Mapping site-level microtopography with Real-Time Kinematic Global Navigation Satellite Systems (RTK GNSS) and Unmanned Aerial Vehicle Photogrammetry (UAVP)

Abstract: Microtopographic mapping has a long history in archaeology and has gained prominence recently owing to the proliferation of digital technologies. With such proliferation, it becomes necessary to compare and contrast different approaches based on a common set of criteria. This article compares the implementation and efficiency of two methods of mapping microtopography – ground-based Real-Time Kinematic Global Navigation Satellite System (RTK GNSS) and Unmanned Aerial Vehicle Photogrammetry (UAVP) survey – assessing the pros and cons of each, including those related to data quality. ‘Off-the-shelf’ solutions for methods were used to create the comparative dataset of microtopographic maps of six Middle and Late Bronze Age sites over the course of four seasons between 2007 and 2013 in the study area of the Central Lydia Archaeological Survey in western Turkey. Comparison of results demonstrate that the methods are similar with respect to ease of implementation, cost efficiency, and the (in)significance of data defects, while, unsurprisingly, UAVP survey can be greater than one order of magnitude more labor efficient than RTK GNSS survey and over two orders of magnitude more detailed as measured by data density. The accuracy of both methods is high, within typical error budgets for site-level mapping, and comparable to other recent digital mapping approaches. Accordingly, the results suggest that, given site suitability, UAVP is the more labor and cost-efficient method in the long run, with significant data quality benefits.

Keywords: Agisoft Photoscan Pro; RTK GNSS; Mapping Microtopography; Photogrammetry; Unmanned Aerial Vehicle (UAV); Turkey; Anatolia; Kaymakçı; Marmara Lake basin; Gediz Valley

1 Introduction

Mapping microtopography, or minute surface undulation, is by no means a new approach in archaeology, with the history of the discipline including many examples in microscopy and both ground-based and aerial approaches to recording and interpreting the intersections of natural and anthropogenic landscapes. Recent digital approaches to mapping microtopography have included ground-based data collection with total stations of various type, Geographic Navigation Satellite Systems (GNSS), and Terrestrial Laser Scanners (TLS), while Airborne Laser Scanning (ALS), also known widely as lidar, have also become well known [1–4]. The ‘point clouds’ of data collected by such methods are typically processed into digital surface models over which virtual light casts shadows, thereby highlighting, as it were, low-relief features; yet other ‘scientific
visualizations’ enabled by complex modeling routines and a growing knowledge of ‘eye-brain processes’ are likewise becoming common [5,p.72;6–8;9,p.36;10;11,p.103–104]. The configuration of low-relief features thus emphasized, all that remains is their proper interpretation – a subject gaining attention as evidenced in recent work [e.g., 3]. The latest addition to the mix is a more sophisticated development of one of the oldest methods of topographic mapping: stereoscopic analysis of aerial imagery. Thanks to advances in computer vision, modern approaches eschew simple stereo pairs for stereo ‘chunks’ of numerous images processed photogrammetrically to produce accurate microtopographic models. Additionally, while use of fixed-wing airplanes and helicopters for such purposes is certainly still valid, remotely controlled or Unmanned Aerial Vehicles (UAVs) have quickly become the low-altitude aerial photographic platform of choice because of their relatively low cost, user-friendliness, and aerial stability.

After reviewing various approaches to microtopography, the aim of this article is to describe and compare two methods of mapping microtopography implemented by the Central Lydia Archaeological Survey in western Turkey (Fig. 1). Contrary to the self-developed photogrammetric and/or UAV solutions used by others [12;13], this article compares relatively ‘off-the-shelf,’ fool-proof solutions with relatively gentle learning curves that, by no means inexpensive, might be within the budgets of many small to mid-sized archaeological projects focusing on site to landscape-scale questions. These methods include ground-based Real-Time Kinematic (RTK) GNSS survey, used to map four sites between 2007 and 2011, and UAV Photogrammetry (UAVP), used to map four sites in 2013 (Fig. 1). The comparison focuses on the implementation, efficiency, and data quality of methods used to create microtopographic data. While recent emphasis on visualizing and interpreting topographic data is certainly appropriate [3;4], it is not of core concern here, where the focus remains the methods of topographic data production, following the idea that the ‘better’ the data, the ‘better’ its subsequent possible display and interpretation [14;15].

2 Mapping Microtopography

As an analytical term, ‘microtopography’ appeared early in scholarship focused on characterizing surface variations in material-science microscopy [e.g., 16] and field ecology [e.g., 17]. Soon thereafter, it proliferated with the cross-fertilization of material and natural sciences – from metallography to dermatology to geology – in describing scales ranging from the microcrystalline to the landscape [18-21]. Use of the term in archaeology results from the initial application of material-science techniques to archaeological materials at microscopic scales [22;23], and, eventually, increasing attention to the natural environment at site and landscape scales, first in passing [24;25], and later more explicitly [26]. Over the last several decades, archaeological analyses of ‘microtopographies’ at multiple scales have increased, from micro-wear analyses to landscape interpretations. Given the multi-scalar nature of the term, ‘microtopography’ is understood hereafter to refer to surface undulations that are minute relative to the scale of observation. ‘Microtopographic mapping,’ then, refers to the recording of such surface undulations, and ‘microtopographic analysis’ to their characterization and interpretation, whether conforming to the remnants of buried sites at the modern ground surface, the intentional surface modulation of sculpted monuments, or the relics of finger grooves on hand-made pottery.

