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Article

Akragas from Above: UAV Multispectral Survey and Photogrammetric Mapping of the Valley of the Temples, Agrigento

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Abstract

In August 2017 the Parco Archeologico e Paesaggistico della Valle dei Templi (Agrigento, Sicily) and Duke University began a programme of unmanned aerial vehicle (UAV) mapping across the heart of ancient Akragas, pairing a senseFly eBee Plus fixed-wing platform with RGB, near-infrared, and red-edge sensors under RTK positioning. The project produced centimetre-resolution orthomosaics, digital surface models (DSMs), vegetation-index layers and photogrammetric 3D models covering roughly two square kilometres of the intramural landscape, together with a dedicated block over the San Nicola sector, where the theater of Akragas had been confirmed by geophysics and excavation only the year before. This article presents the survey architecture, the data products and a first analytical reading of the results against the current state of Akragantine urban archaeology. A 5 cm full-site DSM renders the terraced urban plateau, the excavated insulae of the Hellenistic-Roman quarter and a fabric of candidate buried features as measurable micro-relief; near-infrared and red-edge mosaics, flown at the height of the summer drought, record the vegetation-stress patterning through which the unexcavated city writes itself into the modern surface; and a fully georeferenced 3D map links temples, agora, theater and landscape into a single analytical frame. Read alongside the revived excavation programs in the central public area - which have shown that even the city's grid plan requires re-verification on the ground - the survey demonstrates the role of fixed-wing multispectral photogrammetry at large classical sites: not an illustration of what is known, but an instrument for deciding where to look next.

Keywords: UAV photogrammetry; multispectral survey; near-infrared prospection; Akragas; Valley of the Temples; Agrigento; digital surface model; crop marks; RTK positioning; cyber-archaeology

1. Introduction

Few archaeological landscapes carry the weight of the Valley of the Temples. The ridge south of modern Agrigento holds the most complete series of Doric temples outside Greece, and behind that famous skyline stretches something even larger and far less visible: the whole urban body of ancient Akragas, a city that in the fifth century BC ranked among the greatest of the Mediterranean world. The Parco Archeologico e Paesaggistico della Valle dei Templi, a UNESCO World Heritage property since 1997 [1], protects on the order of 1,300 hectares - one of the largest archaeological parks in existence, and one of the hardest to know. Only a small fraction of the ancient city has ever been excavated. The rest lies under olive groves, almond orchards, fallow fields and modern roads, recorded piecemeal by a century and a half of trenches, historical cartography and geophysical campaigns.

Scale is precisely the problem that aerial robotics addresses [2,3]. In the summer of 2017 the Parco finalized an agreement with Duke University for drone-based research and high-resolution two- and three-dimensional mapping of the park, and the first field campaign flew in early August of that year, pairing a senseFly eBee fixed-wing mapping UAV for the site-wide blocks with a quadcopter for low-

altitude work. The stated aim was to investigate archaeological areas and geomorphological features not visible until then with traditional instruments - and, through the resulting map, to open new research and potentially new excavations. On the Duke side the work belonged to a broader cyber-archaeology program [4,5] (the Bass Connections 'Digital Cities and Cyberarchaeology' project) that joined the Dig@Lab directed by Maurizio Forte with the Marine Robotics and Remote Sensing Lab directed by David Johnston, applying fixed-wing UAS survey to Akragas, with the explicit deliverable of radiometrically calibrated orthomaps, dense point clouds and immersive 3D environments.

The datasets analyzed in this article are the processed heart of that Agrigento record: an RGB DSM at 3.1 cm ground sample distance (GSD); a red-edge orthomosaic at 4.9 cm; a near-infrared (NIR) DSM at 5.0 cm; a dedicated NIR block over the theater sector at 4.9 cm; and a textured 3D mesh with rendered fly-throughs, all delivered in WGS 84 / UTM zone 33N (EPSG:32633). What follows is both a report and an argument. The report describes the platform, the flight architecture, the processing chain and the quantitative character of the data. The argument is that datasets of this kind change the epistemology of urban-scale archaeology: they convert a landscape into a continuous, queryable measurement - centimeter-scale surface geometry co-registered with vegetation physiology - in which hypotheses about the buried city can be generated, tested and mapped without breaking ground. At Akragas that argument has force, because the last decade of fieldwork has shown that even the most basic element of the city's archaeology, its street grid, is less securely known than a century of published plans implied.

2. Akragas: The Historical Frame

Akragas was founded around 582-580 BC by colonists from Gela - themselves of Rhodian and Cretan descent - under the oikists Aristonous and Pystilus [6], on a naturally defended plateau between two rivers: the Akragas (the modern San Biagio) on the east and the Hypsas (the modern Sant'Anna or Drago) on the west. The site rises northward to the twin heights of the Rupe Atenea and the hill of Girgenti - which of the two carried the acropolis of Polybius' description remains a debated question [7] - and falls southward to the long calcarenite ridge, the so-called Collina dei Templi, that would become the city's monumental facade. Under the tyrant Phalaris (c. 570-550 BC) the young city consolidated its territory; under Theron, from 488 BC, it entered its golden age. The victory of Theron and Gelon over Carthage at Himera in 480 BC released an extraordinary flood of wealth and captive labour into the city.

