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Cost-effective, rapid decorrelation stretching and responsive UAS mapping as a method of detecting archaeological sites and features

Rich Potter[1*], Derek Pitman[2], Harry Manley[3] and Robin Rönnlund[4,5]

Abstract

Approaches to aerial photography and remote sensing have become increasingly complex, can rely on opaque workflows, and have the potential to be published with inaccessible language. Conversely, aerial capture has become increasingly accessible with affordable, user-friendly unmanned aerial systems (UAS) now being commonplace in the field-archaeology toolkit. This means that considerable amounts of data are being produced by diverse projects, yet only a limited quantity are subject to advanced processing techniques. This paper aims to address this imbalance through a low-cost, accessible workflow that pairs frequent (multi-temporal) surveys with straightforward, out of the box processing. The results are comparable to more complex methodologies without the need to invest in expensive hardware (although a fast computer will make processing quicker) or abstract workflows. The detail and depth are still available if needed, but the aim is to make the interpretation of a wide range of imagery easier, rather than focus on the mechanics of the phenomena. The results demonstrate an effective, inexpensive and user-friendly workflow that requires only limited computational skills, but which offers robust, highly interpretable results.

Keywords Drones, DStretch, Remote sensing, Structure from motion, Archaeology, Accessibility, NDVI

Introduction

This paper presents an approach to aerial photography in archaeology, which combines rapid, affordable and reactive survey using unmanned aerial systems (UAS) with image decorrelation-stretching techniques commonly used in rock art studies [1–3]. The approach is explored through a case-study at the multi-phase Archaic to Early Byzantine (500 BCE to 800 CE) site of Vlochos in Thessaly, Greece (Fig. 1). This approach uses UAS derived images processed with DStretch, a relatively inexpensive plugin for the open-source software ImageJ, which highlights subtle colour bands in RGB (Red, Green, and Blue) imagery. The results from this approach are compared to those from alternative archaeological prospection techniques such as Normalised Difference Vegetation Index (NDVI) imagery and geophysical survey, which were carried out in tandem at the site.

While aerial photography itself is commonplace in archaeology (see [4] for a concise summary of the approach in Europe, and [5] and [6] for detailed background) the ability to survey on multiple occasions in a variety of lighting and weather conditions using UAS has been relatively under-explored. The flexibility and frequency of UAS flights has created opportunities for significant developments in methodological approach. Additionally, the ubiquity and affordability of UAS technologies means that accessible workflows for the analysis

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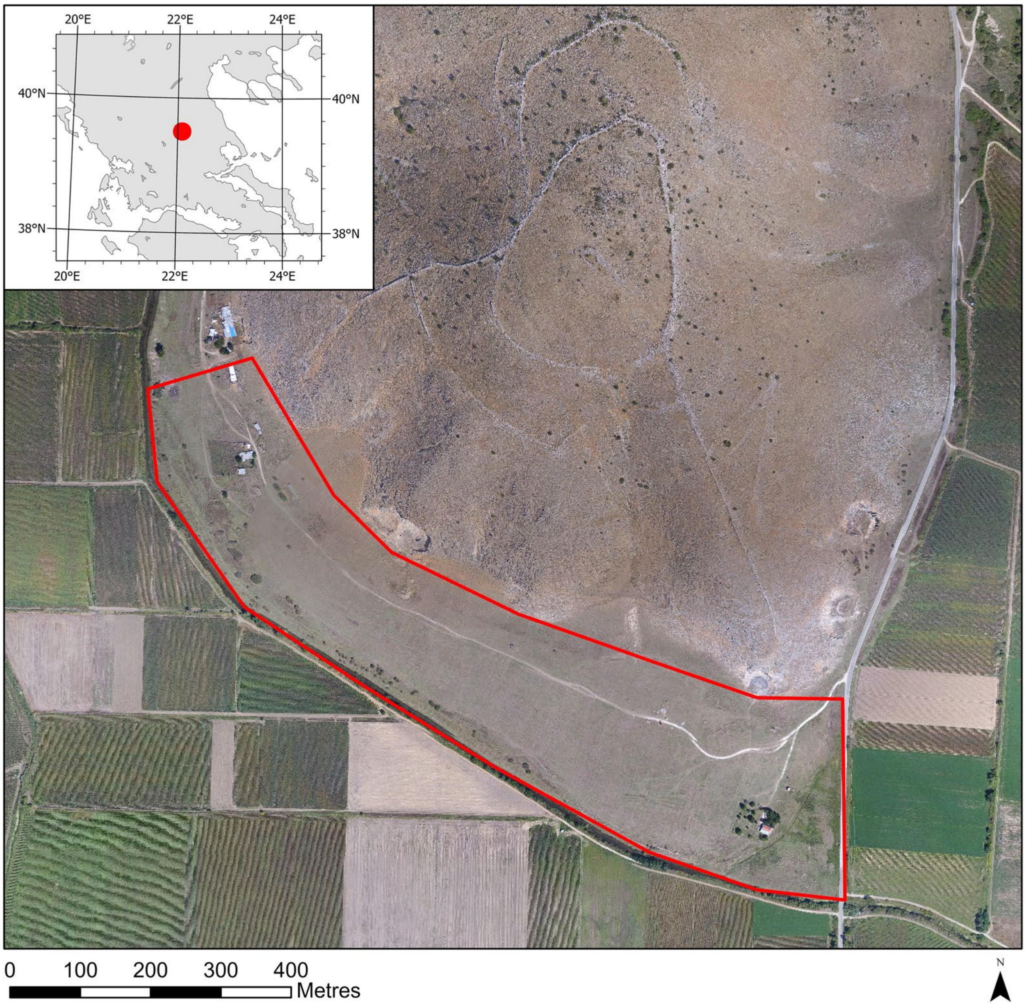

