

Article

Aerial Remote Sensing Archaeology—A Short Review and Applications

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Abstract: Aerial and remote sensing archaeology are tools for identifying marks on images of archaeological remains covered by soil. In other words, they are archaeological prospection tools that fall into the category of non-destructive research methods. In this paper, a short review of these valuable research tools is carried out, presenting the way marks appear, and also the categories of aerial and remote sensing archaeology, depending on the medium of storage of images and the type of platform of transfer of sensors. The timing of the emergence of each category is determined and examples of relevant surveys are presented. Focusing on the use of an Unmanned Aircraft System (UAS) with a multispectral sensor (aerial remote sensing archaeology), their partial utilization is revealed for collecting images in areas outside of the visible spectrum, aiming at the identification of covered archaeological remains. To this end, examples of the use of UAS with different sensors are presented and indexes that have been used so far in respective applications are gathered. Aerial remote sensing archaeology took place in two areas of particular interest in Northern Greece. UAS WingtraOne GEN II was used to collect multispectral images. In both study areas, soil and vegetation or crop marks were detected, possibly covered archaeological remains, initially in RGB orthophotomosaics and then more clearly in the index maps, such as the normalized difference vegetation index, simple ratio, brightness index, second brightness index, and anthocyanin reflectance index 2b.

Keywords: aerial remote sensing; UAS; multispectral sensor; index; marks; archaeology; covered remains



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1. Introduction

1.1. Aerial and Remote Sensing Archaeology

The discovery and documentation of unknown covered archaeological remains allows the protection and preservation of our cultural heritage, which is threatened by uncontrolled agricultural exploitation and increasing urban development.

Towards this direction, aerial and remote sensing archaeology aims at the measurement and thematic documentation of existing above-ground archaeological remains, as well as the identification of unknown possible archaeological remains under soil or vegetation/crop. In other words, they are archaeological prospection tools that fall into the category of non-destructive research methods. This ability to locate new sites of archaeological interest is due to the effect that the structures have on the soils that cover them. In particular, in these soils, there is a lack of moisture (presence of a solid structure under the ground, e.g., building foundations) or excess moisture (presence of open construction under the ground, e.g., defensive ditch) in relation to the adjacent soils (i.e., below soils where there are no structures). As a result, there are differences in height, quality, and temperature of the vegetation or crop above the covered structures in relation to the adjacent vegetation or crop, as well as differences in surface temperature of the bare ground above the covered structures in relation to the adjacent bare ground. These differences are depicted as marks in images [1–3] (Figure 1).

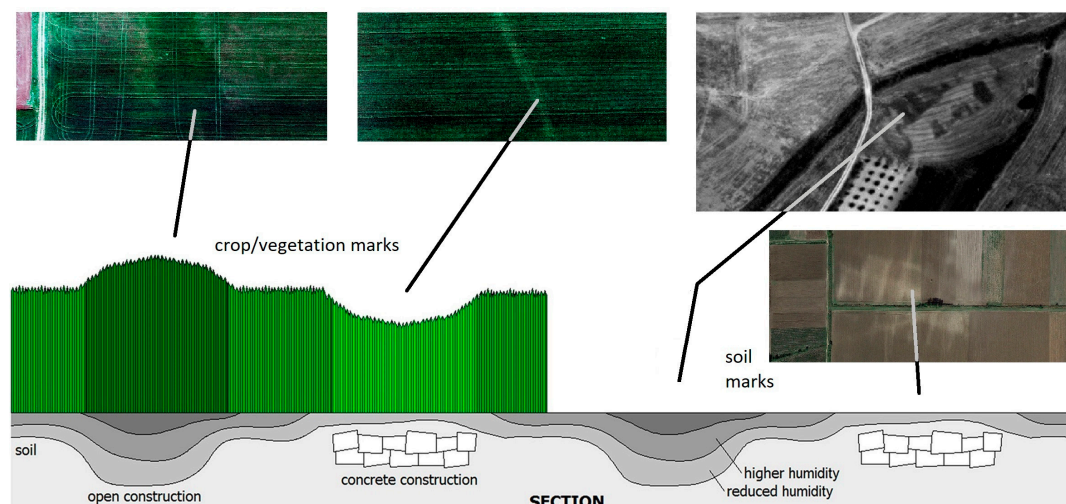


Figure 1. Anatomy of the marks' appearance. Positive crop/vegetation or soil marks (dark) and negative crop/vegetation or soil marks (light). Possible presence of open and compact structure, respectively, under the soil.

Aerial and remote sensing archaeology can be categorized into aerial photography archaeology (e.g., use of film on a manned aircraft [4], use of digital single lens reflex camera on a manned aircraft [5], or on an Unmanned Aircraft System (UAS) [6]), aerial remote sensing archaeology (e.g., use of a Multispectral (MS) sensor on a manned aircraft [7] or on a UAS [8]), space photography archaeology (e.g., use of film on a spaceborne platform [9]), and space remote sensing archaeology (e.g., use of an MS sensor on a spaceborne platform [10]). In reviewing the timing of their appearance, it should be mentioned that the founder of aerial archaeology is O.G.S. Crawford (archaeologist, 1886–1957), who made the first mark identifications in aerial photographs in the early 1920s. He concluded that human interventions of the past in the landscape create surface anomalies that are visible only when viewed from above [11]. While new archaeological discoveries were initiated from that time onwards, 46 years after the first marks were observed in aerial photographs (aerial photography archaeology), linear marks of prehistoric human intervention in the Phoenix, Arizona, area were identified (in 1969) in infrared photographs from the S065 multiband experiment flown on Apollo 11 (space photography archaeology) [12]. Prehistoric sites and roads in Chaco Canyon (New Mexico) were identified 8 years later (in 1977) in the MS images of the Landsat-1 satellite (space remote sensing archaeology). Landsat-1 (1972–1978) was the first satellite system for systematic observation of the Earth's surface and its objects and was capable of generating MS data in digital form [13]. In the 1980s, Airborne Imaging Spectrometer (AIS), Airborne Visible Infrared Imaging Spectrometer (AVIRIS), Airborne Thematic Mapper (ATM), and Compact Airborne Spectrographic Imager (CASI) sensors were created, the digital images of which were exploited in the following years in a variety of archaeological applications [14,15] (aerial remote sensing archaeology).

1.2. UAS and Remote Sensing in Locating Covered Archaeological Remains

To date, there have been countless discoveries of covered archaeological remains with the help of aerial and remote sensing archaeology, utilizing panchromatic (PAN) [2,7,10,16–37], RGB [5,29,31,38–43], multispectral (MS) [7,10,14–19,22–28,32–34,37,39,40,44,45], thermal [2,7,46–49], lidar [22,37,50–57], and radar [58–63] images. Sensor dependency platforms can be manned aircrafts [2,5,7,14,15,20–22,29,31,32,37–57] and satellites [10,16–19,23–28,30–37,58–64]. Unmanned Aircraft Systems (UAS) are widely used in archaeology [50,65–74], but little use is made of them in collecting images in areas outside of the visible spectrum, aiming to locate covered archaeological remains [75,76]. Among these (minimal) surveys [4,8,31,52,76–96], González and Hernández [91] identified marks of a covered ancient Roman road (Via XXXIV on the Antonine Itinerary) that crossed the province of Álava

(Northern Spain), but also of side-covered monuments, utilizing UAS with an MS sensor. NDVI (normalized difference vegetation index) orthomosaics allowed the observation of crop marks. At Ravenshall, Fife (Scotland), Moriarty et al. [85] identified marks of covered archaeological remains using RGB and MS sensors in UAS. The analysis revealed that several vegetation index maps, particularly the simple ratio (SR) and the NDVI, proved instrumental in identifying marks in the multispectral results. Fiz et al. [86] used UAS to identify marks at Vilanera (L'Escala, Catalonia, Spain) in RGB and MS images and produced vegetation index maps. Brooke and Clutterbuck [80] used RGB, MS, and thermal images from UAS to locate and interpret marks at two archaeological sites in Nottinghamshire, UK (Camp Hill, Hexgreave Park, and Shelford Priory). At Camp Hill, thermal imagery, in particular, yielded useful results, revealing many features that appear to be anthropogenic and which relate to the site's former use as a defensive hillfort and enclosure. In addition, the mark of a later Roman road is very clearly delineated on thermal images. In contrast, at Shelford Priory, mainly MS images coupled with Random Forest classification gave useful results, revealing apparent buried archaeology to varying degrees. Ronchi et al. [84] conducted systematic surveys of the archaeological remains of the imperial Domitian villa in Sabaudia (Italy), which is covered by dense pine forest. MS and lidar sensors mounted on UAS were used. Compared to vegetation indexes (from MS images), lidar's product (Digital Terrain Model (DTM)) excels in this survey, as it reveals in the best way the forest-covered remains of buildings, paths, and walls. The study by Casana et al. [95] utilized lidar in UAS at three distinct archaeological sites: tropical forests at Kealakekua Bay State Historic Park (Hawai'i), piñon–juniper forests on Mesa Verde's North Escarpment (Colorado), and mixed deciduous–evergreen forests at Enfield Shaker Village (New Hampshire). The results demonstrated the existence of a multitude of archaeological features at the three study sites, thereby illustrating the potential of UAS-based lidar as a tool in archaeological prospection. The Greater Khingan Range (Northeastern China) is the birthplace of numerous ancient nomadic peoples, including the Xianbei, Khitan, and Mongols. However, the region has only yielded a limited number of archaeological discoveries due to the dense forest cover. In a pioneering study, Li [96] employed UAS-based lidar for the first time to detect and map ancient sites concealed beneath the forest canopy in Shenshan Mountain (southeast of the Greater Khingan Range). The UAS missions achieved remarkable clarity in revealing the extent and complexity of the archaeological structures under the forest, which may date back to the Liao period (907–1125). In a publication, Cao et al. [90] introduced a new UAS-based magnetic system that proved effective in an archaeological area with a complex topography in Huizhou, China. The results demonstrated a high degree of correlation between the target anomaly marked by the UAS aeromagnetic survey and the location of a possible archaeological site. This study demonstrates that the UAS aeromagnetic system may have potential for future archaeological surveys, as it is in the early stages of its development and there are no other relevant bibliographic references.