The ability to map microtopography – or, to record and visualize it at a variety of scales for subsequent analysis and interpretation – has developed hand-in-hand with relevant technologies, from scanning electron microscopy to close-range photogrammetry, laser scanning, and structured light scanning. Archaeological applications of microtopographic mapping have recently focused on characterizing three-dimensional (hereafter, ‘3D’) surfaces or volumes, highlighting not only the interpretive potential of the method, but also its preservation of archaeological heritage for posterity, even if only in a virtual medium [27–30;15]. At the individual artifact and ecofact scale, such 3D modeling of archaeological heritage, whether for archival and/or analytical purposes, has been applied to individual stone, ceramic, and faunal items [31–41], and even to ancient footprints [42]. The 3D volumes and surface characteristics of monumental architecture, caves, and freestanding or rupestrial sculpture have been captured similarly [43; 27–28; 44–57].

At the scale of the excavation trench or site, microtopographic mapping or 3D modeling via diverse methods has been celebrated for its virtual, preservative quality, enabling the potential for completely
reconstructing the pre-exavation situation of all contexts, an extremely important benefit in the ultimately
destructive or subtractive endeavor of excavation \[58–70;71,p.4;72;15;41\]. The heuristic and interpretive
benefits of the virtual reconstruction of archaeological contexts, too, have been recently stressed \[73; 74\].

At smaller scales, from the site to the landscape, the preservative qualities of microtopographic
mapping are supplemented by its interpretive potential as a technique of remote sensing. In characterizing
subsurface archaeological remains remotely by recording surface undulations, microtopographic mapping
has an older pedigree in methods that are less dependent on, but still enhanced by, recent technologies.
Such methods vary in efficiency and data quality and can be divided generally into ground-based and aerial
survey approaches. Satellite-based topographic survey is not considered here, because only recently have
satellite sensors been able to record data considered microtopographic at anything but regional or global
scales, and excellent overviews for such techniques can be found elsewhere \[e.g., 75–79\].

Well before the appearance of digital technologies, ground-based site and landscape survey was
practiced with the compass, plane table, alidade, optical transit and theodolite, and other devices still
advocated by a few surveyors for their mechanical reliability and on-the-ground interpretive potential
\[80–83\]. The greater possible efficiency and data quality provided by digital instruments in mapping

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**Figure 1**: Map of the Central Lydia Archaeological Survey study area in central western Turkey, showing general toponyms and sites mentioned in the text.
microtopography, however, have all but relegated non-digital approaches to the historical archive. Digital Total Station (TS) survey, for example, generally achieves accuracies of ±2–10mm relative to a reference station within a range of c. 2km [84,p.5–6]. TS survey requiring a minimum of two surveyors has thus been used to map microtopography at various site scales by painstakingly recording surface coordinate data at hundreds, if not thousands, of stationary survey points usually selected subjectively around perceived archaeological features of importance [e.g., 85–87]. With similar accuracies, the efficiency of TS survey has been increased greatly by use of the robotic TS, enabling the recording of large numbers of survey points by one surveyor alone in kinematic, or ‘on the fly’, fashion, usually arrayed according to areal units rather than perceived features [1:88].

Similar to the robotic TS in terms of efficiency, differential GNSS (DGNSS) survey with survey-grade GNSS equipment also requires only one surveyor and offers accuracies of ±1–3cm relative to a reference (or base) station within c. 2–3km [89,p.7–8,11] – still an acceptably high accuracy when concerned with site or regional scales of observation. The post-processing method of DGNSS survey used for ‘ground modeling’ or ‘3D surface modeling’ at many archaeological sites provides such accuracies only after the fieldwork, following the processing of collected data [90–91;89,p.14,21;92,p.639;93,p.3–4;2,p.213]. RTK GNSS survey, alternatively, provides accurate data to the surveyor in ‘real time,’ immediately, allowing on-the-spot data-quality checks and subtle changes to survey approaches in the field, as necessary, increasing potential efficiency over post-processing approaches. With their varying applications and benefits, TS and GNSS survey methods have been effectively combined by several projects, but more commonly at excavation-trench to site scales [60–61;64–65], than at site to landscape scales [e.g., 94], where aerial methods have been gaining prominence in recent decades.

Since the advent of aerial photography, archaeological sites have been mapped from the shapes, shadows, tones, and textures of differential interactions between archaeological and natural landscapes that can be identified by raking light and soil and crop conditions, for example [95–100;77;101–103]. While important for such site identification and used non-archaeologically to produce regional topographic maps from stereoscopic image pairs, the scale to resolution ratio of most mid- to high-altitude aerial photographs diminishes their use for microtopographic mapping of individual archaeological sites. Current non-photographic technologies mounted on mid- to high-altitude platforms such as laser scanners, however, achieve resolutions more than suitable for recording microtopography. Airborne Laser Scanning (ALS), also known as lidar (light detection and ranging) and differentiated from Terrestrial Laser Scanning (TLS) by its aerial platform [e.g., 63;104;70], has quickly come to dominate this class of aerial mapping at altitudes of 300–3500m above ground level (agl), with numerous applications across archaeological landscapes [e.g., 105–107;7;108;10;4]. National programs of ALS, in Europe, for example, are making data with typical horizontal and vertical accuracies of 20–50cm and 8–15cm, respectively, more readily available for archaeological use [10], and one hopes that this trend continues globally.

ALS is less common at altitudes below c. 300m agl, where digital photogrammetry used for mapping microtopography has developed out of a fruitful collaboration between digital aerial photography and computer-vision research [109]. Low-altitude aerial photography (or LAAP) has as long a pedigree as its higher-altitude cousin [97;110], and includes a diverse array of platforms employed in archaeological applications: kites [111;101;112], tethered balloons [e.g., 113], powered parachutes [114;88], helikites [102;41], and – a recent introduction – remotely controlled, unmanned aerial vehicles (or UAVs) [12;115–119;13]. The increasing use of low-altitude platforms for aerial photography has coincided with advances in photogrammetry resulting in part from a widespread shift to digital media [120–124], and in part from the development of computer-vision algorithms [125–127]. In particular, ‘Structure from Motion’ (or SfM) [128–129] and ‘Multi-View Stereo’ (or MVS) algorithms [130–134] enable the photogrammetric reconstruction of 3D surfaces from multiple overlapping digital images and achieve accuracies comparable to other aerial and ground-based methods.