Fig. 1 Map showing the extent of the UAS survey and the gradiometry survey in the Patoma area of the Vlochos site

of aerial data are required to unlock the full potential of the dataset. Complex image analysis workflows have typically been reserved for highly specialized remote sensing projects (*cf.* [7, 8]). However, as argued here, if affordable and more accessible workflows can be established, then significant amounts of interpretative detail can be unlocked from the corpus of newly generated UAS data. Ultimately, the combination of affordable aerial capture tools and accessible image processing techniques can add significant value to the use of modern aerial imagery in archaeology.

Within the disciplines of landscape archaeology and archaeological prospection, visible light aerial photography has been supplemented/superseded by alternative techniques such as Light Detection and Ranging (LiDAR), multi-spectral image analysis, and landscape-scale geophysical survey [9–11]. However, the flexibility afforded by UAS photography has seen the technique become more widely used again, as reactive aerial imagery can now be captured routinely on projects when conditions are at their best [12]. This advantage can clearly be seen in the results from Vlochos [13, 14], where snow marks, only visible for a few hours, were captured and mapped using a standard, commercially available UAS, revealing numerous previously unidentified structures. In this paper, we explore this potential in combination with the use of decorrelation stretching, using affordable and accessible tools developed for rock art studies: the DStretch plugin for ImageJ [1]. This paper also considers the wider use of UAS survey in archaeological prospection and seeks to draw on the strengths of the approach, notably its affordability and rapid deployment, to increase the potential for identifying and characterizing archaeological features.

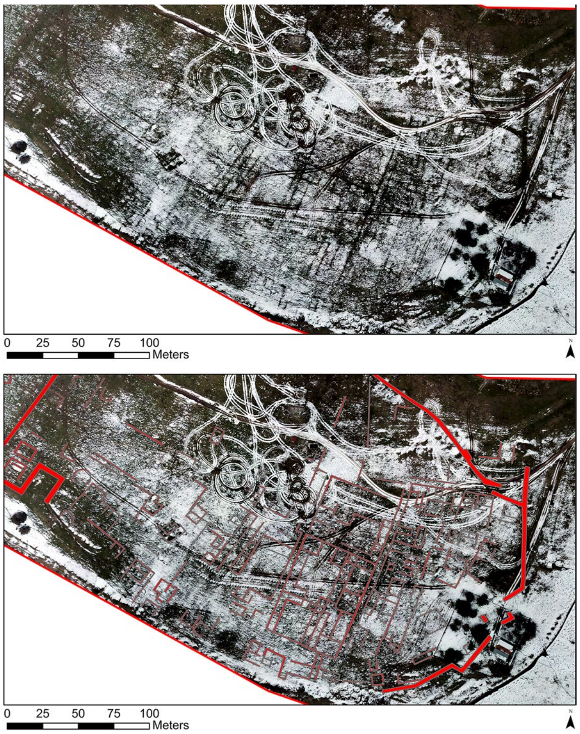

Fig. 2 Underground structures shown by melting snow (Photograph by Lawrence Shaw)

Background

The adoption of UAS survey has accelerated in recent years with projects at all scales routinely using low-altitude aerial photography (i.e. under 120 m) to survey sites as well as to produce digital surface models via Structure from Motion (SfM) [15–17]. However, this is typically employed within field methodologies as part of a like-for-like replacement for traditional aerial photography/LiDAR rather than as a more integrated/reflexive approach [11]. While it is starting to be discussed more in archaeology, recent publications such as [18], focus on the technical and economic aspects of UAS mapping in archaeology rather than the methodological affordances of the technique. Outside of archaeology, the advantages of this approach have been noted in environmental science (e.g. [19]) where there has been a steady adoption of advanced image processing and non-visible light-based approaches.

In terms of image decorrelation stretching, the approach was initially developed for aerial prospection with multiple case studies applying it to satellite remote sensing [20], but it has recently found other uses in archaeology (see below). This is largely down the development of an 'out of the box' plugin for ImageJ which allowed an accessible, open-source workflow to be developed. When decorrelation stretching has been used in archaeological and other types of prospection, it tends to be focused on highly quantitative image analysis rather than more qualitative image appraisal [21]. While the former is of clear value, the vast majority of uses of aerial photography in archaeology focus on the rapid prospection and characterization of sites, similar in scope and interpretive techniques as terrestrial geophysical surveys [22]. Overall, the methods tend to fall into two categories: large-scale approaches focused on automated (AI-based) feature recognition, and more site-specific appraisals that are handled by individual projects. The latter is significantly more routine in modern archaeology, despite the former attracting the bulk of funding and discussion.

Additionally, projects that focus on automation of data processing using machine learning, AI and crowd sourcing [23–25] tend to use relatively unprocessed RGB or multispectral imagery, rather than detailed image processing that aims to extract subtle, archaeological specific elements within aerial imagery.