1.3. Indexes from UAS Sensors for Locating Covered Archaeological Remains

Vegetation/crop and soil indexes number in the hundreds [97–99]. They were developed by (and for) the use of bands of satellite system images. Due to the limited availability of bands from sensors used in UAS, many of these indexes cannot be exploited. Table 1 presents indexes used in applications for detecting covered structures with UAS and remote sensing sensors (aerial remote sensing archaeology). Each vegetation/crop index is designed to analyze a specific parameter of the plant, e.g., vigor (which closely relates to soil conditions and water content), biomass, chlorophyll (which is associated with photosynthesis), anthocyanin content in leaves (which are pigments that shield leaves from excessive light), etc. There are fewer soil indexes and they are correlated with the humidity, the presence of carbonates or sulfates in the soils, etc. (obviously, reference is made to these characteristics of vegetation/crop and soil, as the appearance of marks is affected by the size of the covered structure, its depth, the type of soil, the water content, and the type of vegetation/crop).

Table 1. List of indexes.

Index	Abbreviation	Formula	Comment
NDVI	Normalized Difference Vegetation Index	$\frac{NIR - Red}{NIR + Red}$	Normalized ratio ranging for the measurement of green vegetation [100,101].
GNDVI	Green Normalized Difference Vegetation Index	$\frac{NIR - Green}{NIR + Green}$	Modification to NDVI, increased sensitivity to chlorophyll concentration [84,100,102].
RENDVI or NDRE	Red-Edge NDVI or Normalized Difference Red-Edge Index	$\frac{NIR - Red\ Edge}{NIR + Red\ Edge}$	Monitoring chlorophyll content is possible through the sensitivity and efficacy of the index [78,84,100,103].
NDVIRE or NDRER	Red-Edge Normalized Difference Vegetation Index or Normalized Difference Red-Edge/Red	$\frac{Red\ Edge - Red}{Red\ Edge + Red}$	For modification to NDVI, instead of Near Infrared (NIR) reflectance, red-edge information was used. Measurement of the amount of chlorophyll in the plants [78,100,104].
SAVI	Soil-Adjusted Vegetation Index	$1.5 * \frac{NIR - Red}{NIR + Red + 0.5}$	SAVI and NDVI are almost alike in their formulation, with the only difference being that an adjustment factor is used by SAVI to minimize the effects of soil on the spectral signal [105].
GSAVI	Green Soil-Adjusted Vegetation Index	$1.5 * \frac{NIR - Green}{NIR + Green + 0.5}$	The green band instead of the red is used in the calculation of GSAVI, which, at rest, follows the SAVI formula structure [106].
OSAVI	Optimized Soil-Adjusted Vegetation Index	$1.5 * \frac{NIR - Red}{NIR + Red + 0.16}$	It uses a standard value of 0.16 for the canopy background adjustment factor. This value provides greater soil variation than SAVI for low vegetation cover, while demonstrating increased sensitivity to vegetation cover greater than 50% [78].
SR	Simple Ratio	$\frac{NIR}{Red}$	Simple vegetation distinction is conducted by the ratio of NIR scattering to chlorophyll absorption [85].
MSR	Modified Simple Ratio	$\frac{(\frac{NIR}{Red}) - 1}{\sqrt{(\frac{NIR}{Red}) - 1}}$	Sensitivity to vegetation characteristics is improved by the combination of renormalized NDVI and SR [85].
GCI	Green Chlorophyll Index	$(\frac{NIR}{Green}) - 1$	The content of leaf chlorophyll in various species of crops is estimated through the index [106].
GRVI	Green Ratio Vegetation Index	$\frac{NIR}{Green}$	Simple ratio modification, sensitive to rates of photosynthesis [85].
NGRDI	Normalized Green Red Difference Index	$\frac{Green - Red}{Green + Red}$	Biomass showed a positive correlation to the index [100,107,108].
NLI	Non-Linear Vegetation Index	$\frac{NIR * NIR - Red}{NIR * NIR + Red}$	Linear relationships with vegetation parameters were emphasized by the modification to NDVI [85].
GEMI	Global Environment Monitoring Index	$\eta * (1 - 0.25 * \eta) - \frac{Red - 0.125}{1 - Red}$ where $\eta = \frac{2 * (NIR^2 - Red^2) + 1.5 * NIR + 0.5 * Red}{NIR + Red + 0.5}$	Alters the light seen by the instrument and can cause variations in the calculated values of vegetation indices [76].
TVI	Triangular Vegetation Index	$0.5 * (120 * (NIR - Green) - 200 * (Red - Green))$	Total area of the triangle (with vertices at green, red, and NIR wavelengths) increases with higher chlorophyll absorption [76].
MTVI	Modified Triangular Vegetation Index	$1.2 * (1.2 * (NIR - Green) - 2.5 * (Red - Green))$	Lower values indicate higher chlorophyll content [76].
TCARI	Transformed Chlorophyll Absorption Ratio Index	$3 * ((Red\ Edge - Red) - 0.2 * (Red\ Edge - Green)) * (Red\ Edge - Red)$	Indicates the relative abundance of chlorophyll. It is affected by the underlying soil reflectance [76].
MCARI	Modified Chlorophyll Absorption in Reflectance Index	$((Red\ Edge - Red) - 0.2 * (Red\ Edge - Green)) * \frac{Red\ Edge}{Red}$	Gives a measure of the depth of chlorophyll absorption and is very sensitive to variations in chlorophyll concentrations [76].

Table 1. Cont.

Index	Abbreviation	Formula	Comment
BI	Brightness Index	$\sqrt{\frac{Red^2 + Green^2}{2}}$	Uses the albedo of the terrestrial surface to differentiate between the vegetal covers and the ground [78].
BI2	Second Brightness Index	$\sqrt{\frac{Red^2 + Green^2 + NIR^2}{3}}$	Sensitive to the brightness of soils, which is highly correlated with the humidity and the presence of salts in the surface [78].
CI	Color Index	$\frac{Red - Green}{Red + Green}$	Related to the concentration of carbonates or sulfates in the soils [78].
PSRI	Plant Senescence Reflectance Index	$\frac{Red - Green}{NIR}$	Vegetation health monitoring, plant physiological stress detection, crop production, and yield analysis. The value of this index ranges from −1 to 1, but the common range for green vegetation is −0.1 to 0.2 [78].
RI	Redness Index	$\frac{Red^2}{Green^2}$	Identifies soil color variations [78].
ARI1	Anthocyanin Reflectance Index 1	$\frac{1}{Green} - \frac{1}{Red\ Edge}$	Changes in green absorption relative to red indicate leaf anthocyanins [78].
ARI1B	Anthocyanin Reflectance Index 1B	$\frac{1}{Green} - \frac{1}{Red}$	Uses the red band in the original formula [78].
ARI2	Anthocyanin Reflectance Index 2	$NIR * \left(\frac{1}{Green} - \frac{1}{Red\ Edge} \right)$	A variant of the ARI1, which is sensitive to changes in green absorption relative to red, indicating leaf anthocyanins [78].
ARI2B	Anthocyanin Reflectance Index 2B	$NIR * \left(\frac{1}{Green} - \frac{1}{Red} \right)$	Uses the red band in the original formula [78].
LCI	Leaf Chlorophyll Index	$\frac{NIR - Red\ Edge}{NIR + Red}$	Chlorophyll content in areas with full leaf coverage [84].
RGRI	Red Green Ratio Index	$\frac{(Red + Red\ Edge) / 2}{Green}$	Used to indicate leaf production and stress [85].

2. Study Areas to Identify Marks of Possible Covered Archaeological Remains

2.1. Archaeological Site of Europos, Northern Greece

The archaeological site of Europos (40°53'15.5" N 22°33'20.0" E, Figures 2 and 3) is located approximately 55 km northwest of Thessaloniki (Greece).

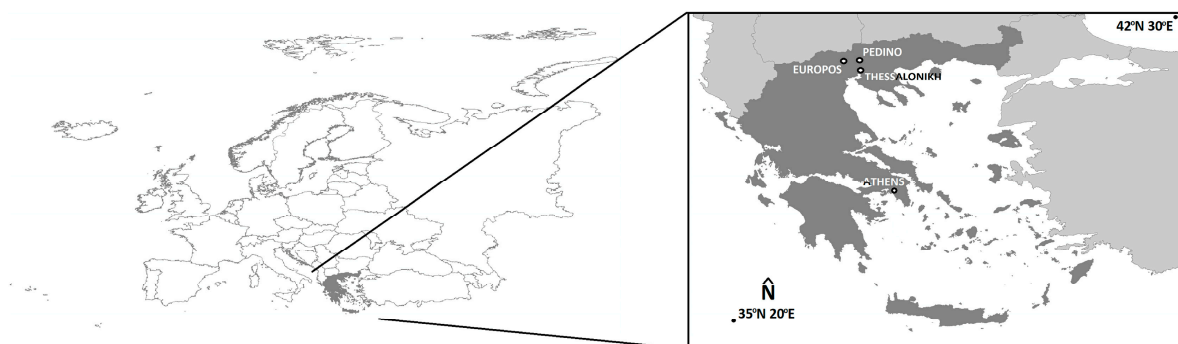


Figure 2. Greece in the European continent and Europos and Pedino locations in Greece.

