In the Heat of the Night: Comparative Assessment of Drone Thermography at the Archaeological Sites of Acquarossa, Italy, and Siegerswoude, The Netherlands

Jitte Waagen 1,*, Jesús García Sánchez 2, Menno van der Heiden 3, Aaricia Kuiters 1 and Patricia Lulof 1

1 Amsterdam School of Ancient Studies and Archaeology (ACASA) and 4D Research Lab, University of Amsterdam, Turfdraagsterpad 9, 1012 XT Amsterdam, The Netherlands; a.kuiters@uva.nl (A.K.); p.s.lulof@uva.nl (P.L.)
2 Instituto de Arqueologia, Mérida (IAM) CSIC-Junta de Extremadura, Plaza de España 15, 06800 Mérida, Extremadura, Spain; j.garcia@iam.csic.es
3 Rijksdienst voor het Cultureel Erfgoed, 3811 Amersfoort, The Netherlands; m.van.der.heiden@cultureelerfgood.nl

* Correspondence: j.waagen@uva.nl

Abstract: Although drone thermography is increasingly applied as an archaeological remote sensing tool in the last few years, the technique and methods are still relatively under investigated. No doubt there are successes in positive identification of buried archaeology, and the prospection technique has clear complementary value. Nevertheless, there are also instances where thermograms did not reveal present shallow buried architectural features which had been clearly identified by, for example, ground-penetrating radar. The other way around, there are cases where the technique was able to pick up a signals of buried archaeology at a time of day that is supposed to be very unfavorable for thermographic recording. The main issue here is that the exact factors determining the potential for tracing thermal signatures of anthropomorphic interventions in the soil are many, and their effect, context, and interaction under investigated. This paper deals with a systematic application of drone thermography on two archaeological sites in different soils and climates, one in The Netherlands, and one in Italy, to investigate important variables that can make the prospection technique effective.

Keywords: drone thermography; remote sensing; ground-penetrating radar; Acquarossa; Siegerswoude

1. Introduction. Performing Thermography with Drones

In the field of thermography for archaeological remote sensing, the deployment of drones is a very promising avenue of research. In the thermal infrared spectrum (wavelength between 8 and 14 µm), it is possible to measure emitted thermal infrared energy of surface and subsurface anomalies, potentially revealing archaeological features [1–6]. Because a drone thermography survey can take place in relatively short time, the potential yield of information is huge, and its effective application very much worth exploring [2] (pp. 591–635). For example, capturing 1.36 ha from an altitude of 100 m, surface resolution of 13 cm, with a series of consecutive overlapping photos, can be achieved in a flight operation of only a couple of minutes. While the potential of thermography to identify otherwise invisible archeological traces has long been recognized [2], the insertion of Unmanned Airborne Systems (UAS) into the equation has really been crucial due to increased resolution and improved imaging. Because of the low recording altitude in comparison to plane-based or space-born thermal remote sensing, spatial resolution is much finer, and atmospheric attenuation has fewer detrimental effects. Their ability to fly autonomously in difficult environments in variable weather conditions, as well as the combination of smart gimbals, autopilots, and mission planning software, significantly improves practical deployment and data quality. This creates opportunities for new approaches to remote sensing and site studies for archaeology, and the possibility to ask new questions, for
example studying longitudinal conservation of buried deposits. It is therefore no surprise that the potential for drone thermography has seen increasing exploration and application in the last few years [7–15]. However, the underlying principles of technique and methods are still under investigated, and there is a clear need to assess fitness for purpose (in general for remote sensing emphasized by Cowley et al. [16]). No doubt there are successes in positive identification of buried archaeology, and the prospection technique has clear complementary value [9]. Nevertheless, there are also examples where thermograms did not reveal present shallow buried architectural features, which had been clearly identified by ground-penetrating radar (cf. [9] (pp. 315–325)). The other way around, there are cases where the technique was able to pick up a signals of buried archaeology, at a time of day that is supposed to be very unfavorable for thermographic recording [15] (p. 9).

The central issue here is that, although we know the potential of drone thermography in general, the exact factors determining its efficacy for tracing thermal signatures of anthropomorphic interventions in the soil are many, and their effect, context, and interaction still need further investigation [9,13]. To name a few, in addition to the thermal properties of the archaeological remains themselves, variables, such as diurnal heat flux, vegetation cover, soil humidity, relative atmospheric humidity, depth of the features, other materials that can create noise, as well as the aforementioned soil composition, affect thermal signals. In order to mitigate this knowledge gap, much more comparative empirical research is needed, along the lines of Casana et al. [9]. This paper deals with a systematic application of drone thermography on two sites in different soils and climates, one in the Netherlands, and one in Italy, as a contribution to this methodological exploration, and to advance the field of drone thermography.

2. Theory: The Mechanics of Thermography

Thermal energy from the sun is differentially absorbed and reflected by objects on earth. There are four significant thermodynamic properties that affect the thermal behavior of material: conductivity, diffusivity, inertia, and volumetric heat capacity. Excellent explanations in archaeological literature exist [1,9] (pp. 311–313), [6] (pp. 1–3), but in order to properly contextualize the methodological discussion in this paper, a concise summary will be given here. Thermal conductivity is a measure of the quantity of heat a material can transport. It is affected by density, i.e., more particles in direct contact conduct more heat, which is positively affected by moisture, because it fills spaces between particles. However, small grain size and the inclusion of organic matter decrease conductivity. Thermal diffusivity then refers to the rate at which this heat transport takes place, partly determined by a materials heat capacity, where a low heat capacity means less heat will be absorbed and thus passes at a higher rate through a material. Heat capacity describes how much heat a material must absorb or exude before its temperature changes, expressed as either specific heat capacity or volumetric specific heat capacity. The final and very important thermodynamic property is thermal inertia, which quantifies the resistance to changes in temperature of a material. This depends on a material’s heat conductivity and volumetric specific heat, where the latter has the greatest influence on inertia. The common example is that of a body of water that can store relatively much heat, i.e., has a large heat capacity, and thus has a high inertia, meaning it changes slowly in temperature. Similarly, given the above definitions, dry and porous soils will typically have low conductivity, low volumetric heat capacity and low thermal inertia, whereas more dense and moist soils will have the opposite characteristics. Stone materials have a high volumetric heat capacity and inertia and will therefore stay warm longer than, e.g., surrounding dry and porous soil ([6]).

