula Plataniotiki (1)	28	50	22	6	single	20%	276	1
Magoula Plataniotiki (2)	28	50	22	5	triple	50%	371	1
Voulokaliva	198	130	160	6	triple	50%	1389	2.7
Acropolis & Hell. city	201	130	160	6	triple	50%	1414	2.7

Figure 3. Operational details of the UAS surveys.

increased sideways overlap is to collect points through pulses with a different inclination towards the surface, increasing the probability of collecting additional ground points.

We processed the data using the free version of the DJI Terra software package for conversion from the proprietary .ldr format (and associated files) to a georeferenced .las file. Then, a basic LAStools processing workflow was used to produce tiles, perform the ground point selection, and rasterize into digital terrain model tiles (see appendix). We then subsequently merged these tiles using the default raster merge tool in QGIS.

To assess the differences between the two lidar data acquisition flights, we visually evaluated the resulting digital terrain models (sometimes combined with a hillshade model for additional clarity),[12] and analyzed them quantitatively (Figure 4). The two sets of lidar-derived visualizations from both operations, as well as the difference model generated by subtracting both digital terrain models, demonstrate some divergence. It is evident that in the second, more optimized survey, the removal of trees on the acropolis of the Magoula Plataniotiki has been executed with greater efficacy. Additionally, there has been a notable reduction in the extent of lower vegetation within the central low-lying area of the site. However, it is important to note that this vegetation has not been entirely filtered out. Furthermore, there exists a degree of spatial variation in the effectiveness of the removal efforts, as certain patches remain largely unchanged, consistent with the data obtained from the initial aerial survey. To give a quantitative indication, the difference model for the area of lower vegetation shows that the mean difference is 3.2cm, with a standard deviation of 8.8cm, again reflecting the subtle improvement, but greatly varying over the whole area. This variation is the result of the density of the branches and foliage, where relatively few of the pulses actually reach the ground, which makes extracting ground points a complex operation. In addition to the flights at Magoula Plataniotiki, more extensive UAS lidar data was collected at the Voulokaliva, and the Hellenistic city including the Acropolis. In case of the latter, the terrain

[12] Kokalj and Somrak 2019.

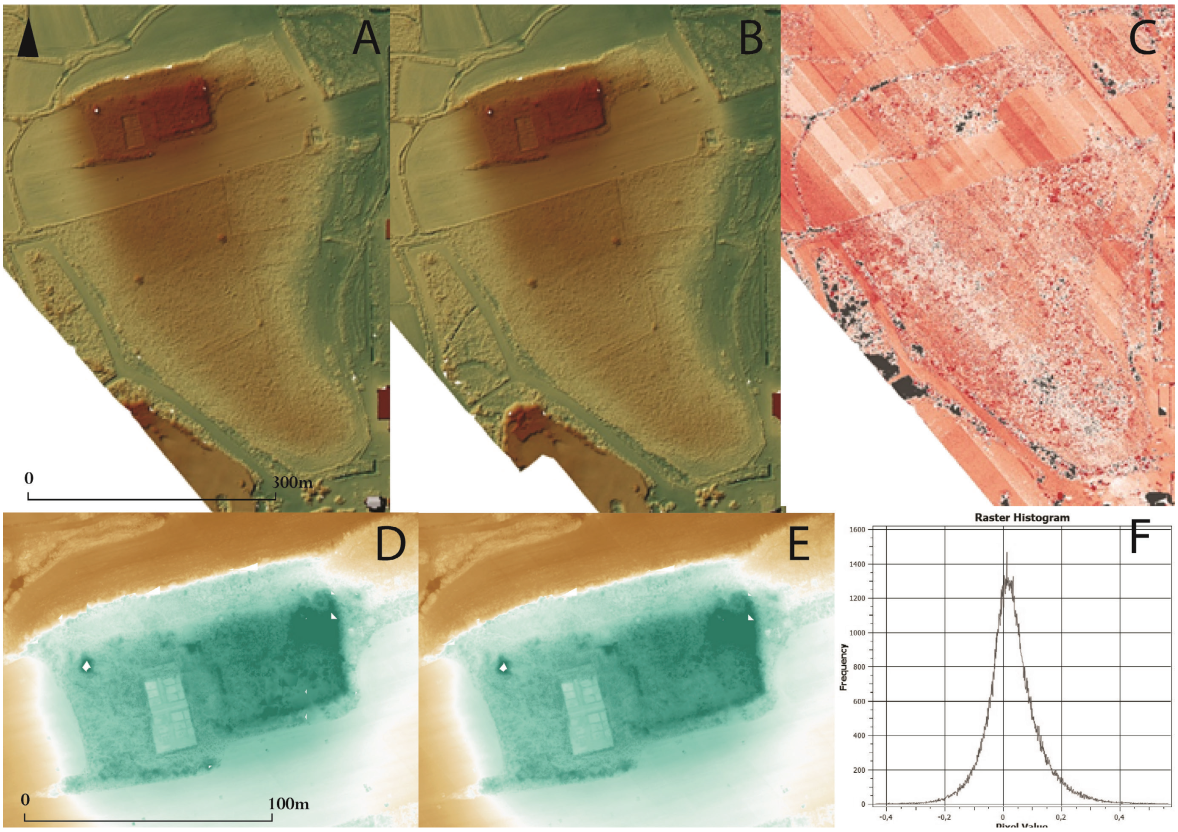

Figure 4. Comparison of flight 1 (A) and 2 (B) at Magoula Plataniotiki (both digital terrain models pixel fused with hillshade models), difference model (C), lower: closeup digital terrain model flight 1 (D), closeup digital terrain model flight 2 (E), histogram of difference model (F). (Illustration by J. Waagen, UvA)

following function was used to maintain a consistent altitude above the ground during flight, ensuring consistent data quality and point density over the variable topography. This was achieved using the available ASTER digital elevation model – the default option in DJI Pilot 2 (Figure 3).[13]