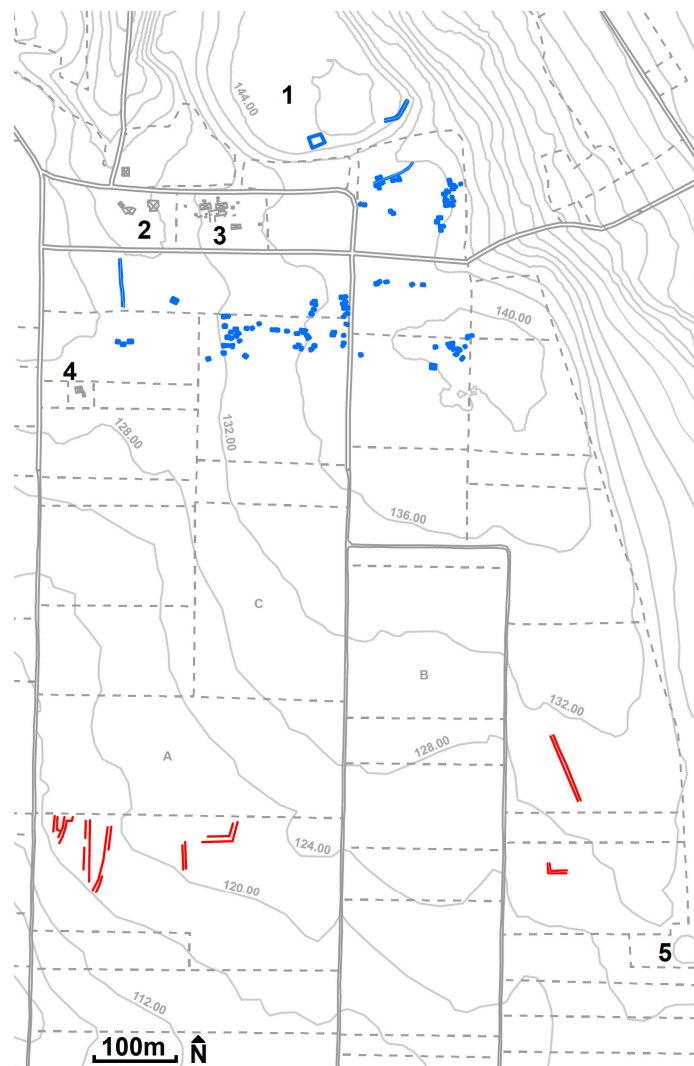


Figure 3. Location 1, the archaic acropolis of Europos. Location 2, a space for visitors to access information about the archaeological site. Location 3, an open-air archaeological area of a cemetery from the Roman and early Christian times, that is either sheltered or not (marked by black solid squares representing existing tombs that are open or closed). Location 4, three tombs from ancient times that are sheltered (Macedonian tomb, cist, and burial vault). Location 5, a burial mound dating to the late-4th and early-3rd century BC. The boundaries of the parcels of land are delineated by a dotted line, while the contour lines are shown in grey with a dimension of 4 m. Only the road west of the acropolis to Location 2 is paved; the rest are rural dirt roads. In blue, the rendering of the marks of previous research, and in red, the rendering of new marks. Center of figure: $40^{\circ}52'56.30''$ N $22^{\circ}33'23.51''$ E.

The archaeological findings of the wider area are of the Classical and Hellenistic era. Seleucus Nicator came from Europos and was the founder of important cities of the Hellenistic period and one of the most important generals of Alexander the Great. During the early Roman Empire, Europos continued to thrive, while the prosperity of the acropolis (Figure 3, Location 1) continued in the 1st to the 3rd century AD. In the 4th century AD, it gradually declined, while in the 5th to 6th century AD, the acropolis was abandoned [109]. Geophysical surveys allowed the mapping of the subsoil of the acropolis [110]. Targeted exploratory excavations uncovered portions of the urban infrastructure of the acropolis, including funerary monuments, among other findings [111]. The area of the Roman and early Christian necropolis (Figure 3, Location 3) situated to the southwest of the acropolis has been transformed into an accessible tourist destination and is situated within the boundaries of the designated archaeological site. Additionally, a three-tomb cluster

(Figure 3, Location 4), comprising a Macedonian tomb, a cist, and a burial vault, has been preserved in the area southwest of the acropolis [109]. In the area south bounded by this cluster of tombs and north by the organized archaeological site, aerial remote sensing archaeology research in 2022 [1] using an MS sensor in UAS led to the identification, among others, of a large number of marks of possible covered ancient tombs (Figure 3, rendering of marks in blue). The search for new marks continued south of the above area until the burial mound (late-4th, early-3rd century BC, Figure 3, Location 5), and its results are presented in this paper (Figure 3, rendering of marks in red).

2.2. Archaeological Site of Pedino Hill, Northern Greece

On Pedino Hill ($40^{\circ}55'1.97''$ N $22^{\circ}53'17.33''$ E, Figures 2 and 4), approximately 40 km north of the city of Thessaloniki (Greece), a walled ancient city of the (at least) early-4th century BC up to Roman times (Figure 4, Location 1) was identified, initially by surface survey and then by systematic archaeological excavation. The site has been protected by archaeological law since the 1980s. The name of the city is unknown; it had a dense urban fabric with a wall at least 4 m high and 5.5 m wide. The area of the ancient city within the walls is approximately 22,000 m². Today, the south monumental central gate of the wall and part, approximately 60 m, of the fortification of the ancient city have been discovered (Figure 4, Location 2).

On the hill and in the area south of it, an aerial remote sensing archaeology survey was conducted using an MS sensor in a UAS, which led to the detection of marks of possible covered ancient remains (Figure 4).

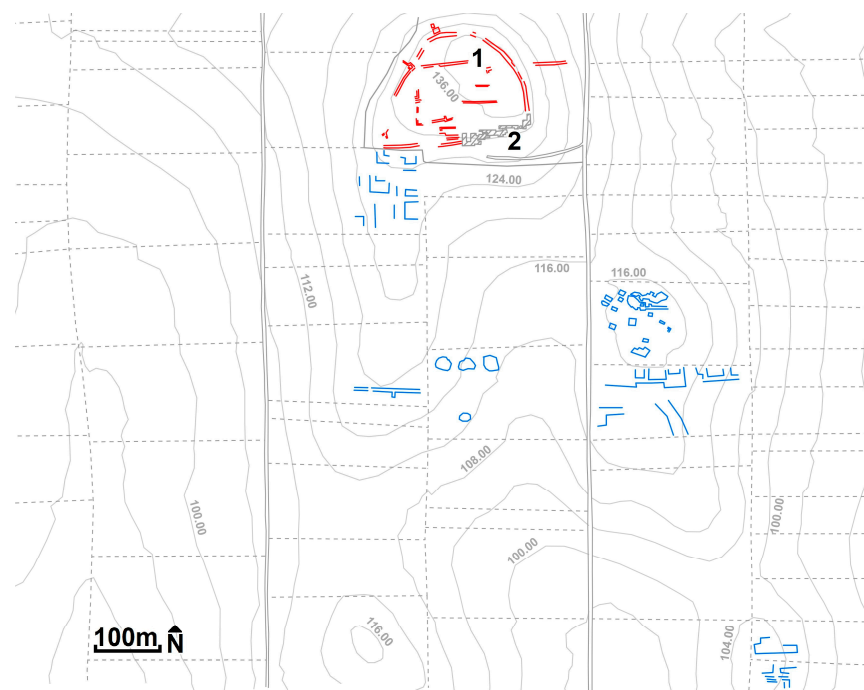


Figure 4. Location 1, the ancient walled city of Pedino Hill. Location 2, with a gray line marking the positions of the excavations of the southern gate and part of the wall. The boundaries of each parcel are delineated by a dashed line and the contour lines are depicted in gray with a 4 m contour. The rural dirt roads are drawn with a continuous gray line. In blue, the drawing of marks outside the hill; in red, the drawing of marks on the hill. Center of figure: $40^{\circ}54'47.42''$ N $22^{\circ}53'15.86''$ E.

3. Equipment

In the above surveys, UAS WingtraOne GEN II was used (Figure 5).



Figure 5. WingtraOne GEN II at the study area. In the background, the hill of Pedino.

The UAS in question is a fixed-wing vertical take-off and landing (VTOL). In order to calculate the center coordinates of the images received, it utilizes an integrated multi-frequency PPK GNSS antenna (GPS: L1, L2; GLONASS: L1, L2; Galileo: L1; BeiDou: L1). All flight parameters and the plan are modelled via the WingtraPilot© (version 2.12.2) software. It features two propellers and an MS sensor (Table 2) [112].

Table 2. Technical specifications of the multispectral sensor [112].

Camera	Technical Specifications
MicaSense RedEdge-MX	Multispectral sensor Focal length: 5.5 mm 1.2 Mpixel (resolution 1280 × 960) Weight: 231.9 g (includes DLS 2 and cables) Five spectral cameras: Blue (465–485 nm); Green (550–570 nm); Red (662–673 nm); Red Edge (712–722 nm); Near Infrared (NIR) (820–860 nm) Ground Sample Distance: 8.2 cm/pixel at 120 m Field of View (FOV): 47.2° Horizontal FOV; 36.2° Vertical FOV

Additionally, the GNSS Topcon HiPer SR was employed (yielding horizontal and vertical positioning accuracy of approximately 10 mm and 15 mm, respectively; GPS: L1, L2, L2C; GLONASS: L1, L2, 2C; SBAS-QZAA: L1, L2C) for the acquisition of the requisite data that enabled the calculation of the coordinates of the acquisition centers pertaining to each image in the Greek Geodetic Reference System 87 (GGRS87).

