Archaeological aerial thermography: a case study at the Chaco-era Blue J community, New Mexico

Jesse Casana a,*, John Kantner b, Adam Wiewel a, Jackson Cothren c

a Department of Anthropology, University of Arkansas, Main 330, Fayetteville, AR 72701, United States
b University of North Florida, 1 UNF Dr., Jacksonville, FL 32224, United States
c Department of Geosciences and Center for Advanced Spatial Technologies, University of Arkansas, JBHT 320, Fayetteville, AR 72701, United States

1. Introduction

Archaeologists have recognized since the 1970s that aerial images which record thermal infrared wavelengths of light (7.5–13 μm) could be a powerful means for recognizing both surface and subsurface cultural remains (e.g., Tabbagh, 1977; Fourteau and Tabbagh, 1979; Berlin et al., 1977), yet technological and cost barriers have largely prevented the widespread application of thermal imaging in archaeological contexts. This paper presents interim results of a National Endowment for the Humanities-funded project to develop techniques for collection of thermal imagery using a UAV, to design workflows for efficient photogrammetric processing of imagery, and to assess the effectiveness of the technology at archaeological sites located in a variety of different environments. Herein we present a case study that provides an illustration of our methodology, conducted at a Chaco-period archaeological community known as Blue J, located in northwestern New Mexico about 70 km south of Chaco Canyon (Fig. 1). Results demonstrate the enormous potential of aerial thermography in archaeology, revealing the organization of occupation at Blue J and aiding in the discovery of many previously undocumented subsurface architectural remains, as well as providing a blueprint for similar investigations elsewhere.

2. Archaeological thermography

The principles behind archaeological thermographic imaging are relatively simple: due to their composition, density and moisture content, materials on and below the ground surface absorb, emit, transmit, and reflect thermal infrared radiation at different rates. Experimental data illustrates the complexity of the variables that affect the potential visibility of archaeological features in a thermal image (Scollar et al., 1990: 593–611). However, in general, such features should be resolvable if when compared to the background matrix they have sufficient contrast in thermal inertia, a product of a material’s thermal conductivity and its volumetric heat capacity (Perisset and Tabbagh, 1981), and if the image is acquired at a time in the diurnal cycle when such differences are pronounced. Several studies have demonstrated that thermography can detect features at or near the ground surface such as pits, ditches and field boundaries as well as buried architectural features up to a half meter below the ground (e.g., Perisset and Tabbagh, 1981; Lunden, 1985; Bellerby et al., 1990).

Despite its potential, archaeological applications of the technology are scarce, largely because few archaeologists had access to...
the highly specialized radiometers used by researchers in the 1970s (Scollar et al., 1990: 614–18), while thermal images acquired from civilian satellites such as Landsat and ASTER are of too low spatial resolution to reveal most archaeological features. Even the aircraft-acquired TIMS (Thermal Infrared Multispectral Scanner) imagery that Sever and colleagues famously utilized to document ancient roadways in the Chaco Canyon area (Sever and Wagner, 1991) and in Costa Rica (Sheets and Sever, 1991) was only 5 m resolution. While a handful of other more recent archaeological investigations have used higher-resolution, aircraft-acquired thermal imagery (e.g., Challis et al., 2009), the exorbitant cost of imagery acquisition, requiring tasked flights of specialized aircraft equipped with advanced sensors, puts the technology well beyond the reach of most archaeologists. Several recent studies have instead explored the archaeological potential of much higher resolution thermal images collected with conventional handheld cameras. Ben-Dor et al. (2001) use imagery collected from a helicopter to detect subsurface stone architecture in Israel, while Buck et al. (2003) use thermal images collected by a camera mounted on a platform to reveal differing concentrations of surface artifacts. A few avocational archaeologists have similarly collected images of archaeological sites using handheld thermal cameras attached to kites, revealing many subsurface remains (Wells, 2011). One of the most systematic studies was undertaken at late prehistoric mound center in Mississippi, where thermal imagery acquired with a handheld camera suspended from a helium blimp was used to successfully document subsurface house remains as well as the diurnal variation in their thermal values (Haley et al., 2002; Giardino and Haley, 2006). Kvamme (2006, 2008) was the first to deploy such an approach on a site-wide scale, flying a handheld thermal camera aboard a manned powered parachute (see, Haley, 2005), at Fort Riley, Kansas and Double Ditch, North Dakota. His results are inspiring in their possibilities as they reveal much of what can be seen in more traditional geophysics, as well as distinct features not recorded by other methods. However, implementing Kvamme’s approach would be very challenging, requiring a microlight aircraft, an experienced pilot, ideal weather conditions, and extensive work to rectify and mosaic the images into a usable map.