Published comparisons of the efficiency and data quality of these varying methods of mapping microtopography demonstrate the broad comparability of recently developed techniques. Ground-based photogrammetry and TLS at the scale of the excavation trench, for instance, have demonstrated accuracies
Mapping microtopography, while they are typically much more efficient [135–136;62;70;72]. Direct comparison of microtopographic data resulting from photogrammetry and laser scanning, at scales ranging from the individual object to the site, show their similar accuracy and labor efficiency, while cost efficiency trends strongly in the favor of photogrammetric solutions [137]. For solutions involving aerial survey, labor and cost efficiencies are rarely compared in detail. While some microtopographic mapping analyses provide equipment costs [e.g., 12], they often eschew tabulations of person-hour or person-day labor estimates in software, equipment, and survey design, survey implementation, and data processing. The prospective mapper of microtopography, therefore, is often left with less than a full comparative analysis of the potential methods available, demonstrating their various pros and cons.

The remainder of this article, then, aims to redress this lacking by comparing not the entire suite of potential ground-based and aerial survey methods available, but only one method from each broad group described above: RTK GNSS survey and UAVP survey. Over the course of four field seasons in western Turkey, the author had the opportunity to design and implement microtopographic mapping surveys of six different sites using relatively ‘off-the-shelf’ solutions for both these methods, providing data for their direct comparison, as discussed below.

3 Study Area

The c. 350km² study area of the Central Lydia Archaeological Survey is centered on the Marmara (ancient Gygaean) Lake basin and its immediate environs in the broad Gediz (ancient Hermus) River valley in the modern province of Manisa, western Turkey (Fig. 1). Archaeological and paleoenvironmental survey work conducted since 2005 has focused on exploring diachronic human-environment interactions across landscapes that have been significantly transformed by both natural and cultural forces throughout the local history of human activities [138]. The project has revealed such activities and landscape transformations dating from the Paleolithic through the recent past [139]. In addition to pedestrian field survey efforts focused in lowland, agricultural territories, upland surveys between 2006 and 2012 identified a series of six previously unknown fortified citadels of the Middle and Late Bronze Ages (c. 18th–13th C. BCE) [140–145]. Each of these citadels is situated on a ridge or hilltop in an easily defensible, strategic location, and each was abandoned in or after the Late Bronze Age, with surface materials providing little to no evidence of subsequent activity [147]. Given evident surface expressions of architectural remains at each of these sites, in 2007 the project began to invest significant time, effort, and funds to map their microtopographies as one among many means of revealing internal spatial organization and, thus, clues about site function and even chronology.

Mapping began in 2007 with RTK GNSS survey at Kaymakçī, the largest of the citadel sites, and was conducted simultaneously with magnetometry and surface material collections, each of which survey methods was implemented across a 20m grid system. The project used RTK GNSS to map Kızbacı Tepesi in 2007 as well, testing a more rapid, long-transect method across its much smaller surface area [142]. Both Gedevre Tepesi and Asar Tepe 2 were mapped via similar RTK GNSS transects in 2008, while the mapped area of Kaymakçī was expanded in 2011 using a 40m grid system, coordinated with simultaneous electromagnetic conductivity survey [143;146]. In 2013, the project employed UAVP to resurvey and expand the microtopographic maps of Kaymakçī and Kızbacı Tepesi and to map two more citadel sites – Asar Tepe 1 and Koca Dere – at the latter of which the project conducted gridded surface collections, as well. The results of these four seasons of microtopographic mapping can be seen in Figs. 4 and 8, below, while their interpretation, still ongoing, remains outside the purview of this article.
4 Methods: Real-Time Kinematic Global Navigation Satellite System (RTK GNSS) Survey

4.1 Equipment, Software, and Field Data Collection

Real-Time Kinematic Global Navigation Satellite System (or RTK GNSS) survey employed a fairly straightforward combination of hardware and software tools. Hardware included three survey-grade Topcon Positioning Systems HiPer® Lite+ receivers – a ‘base station’ set on a tripod over a known or newly established control point and two ‘rovers’ mounted on fixed 2m-tall survey poles – and two Topcon FC-200 data collectors used to record real-time coordinate data as surveyors moved across areas of interest (Fig. 2). Field survey was managed using Topcon’s TopSURV software running on the data collectors. Used in kinematic mode and collecting L1 and L2 signal data from both American Global Positioning Satellite and Russian Global Orbiting Navigation Satellite System satellites, this survey system achieves horizontal and vertical accuracies of ±1cm and ±1.5cm, respectively, relative to a base station set up within 1km [148].

At each site of RTK GNSS survey, surveyors traversed areas of interest in a modified systematic fashion selected based on site conditions, available time and labor, and simultaneous but separate on-site work (e.g., geophysical survey and material collections), holding the survey pole vertically such that its point remained a regular 0.10–0.15m above the ground (Fig. 3). At Kaymakçı, surveyors zigzagged across 20m and 40m grids marked with wooden stakes in traverses set at 1m intervals. At the three other sites, longer, zigzagging traverses set at intervals of 1–2m were selected for similar reasons. In each case the data collectors were configured to record rover coordinates automatically every 1m of horizontal movement, allowing
surveys to proceed slowly and regularly over areas of interest. Where sharp and/or subtle ground-surface changes were apparent, surveyors modified this systematic approach by adopting closer recording intervals to ensure the capture of such features [149]. These field methods resulted in a surface point density of 1.00 point/m² at Kaymakçı and of 0.37–0.94 points/m² at the other sites (Table 1).

Table 1: Sites surveyed between 2007 and 2011 using RTK GNSS, showing average field and processing labor (person-days), average data densities (points/m²), areas of valid DEM produced (ha), and yield (ha/person-day).