4. Methods, Processing, and Products

4.1. Flight Plans and Image Collection

The two flights with the MS sensor south of the archaeological site of Europos took place on 16 April 2024 from 11:30 a.m. to 13:00 p.m. The wind speed was 2.1 m/s (2 Beaufort) and the air temperature was 20 °C. On the hill and south of the archaeological site of Pedino, the two flights with the MS sensor took place on 14 May 2024 from 12:10 p.m. to 13:45 p.m. The wind speed was 6.3 m/s (4 Beaufort) and the air temperature was 24 °C. It should first be noted that all flights were created with the use of 70% side and front overlap images (Figures 6–9). A total of 35 strips were implemented for Europos, with a 100 m flight height (the minimum permitted by the UAS software, WingtraPilot© version 2.12.2, for the MS sensor) on both flights. The anticipated (and ultimately achieved) spatial resolution of the 6.8 cm images, the complete flight duration of 41 min and 14 s, and the total number of 1362 MS images were successfully collected. For Pedino, a total of 58 strips were implemented, with a flight height of 100 m in both instances, while the projected (and ultimately achieved) spatial resolution of the 6.8 cm images, the total flight time of 51 min and 3 s, and a total of 1580 MS images were obtained.

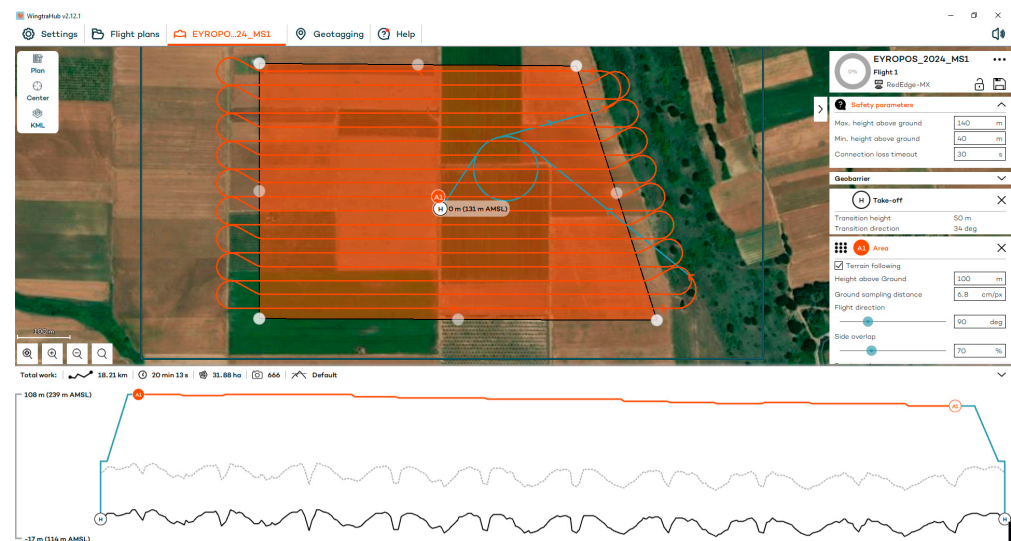


Figure 6. The first flight plan with the MS sensor south of the archaeological site of Europos.

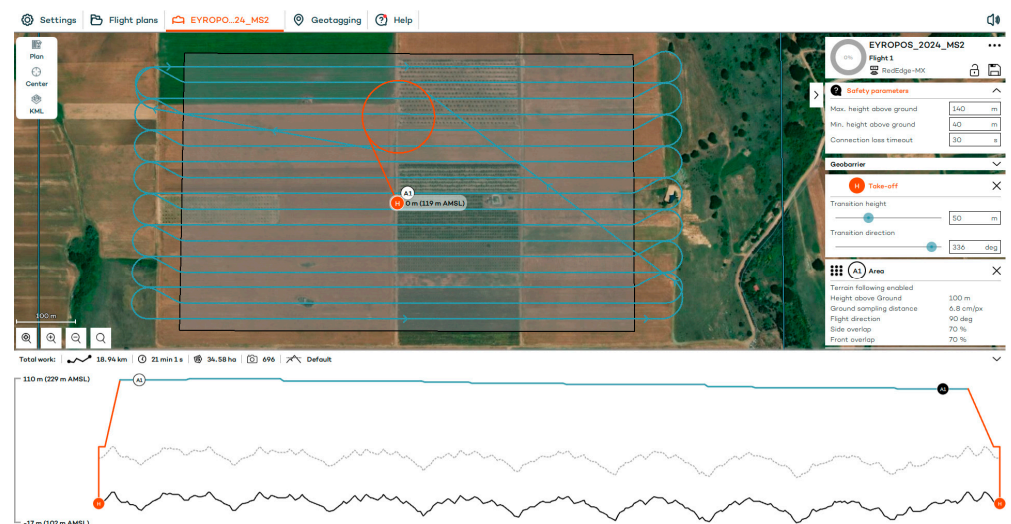


Figure 7. The second flight plan with the MS sensor, south of the flight plan of Figure 6.



Figure 8. The first flight plan with the MS sensor on the hill and southwest of the hill at the archaeological site of Pedino.



Figure 9. The second flight plan with the MS sensor, east of the flight plan of Figure 8.

4.2. Collection of Terrestrial Data, Image Processing, and Production of Digital Surface Models and Orthophotomosaics

The procedure that follows took place twice: once for the archaeological site of Europos and once for the archaeological site of Pedino Hill. The GNSS Topcon HiPer SR was initially utilized to identify the X, Y, and Z coordinates of a randomly selected point (which served as a reference point for subsequent measurements) at a relatively short distance from the home position of the UAS. The GNSS was linked to the national network of multiple fixed stations available to Topcon, and the position (X, Y, and Z) of the point was determined with an accuracy of a few millimeters using the real-time kinematic (RTK) method. Subsequently, continuous measurements of the position were made using the Static GPS surveying method with the same GNSS for the same point over a period of 30 min before the commencement of the first flight, during the two flights of each study area, and for 30 min after the completion of the second flight. In the office, the coordinates of the reception centers of each MS image were calculated using the high accuracy coordinates of the above point, its static measurements, and the PPK GNSS measurements of the UAS. This process yielded a 3D accuracy of the centers of the images ranging from 2 to 3 cm.

Subsequently, the calibration of spectral information with spectral targets is necessary using the Agisoft Metashape© (version 2.0.0) software. Prior to and following the flight, the suitable calibration target of the Micasense RedEdge-MX was mapped [100,113–116]. The target was automatically detected by the Agisoft Metashape© (version 2.0.0) software and the reflectance values of all spectral bands were calculated. This was followed by the resolution of the block of all MS images (without Ground Control Points, as the coordinates of the reception centers of each MS image have been calculated), and for the archaeological site of Europos, the RMSE was 1.4 cm, the produced digital surface model spatial resolution was 12.6 cm, and the orthophotomosaic spatial resolution was 7 cm (Figure 10). For the archaeological site of Pedino Hill, the RMSE was 1.5 cm, and the produced digital surface model had a spatial resolution of 13.7 cm and orthophotomosaic spatial resolution of 7 cm (Figure 11).