The monumental consequences still define the site. The colossal Temple of Olympian Zeus - at roughly 112.7 by 56.3 m on the stylobate the largest Doric temple ever attempted, its entablature carried in part by telamones some 7.5 m tall [8] - was begun in the aftermath of Himera and, according to Diodorus, built with Carthaginian prisoner labour; it was still unfinished when the city fell. Through the fifth century the southern ridge received the sequence of peripteral temples - Heracles, the so-called Concordia, Hera Lacinia - whose preservation is unmatched outside Greece. The same prisoner workforce, Diodorus records, cut the city's celebrated underground aqueducts, named 'Phaeaces' after the engineer Phaiax who oversaw them, and excavated the great kolymbethra, a pool seven stades in circumference [9,10]. Pindar [11], writing for the aulete Midas of Akragas around 490 BC, could already address the city as the most beautiful among the cities of men, the haunt of Persephone; Empedocles, its most famous son, belongs to the generation that followed. Ancient claims of 200,000 inhabitants including resident aliens (Diodorus) are treated by modern scholarship as inflated - current estimates favour a total population in the range of 30,000-40,000 [12] - but the city's physical scale, a walled circuit of some twelve kilometres with nine gates, is not in dispute.

The catastrophe came in 406 BC, when the Carthaginians under Himilco took and sacked the city after a seven to eight months [9]. Akragas never fully recovered its fifth-century standing, but it was far from finished: refounded in the later fourth century under Timoleon with settlers led by Megellus and Pheristus of Elea, it flourished again in the early Hellenistic period - the horizon to which the theater and the monumentalised public area belong - passed violently between Roman and Carthaginian hands in the Punic Wars (taken by Rome in 261 BC and again in 210 BC), and lived on as

Roman Agrigentum, a substantial urban centre into late antiquity. This long stratified life is what the modern surface records: an Archaic and Classical plan, Hellenistic monomialization, Roman rebuilding, late-antique contraction, and two millennia of agriculture on top.

3. The Buried City and Two Centuries of Its Exploration

The scholarly mapping of Akragas began with Julius Schubring's *Historische Topographie von Akragas in Sizilien* [13], the first systematic topography of the ancient city, and continued with Koldewey and Puchstein's architectural survey of the temples at the end of the nineteenth century and Pirro Marconi's excavations and anastyles of the 1920s [14]. The postwar era of Superintendent Pietro Griffo - commemorated in the name of the regional archaeological museum - opened the period of systematic urban excavation, carried forward above all by Ernesto De Miro and Graziella Fiorentini: the San Nicola hill excavations of 1959-1963, the exposure of the Hellenistic-Roman quarter, the identification of the ekklesiasterion during construction of the museum, and the bouleuterion on the northern slope of Poggio San Nicola [15,16].

Aerial evidence entered the story early. The influential reconstruction of the street grid published by Schmiedt and Griffo in 1958 was built substantially on air-photo interpretation [17], and it fixed the canonical image of the city plan: an orthogonal system of long east-west strips defined by major avenues (*plateiai*) around 7 m wide - one main artery reaching some 12 m - crossed at right angles by north-south lanes (*stenopoi*) of about 5-5.5 m, defining *insulae* roughly 35 m wide and up to c. 300 m long, laid across five terraces descending from the northern heights toward the temple ridge. De Miro dated the plan's establishment to the sixth century BC [15], reading the Temple of Olympian Zeus - begun 480 BC and perfectly inserted into the alignments - as its *terminus ante quem*; others have emphasised the Timoleontic refoundation as the horizon of the grid as actually preserved. The excavated Hellenistic-Roman quarter east of the modern *Via dei Templi* shows the module in the flesh: four *insulae* c. 35 m wide, divided by 5 m *cardines* and 7 m *decumani*, containing some twenty-seven excavated houses founded in the second and first centuries BC and redecorated into the third century AD - re-examined most recently by a University of Bologna mission (2016-2021) [18-21].

Two developments of the last decade transformed this picture and set the stage for the UAV program. The first was cautionary: a new instrumental survey of the urban grid [22], using laser scanning and total-station verification, found that only about half of the previously mapped ancient structures could be verified on the ground, and proposed significant revisions to the canonical plan - shorter blocks in the first strips, a broad 13 m *plateia* dividing the southern zone, and more extensive public spaces than the 1958 reconstruction allowed. The published grid is partly a hypothesis, and it needs new, independent, spatially continuous data. The second development was demonstrative: the multidisciplinary program in the central public area begun around 2012-2014 by the Parco with the University of Catania (Luigi M. Calì), the Politecnico di Bari and partner institutions culminated in July 2016 with electrical resistivity tomography over the southern slope of San Nicola, whose concentric semicircular anomalies were confirmed by immediate excavation as the long-sought theater of Akragas - a *cavea* on the order of 95 m in diameter, built at the end of the fourth or the beginning of the third century BC and remodelled after the Roman conquest, opening onto a public plaza estimated at some 50,000 square metres, of a scale comparable to the agora of Athens [16,23-26]. Excavation of the theater and agora has continued in annual campaigns since, joined by the Freie Universität Berlin's re-investigation of the gymnasium - which in 2025 produced a covered auditorium of the second century BC seating some 200 [27] - and by a new international project at the quarter of Gate II. The buried city, in short, is under active interrogation from multiple directions; what it lacked in 2017 was a continuous, centimeter-accurate carrier for all of these threads. That is what the drone survey set out to supply.