Data processing workflows

Apart from the vegetation penetration result, the difference model also shows a marked striping effect, resulting from deviations between measurements made in the different swathes flown by the UAS. Clearly, with altitude variations between swathes of the first and second flight roughly between 1-3cm, this also affects the quantification of the difference model. The sources of error factoring into these deviations can be manifold, but primarily stem from instrumental inaccuracies, which include boresight misalignment, lever-arm errors, and IMU 'drift' – errors that accumulate gradually in the gyroscopes and accelerometers of the IMU during prolonged use within a single survey.[14] This striping effect has also been identified in other archaeological lidar surveys conducted using the DJI M300 RTK and Zenmuse L1 setup.[15] While the absolute geographic precision of the acquired 3D coordinates and the resultant data models may not be critically significant for numerous applications of archaeological remote sensing, the discrepancies observed between swathes do pose notable challenges. For instance, when generating digital terrain model derivatives, such as sky view factor or hillshade visualizations, these inconsistencies can become markedly pronounced, potentially obstructing the detection of archaeological anomalies.

[13] https://asterweb.jpl.nasa.gov/gdem.asp.
[14] Viedma 2022; Yan 2023.
[15] Casana *et al.* 2023.

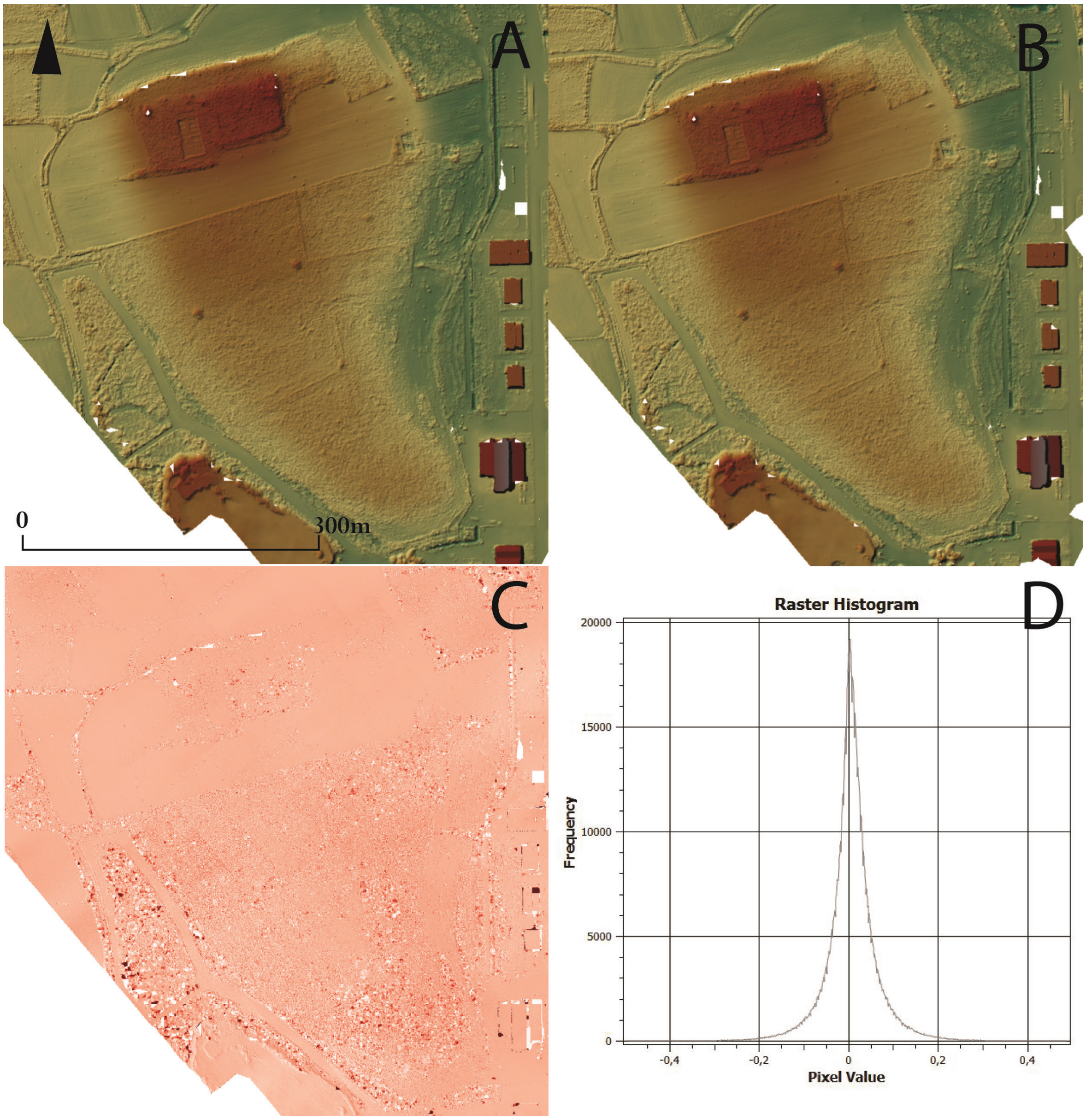

Figure 5. Comparison of DJI Terra Pro (A) and BayesMap StripAlign (B) data processing (digital terrain models pixel fused with hillshade models); difference model (C), histogram of difference model (D). (Illustration by J. Waagen, UvA)