Clearly, these thermodynamic properties of materials determine their behavior in the context of changing heat conditions, i.e., diurnal, seasonal and transient (sudden reversals in) heat flux [9] (pp. 314–316). In the case of a setting sun, where direct radiation disappears, and thus the direct reflection of thermal infrared energy, the differential emission of absorbed heat by objects can be picked up by a thermal camera. Over time, materials start cooling down depending on relative thermal inertia, which may increase contrasts
in the measurable emission. Following from this, objects on the surface of the earth, and even below the surface, with sufficient deviating thermal properties, can therefore be distinguishable due to their divergent thermal energy emission. As Casana et al. [9] (pp. 311–312) explain, this can lead to the identification of archaeological features that may be difficult to discern in the visible spectrum, such as artifact concentrations on the ground, pitch, ditches and earthworks, subtle topographic features, and even subsurface remains.

The potential of thermography for picking up a signal from buried archaeology then depends heavily on the interplay between thermal characteristics of the archaeological feature, the surrounding soil matrix, and the covering soil matrix. An ideal situation for picking up subsurface archaeology is simplified in Figure 1, where there is a topsoil with a high conductivity and diffusivity, i.e., is capable of transferring heat so thermal infrared radiation can reach buried materials, and emitted energy can return to be picked up by a thermal camera. Furthermore, the topsoil layer should not be too thick, as increasing distance will attenuate the signal of features below. The buried features must then have a sufficiently different thermal inertia to create a contrast with the surrounding soil matrix, and a low conductivity and diffusivity to avoid heat transfer to the surrounding soil matrix [1]. Clearly, waterlogged features, i.e., features with a higher moisture retention, or stone features surrounded by a low thermal inertia soil matrix, would create a potentially favorable situation for thermal prospection.

Figure 1. Simplified ideal composition of the thermal properties of covering soil matrix, surrounding soil matrix and archaeological feature.

A Systematic Approach

Following from the explanation of the challenges and the basic principles of thermographic remote sensing for archaeology, we can conclude that we need to expand the empirical evidence for successful application. In this study, two known archaeological sites have been examined, taking the hypothetical influence of various variables into account, which are Siegerswoude, Friesland, The Netherlands, and Acquarossa, Lazio, Italy (further introduced below). The comparative approach is interesting, since both locations have a high probability of archeological remains, buried at a relatively shallow depth of ca. 20–50 cm, presenting a chance for detection through thermographic remote sensing. These sites have different soils, and present quite profound differences in expected archaeological materials, and seasonal heat flux, which are thus variables that can be tested. In order to allow for a useful comparison of factors affecting detection probabilities, both sites have been examined in a relatively wet season and the drone thermography operations have been organized the same way in both cases. In addition, at both sites other archaeological prospection techniques have been deployed that can be used for a comparative assessment of the results; at Acquarossa, GPR has been performed simultaneously with the drone operations, and at Siegerswoude test excavations have been executed after the drone thermography capture. These prospective datasets may be used as complementary datasets for analyzing eventual detected features and the relative efficiency of their deployment.
Drone operations at both sites followed a strict systematic approach. The thermographic recording took place at various moments during the diurnal cycle. The drone was taken aloft directly after sunset, at midnight and before sunrise, in order to be able to compare the differential cooling during the night. Recordings were taken at 100 m, 30 m, and 10-5 m to test for the effect of higher Ground Sample Distance (GSD) and less attenuation versus a smaller coverage per photo, and to see if the quality of thermal measurements improved [17]. During each flight operation, circumstantial parameters were recorded on a flight form; in addition to administrative information, registration of used equipment and operation metadata, recorded variables relevant for the thermographic tests are shown in Table 1.

Table 1. Recorded variables for drone thermography operations.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Explanation/Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight altitude</td>
<td>10, 30 or 100 m</td>
</tr>
<tr>
<td>Current temperature</td>
<td>Temperature at time of flight, record from local weather station, °C</td>
</tr>
<tr>
<td>Day temperature</td>
<td>Maximum daily temperature, record from local weather station, °C</td>
</tr>
<tr>
<td>Night temperature</td>
<td>Minimum nightly temperature, record from local weather station, °C</td>
</tr>
<tr>
<td>Long-term heat flux</td>
<td>Significant change in temperature patterns in the preceding days</td>
</tr>
<tr>
<td>Light conditions</td>
<td>Short-term variability in cloud cover, i.e., clear, overcast, etc.</td>
</tr>
<tr>
<td>Surface anomalies</td>
<td>Record presence, i.e., of reflective materials, potential effect on thermal recordings, i.e., water, metal objects, etc.</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>Record from local weather station, %</td>
</tr>
<tr>
<td>Moisture conditions</td>
<td>Record whether the soil is moist, whether there has been rain</td>
</tr>
<tr>
<td>Irrigation</td>
<td>Have the fields been watered?</td>
</tr>
<tr>
<td>Vegetation type/land use</td>
<td>Brushes, wheat, grass, etc.</td>
</tr>
<tr>
<td>Estimated depth</td>
<td>Of archaeological remains, cm</td>
</tr>
<tr>
<td>Superficial layer</td>
<td>Composition of topsoil layer</td>
</tr>
<tr>
<td>Soil matrix</td>
<td>Composition of surrounding soil matrix (of archaeological features)</td>
</tr>
<tr>
<td>Expected features</td>
<td>What archaeology is expected (i.e., stone walls)</td>
</tr>
<tr>
<td>Topographic features</td>
<td>Ridges, ditches, protruding bedrock</td>
</tr>
<tr>
<td>Surface archaeology</td>
<td>Any visible archaeology above ground (structures, surface artefacts, etc.)</td>
</tr>
</tbody>
</table>