4. Platform and Sensors: The eBee System

The senseFly eBee family is the workhorse of fixed-wing archaeological mapping. The August 2017 campaign flew the eBee then in service alongside a quadcopter for low-altitude detail. The eBee Plus has a flying wing configuration with a wing span of 110cm, weight of 1.1kg, and is hand-launched. With a larger wing than the eBee Legacy and 4900 mah lithium polymer battery, maximum flight times were typically 30-45 minutes. The eBee Plus also has real-time kinematic (RTK) navigation accuracy with large area coverage no multirotor in that time frame could match, making repeated whole-site mapping of an urban landscape practical within short campaigns. Flights are planned and supervised [28] in senseFly's eMotion software as overlapping photogrammetric blocks; the aircraft flies, triggers onboard sensors, and lands autonomously.

Two properties of the system matter most for archaeological work. The first is RTK/PPK positioning: the aircraft carries a survey-grade GNSS receiver whose corrections - applied in real time or in post-processing - bringing absolute image geotag accuracy down to the level of a few centimetres without dense ground control, an enormous logistical advantage on a 1,300-hectare protected site where placing and surveying targets is costly and intrusive. The RTK label carried in the Agrigento file names ('rertk', 'nirrtk', 'rgbtrk') records exactly this workflow, and the internal consistency of the delivered rasters - three independent flight blocks whose georeferencing agrees within a pixel or two - is its visible result.

The second is the payload architecture. For visible-band work, the survey used senseFly's Sensor Optimized for Drone Applications (S.O.D.A.), a 20-megapixel one-inch-sensor camera purpose-built for drone photogrammetry, delivering 2.9 cm GSD at 122 m - the source of the 3.1 cm RGB DSM in the Agrigento dataset. For multispectral work the platform individually carried the Canon S110 red-edge and near-infrared cameras, specially adapted for the eBee aircraft. The multispectral sensors' band set is designed around the physiology of plant stress: chlorophyll absorbs strongly in the red, healthy mesophyll scatters strongly in the NIR, and the steep transition between them - the red edge, sampled here through a deliberately narrow 10 nm window - shifts measurably at the first sign of physiological strain. These are precisely the wavelengths in which buried archaeology writes itself into a summer field.

Photogrammetric processing followed the standard structure-from-motion chain [29] in Pix4Dmapper: automatic tie-point extraction and bundle adjustment over each flight block, dense point-cloud generation, and derivation of orthomosaics and DSMs per image group, with the sensor imagery radiometrically corrected. The 'transparent_mosaic_group1' naming of the delivered orthomosaics is Pix4D's convention for the orthomosaic of the default image group - the software automatically groups images by band count and pixel type, generating one mosaic (with an alpha channel delimiting the flight footprint) per group - while the sensorbands additionally yield per-band reflectance maps within the processing project.

5. Flight Architecture and Campaign Logistics

Translating a 1,300-hectare park into flyable missions is an exercise in constrained optimisation. Ground sample distance scales linearly with flight height, while coverage per battery scales with it: the survey's answer was a tiered architecture. The site-wide blocks were flown at the altitude band that yields roughly 3 cm GSD for the S.O.D.A. and 5 cm for the S110 narrow-band cameras - fine enough to resolve wall-scale features, high enough to close each block in a small number of sorties - while the San Nicola/theater sector received a dedicated block at the same nominal 4.9 cm multispectral resolution but with the denser coverage that a complex, partly excavated, partly wooded terrace system demands; the campaign's quadcopter complemented the fixed wing at low altitude over standing monuments. In eMotion each block is defined by a polygon, a target GSD and forward/side overlap percentages; the software compiles these into lawn-mower flight lines, manages the wind-aware launch and landing, and logs the GNSS trajectory that RTK/PPK correction refines.

The multi-sensor design triples the flying but multiplies the information. RGB and multispectral cameras cannot share the eBee's single payload bay, so each block was flown per sensor - the reason the archive contains separate 'rgbtrk', 'rertk' and 'nirrtk' product families. Flying the pairs close in

time, under comparable sun and soil-moisture conditions, is what makes the layers commensurable: a vegetation anomaly can be interrogated against the surface geometry of effectively the same moment. August conditions in Sicily impose their own discipline - morning flights before thermal turbulence and heat haze degrade image geometry, and before the high sun flattens the shadow component that oblique light lends to micro-relief in the RGB imagery.

The downstream logistics are as real as the airborne ones. A campaign of this design produces tens of gigabytes of raw imagery per day; the processed archive analysed here alone spans some twelve gigabytes across five products, and the full Pix4D projects with dense point clouds are larger still. Processing time, not flight time, is the bottleneck of fixed-wing photogrammetry at park scale, and the delivery format matters accordingly: flat GeoTIFF rasters with world files in a common EPSG:32633 frame, readable by every GIS, are what turn a photogrammetric project into an institutional asset the Parco can layer against its cadastre, its excavation archive, the 2016 grid re-survey and the accumulating geophysics.

6. The Data: Five Products, One Coordinate Frame

The dataset analysed here comprises, in a single UTM 33N frame: (1) the RGB DSM, 5.7 GB at 3.148 cm GSD - the highest-detail surface model of the set; (2) the red-edge orthomosaic, 44,650 by 26,860 pixels at 4.865 cm GSD, spanning 2.17 by 1.31 km; (3) the full-site NIR DSM, 41,902 by 25,038 pixels at 5.022 cm GSD, spanning 2.10 by 1.26 km; (4) the theater-sector NIR block - DSM and orthomosaic, each 10,207 by 15,471 pixels at 4.903 cm GSD, covering a 500 by 760 m window on the San Nicola area; and (5) the photogrammetric 3D mesh (3.6 GB) with two rendered fly-through videos. Within the full-site NIR block, valid surface measurements cover approximately 182 hectares - about 720 million individual elevation samples in that single raster.