<table>
<thead>
<tr>
<th>Site</th>
<th>Field Labor</th>
<th>Processing Labor</th>
<th>Data Density</th>
<th>DEM Area</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asar Tepe 2</td>
<td>4</td>
<td>0.25</td>
<td>0.73</td>
<td>6.53</td>
<td>1.54</td>
</tr>
<tr>
<td>Gedevre Tepesi</td>
<td>4</td>
<td>0.25</td>
<td>0.94</td>
<td>3.07</td>
<td>0.72</td>
</tr>
<tr>
<td>Kaymakçı</td>
<td>74</td>
<td>0.25</td>
<td>1.00</td>
<td>23.20</td>
<td>0.31</td>
</tr>
<tr>
<td>Kızbacı Tepesi</td>
<td>2</td>
<td>0.25</td>
<td>0.37</td>
<td>0.94</td>
<td>0.42</td>
</tr>
<tr>
<td>Totals</td>
<td>84</td>
<td>1</td>
<td>0.76 (AVG)</td>
<td>33.74</td>
<td>0.75 (AVG)</td>
</tr>
</tbody>
</table>

4.2 Data Processing

Following field data collection, coordinate data were exported from the data collectors as text files containing X, Y, and Z values and imported into ESRI’s ArcGIS software package. There the point data was converted to raster surfaces via ArcGIS’ ‘Topo to Raster’ tool, a proprietary, spline-based interpolation method based on version 5.3 of the Australian National University Digital Elevation Model (DEM) program, designed for creating hydrologically correct drainage models that accurately simulate surface characteristics deriving from natural processes [e.g., 150]. The three datasets with densities of 0.73–1.00 point/m² were interpolated to rasters of 0.25m pixel resolution, while that with a density of 0.37 points/m² was interpolated to a lower pixel resolution of 0.50m. As is recently common for display of digital topographic data [3], the DEMs were then subjected to an artificial light source from the northwest (45° angle; 315° azimuth) using ArcGIS’s ‘Hillshade’ tool to produce more communicative hillshade models (Fig. 4). Following these data collection and processing methods for mapping microtopography via RTK GNSS, a total of 33.74ha (or 0.34km²) were mapped and processed in 85 person-days (Table 1).
Figure 4: Hillshade models resulting from RTK GNSS survey of sites listed in Table 1: a) Asar Tepe 2; b) Gedevre Tepesi; c) Kaymakçı; and d) Küzbacı Tepesi.

5 Methods: UAV Photogrammetry (UAVP) Survey

5.1 Equipment, Software, and Field Data Collection

Unmanned Aerial Vehicle photogrammetry (or UAVP) survey required a slightly larger array of hardware and software tools. On the hardware side, these included a 16 megapixel Panasonic Lumix DMC-GH2 digital camera with Lumix G Vario 14–42mm/F3.5–5.6 ASPH./MEGA O.I.S. lens, and a Freefly Systems Cinestar 6 UAV platform – a hexacopter equipped with flight and navigation controls made by Mikrokopter and controlled from a Graupner MX-20 radio-control transmitter (Fig. 5). Requisite software for flight planning and execution included ESRI’s ArcGIS, again, and Mikrokopter’s MKTool software.

Each survey flight was planned beginning in ArcGIS, where a set of waypoints designed to cover an area of interest were saved as a point-based vector file, with coordinates subsequently exported to a text file. A custom Python script written by Emanuel Moss specifically for this project enabled conversion from the text file to the waypoint list (.wpl) format used by Mikrokopter’s MKTool software to contain the programmed
waypoints of individual flights [151]. Absent the script, waypoint coordinates could have been entered directly into MKTool with little difficulty. After experimentation within various constraints, a standard flight routine was established such that the points in each waypoint list corresponded to the mid- and endpoints of four 400–450m-long survey traverses separated by 30m intervals (Fig. 6). A camera focal length of 14mm and flight altitude of 56m agl at the launch site were selected to produce a 1:4000 photographic scale (focal length/altitude agl) suitable for the high resolution desired of resultant outputs. In practice, the focal length of the digital camera was equivalent to a 28mm focal length in a 35mm film camera, and the average flight altitude above the hilly terrain across all flights was around 88m agl (Tables 2–3). Accordingly, the realized average photographic scale was closer to 1:3000, producing data of even higher resolution than planned.

Table 2: Sites surveyed in 2013 with UAVP, showing average field and processing labor (person-days), average data densities (points/m²), areas of valid DEM produced (ha), and yield (ha/person-day).

<table>
<thead>
<tr>
<th>Site</th>
<th>Field Labor</th>
<th>Processing Labor</th>
<th>Data Density</th>
<th>DEM Area</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asar Tepe 1</td>
<td>1</td>
<td>0.5</td>
<td>147.96</td>
<td>13.59</td>
<td>9.06</td>
</tr>
<tr>
<td>Kaymakçı</td>
<td>10</td>
<td>2</td>
<td>11.98</td>
<td>103.75</td>
<td>8.65</td>
</tr>
<tr>
<td>Kizbaci Tepesi</td>
<td>1</td>
<td>0.5</td>
<td>175.96</td>
<td>31.23</td>
<td>31.23</td>
</tr>
<tr>
<td>Koca Dere</td>
<td>2</td>
<td>1</td>
<td>44.64</td>
<td>18.09</td>
<td>6.03</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>14</strong></td>
<td><strong>4</strong></td>
<td><strong>95.14 (AVG)</strong></td>
<td><strong>166.66</strong></td>
<td><strong>13.74 (AVG)</strong></td>
</tr>
</tbody>
</table>
Table 3: Agisoft Photoscan Pro models produced from UAVP, showing number of survey flights, average flight altitude (m agl), numbers of photographs, GCPs, dense point cloud points and mesh faces, and optimal DEM resolution (m).