In recent years, several technologies have emerged that make possible the cost-effective acquisition of high-resolution thermal data at the scale of sites and landscapes. Firstly, unmanned aerial vehicles (UAVs) are rapidly improving in sophistication and reliability, enabling archaeologists to collect aerial imagery from specific altitudes with precise camera orientation at any time of day and in a range of weather conditions. The possibilities for UAVs to aid in archaeological research have recently generated much interest, particularly for documenting sites, monuments and excavations (e.g., Verhoeven and Docter, 2013; Hill, 2013; Chiabrando et al., 2011; Seitz and Altenbach, 2011; Sauerbier and Eisenbeiss, 2010; Eisenbeiss and Zhang, 2006). At the same time, advances in photogrammetric image processing software packages, such as Agisoft’s PhotoScan and Microsoft’s Image Composite Editor (ICE), now make quite straightforward the once laborious process of mosaicking, orthorectifying and georeferencing images, a fact which is rapidly transforming archaeological documentation more broadly (e.g., De Reu et al., 2013; Verhoeven et al., 2012a, 2012b; Eisenbeiss and Sauerbier, 2012; Verhoeven, 2011; Koutsoudis et al., 2007). Finally, commercially available thermal cameras have been significantly improved upon over the past several years, with increased spatial resolution (from 320 × 240 to 640 × 512 pixels) and thermal sensitivity (from 0.2 to <0.05 K), while also being reduced substantially in both size and cost. Through a case study at the Chaco-period Blue J Community, New Mexico, research
presented herein integrates these various technologies and demonstrates an efficient methodology for their deployment in archaeological investigations.

3. The Blue J community

Located in northwestern New Mexico (Fig. 1), Blue J is an Ancestral Puebloan community that was first identified by archaeologists in the 1970s, although official records do not appear until the 1980s and 1990s through cultural resource management reconnaissance efforts (Kantner, 2010). These projects, however, only examined a few of the households located on the edges of the larger prehistoric community. It was not until Kantner’s investigations in the 2000s under the auspices of Georgia State University and the School for Advanced Research that the full extent of the visible surface occupation was identified and the community fully recorded (Kantner, 2013).

The Blue J Community consists of nearly 60 Ancestral Puebloan households loosely clustered over approximately two square kilometers around what was once a large spring (Fig. 2A). The majority of the households were built along a sandstone escarpment, leading to considerable alluvial, colluvial, and aeolian deposits over the community (Fig. 2B). Each household, which is recorded as a separate site, typically includes a masonry roomblock of 3–15 rooms that faces a flat plaza area to the east or southeast. Beyond this, a shallow and usually expansive midden area is typically found. This layout is known in the American Southwest as a “Prudden unit,” named after the archaeologist who first discussed the ubiquity of this layout across the early Puebloan world (Prudden, 1903). In principle, Prudden unit households should also feature subterranean structures in the plaza that are usually interpreted as having served a combination of ceremonial and domestic functions. In the Blue J Community, however, households were buried by up to a meter of eroded sandstone and wind-blown silt, making identification of subsurface deposits difficult without excavation (Kantner, 2013). In fact, the only two subterranean structures identified by Kantner were found through a program of subsurface test excavations. Similarly, although the roomblocks could usually be identified on the surface, their full extent was only revealed through excavation; testing of several roomblocks found that approximately 30% of each roomblock was too deeply buried to be identified on the surface.