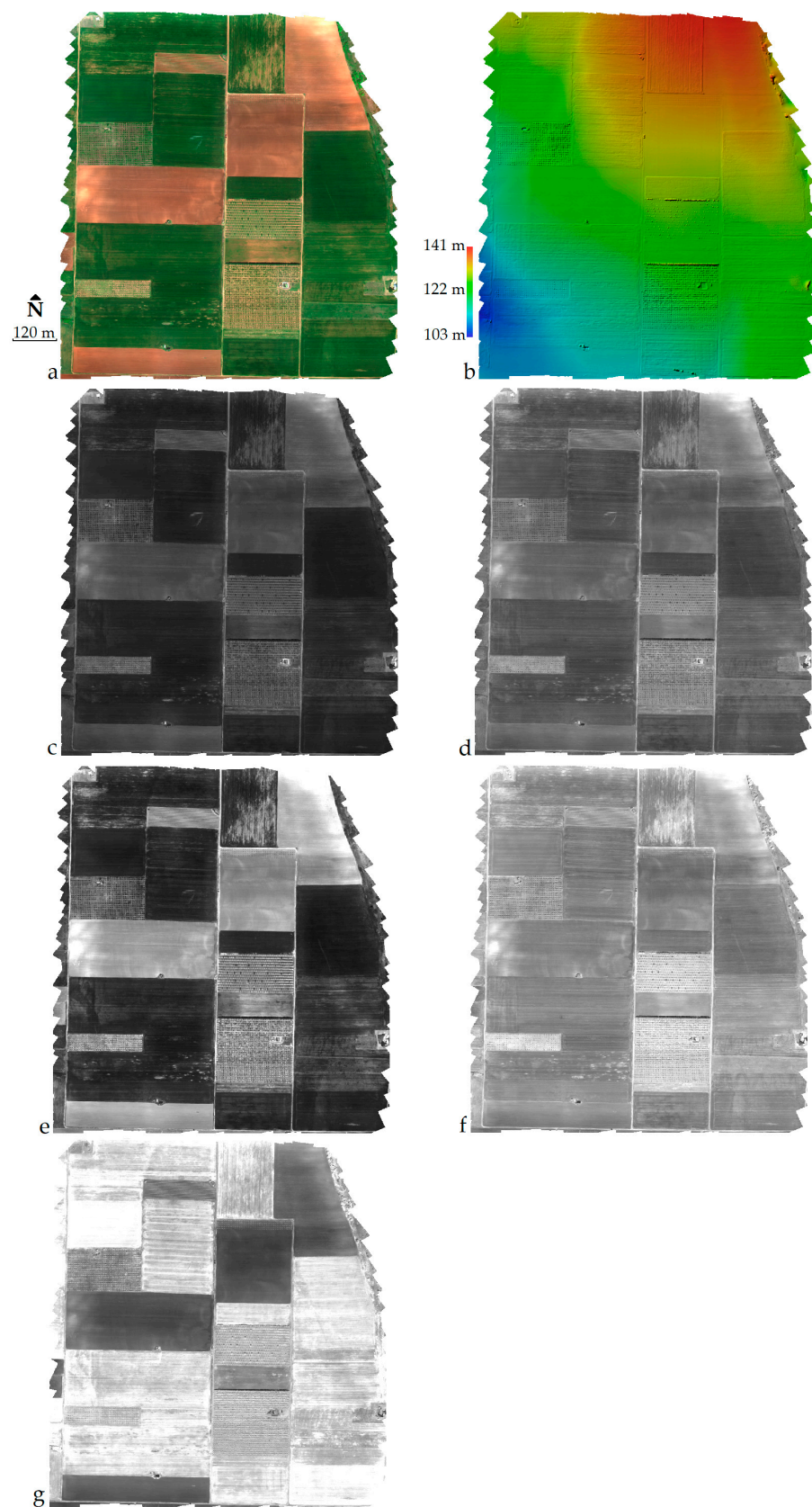


Figure 10. (a) The orthophotomosaic (RGB) of the archaeological site of Europos; (b) The digital surface model; The orthophotomosaics of MS images: (c) Blue; (d) Green; (e) Red; (f) Red Edge; (g) Near InfraRed. Center of images: $40^{\circ}52'49.63''$ N $22^{\circ}33'25.50''$ E.

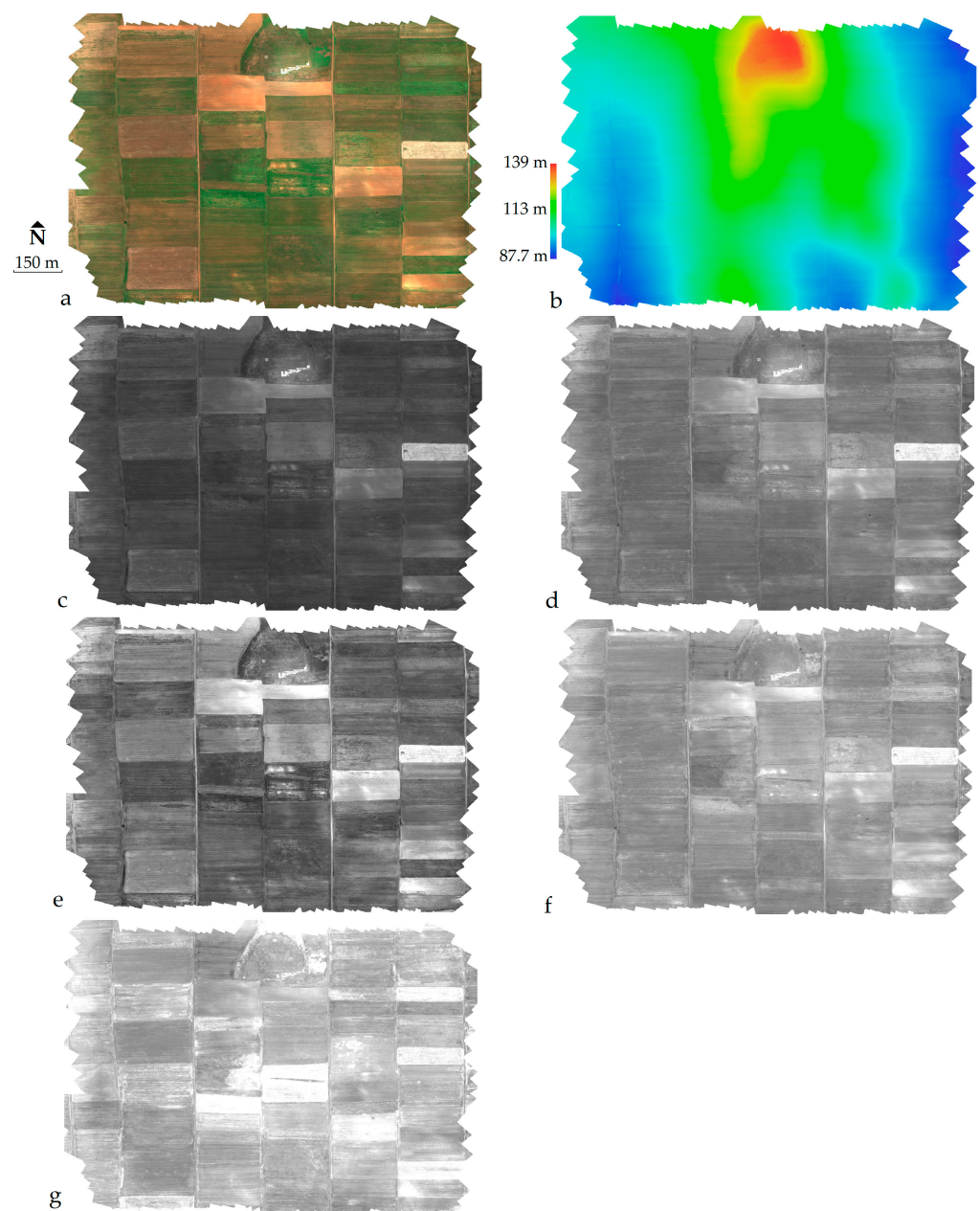


Figure 11. (a) The orthophotomosaic (RGB) of the archaeological site of the hill and south of the archaeological site of Pedino; (b) The digital surface model; The orthophotomosaics of MS images: (c) Blue; (d) Green; (e) Red; (f) Red Edge; (g) Near InfraRed. Center of figure: $40^{\circ}54'47.42''$ N $22^{\circ}53'15.86''$ E.

4.3. Production of Index Maps

The index formulas presented in Table 1 were created in the Agisoft Metashape© (version 2.0.0) software [1] and the corresponding index maps were produced (Figure 12).

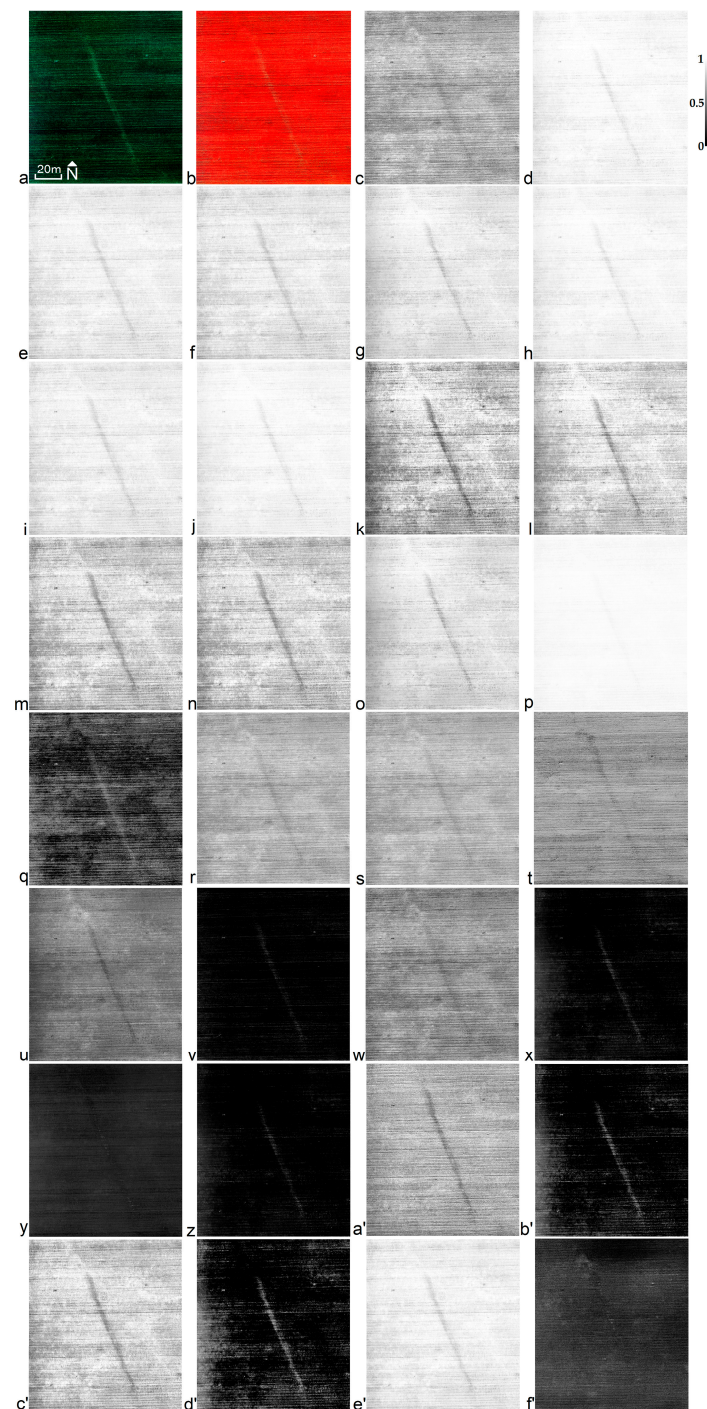


Figure 12. An observation site of negative crop marks 3.8 m wide south–southeast of the acropolis of Europolis (Figure 3, north of Location 5). Excerpts from orthophotomosaics and indexes (a) bands: B-G-R (RGB); (b) bands: B-G-NIR; (c) NIR; (d) NDVI; (e) GNDVI; (f) RENDVI or NDRE; (g) NDVIRE or NDRER; (h) SAVI; (i) GSAVI; (j) OSAVI; (k) SR; (l) MSR; (m) GCI; (n) GRVI; (o) NGRDI; (p) NLI; (q) GEMI; (r) TVI; (s) MTVI; (t) TCARI; (u) MCARI; (v) BI; (w) BI2; (x) CI; (y) PSRI; (z) RI; (a') ARI1; (b') ARI1B; (c') ARI2; (d') ARI2B; (e') LCI; (f') RGRI. The grayscale of the images ranges from 0 (black) to 1 (white), with 0 representing the least favorable and 1 representing the most favorable result of the index. For instance, in the case of NDVI, a value of 0 corresponds to pixels without crop, a value of 0.5 to pixels with poor growth or poor crop health, and a value of 1 to pixels with good growth or healthy crop.