In the paid version of the software, DJI Terra Pro, data accuracy improvement and smoothing algorithms mitigate this striping effect and improve overall quality and local structure. However, these are closed, proprietary, and undocumented procedures, obscuring the actual data manipulation.[16] These black-box algorithms also hinder adherence to the FAIR principles that advocate full transparency of data modelling workflows, which is essential for quality assessment and reuse.[17] Moreover, the paid version of DJI Terra Pro is relatively expensive, posing a significant strain on any archaeological fieldwork budget.[18] It is therefore imperative to explore alternatives for processing the collected lidar data. A good option here is provided by the BayesMap StripAlign

[16] DJI Manual: 'Optimize Point Cloud Accuracy: if enabled, the software will optimize point cloud data collected at different times during processing for higher overall consistency and accuracy. [..] Smooth Point Cloud: Enabling this feature will reduce the point cloud thickness to remove discrete noise and make local structure appear clearer.' https://dl.djicdn.com/downloads/dji-terra/20240118/DJI_Terra_User_Manual_v4.0__EN.pdf.
[17] Lozić and Štular 2021; de Haas and van Leusen 2020; Doneus and Briese 2011.
[18] Costs are approximately 5k euro for a single perpetual license.

Area	Coverage (ha)	System	DJI Terra (min)	BayesMap (min)	LAStools (hr)	QGIS merge (hr)
Magoula Plataniotiki (1)	28	Laptop	12	15	3	2
Magoula Plataniotiki (2)	28	Laptop	12	15	3	2
Voulokaliva	198	Desktop	30	45	14	4
Acropolis & Hell. city	201	Desktop	30	45	14	4

Figure 6. Approximate data processing times (QGIS merge depends on number of tiles as an outcome of LAStools configuration).

software, which is significantly cheaper.[19] As a command line program, BayesMap StripAlign works efficiently by first reconstructing the individual swathes from the raw lidar data, and subsequently applying time-dependent corrections to minimize constant geometric errors and address IMU drift, ensuring proper alignment of the swathes (see appendix for the code used).

Comparing the results of the lidar data as digital terrain models with accuracy optimization and smoothing from DJI Terra Pro with the results of the lidar data processed using the BayesMap StripAlign option, it is clear that they produce comparable results (Figure 5). Indeed, quantifying the difference model gives a mean difference of 7.1mm, with a standard deviation of 5.5cm. The variation represented by the standard deviation is not readily assessable. While this may be affected by the accuracy and smoothing algorithms employed by DJI Terra Pro, the lack of specification regarding the applied algorithms precludes a definitive analysis. Nevertheless, the workflow utilizing BayesMap StripAlign appears to yield satisfactory results.

After the alignment in BayesMap, the corrected swathes are imported in LAStools for further processing. This workflow consists of a tiling procedure, followed by a ground point classification, and finally interpolating the identified ground points into a series of individual digital terrain models, which can then be merged using the GDAL tools in QGIS. Some initial explorations to optimize vegetation removal have been executed, but this remains an ongoing challenge that needs much further consideration. For a fieldwork setting, the processing times are important to the process of experimental data acquisition and inspection in an iterative setup. Working with higher-end laptops, processing times for quite large datasets appear manageable up to *c.* 500-600 million points per pointcloud (see Figure 6).[20] At around this threshold, processing times increase to a degree that the processes cannot be run overnight and become very impractical in a fieldwork setting. For example, to effectively run various iterations of the acropolis dataset, it required a dedicated high-end processing desktop.[21]

Seeing through the thickets – archaeological observations and implications

The continuous experimentation and advancement of technical methodologies in UAS lidar data acquisition and analysis necessitate a critical evaluation in relation to the potential archaeological insights that these innovations may facilitate.

Magoula Plataniotiki

A comparative analysis of the newly acquired lidar-derived imagery of the Magoula with data from prior geophysical investigations, a digital elevation model generated through UAS photogrammetry, and cropmarks discernible in aerial photographs, indicates that the recent

[19] Costs are approximately 500 euro a year for multiple instances https://bayesmap.com/.
[20] Laptop specs: Intel Core i9 12900HX | Nvidia RTX 3080 | 32GB RAM | 2TB SSD.
[21] Desktop specs: Intel Core i9 13900K | 2x Nvidia RTX 4090 | 128GB RAM | 6TB SSD