3. Materials and Methods

3.1. Recording Heat

The recordings have been made with a DJI M210 quadcopter carrying a Zenmuse XT2 radiometric camera. The quadcopter is powered by a pair of DJI TB50 batteries that allow for flight operations of ca. 18 min. The camera is attached to a gimbal system that stabilizes the lens and allows for a constant capture quality. The operator is equipped with a remote control with the DJI Crystal Sky monitor that allows for viewing a live feed of the camera view, which again helps in assuring the quality of the recording.

The camera uses a FLIR TAU 2 thermal sensor, which is built on an uncooled VOx Microbolometer thermal imager (https://www.dji.com/nl/zenmuse-xt2 accessed on 5 January 2022). The thermal sensor has a resolution of 640 \times 512 pixels, with a pixel pitch of 17 µm, recording in the 7.5–13.5 µm spectral band with a sensitivity of 0.05 °C. The thermal camera has a 13 mm lens, allowing for a relatively wide view, which is optimal for recording close to the ground while capturing as much as possible information on each thermogram to benefit the photogrammetric postprocessing. This camera also has an optical sensor that captures normal visible light images at exactly the same moment as the thermal images (1/1.7” CMOS, 12 megapixel). The XT2 is a radiometric camera,
which means that the thermograms have the recorded radiation as metadata attached as a 14-bit dataset with 16,384 values, as opposed to a non-radiometric camera that will spread 256 grayscale values over the range of recorded temperature values. While the latter is often sufficient for direct visualization purposes, for effective post-processing and creating thermal index maps in photogrammetric software, the highly precise 14-bit measurements are important because they allow more accurate photogrammetric alignment and more efficient GIS raster analysis techniques.

The recording procedure followed common principles of UAS-based remote sensing, i.e., capturing a series of overlapping images in a meandering pattern. In the case of thermal images, which have a much lower resolution than the typical camera, it is necessary to ensure a relatively high front and side overlap between the images, in this case, respectively, 85% and 75%. For navigating the drone and capturing the thermal images, DJI Pilot software (https://www.dji.com/nl/downloads/djiapp/dji-pilot accessed on 5 January 2022) on the remote control has been used, which is the only software able to display both the visible light and thermal images at the same time for this set of equipment. At the time of recording, the mission planning part of DJI Pilot was however not yet operational, so all images had to be captured manually. Whereas this is practically somewhat cumbersome, it also brings the advantage of being able to hover at every capture, avoiding any risk of movement blur. During the recording process, a Flat Field Correction (FFC) was executed manually every 30 or so photos to compensate for vignetting effects and pixel-to-pixel sensitivity variations across the sensor, if any. FFC can bring its own issues of sudden temperature recording variation though [13] (p. 6), although strong effects were not expected here.

Ground control was provided by using forex (rigid PVC sheets) targets, which is a quite reflective material with the advantage of appearing as dark on the thermograms, that had been referenced using a differential GPS system.

3.2. Analyzing Heat

The captured thermal datasets have subsequently been calibrated using FLIR Thermal Studio Pro (https://www.flir.eu/products/flir-thermal-studio-suite/, accessed on 5 January 2022) to remove noise and apply a histogram stretch to facilitate easier inspection of individual photos. The processed images, which are of the radiometric JPG type (RJPG), have subsequently been inserted into the drone photogrammetry software Pix4DMapper (https://www.pix4d.com/product/pix4dmapper-photogrammetry-software accessed on 5 January 2022). Since (drone) photogrammetric procedures are well-covered in recent literature in the field of archaeology [18–21], and guides for processing thermal images can be found online (https://support.pix4d.com/hc/en-us/articles/360000173463-Processing-thermal-images#label4, accessed on 22 June 2022), this paper will not go into detail on the associated workflows and algorithms, apart from aspects that are specific to the procedures described below. Of major importance is that Pix4D Mapper uses the radiometric metadata of the RJPGs for the identification of key-points and tie-points, allowing for more information used in the photogrammetric process, which is beneficial to the success of creating thermal orthomosaics. In addition, it is important to mention that Pix4D Mapper produces the final thermal orthophotos using the radiometric metadata of the thermograms to produce index maps with a bit depth of Float32, which means that the actual recorded values are very accurately available in the output. The result of this procedure is a thermal orthophoto that can then be imported into GIS software, in this case QGIS (https://qgis.org/en/site/ accessed on 5 January 2022), for analyses.

Such aerial passive remote sensing datasets are traditionally examined for anomalies that appear as soil marks, cropmarks and/or earthworks (e.g., [2] (pp. 33–75)). While anomalies in beyond-visible light images may also derive from, or have similar origins as, soil marks, cropmarks (i.e., near infrared images) and/or earthworks, pure thermal features, strictly speaking, do not fall within this classification. In order to stay within this terminology and maintain the classification approach of making a distinction between the physical manifestation of the signals, the anomalies identified in the course of this research
will be called ‘spectral marks’. In order to properly analyze the datasets on the occurrence of spectral marks, various products have been produced.