The issue of extensive deposition over the Blue J Community is relevant because of the sites’ potential importance for understanding...
4. Regional dynamics of the Ancestral Puebloan occupation. Investigations in the community show that it was occupied from at least AD 600 to as late as AD 1150, but the greatest intensity of use was in the eleventh century (Kantner, 2013). This is during the fluorescence of an influential ceremonial center in Chaco Canyon, during which the vast majority of Puebloan communities across the northern Southwest constructed two forms of monumental architecture known as "great kivas" and "great houses." Great kivas are large, circular subterranean structures with diameters of 10 m or more that have a deep history in the Puebloan Southwest long predating the Chaco period, but which became more formalized in Chaco Canyon and surrounding areas during the eleventh century. Great houses, in contrast, are monumental surface structures that seem to have been inspired by archetypes constructed in Chaco Canyon beginning perhaps in the ninth century but fluorescing in the late AD 1000s. The presence of both great houses and great kivas in communities across the Puebloan Southwest are thought to reflect the degree of adherence to the ceremonial tradition based in Chaco Canyon (Kantner and Kintigh, 2006; Van Dyke, 2003, 2007).

Kantner's investigations in the Blue J Community have located neither a great house nor a great kiva, making it unusual among its neighbors. In fact, these architectural forms have been identified in every other Chaco-era community in the immediate region, even though few have been the subject of intensive archaeological investigation (Kantner, 2010). Whether the absence of these features is the result of deposition over the community, or whether these structures were never constructed there, is important for understanding when, how, and why communities like Blue J aligned themselves with the ceremonial center of Chaco Canyon (e.g., Kantner and Vaughn, 2012; Lekson, 2009; Reed, 2011). Although some targeted magnetometry and resistivity work has been conducted in the Blue J Community, with mixed results, its considerable size calls for a remote sensing approach that can effectively and efficiently cover a large area.

4. Instrumentation and methods

4.1. Thermal camera

The thermal camera we use is built around FLIR's Tau II LWIR uncooled camera core. The camera records light in the 7.5–13 μm range, with a sensitivity of 0.05 K at f/1.0, effective at ambient temperatures from −40 to 160 °C. The camera has a resolution of 640 × 512 pixels, with a pixel pitch of 17 μm, and records 8-bit video images at a frame rate of 30 Hz. While the resolution of the camera is very low by comparison to color light cameras, it is five times better than the best cameras on the market only a few years ago and among the highest resolution thermal cameras available commercially. To maximize the camera's field of view, and thereby reduce the altitude at which the camera would need to be positioned during aerial surveys, we use a relatively short focal length, the 19 mm lens option. The Tau II camera core, designed more for laboratory than field applications, was attached to a power source and SD card recorder, and fitted inside an aluminum case for aerial deployment (Fig. 3).

4.2. Unmanned aerial vehicle

UAVs offer key advantages over traditional forms of archaeological aerial imaging (cf. Verhoeven, 2009), particularly in their ability to cover large areas at a fixed altitude and speed under a wide range of wind and weather conditions. For aerial thermography, these capabilities are essential, because imagery acquisition is highly time-sensitive. To maximize archaeological visibility, thermal imagery has to be collected at a time of day when the contrast in thermal inertia is highest between the archaeological target and the background soil and ground cover. Moreover, the entirety of the survey area must be covered with as little temporal variability as possible in order to reduce drift in thermal values across a single mosaicked scene. Additionally, the relatively stable and slow moving platform of a copter-type UAV is advantageous because the pixels of the Tau II camera heat and cool continuously as the IR signal is integrated. With an unstable platform, IR frames are comparatively more difficult to mosaic as the imagery is subject to artifacts related to the camera's shutter type (FLIR, 2013).

In this project we utilize a CineStar 8 (Fig. 3), one of the preferred UAVs for aerial cinematography and other similar applications. The eight-rotor "octocopter" can lift around 2 kg (4.4 lbs) of payload, with cameras mounted on an independently operated gimbal suspended below the UAV. The gimbal is capable of a full 360° of motion, enabling cameras to be pointed in a predetermined direction or at a specific point regardless of the motion of the UAV (Freely Systems, 2014). It also has vibration control and stabilization devices that greatly reduce image blur. The flight and navigation controls for the CineStar are produced by industry leader MikroKopter, and are well suited to the needs of surveying. The custom software enables users to download a Google Maps image of the survey area, and then to plan flight paths with up to 35 GPS-guided waypoints (Fig. 4). Users can therefore specify the precise location and speed of the UAV, as well as the camera orientation throughout the survey. A telemetry device enables the craft to be monitored while in flight on a laptop ground control station, and all flight data is recorded on an SD card aboard the craft. Finally, the fact that the craft is sold as a kit means it can be easily customized to suit users' needs, and can also be readily repaired in the event of a crash or other equipment failure.