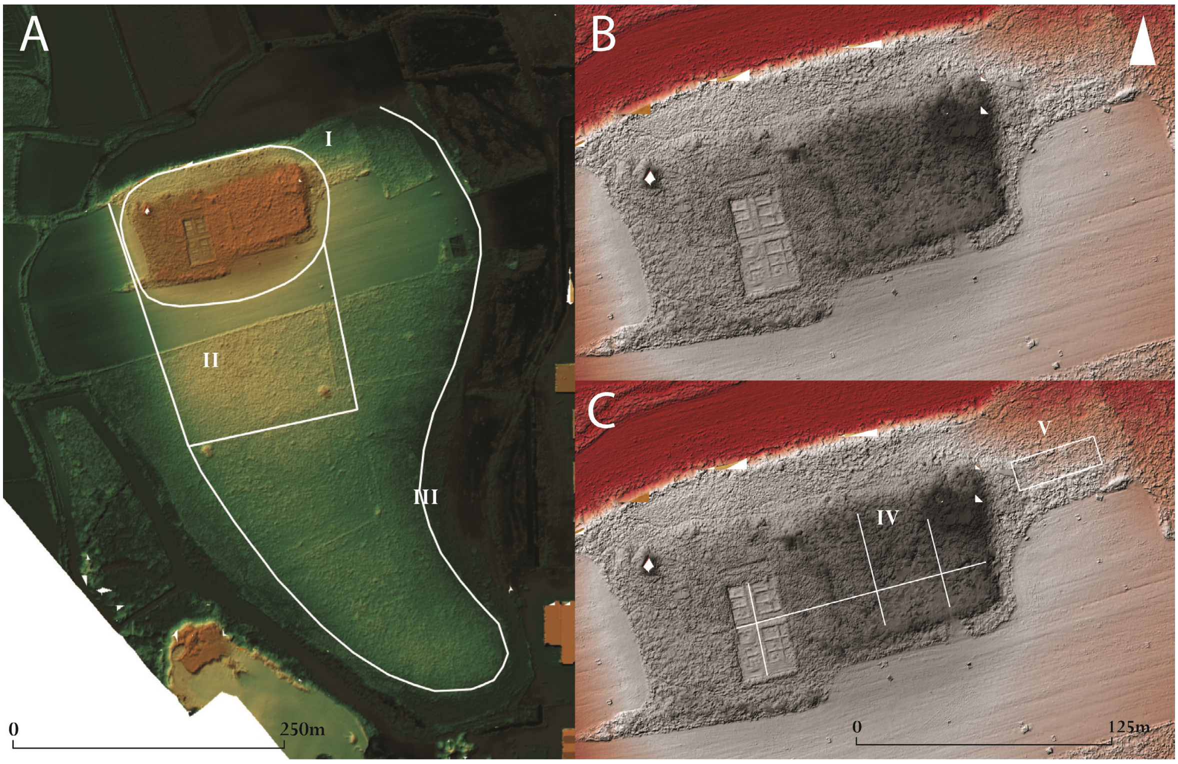

Figure 7. Magoula Plataniotiki. Digital terrain model pixel fused with hillshade model with site levels indicated (A); digital terrain model pixel fused with hillshade model of presumed site core (B), digital terrain model pixel fused with hillshade model with potential interesting features indicated (C). (Illustration by J. Waagen, UvA)

findings largely corroborate previous observations (Figure 7). However, certain subtle features have emerged that merit additional scrutiny (Figure 7A). First of all, the models seems to confirm that the mound comprises three distinguishable levels: a flattened oval at the north end, where the highest elevation is reached, possibly the original core of the site (I); a roughly rectangular shape comprising the northern half of the site, in line with crop marks suggesting the eastern and (more clearly) the western side of the rectangle were delineated by straight linear structures, perhaps a wall, a ditch or a paved street, or a combination of those (II); the comma-shaped elevation running over the site as a whole, also covering the northeastern area where cropmarks, geophysics and excavation do indicate substantial presence of archaeological remains (III). Even though the relatively low elevation of the southern point and northeastern part of the site appear to suggest these areas may not have been built over for a long period, excavation and geophysics in the northeastern part indicate the presence of substantial remains covering at least three centuries. This division into three levels comes out much clearer than in previous mappings. It is also striking that the modern field covering the south side of the presumed original core does not show any features, even though excavations show that in various parts of this field ancient walls appear 10-20cm below the surface. Even very shallow plowing can apparently flatten a surface effectively. In addition to the excavation trenches, there are only two, possibly three, discernible archaeological features present at the site. In the northernmost section (Figure 7C), which is elevated relative to the rest of the area, two indistinct, broad lines appear to align approximately parallel to a north-south alley located immediately to the west within the excavated trench (IV). These features may indicate the existence of additional alleys in the vicinity. It is equally possible, however, that these linear features are the result of recent bulldozing or excavation, since the orientation of the present property and field boundaries is more or less in line with the 3rd century BC, seemingly gridded, plan of the area. In the northeast of the site, a little east of the highest part, a vague square feature, possibly opening on the north site, may be visible; this area also seems part of a slightly elevated bulge extending from the tell core eastward, and geophysics and excavation further south