Alongside the thermal orthophotos, the visible light, or ‘optical’ photos, have been processed as well. These are either the images of the optical sensor of the XT2 camera, or images from a separate flight operation with the Zenmuse X5S camera, which delivers higher quality data due to its superior sensor (CMOS, 4/3”, 20.8 megapixel). Since the same ground control points have been used, these different datasets are still very easy to integrate. Processing the optical dataset delivered a visible light orthophoto, a dense point cloud and a mesh, i.e., high quality geometric data, as well as a derived digital elevation model (DEM).

Having all these combined datasets is extremely important for the analysis. Part and parcel of understanding the information on the thermal orthophoto is to execute an integrative analysis with the visible light orthophoto and the DEM in order to analyze the nature of that information. Anomalies on a thermogram may be caused by vegetation patterns, topographical features, or traces of anthropomorphic activity. For example, a ridge in the terrain at a right angle with the trajectory of the sun and facing it in the morning will receive more direct radiation relative to the contingent terrain at dawn, and less at dusk [9]. A systematic analysis must exclude the possibility that a potential interesting thermal feature is not of natural and/or recent origin, but in fact may represent (buried) archaeology. At both sites, various natural phenomena caused clear thermal expressions (Figure 2).

**Figure 2.** (a): spectral mark of a fairy ring of mushrooms (Siegerswoude, NL), (b): thermal imprint of resting cattle that just left before our arrival (Acquarossa, IT).

In order to create a comprehensive thermal representation of the research areas, thermal 3D models were also produced. The 3D geometry that is produced in the process of creating a thermal orthophoto is generally of a quite mediocre quality, due to the low resolution of the thermograms in combination with increased effects of any kind of distortion (i.e., radial distortions due to temperature differences around the sensor). However, by combining the visual information of the pixels from the thermogram with the mesh derived from the high-quality geometry of the visible light images, it is possible to create a high-quality thermal 3D model (Figures 3 and 4). Adding the 3rd dimension here allows for a more direct assessment of the primary thermal information, visualizing the relation between general patterning in the thermal data and the terrain morphology. However, this is only possible with the basic photogrammetric thermal indices which limits its application, as much of the advanced analysis requires postprocessing in GIS.

It must be mentioned that the process of thermal recording and subsequent processing can be distorted through various factors. For example, the low resolution of the thermal sensor augments the usual problems of photogrammetric processing due to lack of contrast. This is amplified again by low flying altitudes, repeated patterning in the object (i.e., grass) and the risk of movement blur. In addition, there may be global temperature changes during the recording process. This can be either the result of thermal drift (cf. [13] (p. 6), [22] (p. 4)), especially directly after sunset when the temperatures usually decrease quite rapidly, or
because of the gradual change in temperature of the bolometer core of the thermal lens itself, affecting the temperature captured in the sensor diodes [12] (p. 454). It is not the aim of this paper to go into all these issues in detail, and opportunely the effect of some of these issues remained relatively modest due to the operational procedures (hovering, short capture time, alternating altitudes). However, some of these problems did affect the outcome, which will be further dealt with below.

**Figure 3.** Photogrammetric workflow with optical (blue) and thermal (grey) data with a thermal 3D as one of the final products.

**Figure 4.** Example of Acquarossa zona M thermal 3D model.
4. Results

In the sections below, the case studies will be systematically treated. The sites will be described, the drone thermography operation will be explained, and the results will be interpreted in terms of both archaeological interpretation and methodological comparison.

4.1. Siegerswoude

The late medieval site Siegerswoude is situated on the southern edge of a Pleistocene outcrop in the northern province of Friesland, Netherlands (Figure 5). South of the site a large peat area stretches out to the river Koningsdiep. The site is currently located in a meadow on a dairy farm and was discovered by the farmer himself, who also instigated research there [23]. It is clearly visible on various aerial photographs as well as on the Dutch national LiDAR dataset (Algemeen Hoogtebestand Nederland).

![Figure 5. Siegerswoude site location, drone photo and lidar data of Siegerswoude, clearly indicating the rectangular plots.](image)

The site itself consists of at least five, and maybe nine, large, rectangular plots, evenly spaced on a straight line. One of the plots is clearly visible on aerial photographs and is demarcated by what seems to be a ditch that encloses an area of 1200 square meters. The other plots are less apparent, but their existence can be derived from historical sources. Both historical and archaeological records give us more hints about the nature of the site. The village of Siegerswoude is first mentioned in the early 14th century because of its chapel there that was later promoted to parish church. A grange from the regional Benedictine monastery was situated about one kilometer west of the site Siegerswoude. It was first mentioned in the early 16th century, but archaeological research there suggests a 14th century origin [24]. The grange was a small economic settlement that sought to cultivate the hinterland. The place was burned down in the late 16th century by order of the state of Friesland to prevent the invading Spanish army from using it to their advantage. The site resurfaces on an 18th century map where the location is marked with six dots described as old houses.

The research executed in 2019 was focused on the most clearly visible plot. After the thermographic drone survey test trenches have been established both to examine the site and to validate the results from the prospection.
4.1.1. Thermography Capturing Strategy and Conditions

The area is currently in use as grassland, with a ground matrix that is composed of a sandy soil, on top of quite heavy loam at a deeper level. Being rather dense, the soil can be expected to have a high thermal conductivity and diffusivity. Depending on the moisture level, the soil may feature differences in thermal inertia. Expected archaeological features are, based on the existing knowledge on the site, mostly likely interventions in the past, such as the digging of trenches and pits as part of the preparation of the area into plots that may have been planned as areas of habitation and exploitation. The expected depth of archaeological features is between 20–30 cm. Therefore, thermal features can be expected where differences in soil composition as a result of digging, together with altered moisture retention capabilities, will lead to different rates of heating up and cooling down, i.e., disparities in thermal inertia. Due to rain in the days prior to the thermal recording, the sandy top layer of the field was quite moist. The temperature differences between day and night were rather large, with 21 °C during the day and 6 °C at night with alternating cloud coverage and direct sun right before the drone operation. The thermograms were collected at three moments in the night, just after dusk at 20.10, at 01.30 during the night and just before dawn at 6.00, at 10, 30 and 100 m altitude, respectively, resulting in thermal orthophotos of 13.1, 3.9 and 1.3 cm GSD. Due to the variable moments of capturing, relative humidity was different for each flight.