With these advantages, there are still many issues with the system, particularly for novice operators, as a perusal of the discussion boards dedicated to UAVs will quickly demonstrate. While...
the CineStar 8 can have a flight time of up to 24 min if outfitted with a GoPro camera and flown in windless conditions, using a larger camera in real world conditions flight times are considerably less, probably around 15 min (although one would not want to find out the limit during a survey, so some additional buffer time is always required). Thus, flight time becomes the major limiting factor in the size of survey areas. The engineering of many components is also far from robust, and in our experiments with the UAV, we found it prone to frequent failures for a multiplicity of reasons, including faulty electronics, wires of inadequate gage, vibration loosening of propellers, and many other issues. Nonetheless, considering the low cost and flexibility of the CineStar 8, it suits the needs of archaeological aerial thermography reasonably well.

4.3. Imagery acquisition

As discussed above, one of the main strengths of the UAV over other aerial photographic platforms such as kites and balloons is the control it gives users in planning surveys precisely. While the relatively short focal length of our thermal camera (19 mm) increases the area of the ground that can be covered in one image, its small sensor size (8.70 × 10.88 mm) restricts the camera’s field of

![Fig. 4. (A) The MikroKopter-Tool software used to program and pilot the CineStar8, with waypoints, flight path, and telemetry display as used at the Blue J Community, and (B) actual flight path of 7:18am flight as recorded by the onboard GPS, overlaid on a Google Earth image.](image-url)
view to only 26 × 32°. Combined with its rather low resolution of only 512 × 640 pixels, we are faced with a trade-off between the ground area of an image and the resolution of the resultant data, determined by the altitude of the camera. While it would be theoretically possible to simply collect a larger number of high resolution images from a lower altitude, the short flight time of the CineStar 8 at around 15 min, makes this impractical. Thus to maximize the areal coverage of a survey, which is typically the goal, one can either increase the altitude of the UAV, at the expense of image resolution, or increase the speed of transects, at the risk of blurring images during flight. For the surveys at the Blue J site, we selected a compromise of 70 m elevation for the UAV, yielding 6–7 cm ground sampling distance for thermal images (comparable to high-resolution geophysical datasets) and an image footprint of approximately 32 × 40 m. Survey speed was set at 5 m per second (11.2 mph) as our past experiments suggest that at 70 m, flying faster than this will result in an excessive number of blurred images.

In order to ensure that images can be effectively processed in PhotoScan or other photogrammetric software packages (see Section 4.4) a high percentage of image overlap is required, generally 70–80%. In order to reduce the number of transects in a survey, we orient the camera perpendicular to the flight path. The relatively high frame rate of the video feed (30 Hz) means that we will collect many images per meter along each transect, enabling us to extract images with 80% or greater overlap. To align transects with one another, we plan on approximately 40% cross-lapping images. At the altitude and orientation described above, this requires transects to be spaced approximately 20 m apart.

At the Blue J community, we conducted surveys with eight east-west oriented transects of 300 m length, spaced at 20 m, enabling us to image an area of approximately 220 × 360 m in thermal infrared. Color imagery was also collected using a Nikon D6000 camera, with its timer set to take photos at 1 s intervals. The color image helps to interpret results of the thermal data, producing images of 2–3 cm ground sampling distance, and is also used to generate a high resolution digital surface model. The wider field of view of the camera, with focal length of its variable zoom lens set to 18 mm, enables a larger area of the ground (280 × 420 m) to be imaged using the same flight parameters.

To aid in georeferencing of image mosaics, we placed eight ground control targets across the survey area, and using a total station, recorded their locations within the coordinate system used in previous investigations at the site. Targets were made of aluminum sheeting because metals have very low thermal emissivity, and thus tend to appear very dark on thermal imagery. Our targets measured 60 × 15 cm, with the expectation that they would appear as 2 × 10 pixel targets in thermal data. While all of the targets are visible in the thermal data, most tend to blur in the imagery, appearing more as dots than Xs, and so in future surveys we plan to increase their size, perhaps to 1.2 m in length. A larger number of targets could improve the accuracy of the final images, although our results using only eight targets were still very good (see Section 4.4).