5. Discussion

In this survey, as in [1,117], the indexes were not sufficiently indicative of the presence of possible archaeological remains. It is important to note that the term “possible” should be used in such cases, as only systematic archaeological research and excavation can confirm the existence of anomalies in the soil or vegetation and determine whether they are due to the presence of archaeological remains underneath the soil. In this study, the RGB or near-infrared (NIR) bands of the orthophotomosaics were able to detect these possible archaeological remains. In the majority of instances, however, they markedly enhanced the visual observation of the marks, with the indexes that permitted this being SR and ARI2B (see, for example, Figure 12).

The set of new marks identified and their spatial distribution in the study area south of the acropolis of Europos are presented in Figure 3 (drawing of the marks in red). Northwest of Location 5 (Figure 3), there is a linear negative (possible presence of a solid structure under the ground) crop mark of approximately 112 m in length and 3.8 m in width, as well as a smaller length zigzagged negative crop mark, south of the previous one (Figure 13).

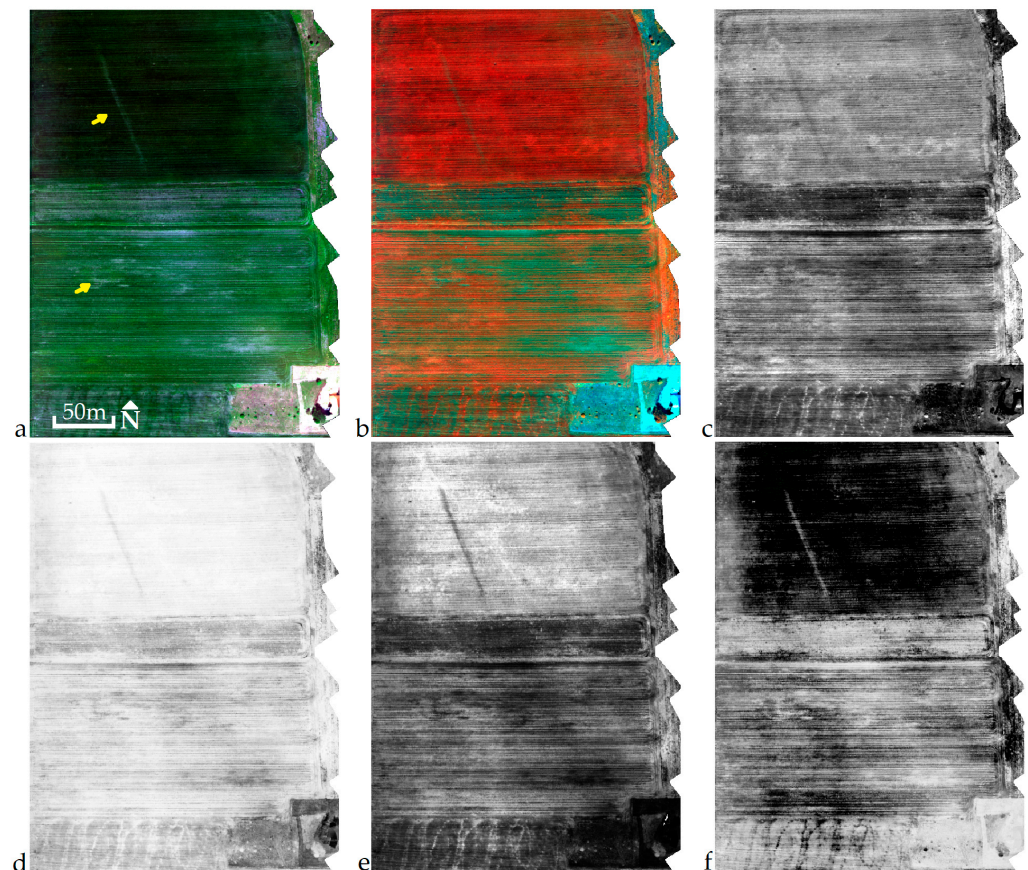


Figure 13. Two negative crop marks are located southeast of the acropolis of Europos, a short distance northwest of the burial mound (Figure 3, Location 5). The burial mound is in the lower right corner of the above images. Yellow arrows indicate the positions of the marks. Extract of orthophotomosaic and indexes: (a) bands: B-G-R; (b) bands: B-G-NIR; (c) NIR; (d) NDVI; (e) SR; (f) ARI2B.

Of all the indexes, those that improved the visual observation of marks were SR and ARI2B. The width of the linear mark does not refer to a covered main (big) road, but perhaps to a secondary covered road that may have been used exclusively for the communication of the acropolis with the burial mound of Location 5 (Figure 3). Interestingly, this linear mark and the linear mark of the previous study [1] (the mark between Locations 2 and 4 of Figure 3, with a north–south direction) have the same width and are spatially contained within the 128.00 m to 132.00 m contour lines. One could assume that these two marks are

related and may possibly belong to the same covered road that provided communication between the acropolis and the three tombs of site 4 and the burial mound of site 5 (Figure 3). As already mentioned, the above are hypotheses that only archaeological research and excavation can prove.

Southwest of the acropolis of Europos, new positive (possible presence of an open structure under the ground) marks were identified (Figure 3 in red and Figure 14).

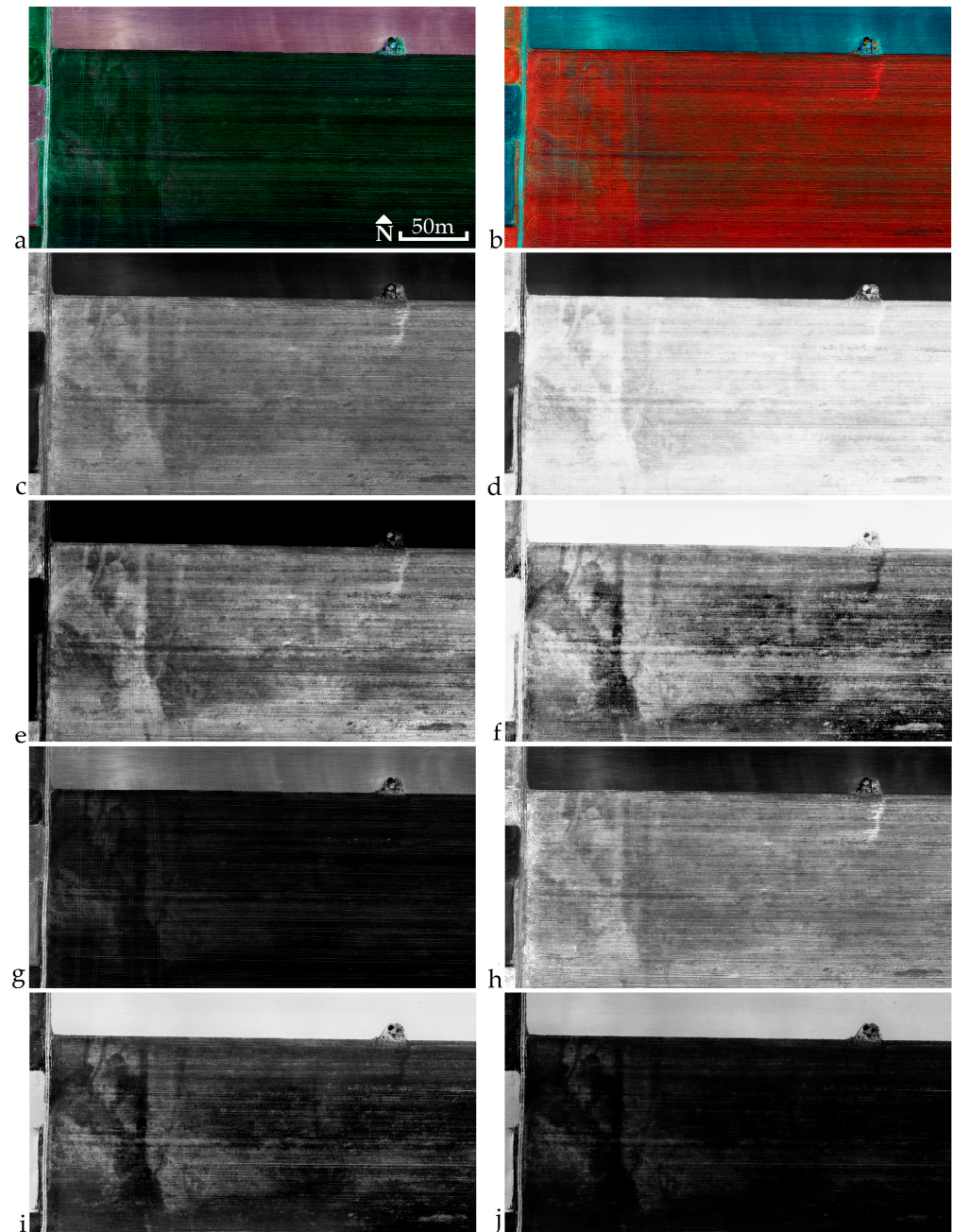


Figure 14. Linear positive crop marks are located southwest of the archaeological site of Europos (in red in Figure 3). Excerpt of orthophotomosaic and indexes: (a) bands: B-G-R; (b) bands: B-G-NIR; (c) NIR; (d) NDVI; (e) SR; (f) ARI2B; (g) BI; (h) BI2; (i) CI; (j) RI.