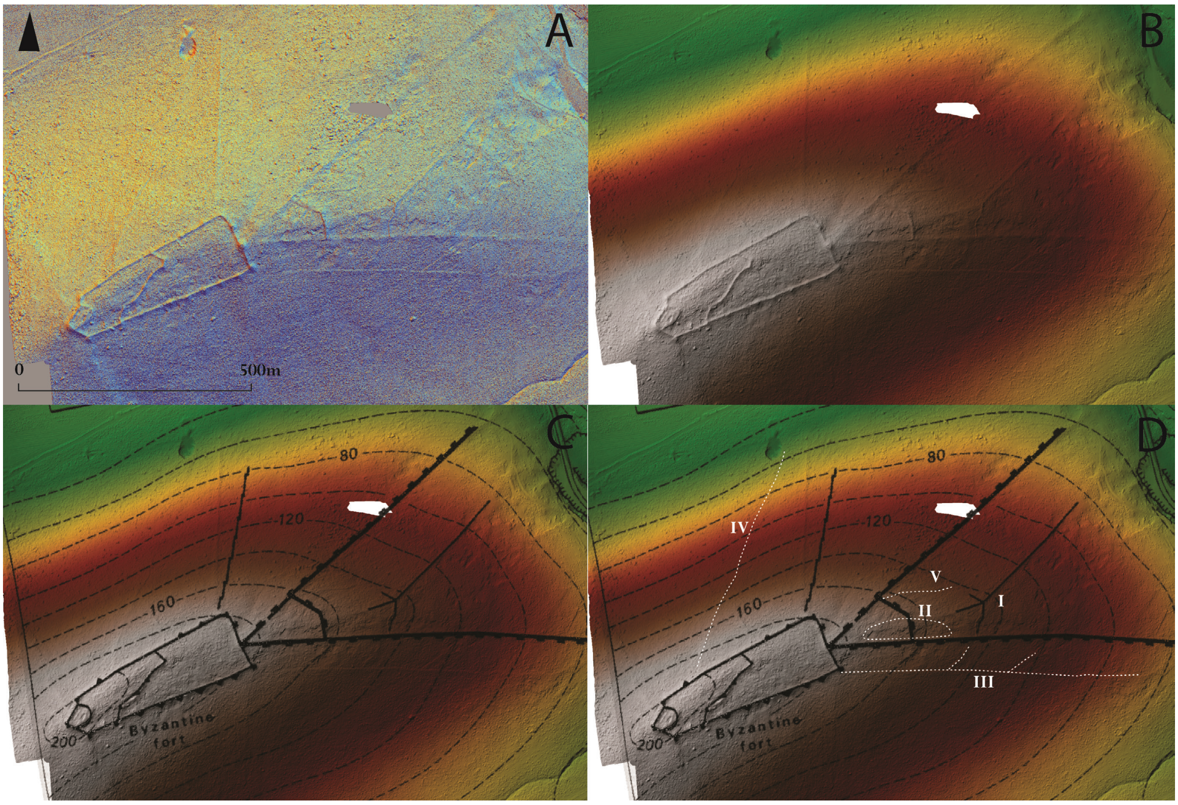

Figure 8. Acropolis of the Hellenistic city. Multiple hillshade model (A), digital terrain model pixel fused with hillshade model (V); with overlay of 1970s mapping (C), and with new archaeological features indicated (D). (Illustration by J. Waagen, UvA)

revealed some substantial walling, belonging to an undefined, possibly monumental building. The partly straight and steep drop-off just northwest of this seems to be related to recent digging (V). One potential explanation is that an early 20th century excavation, documented but not yet precisely located, occurred in this region. The emergence of some blocks in this area, along with the existence of ambiguous linear features identified in the lidar data, may support this hypothesis. However, it is important to note that this interpretation remains speculative at this stage.

Acropolis

The lidar data visualization of the acropolis shows much clearer features than the one of Magoula Plataniotiki (Figure 8). The majority of the immediately apparent architectural features were indeed present in earlier cartographic representations derived from a pre-digital survey conducted in the 1970s;[22] however, using the UAS lidar data allows for their localization with markedly enhanced accuracy and precision. Furthermore, it is plausible to propose additional interpretations regarding the present walls and structures (Figure 8D).[23] The previously recognized broken linear feature situated in the center of the triangular slope leading to the Hellenistic keep, and potentially the Byzantine-Ottoman fortress located at the summit, may now be identified as a roadway (I). This roadway appears to have a branch extending toward the southern wall and beyond. The quarries designated for the extraction of stone utilized in the construction of the southern and northern walls are distinctly observable at the site, although they are not represented in previously published cartographic materials. Their prominence is noteworthy (II). In addition, there are three major features that have not been observed in previous study: the first is a long line running parallel to the south wall, below it, with two branches going up (one already mentioned just above). This seems

[22] Reinders 1988.
[23] Multiple hillshade model produced with https://www.zrc-sazu.si/en/rvt.