### 4.4. Image processing

We rely primarily on Agisoft PhotoScan to produce both color and thermal ortho-imagery. For each thermal flight, we first extract still images from the video feeds recorded by the Tau II camera. Although the camera records at a high frame rate (30 Hz), we found that only one frame per second is necessary for sufficient overlap along flight transects. For color photographs, we selected approximately every fourth image between the first and final waypoints, avoiding inclusion of either blurred or excessively oblique images.

PhotoScan is one of many modern photogrammetric applications which integrate relatively new feature extraction and matching capabilities with traditional aero-triangulation based on the self-calibrating bundle adjustment (Mikołajczyk and Schmid, 2004; Triggs et al., 2000). As such it is capable of creating accurate orthoimagery and digital surface models from overlapping two-dimensional imagery with manual point measurement only required for ground control identification (Verhoeven, 2011; Verhoeven et al., 2012a; De Reu et al., 2013). Briefly put, after adding all photographs from a flight to PhotoScan, the software automatically aligns the images by identifying corresponding features shared among photographs (Agisoft, 2013). The software estimates the locations of these points, from which a sparse point cloud is derived, and more importantly, camera locations are approximated and internal camera parameters are estimated (Fig. 5). Using the estimated camera positions and the actual photographs, PhotoScan then calculates depth maps from which a dense point cloud and meshed model are generated. We used the highest accuracy setting to align photographs and the height field-smooth method to build geometry. Initially, we produced a medium quality model, enabling us to use a guided approach by then placing our eight ground control points. After refining marker placement in each photograph and adding ground control point coordinates, PhotoScan optimizes the alignment to build a more accurate and georeferenced mesh. We used the height field-smooth method to reconstruct geometry to produce an ultrahigh quality mesh from

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**Fig. 5.** Thermal image mosaic from the 7:18am flight illustrating the estimated camera locations along the flight path as calculated in Photoscan.
which we generate color and thermal orthophoto mosaics, as well as a digital surface model.

Microsoft ICE, a freely available panoramic image stitching tool, offers an alternative to PhotoScan, and a particularly good method for processing thermal data because ICE is capable of producing a seamless high-resolution panorama directly from a video feed. While not offering the flexibility to change settings and parameters like Photoscan, ICE requires dramatically less processing time and memory demands, meaning one does not need a high-end computer to process imagery. The software also seems to select images from the video feed that have high contrast and clarity, thereby producing image mosaics on which it can be somewhat easier to recognize archaeological features. After producing image mosaics in ICE, we then simply used our ground control points to georeference the mosaic in ArcGIS. To be clear, ICE does not produce an orthophoto and in areas of high topographic relief, the image stitching application will produce excessive errors. For small scenes over relatively flat terrain, we found results to be visually pleasing and somewhat easier to interpret than the resampled orthophoto produced by PhotoScan.

5. Results

We flew five surveys at the Blue J community, collecting four thermal datasets and one color photographic series. Each flight took approximately 11 min from takeoff to touchdown. The four thermal flights were begun respectively at 9:58pm, 5:18am, 6:18am and 7:18am, while the color photographic flight was begun at 5:45am, just prior to sunup (Table 1). We had intended to collect imagery at peak afternoon heat as well, but on the days of the surveys there were frequent wind gusts of up to 30 mph during the afternoon and early evening, making flights impossible until around 9pm. While the CineStar 8 can fly in far more diverse wind conditions than other aerial photographic platforms, strong, gusty winds make flying challenging even for experienced pilots. On the days in question (June 20–21, 2013), temperature variability was high, as is common in deserts, reaching 32 °C (90 °F) on the afternoon of June 20 and a low of 8 °C (46 °F) in the early morning hours of June 21. Such temperature oscillations may improve the likelihood that archaeological features will appear because the ground will likewise experience more extreme heating and cooling over a diurnal cycle.