The measured surface runs from about 66 m above sea level, in the incised valley on the western edge of the survey area, to just over 222 m on the heights toward the Rupe Atenea in the north-east: some 156 m of relief across the ancient city, with a median surface elevation close to 150 m. The elevation distribution is strongly structured - broad modes corresponding to the artificially flattened urban terraces, sharp tails at the gorge and the summit - and that structure is itself archaeological information, because a terraced Greek city is, in effect, a histogram of platforms. The survey footprint captures the essential cross-section of the ancient city: from the Hypsas-side valley in the west, across the Kolymbethra hollow and the intramural agricultural plateau, past the San Nicola public area, to the temple ridge at the southern rim.

The theater-sector block reads the same way at neighbourhood scale. Its 500 by 760 m window spans elevations from 139 m near the modern road to 217 m at its upper edge, centred on the monumental heart of the city: Poggio San Nicola with the museum, church and ekklesiasterion, the newly confirmed theater on its southern slope, and the excavated insulae of the Hellenistic-Roman quarter to the east. At 4.9 cm resolution the DSM records individual wall lines within the insulae, the kerbs of the 5 m cardines, and the geometry of the terracing that carries the whole public complex - detail at the threshold of what terrestrial survey delivers, but continuous over the entire sector and acquired in minutes of flight time.



Figure 1. Red-edge false-colour orthomosaic of the survey area (4.9 cm GSD, 44,650 x 26,860 px, WGS 84 / UTM 33N). The western gorge frames the site; the excavated Hellenistic-Roman quarter and the San Nicola public area are visible right of centre.

7. Reading the Terrain: Micro-Relief as Archaeology

A DSM becomes an archaeological instrument through visualisation and derivation - a toolbox systematised in the lidar literature [30–32] and equally applicable to photogrammetric surfaces. Hill-shading the full-site model from the north-west (315 degrees azimuth, 40 degrees elevation) strips colour and vegetation tone away and renders pure geometry, and in that rendering the anatomy of the site is immediate: the plateau steps down from north-east to south in long, sub-parallel terraces; the western gorge cuts a deep meandering trench; the temple ridge runs as a continuous structural line along the south; and the excavated insulae of the Hellenistic-Roman quarter stand out as a sharply rectilinear patch in an otherwise organic fabric of field boundaries and olive planting grids.

The archaeologically significant content is in the intermediate texture. Between the excavated areas, the hillshade shows families of linear features - low scarps, terrace lines, shallow linear depressions - whose orientations repeat across fields that are today divided and cultivated independently. Interpretation here must be disciplined, because the Akragantine surface is a palimpsest of at least three rectilinear systems: the ancient urban grid; the historic agrarian fabric of lynchets, clearance banks and terrace walls, which in Sicily can itself be centuries old; and the modern planting grids of olive and almond, whose regular spacing produces a spurious geometry of its own. Three filters help separate them. Orientation: the ancient grid has a known, internally consistent bearing, documented in the excavated quarter and the 1958 and 2016 surveys, while agrarian and planting alignments follow modern parcels. Module: candidate stenopoi should recur at the c. 35 m insula interval, and candidate plateiai at the multi-insula strip interval - a spacing test that continuous 5 cm data make actually performable, transect by transect, for the first time. Persistence: ancient features cross modern property boundaries indifferent to them, while agrarian features stop at the fence line. Lineations in the survey that pass all three filters - and a subset in the northern and central fields does - are strong candidates for streets and terrace walls of the buried city, and several visibly prolong the alignments of the excavated quarter into unexcavated ground.

The theater-sector hillshade is the dataset's showpiece, and its content can now be named precisely. The rectilinear core is the Hellenistic-Roman quarter: its insulae render room by room, its three exposed north-south stenopoi read as clean parallel channels at the documented 35 m rhythm, and the ambitus divisions within blocks are legible as fine internal lines. West of it, the terracing of Poggio San Nicola resolves into discrete engineered steps - the platform system that carries the ekklesiasterion and, on the southern slope, the theater confirmed in 2016. North of the excavation limit, faint rectilinear lineations continue beneath the ploughsoil on the same orientation and at compatible spacing - precisely the class of anomaly that the agora-area programme can test cheaply with targeted geophysics before any trench is cut. It must be stressed that a DSM records the surface, trees and all: photogrammetry does not penetrate canopy as lidar can, and in the olive groves the model measures crowns, not ground. The open fields between groves - a large fraction of the intramural area - are the bare-earth window in which this micro-relief analysis operates.

The two surface models also check each other. The RGB DSM, at 3.1 cm, is the sharper instrument - resolving kerbstones, column drums and the fabric of standing masonry - while the 5.0 cm NIR-flight DSM used for the site-wide analysis here trades a little acuity for a fully co-registered link to the spectral record. Where both surfaces record the same lineation, sensor artefacts can be excluded; where a feature appears in one epoch of flying and not another, the difference itself is data, flagging vegetation change, ploughing or disturbance between sorties. And the surfaces are a baseline as much as a snapshot: an RTK-referenced DSM at 3–5 cm is a dated, repeatable measurement of the entire park, and differencing it against future re-flights detects erosion, terrace failure and disturbance at centimetre scale across hundreds of hectares - conservation monitoring as a by-product of

prospection. Applying the fuller visualisation toolbox - multi-directional hillshade, sky-view factor, local relief models [33] - to these surfaces is the obvious, low-cost next analytical step.