The site used in this case study is commonly referred to as Vlochos (Fig. 1), and features the remains of a series of urban settlements of classical antiquity currently under investigation by the Palamas Archaeological Project (PAP). The project has produced a large amount of geophysical data, employing gradiometry,

Table 1 Table showing the details of all of the flights taken during the surveys

Survey date	Type/ resolution	Photos taken	Height	Ground resolution
8th May	RGB (12mp)	875	49	1.8 cm/pix
9th May	RGB (20mp)	781	49	1.4 cm/pix
	NiR (1.1mp)	133	49	5.7 cm/pix
11th May	RGB (12mp)	601	60	2.1 cm/pix
13th May	RGB (12mp)	686	60	2.1 cm/pix
16th May	RGB (12mp)	999	60	2.1 cm/pix
	NiR (1.1mp)	540	60	5.7 cm/pix
18th May	RGB (12mp)	618	60	2.1 cm/pix
19th May	RGB (12mp)	620	60	2.1 cm/pix
20th May	RGB (12mp)	626	60	2.1 cm/pix
	NiR (1.1mp)	611	60	5.7 cm/pix

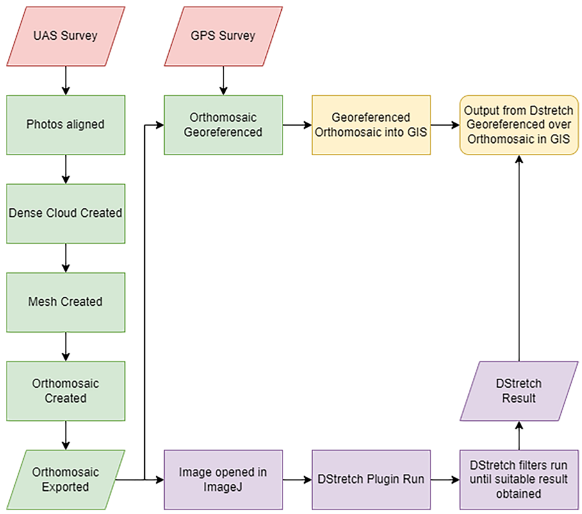

Fig. 3 Flow chart showing the creation process of the DStretch data

ground-penetrating radar (GPR), earth resistance, and a range of additional survey methods [13, 14, 25]. Excavations have also been carried out at the site in 2021 and 2022 [11]. The site has both deep and shallow archaeological features associated with substantial urban remains, including walls, cobbled roads, domestic and public buildings, etc., and represents an ideal test-bed for remote sensing approaches.

UAS-based aerial photography has been part of the package of methods used at Vlochos since the project inception in 2016. The initial aim was to use a combination of orthographic photomosaics, digital elevation models (DEM), and geophysics to map the site non-invasively and acquire an integrated digital dataset that could be used to explore the breadth of urbanization. Four techniques were used in total: gradiometry; earth resistance; GPR; and electromagnetism (EM) [13, 14, 25].[1] Each approach revealed different sub-surface features to varying extent. The gradiometry identified the full urban layout, but the spatial resolution was comparatively coarse. As such, GPR, earth resistance and EM were used in specific locations to reveal higher spatial resolution architectural details. However, some of the most detailed architectural results were revealed by the serendipitously captured snow marks (Fig. 2; [14]). The clarity of the results highlighted the potential of aerial photography as a prospection tool in itself, and a programme of seasonal RGB and Near Infra-red (NiR) photography was initiated. Both approaches were piloted in 2021 and initial results from NiR/NDVI were promising [14] with clear structured variation visible in the data which correlated with geophysical anomalies.

Study area

The study area at Vlochos has never been cultivated and consists of periodically grazed rough pasture-land covered in dense thistles and chamomile. As with cereal and legume crops, the differential growth of this vegetation during spring and early summer can be used as proxy for buried, near-surface archaeology. As such, the UAS surveys presented here were carried out in May 2022, when the vegetation at the site was just beginning to grow following an extended colder and wetter period in early spring followed by a period of warmth. This resulted in vegetation growing over near-surface archaeological features to dry out and turn brown. In certain areas, a simple visual appraisal of vegetation colour-differences indicated the presence of archaeological remains below the ground, but in other areas, the details were more ephemeral and could not easily be distinguished from either ground-level or from the unprocessed orthographic photomosaic.

Method: UAS image capture

Aerial surveys were carried out at the site every second working day to evaluate if the changing levels of soil moisture would affect vegetation growth, and in turn indicate buried archaeological features.

For the initial drone survey, a total of 865 photographs were captured using a Mavic 2 Air from a height of 49 m (though further surveys were conducted at 60 m) with 15 ground control points (GCPs) measured using an NRTK-GNSS unit included in the imagery. The survey area of interest consisted of approximately 25.5 hectares. (details of each flight can be found in Table 1, note that some flights included additional areas and may include extra photos). The survey took about 35 min, including setup time and programming of the flight. Photographs were taken at a speed of 5 m/s with an overlap of 75% front overlap and a 70% side overlap. The images were processed into a mesh in Agisoft Metashape[2] using a standard Structure from Motion methodology [26–28]. Following photographic alignment, a dense point cloud was created and points with too low an alignment confidence value (in this case, points with a confidence below three) were removed. The dense cloud was then

[1] Earth resistance uses an electronic signal to detect variation in moisture beneath the surface and is often used for mapping buried walls and foundations. Ground penetrating radar uses radio waves to detect buried features. Electro magnetism uses an electromagnetic field to identify contrast in conductivity in the soil. Gradiometry uses the earth's magnetic field to detect subtle variation in magnetism in buried deposits. The latter is the quickest technique and therefore gives extensive coverage. More details about these methods and how we employed them can be found in our previous publications [13, 14, 25].