<table>
<thead>
<tr>
<th>Site</th>
<th>Flights</th>
<th>Photographs</th>
<th>Altitude</th>
<th>GCPs</th>
<th>Points</th>
<th>Faces</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asar Tepe 1</td>
<td>2</td>
<td>161</td>
<td>90.07</td>
<td>6</td>
<td>822,962</td>
<td>17,382,523</td>
<td>0.043</td>
</tr>
<tr>
<td>Kaymakçı</td>
<td>21</td>
<td>2020</td>
<td>76.80</td>
<td>15</td>
<td>10,084,501</td>
<td>147,761,050</td>
<td>0.034</td>
</tr>
<tr>
<td>Kızbacı Tepesi</td>
<td>4</td>
<td>426</td>
<td>105.28</td>
<td>6</td>
<td>2,085,379</td>
<td>32,862,701</td>
<td>0.051</td>
</tr>
<tr>
<td>Koca Dere</td>
<td>4</td>
<td>215</td>
<td>79.49</td>
<td>32</td>
<td>1,005,390</td>
<td>37,210,937</td>
<td>0.038</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>31</strong></td>
<td><strong>2822</strong></td>
<td><strong>87.91 (AVG)</strong></td>
<td><strong>15 (AVG)</strong></td>
<td></td>
<td></td>
<td><strong>0.042 (AVG)</strong></td>
</tr>
</tbody>
</table>

To approach the idealized value of a 60% overlap between sequential images for successful aerial photogrammetric processing [121], a 20m photo-sampling interval was set along each 400–450m long survey traverse. The simple relationship of distance = rate × time helped implement the 20m interval, such that the flight speed of the UAV was programmed to 5 m/s and a smartphone metronome app audibly spurred the RC pilot to trigger a shutter release every four seconds. In the zigzagging path of each flight, then, the UAV collected an average of 90 photos in RAW format [124], traversed an average aerial plane of 3.8ha, and collected a set of contiguous, overlapping digital images covering an average ground area of 5.5ha. At all but one site surveyed via UAVP – Kızbacı Tepesi – ground control points (GCPs) for use in georeferencing the collected images were surveyed ahead of time with the RTK GNSS system and marked with powdered lime so as to remain visible in the aerial images. As a comparative test, GCPs at Kızbacı Tepesi were retrieved following field data collection by identifying seemingly corresponding points on the previously processed hillshade model derived from RTK-GNSS survey and the aerial images from UAVP survey.
5.2 Data Processing

Following field data collection, the RAW format aerial images were reformatted in a lossless fashion to TIFF files and uploaded to Agisoft’s PhotoScan Pro for processing. Following Agisoft protocols for DEM production [152–154], the images from each flight were added into individual, manageable ‘chunks’ of an average of 90 photos each and then batch processed to align the images, build dense point clouds and surface meshes, align the chunks, and then merge the chunks (Fig. 7). Ground Control Points were registered in the photos for their orthographic rectification to a projected coordinate system (World Geodetic System 1984, Universal Transverse Mercator zone 35N), spatially anchoring the images to the real world via a seven-parameter Helmert similarity transformation [155]. Although relatively simply executed in PhotoScan Pro, these steps of image processing were processor-intensive, even for the relatively robust workstation employed: a Dell™ Precision™ T1650 with an Intel® Xeon® E3 1270 V2 (Quad Core, 3.5GHz, 8MB) processor, 16GB DDR3 1600MHz ECC-UDIMM (2x8GB) memory, a 1GB NVIDIA Quadro K600 graphic card, and a 64-bit operating system (Windows Server 2012). The final step of data processing is data export, with a variety of formats available. A significant benefit of UAVP, in fact, is its output of high-resolution orthographically rectified photographs, or orthophotos [168]; yet this benefit is intentionally omitted from detailed discussion because of the focus of this article on microtopography. For consistency with the RTK GNSS data described above, then, each set of PhotoScan Pro data was exported as a 0.25m-resolution DEM and then subjected to ArcGIS’s ‘Hillshade’ tool to produce a hillshade model (Fig. 8). Following these data collection and processing methods for mapping microtopography via UAVP, a total of 166.66ha (or 1.67km²) were mapped and processed in 18 person-days (Table 2).

Figure 7: Perspective view of Asar Tepe 1, showing the camera positions associated with each aerial image and the resultant digital surface model (here textured with the aerial photos themselves).
6 Comparative Discussion of Results

The two independently conducted microtopographic mapping surveys described above provide robust datasets for broad comparison of their ease of implementation and labor and cost efficiency. The overlapping application of the methods at two sites allows for direct comparison of data quality, including detail and accuracy. The remainder of this article will discuss these and other concerns, including the all-important issue of the suitability of particular methods to certain sites.

6.1 Implementation

Neither RTK GNSS nor UAVP survey is easy to implement. Both require training and experience to produce data of acceptable qualities, and both require a working comfort with computers, a working knowledge of GIS, and some basic geospatial processing skills. RTK GNSS survey requires more physically, while UAVP survey presents steeper learning curves and greater risks.

Figure 8: Hillshade models resulting from UAVP survey of sites listed in Table 2: a) Asar Tepe 1; b) Koca Dere; c) Kızbacı Tepesi; d) Kaymakçı. Areas 1 and 2 at Kaymakçı refer to those areas compared in more detail below.
After setting a base station on a tripod over a known point and configuring the RTK GNSS system correctly, the most difficult aspects of RTK GNSS survey are related purely to stamina and coordination. Traversing every square meter of a landscape can be grueling work, especially in the c. 35–45° C. heat of western Turkish summers. Surveyors in good physical shape are accordingly most productive. Add to that the requirement of carefully monitoring and maintaining one’s position on the data collector while navigating the landscape, and one can see why a certain level of coordination is required. Such coordination is not innate to many, yet we have seen that efficiency increases with experience, and training increases data quality. On the data processing end of the method, the recorded point data need only be exported from the data collector, imported into a GIS, interpolated, and displayed as desired to reach a stage ready for interpretation.