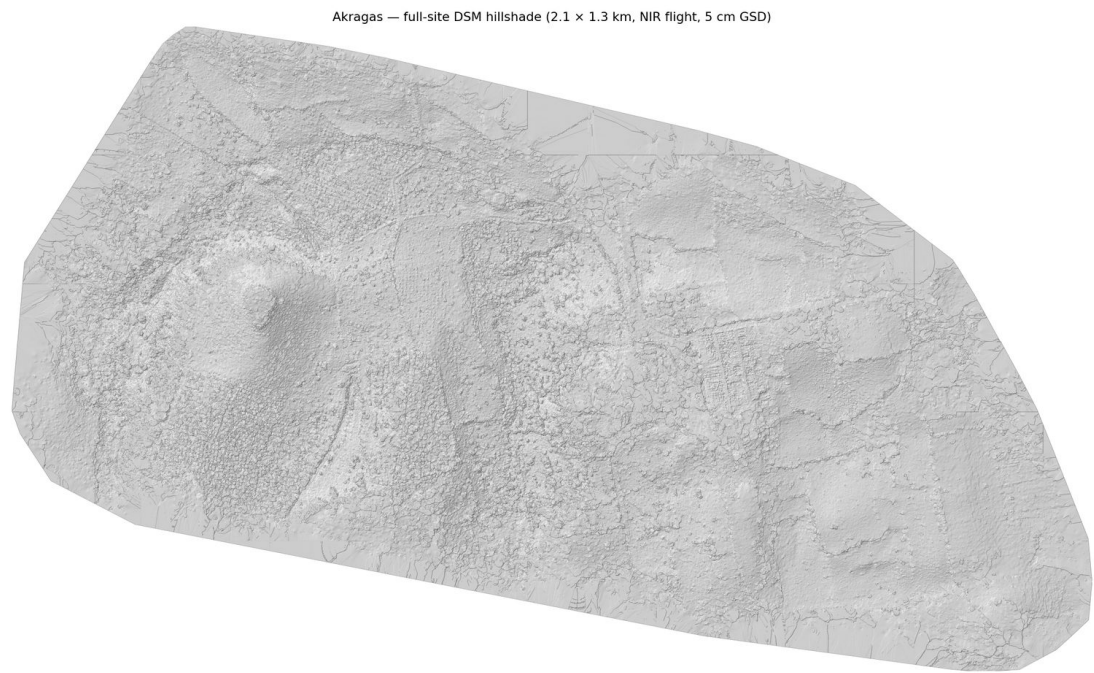


Figure 2. Full-site DSM hillshade (5 cm GSD, illumination 315/40 degrees). Urban terracing, field systems and the rectilinear texture of the excavated quarter render as pure micro-relief.

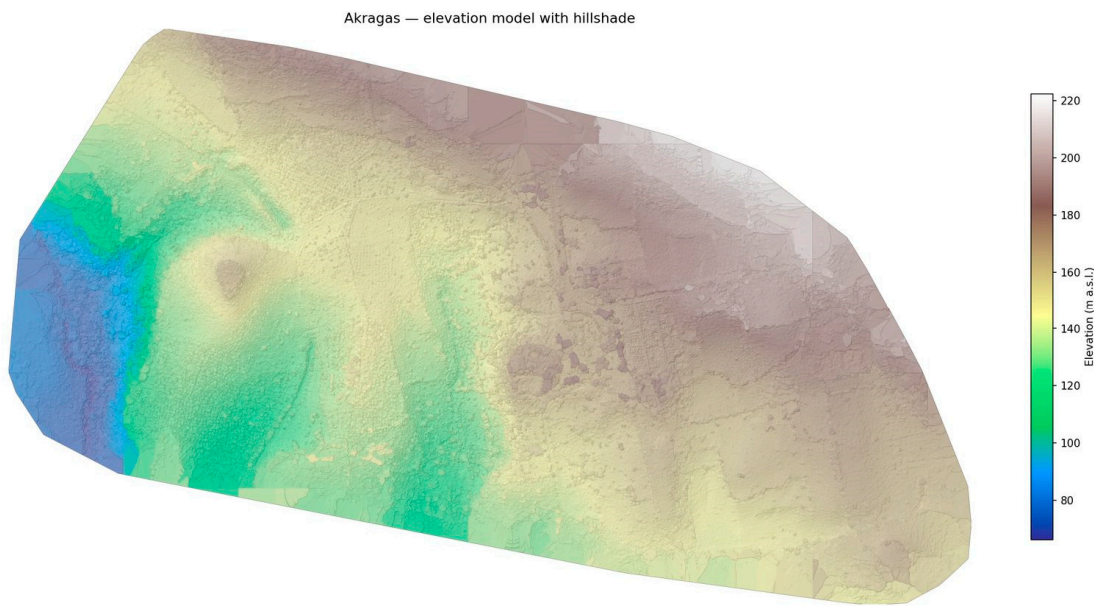


Figure 3. Elevation model with hillshade: 156 m of relief from the western valley (66 m a.s.l.) to the north-eastern heights (222 m), across the five-terrace fabric of the ancient city.