[2] There are also open-source options available to process Structure from Motion models, but since we are experienced with Agisoft Metashape we chose to use this software.

Fig. 4 Un-processed RGB orthographic photograph of the site from May 16th 2022

calculated into a mesh which was georeferenced using the NRTK-GNSS control points. From this mesh, a georeferenced orthophoto with a high spatial resolution (0.05 m) was produced. The orthographic photomosaic was then processed using a decorrelation stretch process as outlined below. An additional UAS fitted with a Sentera High-Precision Single NiR sensor[3] was used to simultaneously capture standard RGB and NiR imagery.

Decorrelation stretching

Decorrelation stretching is a tool that was initially developed for processing aerial photography and satellite imagery [29] within general earth observation systems. It has been used most extensively in archaeology in legacy and archive imagery [30], though similar work with UASs has previously demonstrated its effectiveness when combined with other processing techniques [31]. The process has, however, been successfully and routinely applied to rock art identification and interpretation [32–34]. While decorrelation workflows can be complex (e.g. [21, 35], here we drew on the previous work by De Reu et al. [31] by using a simple tool called DStretch. DStretch is a plugin for the image processing software ImageJ, commonly presented as a tool for the evaluation and enhancement of poorly visible or pigmented paintings and rock art (e.g. [1–3]).

Within the plugin there are a number of different colourspaces: a specific subset of the colour spectrum, limited by the software [1]. While De Reu et al. [31] successfully used Lab and LRE colourspaces, there are also a number of other options, the details of which can be found in the plugin documentation [1]. It is important to note that this technique is highly condition dependant. Numerous variables can influence the choice of best colourspace such as the time in the vegetation cycle, ground cover, vegetation type as well as a range of localised conditions such as agricultural practices. The most straight forward approach to this is to experiment with each colourspace to identify the most effective for any given conditions (see [3] for an in-depth description of decorrelation stretching).

Within our suggested workflow, an orthographic photomosaic was exported from Agisoft Metashape as a jpeg-file (as ImageJ cannot natively open tiled tifs and

[3] More information about the sensor can be found here: https://sentera.com/wp-content/uploads/2022/08/Sentera-SingleSensor.pdf