4.1.2. Spectral Marks

The most notable spectral marks will be discussed here. In the thermal orthophoto there are clearly some traces visible that are lighter (warmer) and darker (colder) against the background. The colder spots recognizable in the image are probably anomalies that retain more moisture and heat up less quickly than the immediate surrounding soil matrix. Another explanation may be that subsoil archaeology may affect plant transpiration that will appear as colder anomalies, although the exact relationship appears not yet fully understood [2] (p. 631), [25]. The warmer spots on the other hand may be the result of less dense vegetation, which causes the underlying soil to retain less moisture and thus heats up faster under the influence of direct radiation.

The main ditch surrounding the plot which is also visible on the aerial photo and lidar data has a clear thermal signature (Figure 6, anomaly A). The northern ditch is recognizable as a double line, which is minimally visible on the orthophoto and not on the LiDAR data. In the center of this plot is a dark line in the form of a rounded rectangular spectral mark (Figure 6, anomaly B). The feature appears to be in the same orientation as that of the wide ditch, as well as that of a depression that can be seen on the LiDAR data, and even more pronounced on the drone photogrammetry (see below). The rounded rectangle appears to be just overlapping this depression (Figure 7).

The ditch of the plot immediately east of the western plot (Figure 6, anomaly D) rounds the corner where a trench can be seen with a spectral mark appearing as a double line (Figure 6E), which again demarcates a plot. Although recognizable on the LiDAR data as a trench, the double line is only apparent on the thermal image. The spectral marks (Figure 6, anomaly B,D) are similar in temperature and width to other features, especially the lines running from southwest to northeast, of which (Figure 6, anomaly C) stands out the most. This feature is not visible on the orthophoto but can be traced on the LiDAR data. However, the thermal orthophoto presents the sharpest view; here you can clearly see that the spectral mark continues towards the southwest.

As for the systematic comparison of different capturing moments and altitudes, some interesting observations can be made. First of all, the thermal orthophotos composed of the recordings at 100 and 30 m do not differ substantially (Figure 8). Apparently, the reduction of atmospheric attenuation and the higher resolution in this case do not lead to a significantly better thermal image. The recording at both levels does still have its merits though, as it allows for a control set of images of identified spectral marks. Since the spectral marks can be vague sometimes, and perhaps uncertain due to pixilation effects, having
a complementary set from another altitude can reinforce the identification of features. However, generally, a higher capturing altitude would be preferred as it allows for a larger area to be captured. At a lower altitude, here 5 m, the thermograms were very difficult to use for very practical reasons; due to the repeated patterning of grass, relatively low resolution of the photographs and distortive lens effects, the images proved to be difficult to process photogrammetrically. As individual thermograms, they were simply too close to the ground to provide useful information.

Figure 6. Thermographic orthophoto with enhanced contrast from 01.30 at 100 m, 13.9 cm GSD, with spectral marks (A–E) indicated, temperatures are only approximations.

Figure 7. Elevation model based on drone photogrammetry with indication of anomaly (B).
As for the different capturing moments, there is a clear development visible in the thermograms (Figure 9). While the difference between 20.10 and 01.30 is not very significant, there clearly is an overall cooling down. As the extremes in temperature are reducing, the distribution of sensor readings covers a smaller range. Therefore, there are more gray scale values available for the visualization of different values, and the histogram stretched thermograms of 01.30 show a bit more contrast. The thermograms at 06.00, however, show a very clear decrease in heat variation of different features, where temperatures have come closer to each other after a full night of cooling down.

4.1.3. Excavations

The archeological excavation focused on the most visible plot. Three long trenches were placed over the plot in order to gain an understandingof the wide ditch itself and the
interior that was thought of as dwelling ground. With this strategy any known house type from this era should be found (based on its size). In addition, the smaller northern ditches were examined by small trenches.

The wider ditch marking the plot was four meters wide and approximately two meters deep. Below the sandy glacial deposits there is a very sturdy layer of loam that has been used to create a platform in the northern half of the plot. It seems likely the platform was raised in order to create a dry surface to build a farmstead, but there have been no traces of an erected structure uncovered. In the center a well has been dug, surrounded by several smaller pits and postholes. None of those postholes provided an indication for a roof bearing construction. Finds were low in number and consist of pottery shards only. Some were found on the northern half of the platform, but most came from the lowest levels of the surrounding ditch. The cross section of the wide ditch shows that once it was dug, it started to slowly fill up with peat. It has been cleared out at least two or three times. Notwithstanding the efforts to clear out the ditch it finally grew thick with peat. The northern ditches were comparatively small and sometimes hard to recognize in the tilled soil. They connect to the bigger one surrounding the developed plot and have been traced up to some hundred meters to the north.

4.1.4. Interpretations

Based on the excavations, it is likely that while efforts had been started in the past to create a farmstead, or a series of farmsteads for cultivation of the area, this goal was eventually not pursued. A farmstead was not found, which can either mean that there never was a farmstead or that it was built in a way invisible to the modern-day archaeologist. The spectral marks traced on the thermal orthophotos relate to ditches that have been used for drainage purposes, either the broad ones for the creation of the plots, or the narrower ones that were probably for the fields with an agricultural purpose themselves. The thermal orthophotos provide a very clear view of the area; already identified ditches are clearly visible, at places quite more distinct or detailed (Figure 6A,E). In addition, tracts of ditches have been identified where they were not visible before (Figure 6C). Finally, a completely new feature was identified in the center of the investigated plot (Figure 6B). The trial trenches have not clearly identified the narrower ditches, which are probably hard to recognize in the tilled soil. Their partial identification on the LiDAR data confirms their presence, and apparently they retain more moisture and thus give a clear thermal signal; however, due to lack of excavation data, their exact nature cannot be further established. Nonetheless, the thermal recordings at Siegerswoude evidently provide a useful complementary dataset that increases our knowledge of the site.