Figure 4. Theater-sector DSM hillshade (4.9 cm GSD, 500 x 760 m). The insulae and stenopoi of the Hellenistic-Roman quarter resolve wall by wall at the documented 35 m module; the terraces of Poggio San Nicola step down toward the theater slope; faint lineations continue beneath the fields to the north.

8. Seeing in Infrared: Vegetation as a Sensor

The multispectral products convert the park's vegetation into a distributed sensor of what lies beneath it. The physical chain is well established [34,35]: buried masonry thins the soil above it, reducing available water and stunting the plants rooted there - a negative crop mark; buried ditches, pits and robber trenches deepen and moisten the soil, producing enhanced growth - a positive mark. The contrast is expressed first and most strongly in the near infrared and the red edge, where reflectance responds to cell structure and chlorophyll activity, and it is routinely quantified through normalised-difference indices of the NDVI family [36]. Systematic comparisons [37] show such indices out-performing visible imagery for archaeological feature detection in grass-dominated

environments - and centimetre-scale UAV imagery brings the method from the satellite scale of entire sites to the scale of individual walls.

The Agrigento survey flew in the ideal window for the negative-mark regime: the height of the Sicilian summer drought, when herbaceous cover is under maximum water stress and differential access to soil moisture is most visible. The index maps computed from the red-edge and NIR mosaics show exactly the expected structure. Tree crowns and the few irrigated plots register as strong, healthy signal; the open fields lie in a low-index range in which subtle spatial patterning stands out; roads, paths and bare surfaces read near zero. Within the fields, the maps show linear and rectilinear index anomalies - some coincident with micro-relief features in the DSM, which is the strongest situation in archaeological prospection: two physically independent sensors, geometry and physiology, agreeing on the same buried cause. The interpretive filters applied to the terrain record apply here equally - orientation, module, persistence across parcels - with one addition specific to vegetation: an archaeological mark should be indifferent to crop type, reappearing across field boundaries where the underlying cause continues, while purely agronomic patterning (plough lines, irrigation reach, harvest state) respects them.

The relationship with geophysics is complementary, not competitive. Resistivity and radar interrogate the subsurface directly but at walking pace, in transects and grids that must be chosen in advance; the aerial multispectral record interrogates the surface expression of the subsurface everywhere at once, but inferentially. The efficient prospection cycle uses each where it is strong: the UAV layers nominate anomalies across the whole intramural area; geophysical crews verify and characterise the strongest candidates; excavation, the scarcest resource, is committed only where independent lines of evidence converge. This is not a hypothetical protocol at Akragas - it is a generalisation of the sequence that actually produced the theater, where ERT anomalies read in 2016 were confirmed by trenches within weeks [23].

Two methodological cautions apply. First, single-date imagery records one moment of one season; crop-mark expression varies dramatically with weather, crop and date, and the full power of the method arrives with repetition - a time series of index maps across seasons and years, which the eBee's coverage economics make realistic for the first time at this site. Second, the delivered mosaics are rendered composites; quantitative reflectance work - index arithmetic on calibrated bands, anomaly detection, classification - properly proceeds from the radiometrically corrected per-band reflectance maps in the processing project, of which the products analysed here are the visual expression.

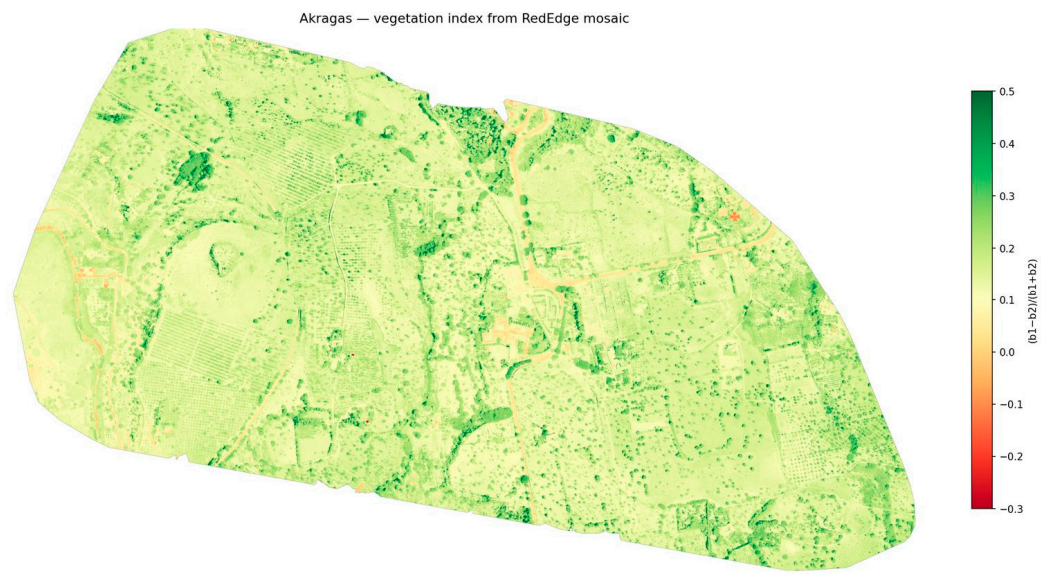


Figure 5. Vegetation index computed from the red-edge mosaic. Summer drought maximises the legibility of stress patterns; linear anomalies in the intramural fields are candidate traces of the buried street system.