As outlined in Section 4.4, color and thermal imagery was orthorectified, and georeferenced mosaics of each flight were produced. Each thermal orthophoto mosaic was composed of approximately 350 still frames while 118 color images were used to create a color orthophoto mosaic (Fig. 6) and digital surface model of the site (Fig. 7). Alignment of the thermal images was based on at least 200,000 matched features across the scene. Interior orientation of the camera followed Brown’s model (Triggs et al., 2000) with only the focal length, principal point, pixel aspect ratio and three radial distortion parameters treated as unknowns. In all cases, the resulting estimated parameters (19.80 mm calibrated focal length, 3% longer in the camera x direction) did not deviate significantly from our initial estimates. Four of the surveyed ground points were used in the alignment while the other four were withheld and used as check points (Fig. 7). The alignment (or aero-triangulation) resulted in control point RMSE errors of approximately 6 cm horizontal and 3 cm vertical. With so few control points this is expected and so we rely on the check point errors to indicate the quality of the alignment. Check point errors at each of the four points for the 6:18am flight are shown in (Table 2). Horizontal and vertical errors at the check points are larger than at the control points — again, expected — but still only about the size of a pixel in the final orthophotos.

In all thermal images, the modern road, an unimproved dirt track, appears very clearly at the top of the image, as does the tarp used to launch the UAV (in order to minimize dust particles from getting inside the motors) (Fig. 6). Our two vehicles and team members also appear at the upper left of the images. Because the UAV tends to swing as it adjusts to new waypoints, we collected more oblique images at transect ends than we had anticipated. The best image for archaeological visibility is the 5:18am flight (Figs. 6 and 8A), which reveals many surface and subsurface features. The ambient warming of the vegetation at the site by 6:18am results in increased noise (Fig. 8D), while by the time the 7:18am image, intense raking sunlight covered the entire site, producing an image that primarily records how surface features differentially reflect thermal radiation (Figs. 7 and 8E). While subsurface features are far less apparent in the 7:18am image, the fact that the relief of the ground surface is so clearly visible makes archaeological features with topographic expression quite evident. Experimental data from the 1970s show that in some cases the ability of early morning thermal imagery to reveal micro-relief can be used to extensively map archaeological remains (Scollar et al., 1990: 623–8).

In all nighttime images, modern vegetation creates a very strong signature, as the water in trees and plants tends to retain heat much more readily than the dry desert soils. In the 9:58pm image, there is more vegetation noise than in the pre-dawn images, as even grasses and small shrubs produce high thermal infrared values (Fig. 8F). By the following morning, the larger trees and woody shrubs still appear as high value spots, while most of the grasses and smaller plants had cooled, reducing noise and increasing the likelihood that archaeological features will appear (Fig. 8A). Similarly, the complex geology of the cliffs and talus slopes at the northern edge of the survey produce very strong thermal noise (Fig. 6), with extreme high and low values, and thus make detection of potential archaeological remains unlikely. In both evening and pre-dawn images there are numerous low value, round features measuring 1–3 m in diameter, some of which could be ancient storage pits, which are commonly found on Puebloan sites in the region (Kantner, 2004). However, comparison with the color imagery shows that most of these features correspond with patches clear of vegetation, and ground truthing reveals that most of these features are ant mounds. In the 7:18am image, many of these features have a small mound at their center, confirming this interpretation (Fig. 8E).

After images were georeferenced, we plotted the locations of all the archaeological sites and features that were previously identified through surface survey at Blue J in order to evaluate whether and how these features appear on the thermal imagery. Careful analysis of the thermal image datasets in comparison with the color image enables us to quickly eliminate those features in the imagery that are caused by modern, surface landscape features from those that likely represent subsurface archaeological remains. Section 5 outlines key findings and their interpretation.