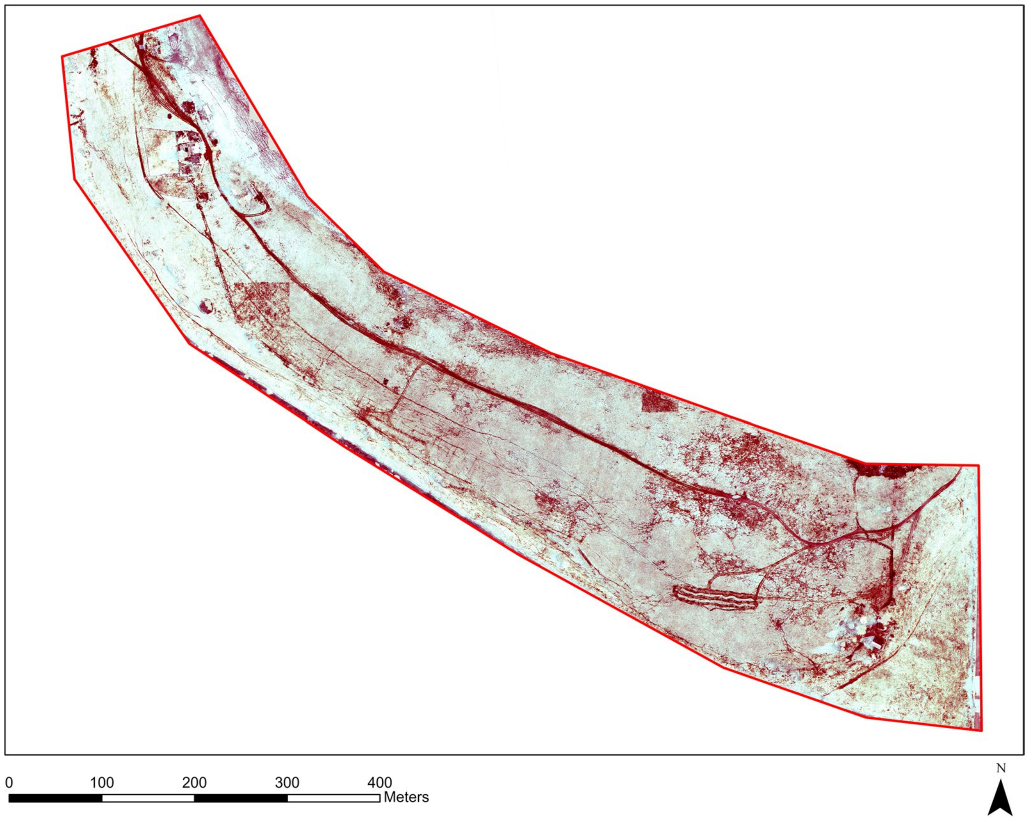

Fig. 5 Decorrelation stretched image from May 16th 2022, same extent as Fig. 4

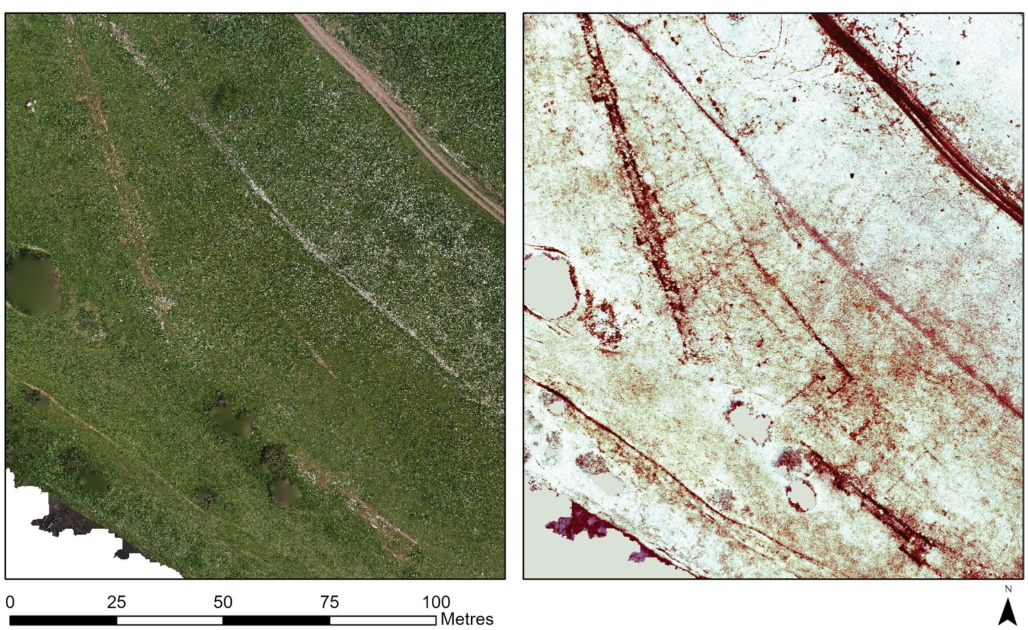

Fig. 6 Detail of the area containing a probable stoic building (at centre), showing the difference between unprocessed RGB imagery and decorrelation stretched data

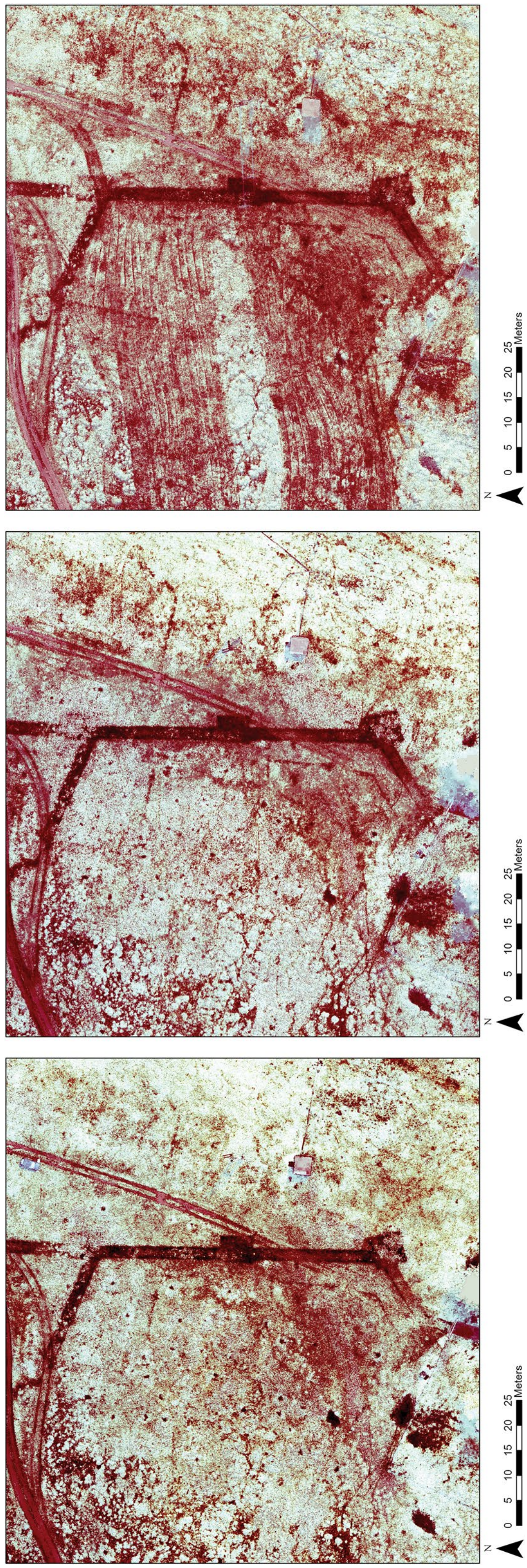

Fig. 7 Series of decorrelation-stretched aerial captures over the two-week period progressing from left to right. Buried fortifications are clearly visible. There are more wheel tracks on the latest image as the field had recently been mowed