4.2. Acquarossa

Acquarossa is the name of an archaeological site consisting of the remains of an Etruscan settlement on the tuff plateau Colle San Francesco, in the province of Lazio and ca. six kilometers north of Viterbo, Italy (Figure 10). The original name of the settlement is however not known. Although Acquarossa is situated in the center of the ancient Etruscan territory, close to the Lago di Bolsena, it is regarded as a town situated in the hinterland because of its remoteness from the primal Etruscan coastal cities. The site is named after the red-colored water of the creek surrounding the site. The dimensions of the plateau are roughly $1.2 \times 0.5$ km, shaped to the south as a quite irregular and slightly bent rectangle, with an elongated stretch pointed at the northeast. To the west of the plateau is Pian del Sale, which is a small triangular plateau situated at a slightly lower altitude and is currently separated from the rest of the plateau by bushes. Previous excavations of the Swedish Institute in Rome (1966–1978) uncovered substantial urban remains throughout the area. They revealed various zones with Etruscan houses and public buildings which were inhabited from the late eighth century BC until shortly after the middle of the sixth century BC, when it was abandoned, presumably after an earthquake [26]. With remains of foundations, walls, decorated roofs, and thousands of household utensils, it is one of the scarce examples of
an intact Etruscan townscape. The architectural terracottas and some other find categories have been studied in detail, and several exhibitions were organized [27]. Although the various excavations have been reported in a series of publications, the complete synthesis of ten years of excavation has never been fully published [28,29].

Excavations in the outermost northeast tip of the plateau brought to light remains of Archaic habitation, with a structure interpreted as a domestic building dating from the last half of the seventh to the sixth century BC [30] (p. 36). The archaeological remains were found in the southern part of a trial trench, which extended from the north edge to the south edge of this part of the plateau. In a later phase of research, a trench was set out at the south side of zona M in which parts of a southeast-northwest oriented house was laid bare at around a depth of about 30–50 cm.

The drone survey was oriented at zona M, because of the attested remains of structures at a probably shallow depth. The drone operations were accompanied by a GPR survey, to generate a complementary dataset for the analysis of the efficacy of the remote sensing efforts.

4.2.1. Thermography Capturing Strategy and Conditions

The complete central plateau is covered with grassland and is presently used as grazing grounds for cattle. The ground matrix consists of sandy soil on top of a soft and partly eroded tufa bedrock. As there has been no recent agricultural activity, such as ploughing, the soil matrix can be expected to be relatively compact, with particles densely packed together. With relatively large grains of sand in close contact with each other, this likely results in good thermal conductivity, diffusivity, but low thermal inertia. This also makes for a good permeability for water, which can be transported through the soil and via the stratified tuff layers flow to the lower parts of the plateau. Based on the earlier excavations, clearly, we can expect archaeological features, of which the most prominent will likely be
stone structures. Thermal features can thus be expected where such structures are close to the surface and/or affect subsoil water drainage. In the first case, spectral marks could be present due to stone that has a relatively high volumetric heat capacity and thus higher thermal inertia than the sandy soil surrounding it, almost twice as large. After sunset on a day of direct radiation of sunlight, stone may retain heat longer than the surrounding soil, resulting in warmer spectral marks. In the second case, water retention could create moist pockets that, again due to a high volumetric heat capacity, have relatively high thermal inertia. Since water has almost twice the volumetric heat capacity in comparison to the average stone material, the change in temperature of the material happens at a much slower rate, and water pockets may be cooler or warmer than the surrounding soil, depending on the specific temporal atmospheric circumstances (for comparison of volumetric heat capacities of different materials see [31]). A potential caveat here could be that tufa bedrock that protrudes high in the topsoil layer can show similar thermal behavior as a stone structure, which is a potential bias that must be carefully considered in the analysis.

The weather conditions during the drone and GPR operations at Acquarossa were rather wet. Flying opportunities were limited due to intermittent showers of rain, causing the soil to be very moist, and at the same time some sun was breaking through the clouds. Temperature differences between day and night went from 13 to 6 °C., with an average daily temperature of 10 °C. The thermograms were collected at two moments during the night, at 17.30 and at 06.00. The 17.30 flight was possible that early due to early heavy cloud cover resulting in a complete blocking of radiation from the sun. A midnight flight, however, was impossible due to heavy rain at the planned moment. Instead, an additional flight was executed at 09.00, to see how a thermal recording would perform after dawn, still cloud covered. Capturing altitudes were at 15, 30 and 100 m altitude, with the flight at 09.00 only at 100 m. Due to the variable moments of capture, relative humidity was different for each flight.

4.2.2. Spectral Marks

The most striking results are observable on the 17.30 thermal recording at 100 m (Figure 11), of which the thermal orthophoto shows a variety of warmer and cooler spots. Very clear is a ca. 20 m wide band of cooler marks that runs in a southeast to northwest direction of around 150 m length, only cut off on the east due to the limits of the orthophoto (Figure 11b, anomaly A). The band runs perpendicular over a slightly downwards sloping part of zona M. Judging from the size of the thermal anomaly, its irregular shape and seemingly natural relation to the local morphology of the terrain, the anomaly most likely must be interpreted as moist areas or even subsoil water conduits, where the water as a result of the rain runs off to the edges of the plateau to the south and southwest. The water is most likely cooler than the surrounding soils that have been sporadically heating up due to the pockets of direct sun, where the water due to its high thermal inertia was only marginally affected. Again, given the vegetation on the plateau, it is possible that there is also a connection to plant transpiration affected by subsoil phenomena.