6. Discussion

In the 5:18am image, most of the previously identified sites at Blue J can be recognized, and in many cases it provides a detailed

Table 1

<table>
<thead>
<tr>
<th>Time</th>
<th>Camera</th>
<th>Conditions</th>
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<tbody>
<tr>
<td>9:58pm</td>
<td>FLIR Tau II</td>
<td>22/72, Dark, occasional wind gusts</td>
</tr>
<tr>
<td>5:18am</td>
<td>FLIR Tau II</td>
<td>10/50, Dark, no wind</td>
</tr>
<tr>
<td>5:45am</td>
<td>Nikon D6000</td>
<td>11/52, Light on horizon, no wind</td>
</tr>
<tr>
<td>6:18am</td>
<td>FLIR Tau II</td>
<td>13/55, First sunlight on site, light wind</td>
</tr>
<tr>
<td>7:18am</td>
<td>FLIR Tau II</td>
<td>16/61, Strong raking sunlight, light wind</td>
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view of subsurface remains, including the size and orientation of roomblocks, individual walls, and potential subterranean features (Fig. 6). Field investigations show that many of these sites are remains of stone-built architectural roomblocks, often visible at the surface today as piles of rubble and artifact scatters (Fig. 2B; Kantner, 2013). These features generally appear on the early morning thermal imagery as high value clusters, presumably because the stone walls and collapsed masonry retain heat longer than surrounding desert soils. The deepest middens, such as the one just east of LA 170609, also appear as high value patches, probably because they similarly contain dense concentrations of stone and artifacts.

Significantly, at many of these sites we are also able to distinguish subsurface architectural remains. One of the best examples comes from LA 170609 (Fig. 8). First identified during survey operations in 2004, this domestic roomblock and its associated plaza and midden areas were tested and completely backfilled in 2006 (Fig. 8B). Excavation of the roomblock was limited to uncovering the tops of the buried walls in order to determine masonry type, room sizes, and structure orientation. While the survey estimated roomblock size at five rooms based on the surface rubble, excavations revealed at least six and probably eight buried rooms and, most notably, a lengthy masonry wall surrounding the plaza area to the southeast of the roomblock. This feature was not visible on the surface, but can readily be seen as a high-value arc in the thermal data that may, in fact, extend farther north than the test excavations identified (Fig. 8A). A dark circular area indicating lower thermal values just
inside the plaza wall might indicate a subsurface structure such as a kiva, but this area was not tested during the 2006 operations. The subtle topographic expression of architectural features at LA 170609 is also evident in the 7:18am thermal image, which reveals the micro-relief of the site quite well (Fig. 8E). The previous partial excavation of LA 170609 may somewhat improve the clarity with which it appears on thermal imagery, although architectural details of numerous other roomblocks that have never been excavated can also be resolved quite clearly, as described below.

At nearby LA 170607, just 30 m to the southwest, surface manifestations were especially difficult to discern during survey operations due to dense vegetation growing over the site (Fig. 9B). Thermal data, in contrast, provide a clearer indication of the roomblock’s layout because by comparing thermal and color imagery we can...
easily eliminate high value features caused by vegetation. Analysis reveals what is likely a long arc of rectilinear rooms flanking a central plaza area and a smaller architectural feature, perhaps an enclosure wall like the one that identified at LA 170609 (Fig. 8), to the east. Similarly, at LA 170613 (Fig. 10A), thermal data reveal a rectilinear roomblock facing east towards a small plaza or courtyard area and a smaller arc of rubble to the east that may also be an enclosing wall. Several other similar clusters of architectural

![Fig. 8. Roomblock LA 170609 as it appears in the (A) 5:18am thermal image and (B) architectural plan produced by test excavations. Compare with the (C) color image, and thermal images from (D) 6:18am, (E) 7:18am, and (F) 9:58pm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image-url)
remains are clearly visible in the thermal data, but none of them are evident in color imagery, highlighting the potential of our approach for identification and mapping of such features at regional scales.

As mentioned previously, identification of subsurface features such as domestic pithouses and kivas has been difficult in the Blue J Community. Thermal imagery, however, reveals several features that may prove to be such structures. One such case discussed earlier is the possible pit structure in the plaza area of LA 170609 (Fig. 8). Another example is at LA 170612, where surface survey discovered a low-density scatter of artifacts but no indication of stone architecture (Fig. 10B). Unlike the high-value clusters that typify the buried masonry roomblocks, a 10 m diameter, circular low-value feature with a large number of plants growing inside it is visible at LA 170612. Its size and configuration indicates it could be a buried great kiva, a feature expected but not yet identified in the Blue J Community. It could also be some other type of subsurface feature like a large pit house. Recent ground-truthing at LA 170612 found nothing on the surface to conclusively indicate the presence of a subsurface feature, nor did it identify another reason for the low-value circular signal. Certainly, if a deep kiva structure or large pit house had been filled by aeolian and slope wash sediments, the differences in composition and porosity could reasonably be expected to create a low-value (i.e., cool) thermal anomaly. Of course, subsurface testing will be needed to determine what the feature is, but it offers an example of the many features that might be revealed by future thermal imaging.