UAVP requires significantly more training on the front end but is much physically easier, though riskier, to implement in the field. In my own case, in preparation for the 2013 field season, I trained using a hobby-grade quadcopter and PC flight simulator in evenings and on weekends over two months before a first test flight of the pre-assembled hexacopter itself. Next came camera-mounted flights, and finally, once in the field, the refinement of the method to fly programmed missions, as described above. Given the use of ‘off-the-shelf’ software, survey-flight preparation and planning was a relatively straightforward matter, made even easier with Moss’ Python scripts [151], contrary to the routines associated with self-programmed software or independently developed UAVs [e.g., 13;156].

Once a UAV is airborne, the procedure is rather basic and monotonous, but requires a certain amount of coordination and sensitivity, especially in landing. In all UAVP work, archaeologists are well advised to adhere to the guidance of more experienced RC pilots on several points: 1) “A good landing is one where all the copter’s bits arrive close together. A great landing is when the copter can take off again right away;” and 2) “Never fall in love with anything you’re flying with radio control. You will crash it. It’s just a question of when and how badly” (A. Johnson-Laird and C. Van Nyhuis, respectively [157,p.11]). The risks, then, are inherently financial, but also bodily, requiring a certain attention and care when surveying.

UAVP data processing is more intensive than that of RTK GNSS data, but by no means particularly difficult. The image alignment, dense point cloud construction, mesh building, and GCP-registration stages of DEM production in PhotoScan Pro are processor intensive, but the vast majority of processing time is ‘passive,’ requiring no user input, and can be partially automated using a variety of the software’s automation and batch-processing tools. Following this stage, again, the resultant DEM need only be imported into a GIS and displayed as desired to reach a stage ready for interpretation.

### 6.2 Labor and Cost Efficiency

RTK GNSS survey and data processing produced microtopographic maps covering a total of 33.74ha (0.34km²) over 85 person-days. The average yield among the four sites surveyed was 0.75 ha/person-day, with minimum and maximum yields of 0.31 ha/person-day and 1.54 ha/person-day, respectively (Table 1). This range of RTK GNSS productivity results from numerous factors, primary among which are grid or transect dimensions, surveyor experience and skill, and topography. Because it takes surveyors time to slow down and stop at the end of each transect and to turn and reorient before setting off on the next transect, survey efficiency increases proportionately with grid size and transect length. The longer the transect, conversely, the more difficult it is for a surveyor to maintain course, requiring experience and skill. Steep or sharply varying topography, too, reduces efficiency as it slows surveyors, who need to take care not only to maintain course, but also to maintain upright.

UAVP survey and data processing produced microtopographic maps covering a total of 166.66ha (1.67km²) over 18 person-days. The average yield among the four sites surveyed was 13.74 ha/person-day, with minimum and maximum yields of 6.03 ha/person-day and 31.23 ha/person-day, respectively (Table 2). This range of UAVP productivity results almost entirely from surveyor experience, whereby yield increases with the progression of sites surveyed, as flight planning and field protocols were refined. On average, then, and unsurprisingly, UAVP was on average 18 times more labor efficient per area covered than RTK GNSS in this study.
As to cost efficiency in US dollars, both RTK GNSS and UAVP are expensive, but within the range of most small to medium sized project budgets (Table 4). Omitted from comparison here are items required by both methods: travel and personnel costs (both methods require training and at least one person on the ground); and GIS software licenses (while ESRI’s ArcGIS 10.1 was available to this project through Boston University’s site license, other GIS packages may suffice equally well). As one can see in Table 4, the hardware and software costs are not extremely divergent, ranging from $13,625 for UAVP and $14,895 for RTK GNSS, and are at the lower end of published cost ranges for similar systems [e.g., 12]. It bears mention, however, that high-accuracy surveying equipment, a relatively inexpensive TS if not an expensive RTK GNSS, is required to establish the GCPs necessary for UAVP, so the costs associated with UAVP should actually be slightly higher.

Table 4: Costs associated with RTK GNSS and UAVP survey in $US. Note that, aside from the camera, all other hardware and software costs reflect educationally discounted rates.

<table>
<thead>
<tr>
<th>Item</th>
<th>RTK GNSS</th>
<th>UAVP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topcon HiPer® Lite+ system</td>
<td>$14,895</td>
<td></td>
</tr>
<tr>
<td>Preassembled Cinestar6 system</td>
<td></td>
<td>$12,277</td>
</tr>
<tr>
<td>Panasonic Lumix camera</td>
<td></td>
<td>$799</td>
</tr>
<tr>
<td>Agisoft PhotoScan Pro</td>
<td></td>
<td>$549</td>
</tr>
<tr>
<td>Total</td>
<td>$14,895</td>
<td>$13,625</td>
</tr>
</tbody>
</table>

6.3 Data Quality

The detail and accuracy of data collected with both RTK GNSS and UAVP methods are very high, but each dataset can suffer from particular data defects. To facilitate a detailed comparison of results, two areas of interest at Kaymakçıl were selected for their close proximity to ground control points (Figs. 8 and 9). Each hillshade model is derived from a 0.25m DEM of the relevant area of interest and displayed with identical lighting parameters. The difference in microtopographic detail visible in the models is primarily a function of data density, with the average data density of UAVP (95.14 points/m²) more than 125 times greater than that of RTK GNSS (0.76 points/m²) (Tables 1–2). The high UAVP data density corresponds to the very small Ground Sample Distance (or GSD) of the digital imagery, ranging between 0.019–0.026 m/pixel (Table 5), a resolution on par with other recently published UAVP tests [137, p.119]. Accordingly, the UAVP models of microtopography appear much more detailed, with individual stones, patches of low vegetation, and even a modern tractor path readily identifiable.