The archaeologically most interesting anomaly however is the somewhat rectangular shape visible as cooler spots in the north of the thermal orthophoto (Figure 11b, anomaly B). The anomaly is situated at a slightly elevated area of zona M, and clearly stands out against the surrounding soil. While the spectral marks are again quite spotty or smeared, and less cool than the band mentioned above, the overall shape and size could correspond with a subsoil structure. This composition may be explained by walls or ditches, locally preventing or slowing part of the rainfall draining off to the lower parts of the area, causing local spots of moisture and thus cooler soils than the soils directly surrounding the anomaly.

Finally, there are also some clear warmer marks in the 17.30 orthophoto. Very prominent are the spots representing the fieldwork vehicles, equipment and team present for the drone operation and GPR recording. Due to the logistics of the terrain and limited opportunity to execute the fieldwork, this was unavoidable. More subtle warmer features appear as more or less straight, and at some point, angular lines here and there, but they
are far from clear. Even if they are related to, for example, stone materials that retained more heat after dusk than the surrounding soil, it is still very difficult to differentiate them from protruding tufa bedrock.

The systematic comparison of different capturing moments and altitudes also allows for some notable observations. The recording at 17.30 at 100 m provided the best thermal model with the clearest features. The altitude of 100 m with 13.9 cm GSD resulted in thermograms with a large enough contrast to facilitate photogrammetric postprocessing, whereas it appeared to be too problematic to properly process the 30 m and 15 m recording. The 30 m flight still produced useful individual thermograms that can be used for comparison, albeit more difficult to read because of the relatively small footprint of the individual captures. Inspecting the recordings at 6.00 and at 9.00, clear differences can be attested. At 6.00, thermal contrasts have decreased significantly, probably due to cooling down during the night, converging the relative temperatures between moist and less moist areas. The anomaly in the north of zona M disappeared completely, which appears consistent with the fact that the marks there were less prominent, probably due to less moisture being retained there. Looking at the 9.00 recordings finally, thermal contrast completely changed to a very fine-grained global pattern of spectral marks caused by the grass in the area.

4.2.3. Ground-Penetrating Radar

Ground-penetrating radar or GPR is a well-known geophysical technique that is seeing increased application in archaeological fieldwork in the last decades [32–34]. Currently, the advances in geophysical equipment, such as multichannel antennas, 3D antennas, and major improvements in software both for the purpose of processing and visualization, are progressing the incorporation of GPR in many site- and landscape-oriented projects. GPR
is a geophysical technique which works with radiofrequency electromagnetic radiation to detect archaeological or natural features in the subsoil based on dielectric permittivity, magnetic permeability, and electric conductivity of both buried target and surrounding medium [35] (p. 3). The methodology employed in most of the GPR applications is the survey of parallel lines or radargrams of a grid. Each radargram then records many reflections as the EM signal crosses through materials of different electric characteristics. During postprocessing the results can be processed both in two and three dimensions. The final and most common GPR product in archaeology is a series of slices showing the recorded reflections at different depths as a function of the time measured in nanoseconds that elapses between the emission and return of the radio signal by the antenna [32] (p. 13).

The GPR survey in Acquarossa has been executed using a Sensors and Software Noggin 250 MHz antenna transported on a cart for single-person operation. The radiofrequency employed in this project has been compared against antennas of different frequency and manufacturer [36], and demonstrated its capability to produce clear archaeological results [37]. The grids in zona M measured 40 by 80 m, albeit the actual surveyed surface was 3035 sqm due to irregular edges of the area. Processing was performed using Ekko Project v.5 following a workflow similar to the one implemented at Lechaion, Greece [38]. The resulting 20 cm depth slices were exported to tiff format and visualized in QGIS.

At a depth of 50–60 cm below the surface, other possible structures could be discerned by the edge of the survey area (Figure 11c, corresponding to the spectral mark B in Figure 11b). The limits of these structures are not fully clear to the bad ground conditions, and perhaps also due to the presence of fillings or collapsed material. Underneath the possible archaeological features, we detect elongated and sinuous areas of low amplitude reflections that seem to be water streams or geology crossing the survey area (corresponding to the spectral mark A in Figure 11b), apparently running from west to east in the lower part of the area. GPR depth slices closer to the surface show the marks of a pathway crossing the plateau and heading to a gate in the fence. This feature could be interpreted as...
compacted soil due to the continuous passing of vehicles heading to the gate. Moreover, a large area with high-amplitude reflections may relate to water trapped close to the surface. Deeper layers present a series of high and low reflections which have been interpreted as the contrast between wet and dry geological layers, which most likely represents the tufa bedrock geology abovementioned in the description of the site.

4.2.4. Interpretations

Based on the combined data projections of both the thermal recordings and the GPR measurements, a few tentative interpretations can be suggested. Both the thermographical and the GPR survey did not detect the trenches of the 1970s excavations, neither the trial trench nor the larger trench, or the walls identified within them. It is likely that the moisture in the area of the identified thermal ‘band’ completely masks the more subtle remains of walls that are buried there. The GPR data do appear to confirm the existence of these subsoil water streams, and a rough correlation can be seen at the 900–1200 cm GPR slices (Figure 13). The identified spectral mark in the north, however, does seem to be complemented by likely archaeological features observed in the GPR slices at 50–60 cm depth. It must be admitted that the orientation of the features as they have been observed from the GPR data appear to be differently orientated, but this may be an inaccuracy due to earlier mentioned interpretation problems. A tentative confirmation of GPR and thermography tracing the same features can be found in the anomaly further east, which shows as an angular structure on the GPR data and has a clear thermal signature as well.