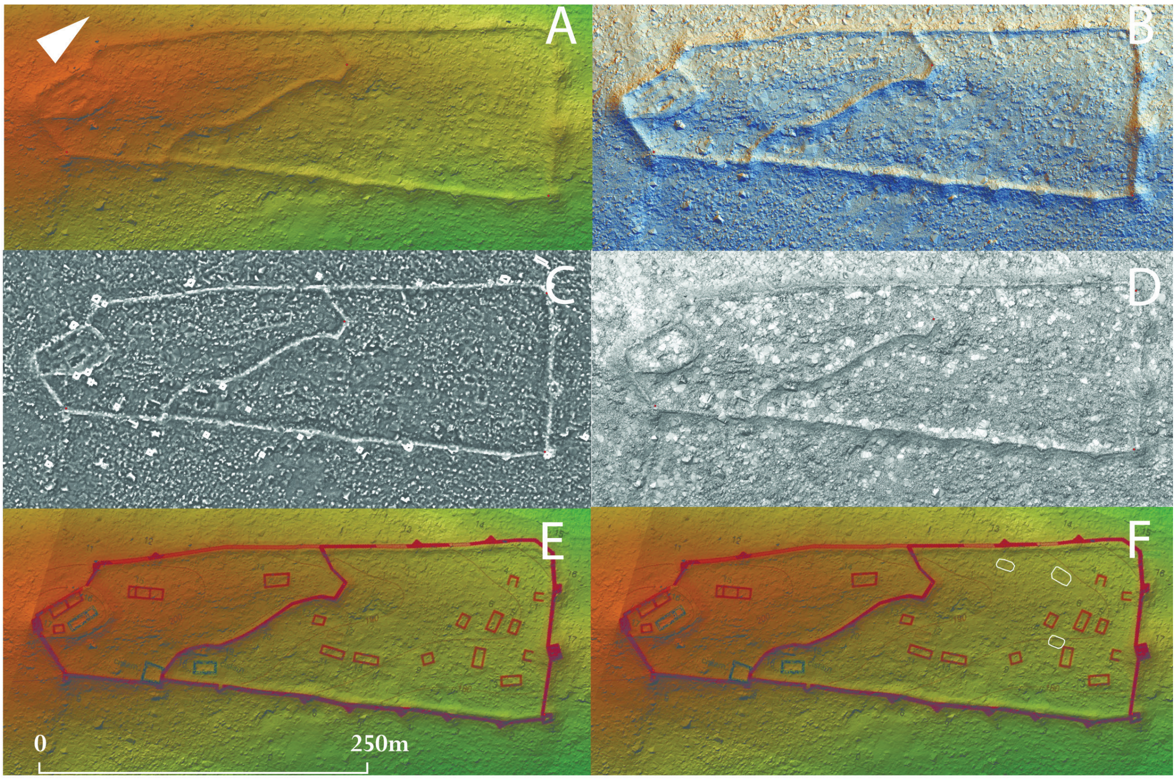

Figure 9. Fortification on the acropolis of the Hellenistic city. Digital terrain model pixel fused with hillshade model (A), multiple hillshade model (B); local relief model (C), anisotropic sky view factor model (D); with overlay of 1970s mapping (D), and with new archaeological features indicated (E). (Illustration by J. Waagen, UvA)

to be a path of unclear date and role (III). The second is a route that descends in a northeastern direction from the Byzantine fortress, terminating at an undated quarry. Given the relative brevity and ease of this descent, coupled with its proximity to the Kephalosi spring – a significant water source adjacent to an Ottoman hamlet and a preceding archaeological site – it is plausible that this path served as a principal access route to the fortress (IV). The third is an unclear linear feature inside the north wall, just northeast of the Hellenistic keep (V). This might be another path, but this interpretation is difficult to substantiate without further ground assessment. The same holds for a series of other unclear possible features on the slopes further east. Further refinement of the data and visualization could contribute towards a better understanding of scattered remains on the slope.

Finally, a detailed examination of the fort's interior reveals several distinct features. While many of these characteristics have been documented in prior studies, there are notable elements that have previously gone unnoticed and are absent from the 1970s surveys. These pertain for a large part to what appear to be rounded rectangular shaped structures that resemble the earlier mapped structures in size and orientation (in white on Figure 9; Figure 10).[24] Moreover, these new visualizations contribute towards a more detailed and precise articulation of the already known features.

Voulokaliva

Lidar-based visualizations of the Voulokaliva funerary area showcase a multi-scalar approach to an extensive archaeological landscape (Figure 11A). Lidar data were collected alongside several other remote sensing techniques in the framework of an integrated survey, complementing the

[24] Multiple hillshade model, local relief model, and anisotropic sky view factor model produced with https://www.zrc-sazu.si/en/rvt.

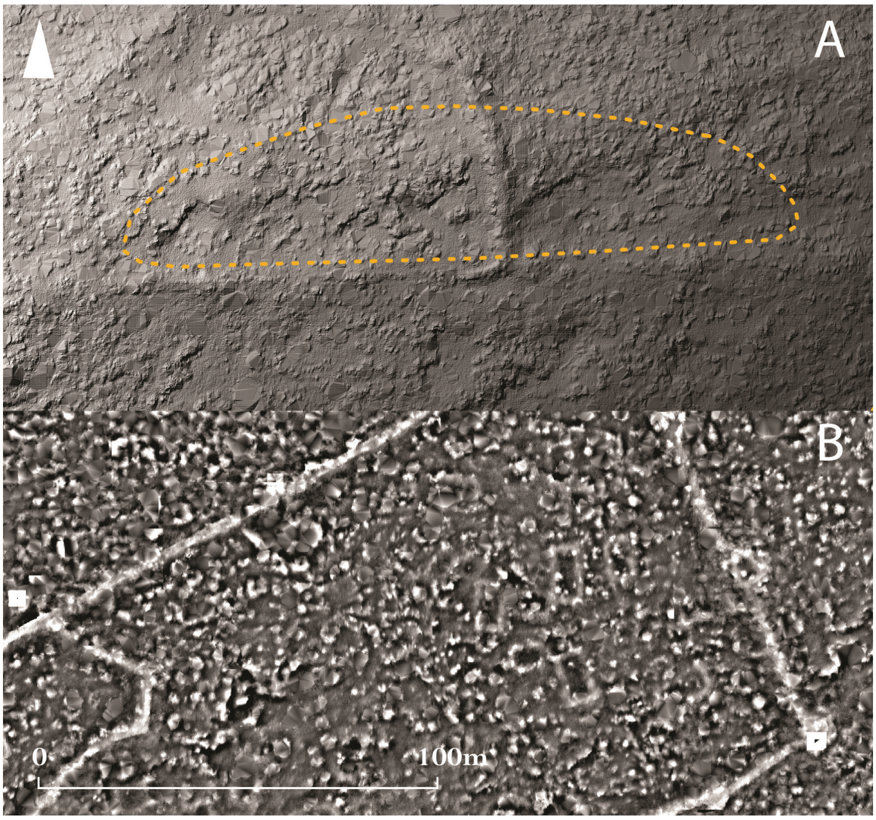

Figure 10. Details of features attested on the acropolis. Quarries identifiable by their sharp edges on digital terrain model, pixel fused with hillshade model (A), structures within the fortification walls visible on local relief model (B). (Illustration by J. Waagen, UvA)