7. Conclusions

The aerial thermographic imaging presented here produced valuable insights regarding our study site, the Blue J Community, and show both the potential of the methodology for archaeological investigations at sites in similar environments as well as for rapid archaeo-geophysical data collection over very large areas. At Blue J itself, the thermal imagery we collected reveals nearly all archaeological features that had been previously recorded through pedestrian survey and subsurface testing, suggesting that in the future, thermography could be used as a means to identify sites ahead of field survey. The data also reveal many features that were not evident on the ground surface and which merit additional investigation. This includes the possible northern extension of the enclosing wall at LA 170609 that testing may have overlooked (Fig. 8), the roomblock layout at LA 170613 that dense vegetation otherwise obscured (Fig. 9B), and the low-value circular features at LA 170609 and LA 170612 that may be buried pit structures or kivas (Figs. 8 and 10B). Future fieldwork at the Blue J Community will be able to target these areas for additional investigation.

Previous studies have already demonstrated thermography can be a powerful complement to conventional archaeological geophysics, by revealing a distinct set of physical phenomena (e.g., Kvanme, 2006, 2008). Moreover, investigators working at sites in the American Southwest that are similar to Blue J, where soils are very dry and architecture is built of stones with little or no...
magnetic signature, have often found that both electrical resistivity and magnetic gradiometry yield poor results (e.g., Ernenwein, 2008). The extremely rocky, topographically complex surface at Blue J, combined with the dense, thorny vegetation would likewise make ground penetrating radar survey extremely challenging. Our aerial thermographic method thus offers a key tool to complement other more conventional archaeological geophysics, and an approach that is of particular value to investigations in the American Southwest as well as at sites in other similar environments worldwide.

Finally, the method for UAV-based thermography outlined in this paper offers a means to collect and process thermal imagery over very large areas extremely rapidly, which is perhaps its greatest advantage. For example, the technique could be a powerful method for investigations of large sites where conventional geophysics may require many months of fieldwork, as well as in situations where more ephemeral remains are scattered over extensive areas. It could also provide a valuable complement to regional archaeological surveys, by revealing the likely location of archaeological features across large areas. While it would likely be difficult to acquire archaeologically useful thermal data in situations where cultural remains are covered by dense vegetation or are deeply buried, the methods we have described herein have broad applications in many contexts worldwide. Moreover, the ease with which imagery can now be acquired opens up many new avenues of future research. Investigators could, for example, exploit diurnal and seasonal differences in the appearance of archaeological features to enhance their visibility or determine their depth. Similarly, the differential thermal properties of vegetation could be used to indirectly detect archaeological features, as could the subtle topographic relief that is recorded in early morning thermal imagery (Fig. 7). Likely improvements in the reliability and simplicity of UAVs will make acquisition of thermal imagery increasingly easy and inexpensive, facilitating continued research into its many possibilities and ultimately making aerial thermography a standard stage in archaeological investigations.

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Fig. 10. Sites LA 170613 (A) and LA 170612 (B) in 5:18am thermal image (left), interpretive plan (center), and color image (right). The low-value circular anomaly evident at LA 170612 may indicate the location of subterranean pit house or kiva. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Kvamme also offered useful suggestions regarding data acquisition and processing, and the development of our methodologies benefited from collaboration with Kevin Fisher and Andrew Clark. Finally, we owe enormous thanks to the student volunteers who piloted the UAV during all flights undertaken as part of this project.

References

FLIR, 2013. Is the Tau/Quark a Rolling Shutter Camera or a Framing Camera?.
Verhoeven, G., 2011. Taking computer vision aloft e archaeological three dimension reconstructions from aerial photographs with photoscan. Archaeol. Prospect. 18, 67–73.
Verhoeven, G., Docter, R., 2011. Taking computer vision aloft e archaeological three dimension reconstructions from aerial photographs with photoscan. Archaeol. Prospect. 18, 67–73.