Of all the indexes, those that improved visual observation of the marks were SR and ARI2B. Marks do not refer to some typical possible structures under the ground that retain moisture, but their study is recommended in the future. North of the central parcel of land of Figure 14 (where marks are also located), there is a parcel of land without crops. For

this reason, images from indexes (BI, BI2, CI, and RI) related to the soil were added to Figure 14 to check if the marks extend further north. Unfortunately, however, the above parcel of land without crops (Location A in Figures 3 and 15), as well as the parcel of land of Location B (Figures 3 and 15), had been irrigated with tons of water the day before the image collection (according to the in situ testimonies of their owners). A parcel of land of Location C (Figures 3 and 15) was irrigated from the dawn of the same day of image collection (as shown by the irrigation system in Figure 15, below the letter C). The above did not allow marks to appear on UAS images. It is unknown how many other parcels of land of the study area had been subjected to intense irrigation, which is abnormal for the season due to prolonged drought.

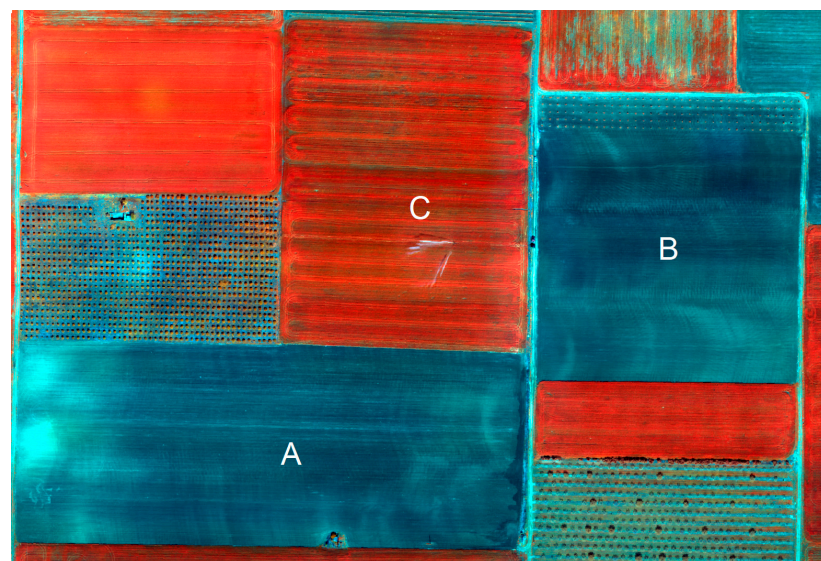


Figure 15. Parcels of land A, B, and C with high surface moisture. Bands: B-G-NIR.

The marks found in the study area of the archaeological site of Pedino Hill are shown in Figure 4.

Negative vegetation marks (Figure 4, Location 1, drawing of the marks in red) of possible internal structures (e.g., streets and/or buildings) and the wall of the ancient city (drawing of the marks in yellow in Figure 16) were identified on the hill. The same marks were found in the geophysical survey carried out on the hill years ago by Professor Grigoris Tsokas (Director of the Laboratory of Exploration Geophysics, School of Geology, Aristotle University of Thessaloniki, Greece) but have not yet been published. In the parcel of land southwest of the hill (in contact with the hill), linear negative soil marks (Figure 4, drawing of the marks in blue) were found that refer to possible solid structures under the ground. This parcel of land has no crops and, for this reason, images from indexes (BI, BI2, CI, and RI) related to the soil were added to Figure 16 (drawing of the marks in blue). Of all the indexes, those that improved the visual observation of the marks were NDVI, SR, BI, and BI2.

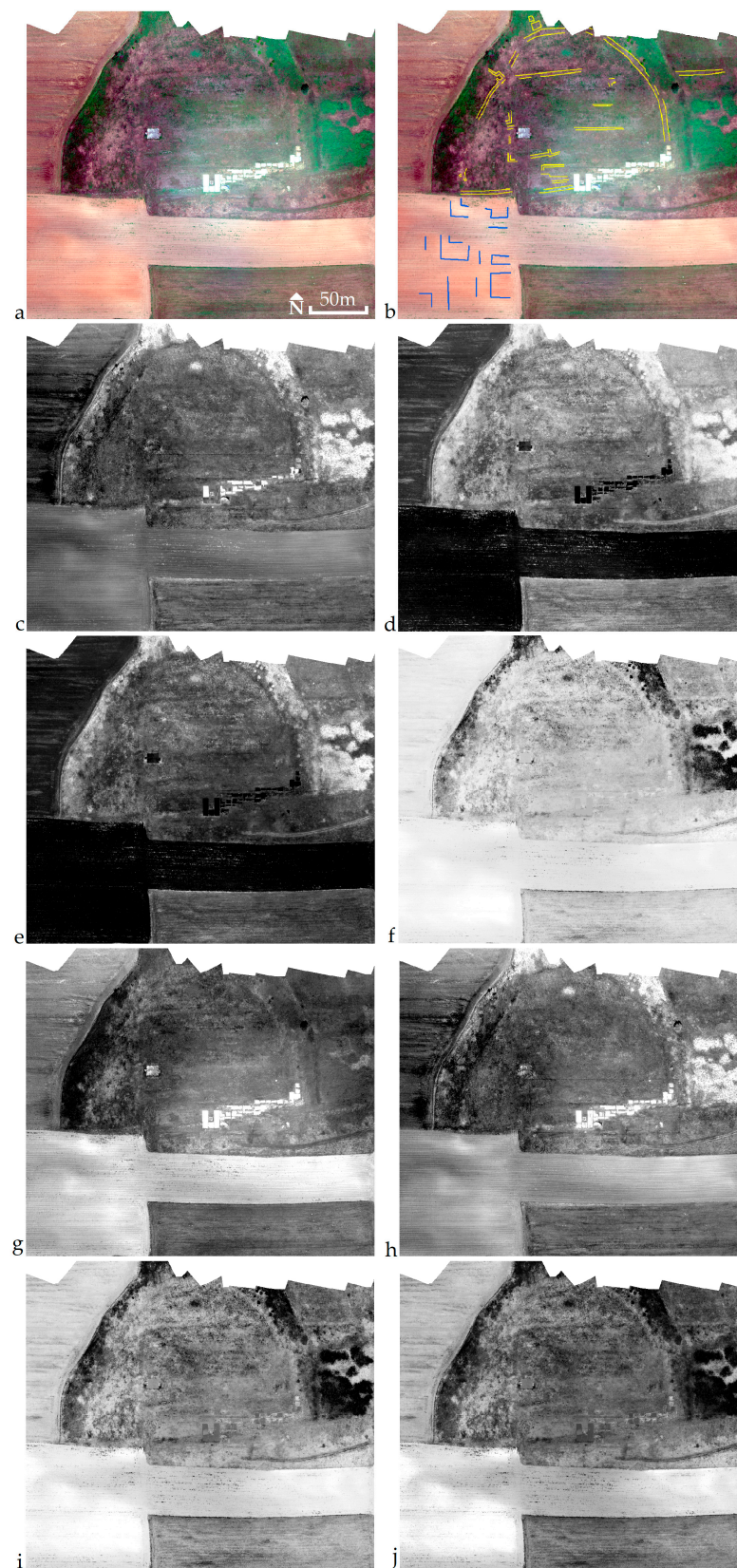


Figure 16. The archaeological site of Pedino Hill. Negative vegetation marks were found inside the walls (drawing of the marks in yellow) and soil marks (drawing of the marks in blue) outside the walls. Excerpt from orthophotomosaic and indexes: (a) B-G-R; (b) drawing of the marks; (c) NIR; (d) NDVI; (e) SR; (f) ARI2B; (g) BI; (h) BI2; (i) CI; (j) RI.

In the center of the study area (Figure 4), four circular negative crop marks ranging from 14 to 22 m in diameter were identified, along with one linear negative vegetation mark (Figure 17, drawing of the marks in yellow), with a width of approximately 4 m and a length of approximately 80 m. The contour lines (Figure 4) do not justify the presence of circular marks (i.e., they are not small hills). Of all the indexes, those that improved the visual observation of the marks were NDVI and SR.