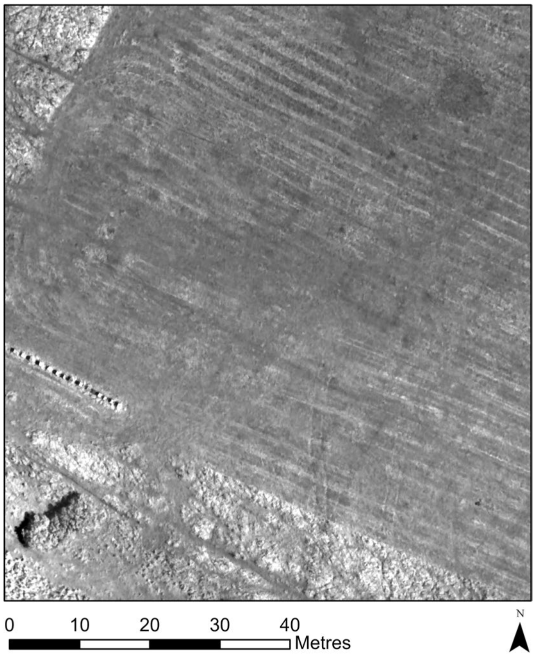

Fig. 8 Data from the NDVI survey

struggles with larger files), and imported into ImageJ and processed using the DStretch plugin (Fig. 3).

Once the images were imported into ImageJ, we applied each colourspace in turn. Each colourspace offers a slightly different output, which can be used interchangeably depending on the type of data analysed and the features sought. In this case, the "YRE" colourspace (which enhances and draws out red in the images) proved the most effective (see results below). This is perhaps not surprising given the red channel in a RGB composite is indicative of vegetation health, i.e. through drier plants or sparser vegetation cover. By enhancing the areas within this band, the influence of near-surface archaeological remains on plant health could be used as an indicator of buried archaeology. Other colourspace filters were less effective at enhancing sub-surface features in this case. However, since the results are dependent on the type of visible phenomena, they may prove useful on other types of sites.

Results

Overall, the results from the DStretch-processed images were promising. Numerous features that were visible in the geophysics were also clearly visible in the DStretch-processed UAS data. Crucially, very few of these features were visible in the raw data (Figs. 4 and 5). The data also indicated several new areas of archaeological potential that were previously unidentified by the geophysical survey due to both terrain constraints and magnetic "noise" from adjacent pasture buildings at the eastern end of the site.

Over the course of the field season, with continued warm and dry weather, the details of buried features became more and more visible from the DStretch-processed orthographic photographs. However, the best results came following a night of rain before the penultimate survey. This made the soil slightly darker which provided more contrast in the YRE filter.

In addition to the drying-out of the site, work was also carried out to remove some of the higher vegetation. While this helped to enhance the results to an extent, it also meant that more of the soil became visible, which actually reduced the contrast of the DStretch data. Conversely, the NDVI data in the freshly mowed areas of site became clearer (Fig. 6).

Its notable that the use of multiple flights revealed subtle changes throughout the season. As can be seen in Fig. 7, the levels of contrast improved in some areas towards the end of the season. This reinforces the argument for taking multiple captures throughout the season/year where possible. This again is a clear advantage of rapid UAS photography. Similarly, the impact of mowing can be seen in the DStretch-processed imagery with some features becoming less clear in the mowed areas. This is contrasted with the NDVI data, which conversely became clearer in these mowed zones (Fig. 8).

Most importantly, in the context of the case study, the approach revealed new features in areas that were inaccessible to other techniques (Fig. 9). Extramural areas that have significant metallic contamination (making gradiometry survey-techniques difficult) can be clearly seen to contain structural remains (Fig. 10), and buried foundations of monumental architecture can be seen in areas previously thought to have been truncated by modern quarrying activities.

Discussion

Each technique used in this experiment led to the identification of apparent archaeological features. Given that the site had already been surveyed in detail using geophysical survey methods later confirmed through targeted excavation, it was possible to appraise the aerial imagery data rapidly.

Both the decorrelation stretching and the NDVI approaches identified features previously seen in the geophysical data, yet the DStretch approach revealed details that were previously unknown. In addition, where features appeared in both the geophysical and newly obtained datasets, the DStretch data displayed a sharpness and clarity that was lacking in the extensive gradiometry data, and which could only be identified geophysically through much slower techniques such as