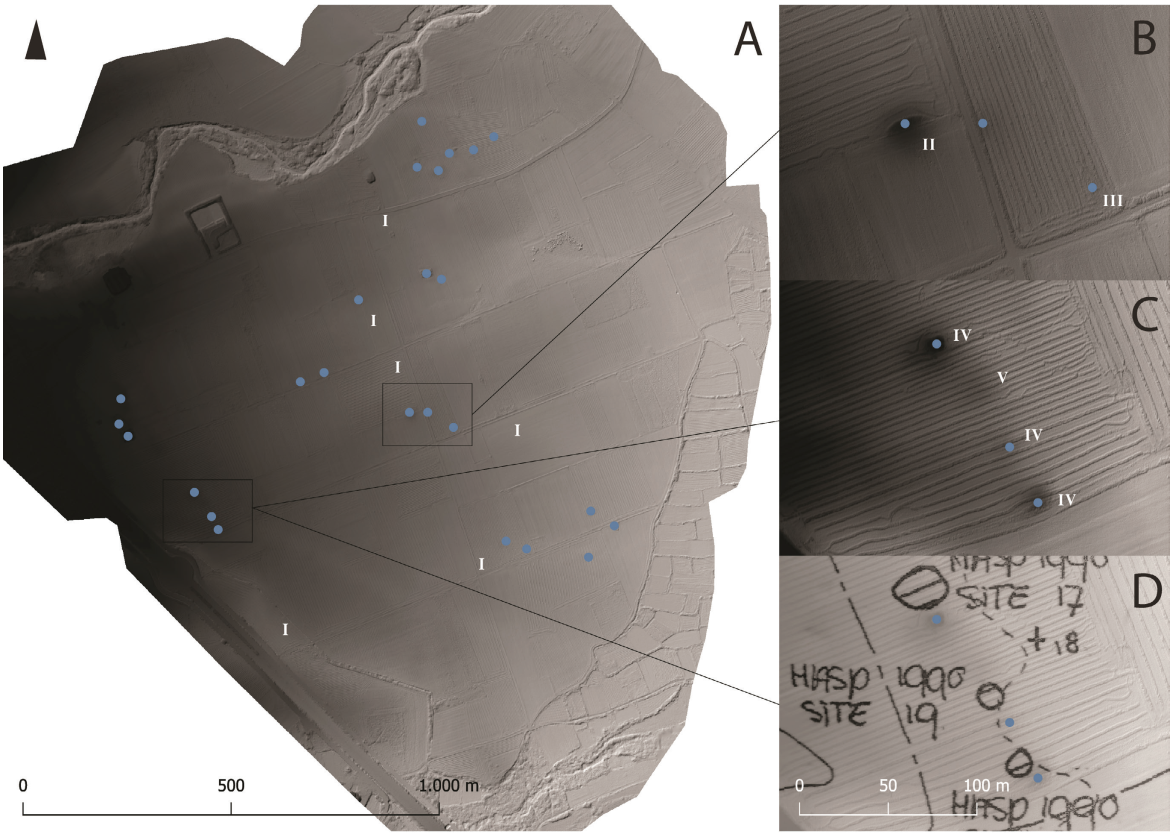

Figure 11. Voulokaliva. Digital terrain model pixel fused with hillshade model with mounds indicated in blue and potential old watercourses (A); digital terrain model pixel fused with hillshade model showing different appearance of surveyed mounds (B), digital terrain model pixel fused with hillshade model with potential unidentified mound V (C); 1990 survey map with site indications compared to lidar-based plotted mounds. (Illustration by J. Waagen, UvA)

field survey of the area in 1990 and later revisits and pottery study.[25] The creation of detailed lidar-derived imagery and a photogrammetric model based on UAS made aerial photographs of an archaeological landscape measuring close to 2km^2 imposing challenges concerning the size of the dataset, but enables the study of the landscape at different scales or resolutions.

Imagery of the area as a whole helps us to contextualize the various funerary sites within the landscape, indicating the relief across the alluvial fan and specific morphological features, such as possible old watercourses and/or roads (I). More significantly, comparative analysis of the different visualizations allows us to map the archaeological landscape with more precision. With the existing field survey maps of the area mostly based on observations in the field and subsequent analysis of the ceramics, large scale UAS imagery refines, complements, and in some cases offers a correction to the manually produced maps (Figure 11D).

When analyzing the area on a smaller scale, we can validate features visible in the field, such as the characteristic stone heaps created over time by the gradual ploughing out of archaeological features and depositing these stones on a heap. Some of these heaps are located on a circular elevation in the relief, providing clear indication of a (partially) preserved tumulus under the surface (e.g. site 1990/22, II, Figure 11B). Other stone heaps, previously identified as sites, cannot be associated with a circular morphological feature and might point to a different origin (e.g. site 1990/40, III, Figure 11B). It is possible in such a case that stones and other material (e.g. construction waste) were deposited on or near the edge of the field, although the site was classified as such based on an Early Iron Age pottery scatter. The differentiation between such features and the varying preservation of the sites due to the ongoing agricultural use of the area, can be effectively observed and documented based on the lidar data visualization. These images provide an effective means to sharpen the perspective on the relation between visible characteristics in the field and more subtle features in the landscape. Elsewhere, the lidar images provide indication of sites that were not or can no longer be observed in the field. For example, three sites were identified in the survey (sites 1990/17, 19, 20, IV, Figure 11C), where the lidar imagery indicates an additional circular elevation – and possible site – in between the others (V).