Table 5: Georeferencing accuracy of UAVP models produced in Agisoft’s PhotoScan Pro. Pixel root mean square error (RMSE) is provided in dimensions of pixels, while Ground Sample Distance (GSD) represents the ground dimension of an individual pixel in m. The total RMSE of x-, y- and z-coordinates estimated by PhotoScan Pro against GCPs established by RTK GNSS are provided in m, along with the total RMSE in m for each individual dataset. The two areas of interest from Kaymakçıl are excluded from all averages.

<table>
<thead>
<tr>
<th>Site</th>
<th>Pixel RMSE</th>
<th>GSD</th>
<th>RMSE (x)</th>
<th>RMSE (y)</th>
<th>RMSE (z)</th>
<th>Total RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Asar Tepe 1</td>
<td>0.716</td>
<td>0.022</td>
<td>0.052</td>
<td>0.059</td>
<td>0.043</td>
<td>0.090</td>
</tr>
<tr>
<td>Kaymakçıl</td>
<td>0.667</td>
<td>0.017</td>
<td>0.243</td>
<td>0.196</td>
<td>0.202</td>
<td>0.372</td>
</tr>
<tr>
<td>– Area 1</td>
<td>0.578</td>
<td>0.015</td>
<td>0.068</td>
<td>0.089</td>
<td>0.069</td>
<td>0.131</td>
</tr>
<tr>
<td>– Area 2</td>
<td>0.656</td>
<td>0.017</td>
<td>0.123</td>
<td>0.150</td>
<td>0.030</td>
<td>0.196</td>
</tr>
<tr>
<td>Kızbacı Tepesi</td>
<td>0.845</td>
<td>0.026</td>
<td>0.677</td>
<td>1.456</td>
<td>0.248</td>
<td>1.625</td>
</tr>
<tr>
<td>Koca Dere</td>
<td>0.736</td>
<td>0.019</td>
<td>0.055</td>
<td>0.054</td>
<td>0.141</td>
<td>0.161</td>
</tr>
<tr>
<td>Averages</td>
<td>0.741</td>
<td>0.021</td>
<td>0.257</td>
<td>0.441</td>
<td>0.159</td>
<td>0.562</td>
</tr>
</tbody>
</table>
With respect to data defects, bad data in RTK GNSS datasets derive primarily from base station to rover radio-communication loss, resulting in isolated data spikes that can be identified and removed manually with ease. Minor but more pervasive striping defects, such as those visible in Fig. 9, correlate to the walking traverses of individual surveyors. These linear defects reflect elevation differences of 0.05–0.10m and result from surveyor gait and/or survey pole repositioning between lines. They are fairly common to microtopographic surveys employing walking surveyors [e.g., 92,p.639;2,p.213], and can be removed using global smoothing and/or local periodic filters.

Data defects in UAVP datasets include gaps and overlap processing errors (e.g., at Kaymakçı and Koca Dere, Fig. 8). Data gaps result either from poor survey flight planning or implementation, where flight paths or photo-sampling intervals provide insufficient image overlap between transects, and/or from prevailing winds, which may blow a UAV off its planned flight path. While the latter problem is mitigated with insertion of waypoints between transect endpoints, the former is simply a matter of planning. Overlap processing errors occur at the junctures of images processed initially in separate chunks and later aligned and merged.
in Agisoft PhotoScan Pro and thus primarily affect datasets associated with larger UAVP projects of multiple chunks. Such errors are common also to ALS datasets and can be corrected by various adjustments [e.g., 158–162]. Maintaining a common photographic scale between contiguous flights in UAVP survey can minimize such errors.

Perhaps the most important assessment of the quality of data resulting from these methods of mapping microtopography concerns accuracy. With respect to the RTK GNSS data, there is no reason to suspect anything other than the published horizontal and vertical accuracies of ±1cm and ±1.5cm, respectively, relative to a base station always within 1km [148]. The precision of the RTK GNSS system has been checked repeatedly between 2007 and 2013 and accords with the ±2.5cm error budget for kinematic survey observed by the project. The accuracy of the UAVP data, alternatively, can be assessed both internally and against the GCPs established with the RTK GNSS system. Several recent studies have demonstrated the high internal accuracy of models produced with Agisoft PhotoScan Pro [e.g., 70;163;15], and the current study only confirms such conclusions. Accuracy is determined in PhotoScan Pro as root mean square error (RMSE) [164;165], and the average RMSE of pixel alignment among the four primary models is 0.741 pixels (Table 5). When the pixel RMSE associated with each model is factored against its corresponding Ground Sample Distance (GSD), or the size of each pixel in meters on the ground, the average internal image-alignment error is 0.016m, with a minimum of 0.011m and a maximum of 0.022m.

The accuracy of the UAVP model as measured against the GCPs is also given in RMSE for each coordinate axis and as a total (Table 5). The rather high average total RMSE of 0.562m among the four sites is skewed by the anomalously high total RMSE of 1.625m for Kızbacı Tepeşi. As described above, Kızbacı Tepeşi was the only site surveyed without use of GCPs. The very large total RMSE of the model demonstrates the importance of marking and surveying GCPs on the ground prior to survey flights and the imprecision of deriving GCPs from legacy DEMs in later stages of processing.

If Kızbacı Tepeşi is removed from the tally, the average total RMSE becomes 0.210m. On the 1:100, 1:500, and 1:1,000 scale maps typically used by this project to analyze microtopography, this error corresponds to 2.1mm, 0.4mm, and 0.2mm, respectively, and is well within acceptable ranges for such scales of analysis [15,p.1112]. A further improvement of UAVP accuracy could no doubt be accomplished with the use of more formal GCPs, as used in other aerial surveys [e.g., 163;13,p.5, Fig. 3]. In contrast to the more measured approaches to establishing and surveying GCPs in such studies, the present study established GCPs in kinematic and non-permanent fashion as part of a multicomponent survey project needing to cover ground quickly given field-season scheduling constraints and desiring to leave little behind. Nevertheless, UAVP model accuracy as determined by total RMSE is acceptable given the scale of analysis, and is made even clearer by difference rasters representing the subtraction of the RTK GNSS DEM from the UAVP DEM for each of the areas of interest at Kaymakçı (Fig. 10).