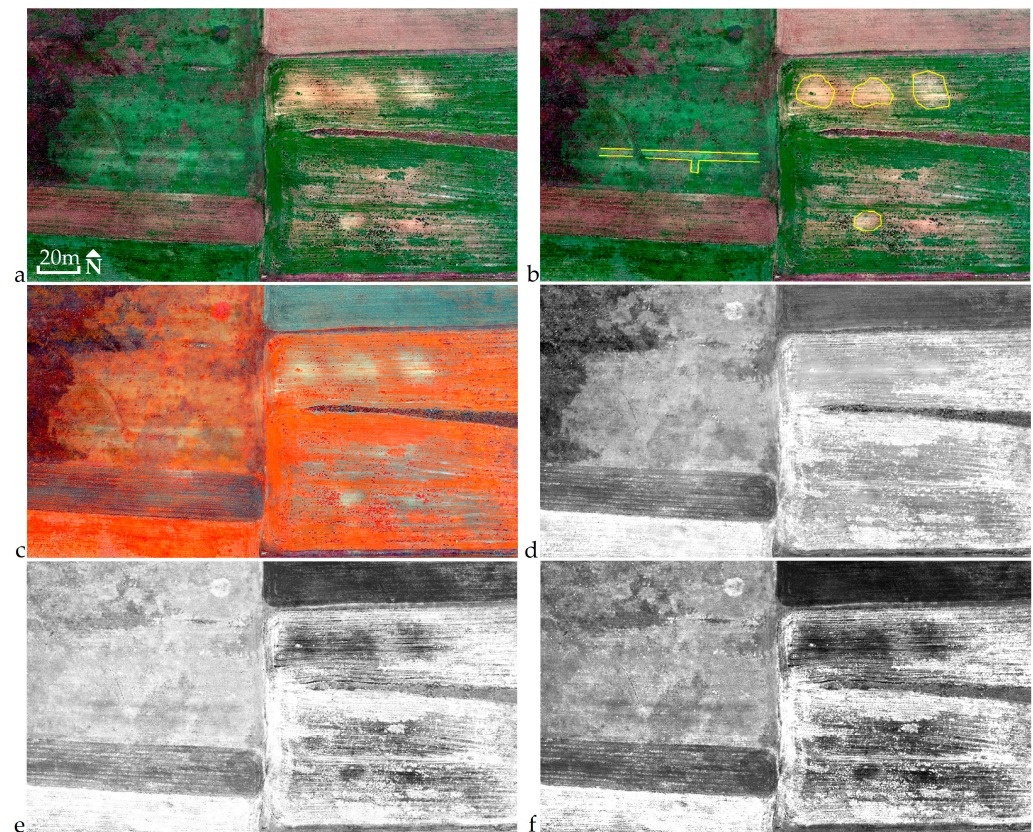


Figure 17. The negative crop/vegetation marks in the center of the study area of the archaeological site of Pedino Hill. Excerpt from orthophotomosaic and indexes: (a) B-G-R; (b) drawing of the marks; (c) B-G-NIR; (d) NIR; (e) NDVI; (f) SR.

East of the study area of the archaeological site of Pedino Hill (Figure 4), square positive crop marks of dimensions from 2.5×6.5 m to 8.5×8.5 m were identified, as well as irregularly shaped positive crop marks (at the top of the images of Figure 18). Linear negative soil marks were also detected (at the bottom of the images of Figure 18). Of particular interest are the positive crop marks, as they are located in a hill of the study area (Figure 4). Of all the indexes, those that improved the visual observation of the marks were NDVI, SR, BI, and BI2.

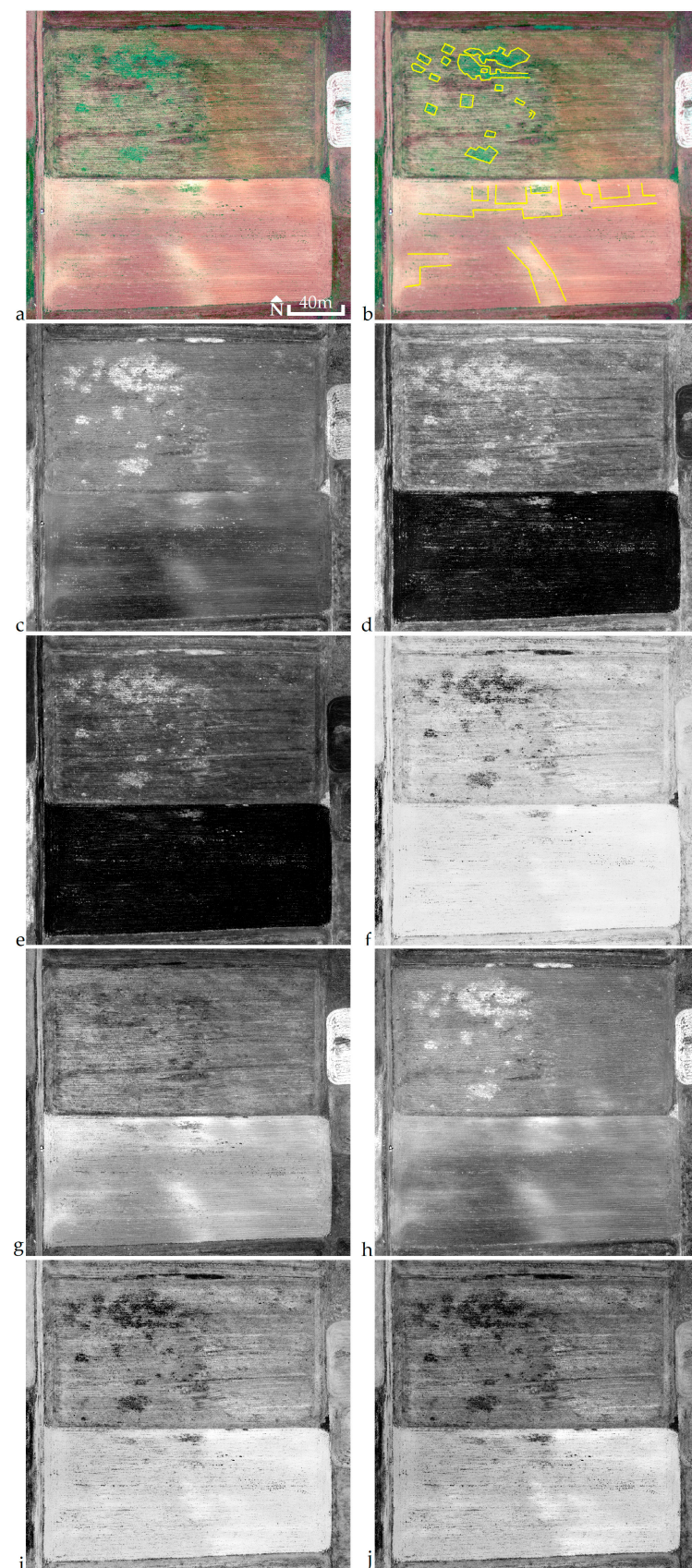


Figure 18. Positive crop marks at the top and negative soil marks at the bottom of the images, east of the study area of the archaeological site of Pedino Hill. Excerpt from orthophotomosaic and indexes: (a) B-G-R; (b) drawing of the marks; (c) NIR; (d) NDVI; (e) SR; (f) ARI2B; (g) BI; (h) BI2; (i) CI; (j) RI.

6. Conclusions

Aerial and remote sensing archaeology are tools of archaeological prospection. They are exploited by interdisciplinary teams (surveyors, archaeologists, historians, etc.) on the one hand for the discovery of new covered archaeological remains, and on the other hand for the efficient management and allocation of human resources in fieldwork, carrying out surface surveys and/or excavation in specific geospatial locations. This reduces the time and cost of surveys (avoiding extensive surface surveys and/or excavations). Through the marks, the “resilience” of structures and historic complexes beneath the soil is revealed. While not visible when walking in the field, they have the potential and ability to cause “alterations” to the soil or vegetation/crop, which allows them to be observed in aerial and satellite images.

On the other hand, the resilience of historic landscapes refers to their potential to retain their cultural, natural, and historic values despite environmental and anthropogenic pressures. Aerial and remote sensing archaeology reveals historic landscapes that were unable to survive and maintain these values when the aforementioned pressures were triggered. For example, extreme weather events, earthquakes, and other natural disasters led to the levelling of ancient structures, which over time were abandoned and covered by soil. The transformation of large areas of land in the early-20th century into fertile farmland led to the covering of ancient roads and other structures.

Currently, there is a partial use of UAS with an MS sensor for collecting images in areas outside of the visible spectrum, aiming at the detection of covered archaeological remains. Almost all UAS can, at a relatively small cost of EUR 4000–6000, be equipped with MS sensors as well. The benefits will be manifold since the marks either appear for the first time in their images or are more clearly visible than in RGB images. Of particular interest is the use of a UAS aeromagnetic system for the detection of covered archaeological remains, a technique that will be of particular interest to researchers in the near future, as it is currently in the early stages of development.

Of the indexes utilized in aerial remote sensing archaeology, it seems that it is no coincidence that many researchers use NDVI and SR to locate marks, as both indexes gave good results in this study. It is also evident that there is room for the creation of new indexes after experimentation and systematic study of the spectral information of the sensor bands used in UAS.

Climate change adds an unpredictable cause, among those (size of the covered structure, its depth, type of soil, water content, and type of vegetation/crop) responsible for the appearance and intensity of visual observation of the marks. According to the phenological cycle of the dominant crop (wheat) in both study areas, the ideal period for detecting marks is theoretically from mid-April to mid-May. In Europos, while the timing of the image collection would have been ideal under normal climatic and meteorological conditions, the prolonged drought and the forced heavy irrigation by farmers did not allow the appearance of a large number and visually bold marks.

Both study areas identified soil and crop or vegetation marks, which could be attributed to archaeological remains beneath soil. This, however, is a hypothesis that can only be substantiated after systematic archaeological research and excavations.

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