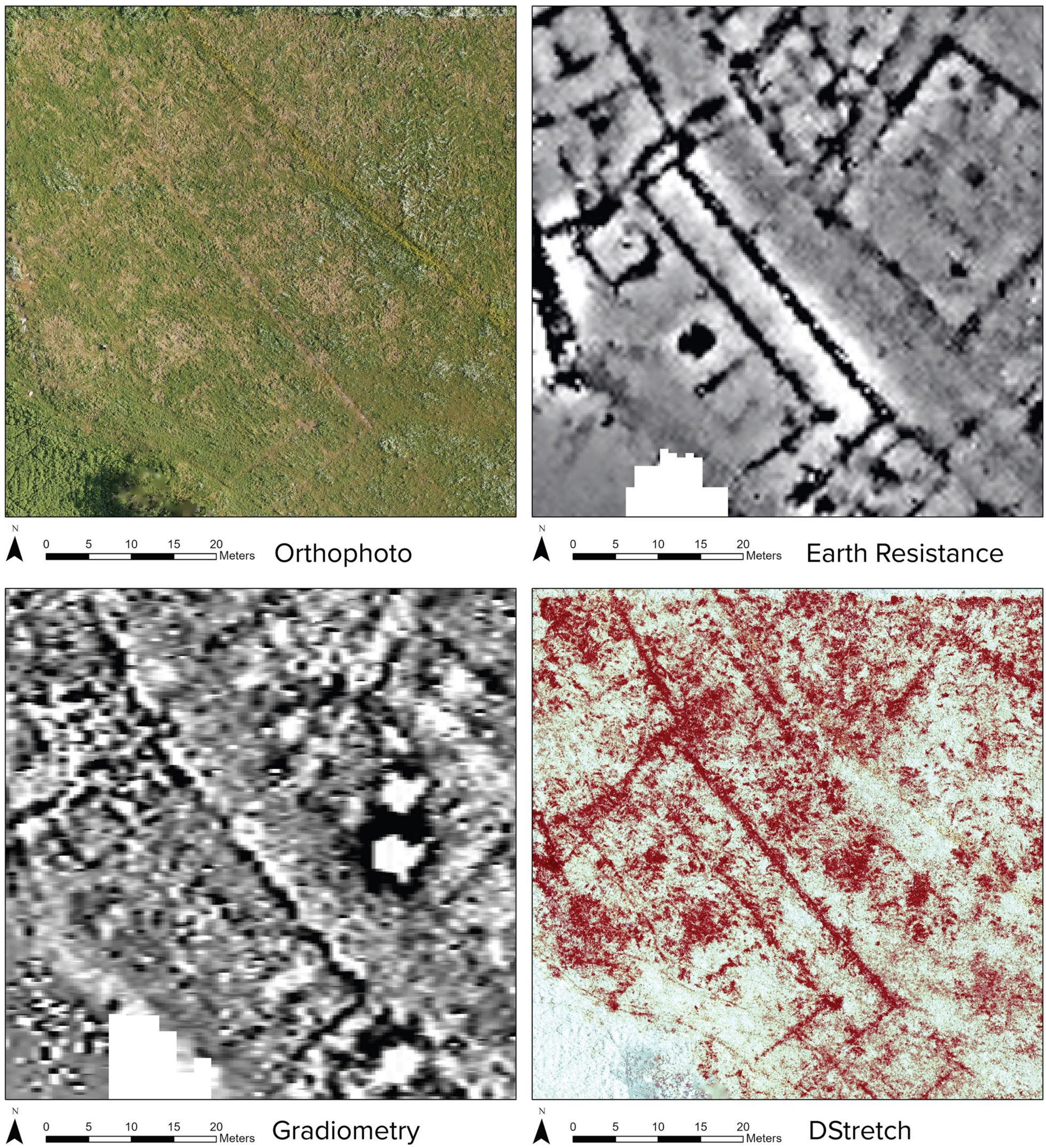

Fig. 9 Comparison between multiple techniques (Earth resistance: black = high resistance, white = low resistance. Gradiometry: black = low magnetism, white = high magnetism)

earth resistance and GPR. This means that significant portions of the site can now be understood at a much finer spatial resolution than before, with far less investment in terms of both time and funds. The use of multiple flights during the field season allowed for subtle variations in sub-surface architecture to be revealed in a way that would not have been possible with only a single flight.

The results presented here highlight the value of the responsive nature of UAS photography. Different

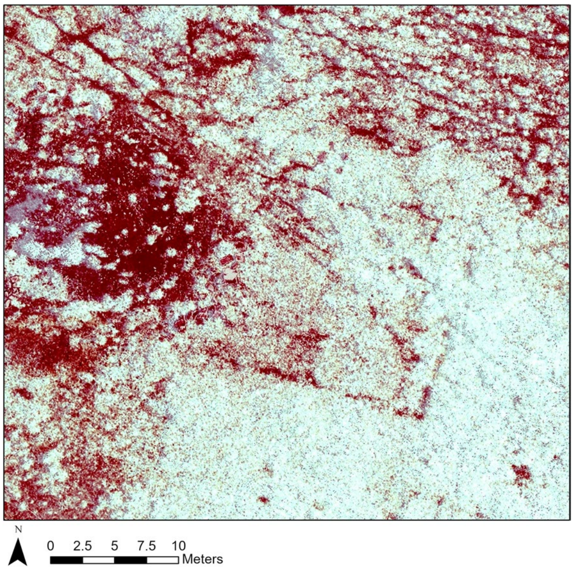

Fig. 10 Area within the ancient urban settlement which was unavailable for geophysical surveying, but which appears to show architectural remains

features, and different areas of the site varied in clarity day by day and under different weather conditions. While it has long been acknowledged that aerial photography is highly condition dependent [22], the ability to survey on multiple occasions—which is afforded by UAS technologies—has the possibility to revolutionize site prospection and characterization. The data presented here demonstrates that there exists an affordable and relatively user-friendly workflow for the processing and interpretation of the vast quantities of aerial data that are currently being produced by projects worldwide (Fig. 11).