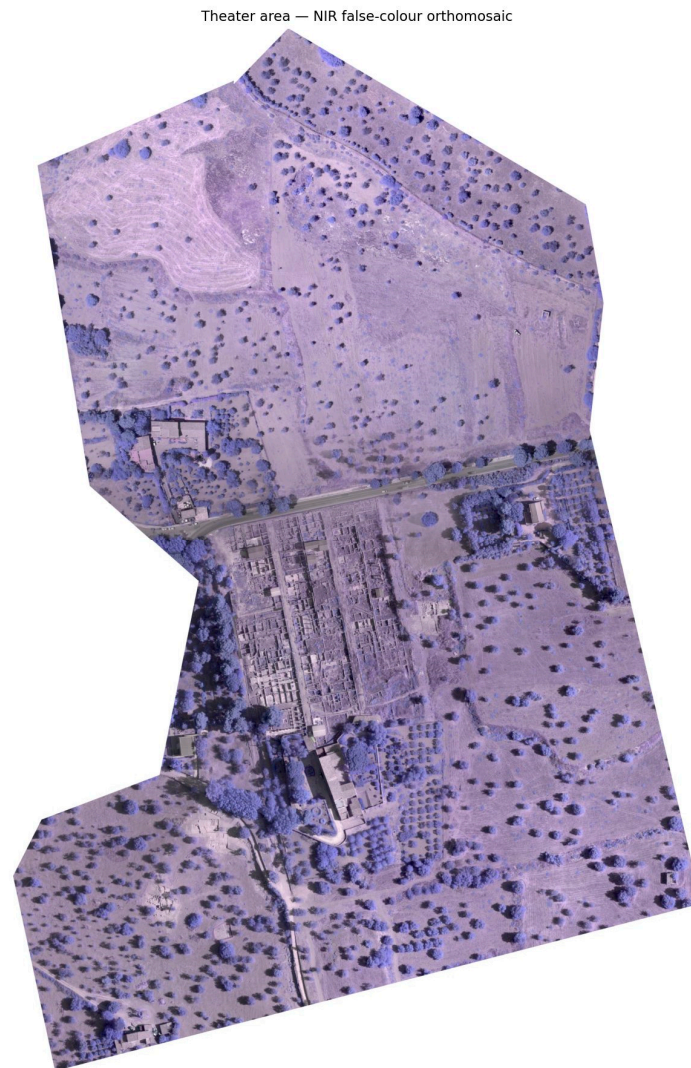


Figure 6. NIR false-colour orthomosaic of the theater sector: vegetation contrast complements the micro-relief record of the same block.

9. A prospection Agenda for the Buried City

Read against the current excavation programmes, the survey's layers suggest a concrete agenda - a set of places where the aerial record and the open questions of Akragantine archaeology intersect. First, the grid itself. The 2016 re-survey's finding that only about half of the previously mapped structures could be verified makes the DSM the natural arbiter: a systematic transect analysis of the intramural fields, testing micro-relief lineations against the documented orientation and the 35 m module, would produce an evidence-based revision of the Schmiedt-Griffo plan - block lengths, plateia positions, the debated 13 m southern artery - without a single new trench. Second, the agora complex. The plaza behind the theater, estimated at some 50,000 square metres, is largely unexcavated; the DSM's terrace geometry and the index anomalies on Poggio San Nicola's slopes are the cheapest available guide to its internal articulation, porticoes and access ramps, and to how the ekklesiasterion, bouleuterion, theater and gymnasium were knitted into one monumental system between the fourth and second centuries BC.

Third, the hydraulic city. The hypogea of Phaiax run for kilometres under the plateau, and their access wells, collapses and maintenance shafts have surface signatures - localised depressions, damp-loving vegetation, anomalous growth in drought - that the combined DSM and index layers are well suited to catch; the Kolymbethra hollow, within the survey footprint, ties the underground system to its monumental outlet. Fourth, the margins: the fortification circuit and its nine gates, where wall

lines surviving as terrace scarps and robber trenches surviving as positive marks can refine the course of the 12 km circuit, and the quarter of Gate II now under renewed excavation, for which the survey provides the wider urban context. Fifth, and least glamorous, the modern threats: the same layers that find ancient features also map gully erosion on the terrace edges, visitor-path wear and agricultural encroachment - inputs the Parco can act on directly.

None of these targets requires new flying; they require analysis of data already in hand, and each analysis sharpens the next campaign’s design. That is the practical meaning of survey-as-infrastructure: the marginal cost of a new archaeological question drops toward the cost of a GIS session.

10. The Third Dimension and the Immersive Turn

Because every pixel of every product is measured, the survey’s third deliverable is fully navigable 3D: a textured photogrammetric mesh of the survey area and rendered fly-throughs of the model. The 3D perspective makes the city’s siting legible at a glance - the defended plateau, the temple ridge as its southern rampart, the gorges as natural walls - a geography that explains the ancient admiration for the city’s beauty and strength better than any plan. The fly-through frames render tree canopy, standing ruins and terrain in continuous detail; the watermark of Duke’s Marine Robotics and Remote Sensing Lab on the rendered videos records the project’s collaborative architecture, which joined archaeological direction with a laboratory whose daily business is drone-based measurement science.

These models sit within a deliberate methodological frame - the cyber-archaeology programme developed by Forte and colleagues [4,38], in which digital models are not end-products but working environments: spaces where interpretation happens, is recorded, and remains revisable. The 2017 agreement explicitly envisaged a virtual reconstruction of the park to be studied in the DIVE, Duke’s six-sided CAVE-type immersive environment, where the georeferenced model becomes a walkable space: excavators, epigraphers and historians standing in the same virtual trench at true scale, with index maps and hillshades draped over the terrain under discussion. The epistemic gain is real - pattern recognition, the core act of landscape archaeology, works differently and often better at body scale than at screen scale - and the same assets feed the park’s public mission: virtual access to fragile or closed areas, museum installations, and a documented state-of-the-site against which future change can be shown to visitors as well as measured by scientists.