Discussion

The lidar documentation of the archaeological landscape of ancient Halos clearly shows that this technology can be deployed very effectively. The technology allows for the gaining of high-resolution data in relatively large areas which it can capture in very high detail, which is difficult to obtain through other means, in particular because of the production of terrain models, removing large parts of the vegetation. As such, it allows for detailed analysis on multiple scales, from complete landscapes and urban site morphologies to a large diversity of archaeological features, from roads and walls, burial mounds, to individual structures, mapping known features in much higher detail but also uncovering more ephemeral archaeology. Due to its geographical accuracy, lidar data visualizations can also effectively correct archaeological surveys executed with older, less accurate techniques. It is worthwhile to underline that the lidar capture and processing did not take a huge effort in time and processing resources and would be advisable in many archaeological landscapes in which similar features appear or may be expected. It is also recommended to do that as early in a research project as possible, to be able to have a broad aerial perspective that allows us to zoom in on particular areas in subsequent stages. For example, in the challenging context of the acropolis, lower altitude lidar capture could be very worthwhile to get more grip on the architecture morphology, up to the individual stone.

[25] Stissi *et al*. 2004; 2015b.

Conclusions

The technical and methodological explorations with UAS lidar data using the DJI M300 RTK plus Zenmuse L1 sensor have yielded significant insights. These findings encompass advancements in data acquisition strategies, an understanding of the scalability potential of UAS lidar applications, and the refinement of data processing workflows, quality assessments, and processing efforts. Such insights are poised to inform the continued evolution of UAS-based remote sensing research methodologies, thereby enhancing their integration within a comprehensive research framework focused on archaeological landscapes.

As for the preliminary archaeological results, the lidar imagery provides a nuanced and varied dataset. At Magoula Plataniotiki, the dense and low-lying vegetation, the tell structure, and disturbances caused by modern agriculture seem to limit the potential of UAS lidar compared to other survey methods, although of course data acquisition was much faster than with the traditionally produced DEM. Indeed, the vegetation present in the unplowed sections of the tell poses significant challenges for classification and filtering of the collected lidar data. Moreover, one may still question the efficacy of a well-filtered digital terrain model in providing substantive insights, considering findings from other areas within the site. At the Voulokaliva and on the acropolis, on the other hand, the new images have revealed surprising new information. At Voulokaliva a more detailed characterization of the Iron Age mounds and surrounding landscape can be made, where previous mappings of the large area provided a limited view on the site. On the acropolis, where the rocky surface, slopes and maquis limit accessibility and visibility for other methods, some rather substantial remains were discovered that had gone unnoticed. Currently, it is not possible to assign a chronological framework to these features at the acropolis; however, it is anticipated that ground assessment may provide clarity in this regard. Additionally, it has been observed that the challenge in classifying and filtering vegetation may obscure certain areas, although the extent of this effect appears to be less fundamental than at the tell site.

In conclusion, the application of UAS lidar in the archaeological landscape of ancient Halos has proven useful, both for technical and methodological explorations, as well as for generating valuable archaeological insights. However, it is also evident that there is still much to be gained from further refinement of the data acquisition, processing, and analytical workflows, as well as the development of further comparative frameworks including different UAS lidar setups as well as lidar data sets derived from other platforms, such as airplanes. In this context, promoting interdisciplinary dialogue, facilitating the exchange of expertise, and sharing data – including the publication of findings and the archiving of both raw and metadata – are crucial for advancing the field.

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Appendix

BayesMap command line code example:[26]

```
stripalign -uav -cut -i E:\Halos_2024\drone\modeling\20240701_lidar_MP\Halos_2024_lidar_MP_40m_merged\lidars\terra_las\merge\cloud_merged.las -po E:\Halos_2024\drone\modeling\20240701_lidar_MP\Halos_2024_lidar_MP_40m_merged\lidars\DJI_20240702073133_0001_Zenmuse-L1-mission_sbet.out -odir E:\Halos_2024\drone\modeling\20240701_lidar_MP\cut
```

```
Stripalign -uav -align -i E:\Halos_2024\drone\modeling\20240701_lidar_MP\cut\*.laz  -po E:\Halos_2024\drone\modeling\20240701_lidar_MP\Halos_2024_lidar_MP_40m_merged\lidars\*sbet.out -po_att 2 -att_imu -mount E:\Halos_2024\drone\modeling\20240701_lidar_MP\cut\mount.txt -wkt E:\Halos_2024\drone\modeling\20240701_lidar_MP\cut\32634.txt -odir E:\Halos_2024\drone\modeling\20240701_lidar_MP\clean -CB35
```

LAStools script:

```
mkdir 1-tiles

lastile -i *.las -tile_size 10 -buffer 1 -odir 1-tiles -o tile.laz

cd 1-tiles

mkdir 2-ground

lasground -i *.laz -odir 2-ground -o ground.laz -coarse -wilderness

cd 2-ground

mkdir 3-dem

las2dem -i *.laz -odir 3-dem -o dem.tif -use_tile_bb -keep_class 2 -step 0.01 -kill 50
```

[26] Code instructions derived from 'StripAlign 2.23 – DJI L1/L2 alignment instructions' pdf by BayesMap.