It is important to acknowledge that the DStretch method worked especially well with this site because of the shallow buried archaeology (which we have found through excavation to range from surface to 30 cm deep [14]) and because the vegetation was in exactly the right phase of growth. The method will consequently not be useful at all sites. However, due to the low cost of the DStretch software, the wide occurrence of crop marks, and the fact that a large number of archaeological projects have access to UAS systems, we would argue that this method offers an excellent first step when assessing

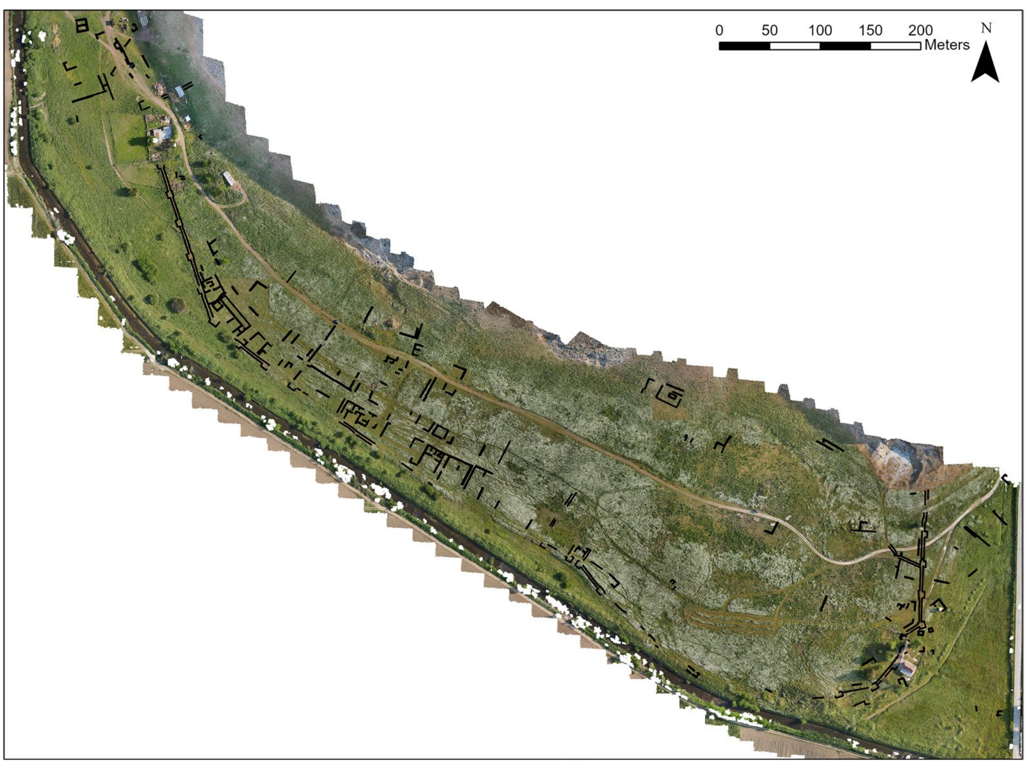

Fig. 11 Interpretation of results from UAS survey from the site

the location of new sites, or when attempting to get a good overview of the archaeological remains. This is especially true given the fact that UAS techniques can be deployed at relatively short notice when conditions are optimal for visible cropmarks.

Conclusions

This paper has shown that decorrelation stretching, using the DStretch plug-in, offers a viable tool for highlighting archaeological features in aerial imagery. The method demonstrated is inexpensive, easy to use, rapid, and provides results that can be used as a precursor to geophysical surveys or as a cost effective and rapid alternative/compliment to traditional terrestrial surveys. Employing it at the site in Vlochos, we were able to identify new archaeological features in areas that we had not been able to cover geophysically due to terrain constraints or magnetic contamination. It is hoped that this method can be developed further in the future and be used as a rapid evaluation tool for archaeological projects prior to the application of expensive geophysical surveys and other more intrusive methods. As most archaeological field projects are (or at the very least should be) using aerial survey as a recording tool, it would take very little effort to adopt the DStretch image analysis process outlined above to the wider survey method.

Abbreviations

UAS	Unmanned aerial systems
NDVI	Normalised Difference Vegetation Index
RGB	Red, Green, and Blue
SfM	Structure from Motion
LiDAR	Light Detection and Ranging
DEM	Digital Elevation Models
GPR	Ground Penetrating Radar
EM	Electromagnetism
NiR	Near infra-red

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Author contributions

All authors contributed to the writing and production of the article with Rich Potter taking the lead. Drone fieldwork was carried out by Rich Potter and Harry Manley. All authors critically reviewed the paper.

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Availability of data and materials

The data was generated by members of the Palamas Archaeological Project, and can only be acquired with permission from the Greek Ministry of Culture and Sports.

Declarations

Competing interests

The authors have no relevant financial or non-financial interests to disclose. The authors have no conflicts of interest to declare that are relevant to the content of this article. All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript. The authors have no financial or proprietary interests in any material discussed in this article. The authors declare that there are no known competing interests.

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