![Figure 13. GPR all slices identified anomalies, GPR amplitudes have been normalized and visualized using a red–blue RGB color ramp.](image-url)
Although the interpretation of the sensor readings as a structure remains at a hypothetical level, it is nonetheless interesting to compare the anomaly with structures attested in previous excavations. One of the most prominent eighth–seventh century BC buildings has been excavated at Pian del Sale, zona N. If we overlay the excavation plan of the unearthed houses over the anomaly, we see a coarse correspondence in shape and size of both the thermal anomaly as well as the features identified on the GPR slices (Figure 14). This might reinforce the possibility that the identified anomaly could indeed point to a subsurface structure in this area.

Figure 14. Architecture drawing from the excavations at Pian del Sale projected onto the thermal orthophoto from 17.30 at 100 m, 13.9 cm GSD, temperatures are only approximations.

5. Discussion. The Performance of Drone Thermography in a Comparative View

In these two case studies, empirical data have been collected that can now be reviewed in the context of the conditions for drone thermography performance. The initial comparison already pointed out some comparable aspects of the sites and the fieldwork circumstances. Both sites likely feature shallow buried archaeological features, land use in the form of pasture, and both were investigated on a moment of quite wet weather with temporal pockets of direct radiation from the sun. Furthermore, although very different in origin, both sites feature what can be described as dense sandy soils, which can be expected to have high thermal conductivity and diffusivity, and in both cases thermal inertia of the soil will mostly be affected by moisture content. Although the sites feature permanent grassland, which is usually regarded as less than optimal for thermal feature detection (Perisset and Tabbagh, 1981), in either case spectral marks have been attested. The success of detecting potential archaeological anomalies using thermography in these cases is interesting given the differences in absolute diurnal heat flux, which were 7 °C. at Acquarossa and 15 °C. at Siegerswoude. From these cases one may infer that the distance between maximum and minimum in absolute diurnal temperature flux is less important than the fact that there is a sharp sequence of heating up and cooling down. Apparently, the moisture in the ground retains the lower temperatures during the day, where the radiation appears to raise the temperature of the dryer soil to a relative high level, such that it is
traceable on the thermograms in contrast with the moist soil. Following from this, we can infer that in both cases we do not directly pick up spectral marks of archaeological features, but rather marks created by the moisture conditions that appear to be affected by them. The thermal inertia difference between moist areas and less moist areas is the most profound thermal effect that is registered. It must be mentioned that these factors are beneficial to the tracing of spectral marks at a relatively low depth, i.e., related to differences in moisture of the topsoil layers. The detection of these features appears to corroborate the notion that, although deeply buried features may be difficult to detect based on the temperature differences caused by the diurnal flux, shallow buried features could still be traced [2].

Furthermore, on both sites the optimal moment of thermographic capture was clearly directly after sunset. Consistent with the interpretation above, curves of temperature change diverge during the day, and the transition from direct radiation to no radiation after dusk immediately results in a cooling process that eventually makes the temperature curves converge in the course of the night. This conclusion echoes those of others, observing the same phenomenon (e.g., [13] (p. 9)). An additional effect may be caused by the increase in relative humidity and the approaching of the dew point, which is known to have a negative effect on thermal recording due to absorption effects (cf. [39] (pp. 80–81), [13] (p. 9)). The Acquarossa case shows a consistent relative humidity of 72–75% through the night, a very slight increase, and the Siegerswoude case shows a slightly more significant increase, from 72–93% through the early night, but a reduced 83% in the morning. This may be interesting, as the reduction appears rather inconsequential to the general trend of converging temperature. A reason for the limited effect of the relative humidity could be that the dew point was never actually reached, in which case condensation that is likely to mute thermal differences would appear (cf. [13] (p. 9)). Although this is a single observation, it does raise the question of the exact relative weight of these factors for effective drone thermography; what is more important, the fluctuations in relative humidity or the temperature flux of the soil during the night.

The capturing altitude also produced comparable results; in both cases, the very low recording did of course result in higher resolutions, but in these cases that did not add much information. It did create however a lot of problems for the post processing steps, even using the wide 13 mm lens. These problems may be further mitigated by improving the recording operation strategy, although one can still doubt whether the increased resolution at the sacrifice of, due to battery limitations, decreased spatial coverage is effective. It must be noted of course that this conclusion is drawn based on sites with rather sizeable spectral marks, and where one can expect more subtle features to appear in thermograms, it may warrant lower altitudes.

On the whole, we can conclude that in both cases, drone thermography provided a valuable complementary dataset for the analysis of the site. In general, the higher altitudes (from 30–100 m) provided useful information and a suitable set of images for processing. The recordings directly after dusk in these cases provided the best capturing moment, as the specific circumstances at the sites showed the most profound temperature differences at that moment, with converging ground temperatures during the night.

6. Conclusions

In the end, this study has been prompted by the promise of drone thermography as well as by acknowledgement that there is a need for more case studies to increase the knowledge on its performance in different conditions. In fact, it would be beneficial to build an international database of cases in which the factors that appear to determine failure or success of drone thermography can be systematically recorded and compared. The work of, for example, Casana et al. [9], Hill et al. [13] and James et al. [14], provide encouraging examples of cases to enter into this database through their comparison of different sites in various soil, vegetation, atmospheric circumstances or at different recording moments in the annual cycle, as well as the recording and processing procedures. Eventually, we can succeed in learning lessons from this, essentially, multivariable conundrum and arrive at...
some sort of, possibly pyramidal, decision-tree for the estimation of successful application of drone thermography in diverse environments.

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**References**