Where the ground surfaces of the areas of interest are visible in the images, the vertical difference between the two DEMs is ≤ 5cm; where they are bluish, the UAVP data is lower than RTK GNSS data, and where they are reddish, the UAVP data is higher than the RTK GNSS data. These differences are shown in the graphs, as well, where the general trend lines are parallel and the smoothness of the blue RTK GNSS lines relative to the red UAVP lines results from differences in data density, as described above. Interestingly, and as a further confirmation of accuracy, the areas of divergence between the two sets of elevation data are attributable almost entirely to surface conditions at the time of UAVP survey.

Areas where the UAVP DEM is higher than the RTK GNSS DEM were covered in low thistle and other non-dense, ground vegetation in 2013. RTK GNSS surveyors would have been able to walk through such vegetation with little problem, maintaining the regular height of the survey pole above the ground, while the density of the vegetation was just enough in 2013 to appear like a solid surface in the UAVP DEM. Areas where the UAVP DEM is lower than the RTK GNSS DEM were grazed or worn nearly completely to the ground in 2013. This is most readily apparent in the tractor ruts of area of interest 2, around 65–70m along the A–B transect in the graph, where the UAVP DEM represents the actual, worn down ground surface, and the RTK GNSS DEM represents the slightly raised height at which surveyors held the survey poles as they traversed the area. Our ability to explain slight differences in the microtopographic expressions of these datasets
in this way only confirms the high accuracy of both methods, while again emphasizing the level of detail achievable through UAVP survey.

6.4 Other Concerns

Aside from the aspects of mapping microtopography discussed above, the most significant single concern in applying both methods is site suitability. In western Turkey, sites considered here were relatively blessed with beneficial topography, ground cover, and land-use strategies, where low-slope terrain given over to agricultural and grazing purposes has little to no vegetation. Where local topography is varied or interspersed with mid-size trees – olives, for example – topographic rises or groups of trees can create radio-signal shadows for RTK GNSS, resulting in local data errors and/or the need to establish multiple base-station points. Broad canopy trees that create satellite-signal shadows and dense, low vegetation that obstructs regular traverses thwart RTK GNSS survey altogether. Vegetation can cause problems for UAVP survey, too, where low grasses and seasonal thistle are modeled instead of the actual ground surface, as discussed above.
A final concern worth mentioning here is working range. The advertised range of the radio communications in the Topcon RTK GNSS system is 2km, but, given ground cover and topography, a range on the order of 500–750m was observed in practice. A combination of legal and technical limits restrict the range of the UAVP system used in this study, also, to between 250m, the legal range of GNSS-enabled flight in many countries, and 500m, the estimated range of the 2.4 GHz radio transmitter. Both methods are thus limited to similar ranges, and given their areal coverage efficiencies, neither range proves a significant obstacle to mapping progress.

7 Conclusions

Microtopographic mapping has a long history in archaeology and has gained prominence recently owing to the proliferation of digital technologies. With such proliferation, it becomes necessary to compare and contrast different approaches based on a common set of criteria. This article has compared the implementation and efficiency of two methods of mapping microtopography, assessing the pros and cons of each, including those related to the all important criterion of data quality. Both RTK GNSS and UAVP survey are roughly comparable vis-à-vis ease of implementation, monetary cost, and the significance of data defects, while both are characterized by challenges particular to each method. While the monetary cost of UAVP survey might be further reduced with less expensive (and sometimes less ‘off-the-shelf’) solutions that use relatively inexpensive but highly accurate TS survey for the establishment of GCPs [e.g., 12–13], that of RTK GNSS survey is rather less negotiable. With respect to accuracy, as well, both methods are highly acceptable for site-level mapping, well within typical error budgets and comparable to similar-scale surveys using ALS. Difference rasters demonstrate this accuracy through illustration of the differential effects of the two survey methods. Nevertheless, UAVP model accuracy cited here could be increased with more measured protocols of GCP establishment. Given site suitability, the most significant differences between the two methods include efficiency and data detail, wherein UAVP survey is greater than one order of magnitude more efficient in areal coverage than RTK GNSS survey and greater than two orders of magnitude more detailed as measured by data density. In addition to requiring less time and producing higher resolution data, as indicated above, UAVP survey produces an entirely separate category of information – orthophotos – that enable documentation and interpretation that moves well beyond the subject of microtopography.

Although this comparative analysis has eschewed issues of interpretation, a final note of concern is the potential that the vastly increased efficiency and detail of UAVP survey might effectively decrease an archaeologist’s time on the ground, inspecting sites with their own two eyes. A definite benefit of RTK GNSS survey, in fact, is that it forces an intimate, grounded familiarity with an area of interest, allowing for reflection, if not reflexivity, in the recursive processes of observation, description, and interpretation [80–81;5;166–167]. As with many good things, however, a middle ground that leverages the benefits of the extremes probably shows best ways forward. In other words, an ideal survey might combine ground-based TS or RTK GNSS survey – quickly establishing a network of internally accurate GCPs and allowing surveyors the ability of first-hand observations – with immediately subsequent UAVP survey, to implement the most efficient, accurate, and data dense microtopographic mapping protocol possible. The added benefit of high-resolution orthophoto production from UAVP survey would allow iterative ground-truthing and further observation and interpretation as desired. It is thus to the combination of these methods that this comparative analysis might point, establishing an extremely efficient method while maintaining a hands-on, boots-on-the-ground knowledge of the microtopographies of archaeological sites.

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