Finally, the archive dimension deserves emphasis. Datasets of this quality are scientific instruments for researchers not yet born: a centimetre-accurate, absolutely georeferenced record of the park’s surface in 2017 will be differenced against its successors for decades, and the products’ plain-raster delivery - GeoTIFF, world files, standard projections - is what keeps them usable as software generations turn over. Curating them alongside the excavation archive, with flight metadata and processing reports, converts a season of flying into permanent infrastructure for the site.

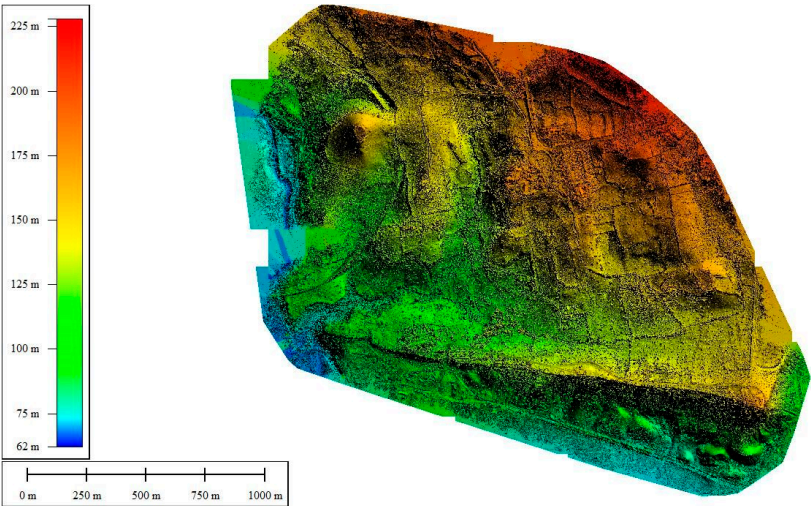


Figure 7. The digital elevation model in 3D perspective (62-225 m a.s.l.): the defended plateau of Akragas with the temple ridge as its southern rampart.



Figure 8. Frame from the rendered fly-through of the photogrammetric model (Duke Marine Robotics and Remote Sensing Lab).

11. Conclusions

The Akragas UAV programme demonstrates a mature methodology for very large classical sites. A fixed-wing platform delivers the coverage; RTK georeferencing removes the ground-control bottleneck; a paired RGB and multispectral payload captures geometry and physiology in the same campaign; and photogrammetric processing binds everything into a single centimetre-accurate frame - roughly 190 hectares per flight block, five primary products, one coordinate system. On the evidence analysed here, the approach delivers on its archaeological promises: micro-relief mapping that renders the excavated quarter wall by wall and extends its alignments into unexcavated ground; vegetation-index prospection that independently flags candidate features in the same fields; and a 3D framework that unifies temples, agora, theater and landscape for analysis, monitoring and public engagement alike.

The historical arc matters. Aerial evidence has shaped the image of Akragas since the air-photo-based plan of 1958; the 2016 ground re-survey showed how much of that inherited image was hypothesis; and the 2017 drone campaign answered with a new kind of aerial record - not oblique photographs interpreted by eye, but continuous, absolutely georeferenced measurement at five centimetres, repeatable at will. Where the 1958 plan could assert a grid, the 2017 surface can test one: orientation, module and persistence are now quantities, computed transect by transect against the excavated ground truth of the Hellenistic-Roman quarter. The revision of the city plan that the 2016 survey called for is, in large part, an analysis now waiting inside data already collected.

The epistemological point generalises beyond Agrigento. For a site of 1,300 hectares, excavation will always be the exception; the discipline's real currency is the intelligence with which its rare occasions are chosen. The theater's confirmation - geophysical anomaly to excavated cavea within weeks - showed the value of choosing well. The UAV record industrialises the front end of that pipeline: every anomaly it registers is a hypothesis with coordinates, an orientation, a module and a physical mechanism attached, ranked and ready for the resistivity crew before anyone lifts a trowel. In this division of labour the drone does not replace the excavator any more than the excavator replaces the historian; it re-orders them into a sequence in which each method spends its strength where the previous one has already narrowed the question.

The near-term agenda follows directly. Analytically: systematic grid-transect analysis against the 35 m module; application of the full relief-visualisation toolbox to both DSMs; quantitative index work on the calibrated reflectance bands; and formal co-registration with the 2016 laser-scan survey and the accumulating ERT grids of the agora programme. Operationally: seasonal re-flights to build the crop-mark time series that single-date imagery cannot supply; thermal acquisition, which adds a third independent physical mechanism (differential heat capacity) to geometry and physiology; lidar under the olive canopy, where photogrammetry is blind; and DSM differencing as a standing conservation service to the Parco. Institutionally: curation of the 2017 products as the reference epoch of a growing time series, and their publication alongside the excavation record so that the aerial and the stratigraphic archives of Akragas mature together.

The city that Pindar called the most beautiful of mortal cities has been waiting under its fields for a very long time. It has rarely been looked at this closely - and never in a form so ready to answer the questions its excavators are now asking.

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