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The Kolun Hillfort (Mrežica, Bosnia and Herzegovina): An Integrated High-Resolution Geospatial Documentation of a Fortification Provisionally Attributed to the Illyrian and Medieval Periods

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Abstract

The Kolun Hillfort, located near the village of Mrežica in the municipality of Foča, Bosnia and Herzegovina, is a recently recognized fortified site provisionally attributed to the Illyrian period, with probable reuse during the Middle Ages based on surface morphology and typological comparison with regional hillforts; this chronological attribution has not yet been confirmed by excavation or absolute dating. Despite its archaeological potential, the locality has not previously been investigated through systematic archaeological, geodetic, or geospatial research. No detailed topographic survey, LiDAR dataset, UAV photogrammetric model, or GIS documentation has been available. A comprehensive geospatial survey was therefore undertaken using RTK-GNSS measurements, Total Station surveying, UAV photogrammetry, airborne LiDAR, digital terrain modeling, and Geographic Information Systems (GIS). The integrated survey produced a centimeter-level digital model of the hillfort and its surrounding landscape. The resulting dataset documents the preserved dry-stone fortifications, natural defensive cliffs, internal plateau, terrain morphology, and principal access routes. Rather than offering archaeological interpretations, this paper establishes a reliable spatial framework for future investigations. The digital documentation provides an objective reference for archaeological excavation, landscape analysis, architectural reconstruction, defensive studies, and other multidisciplinary research. The workflow presented here may also serve as a practical model for documenting fortified archaeological sites elsewhere in the western Balkans.

Keywords

Kolun Hillfort, Illyrian Hillfort, Bosnia and Herzegovina, Geodetic Survey, RTK-GNSS, UAV Photogrammetry, LiDAR, GIS, Digital Terrain Model, Dry-Stone Fortification

1. Introduction

Fortified hilltop settlements represent one of the most characteristic archaeological features of the western Balkans. Built primarily during the Late Bronze Age and Iron Age, these sites occupied naturally elevated positions that offered extensive visibility over surrounding valleys and communication routes. Massive dry-stone walls were commonly combined with steep cliffs and rugged terrain, creating defensive systems that relied on both natural and constructed barriers. Many of these settlements continued to be occupied or reused during later historical periods, including the Roman and medieval eras, reflecting their long-term strategic value [1]-[3].

Despite more than a century of archaeological investigations throughout southeastern Europe, a considerable number of hillforts remain only partially documented. Earlier studies concentrated primarily on excavation results, architectural descriptions, pottery assemblages, and cultural chronology. Precise three-dimensional documentation of entire fortified landscapes has often remained secondary, largely because modern surveying technologies were not yet available. Consequently, many published plans are based on conventional field measurements and simplified topographic sketches, limiting detailed spatial analyses and comparisons between sites [4] [5].

During the last two decades, archaeological documentation has undergone a major technological transformation. High-precision RTK-GNSS surveying, robotic Total Stations, UAV photogrammetry, airborne laser scanning (LiDAR), and Geographic Information Systems (GIS) now permit the production of highly accurate digital terrain models and three-dimensional representations of archaeological landscapes. These methods reveal subtle topographic features hidden beneath vegetation, document preserved architectural remains with centimeter-level accuracy, and provide permanent digital records suitable for future excavation and multidisciplinary research. Integrated geospatial datasets have therefore become an essential component of archaeological documentation rather than simply a supporting mapping tool [6]-[9].

Bosnia and Herzegovina possesses hundreds of prehistoric hillforts, yet only a limited number have been documented using an integrated geospatial approach. One of the least investigated examples is the hillfort situated on Kolunsko Brdo near the village of Mrežica, Municipality of Foča, in the southeastern Dinaric Alps (**Figure 1**). The fortified plateau occupies the summit at approximately 1190 m above sea level, overlooking the surrounding mountain landscape and controlling natural communication corridors through the region. The settlement of Kolun lies at 43˚34'48"N and 18˚39'22"E, while the summit of the hillfort is situated at approximately 43.5949˚N and 18.6443˚E. The present geospatial documentation was carried out using the integrated UAV/LiDAR platform shown in **Figure 2**.

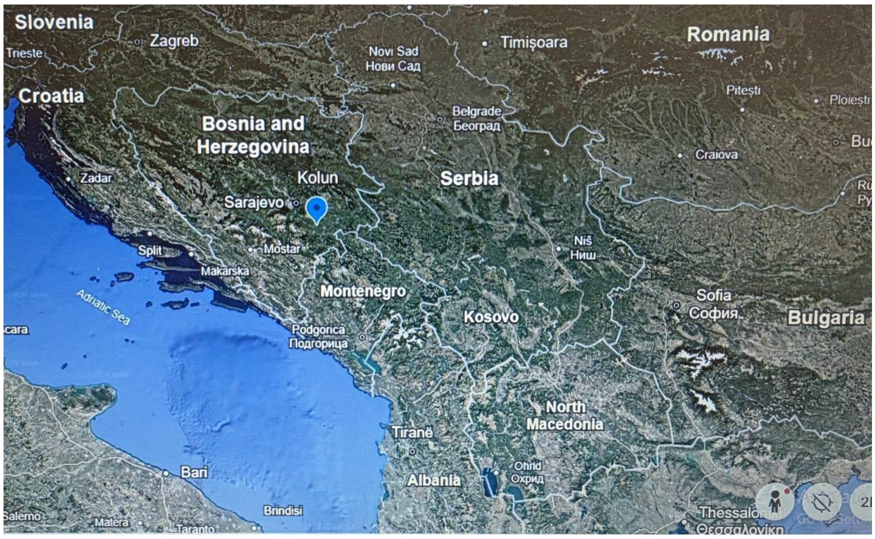

Figure 1. Location of the Kolun Hillfort near the village of Mrežica, Municipality of Foča, Bosnia and Herzegovina. The fortified hilltop occupies the summit of Kolunsko Brdo (approximately 1190 m above sea level) in the southeastern Dinaric Alps. The settlement of Kolun is located at 43˚34'48"N, 18˚39'22"E (43.5800˚N, 18.6561˚E), while the summit of the hillfort is situated at approximately 43.5949˚N, 18.6443˚E. The map illustrates the regional setting of the archaeological site within the western Balkans.

The locality was recognized only recently during field reconnaissance conducted by the Foundation "Čuvari baštine-Bassania." A recent anthropological assessment has discussed the landscape setting, defensive characteristics, and possible symbolic significance of the hillfort, while emphasizing that its chronological attribution remains provisional pending archaeological excavation and absolute dating [10]. Before this project, no archaeological excavations, professional geodetic survey, UAV photogrammetric documentation, airborne LiDAR survey, GIS database, or detailed geomorphological analysis had been undertaken. Existing knowledge was therefore limited to visual observations of preserved dry-stone wall remains and natural limestone cliffs that define the defensive character of the hilltop (**Figures 3-8**).

This contribution provides the first comprehensive geospatial documentation of the Kolun Hillfort. Rather than attempting archaeological interpretation of a site that has never undergone systematic excavation, the study establishes a high-resolution spatial reference framework based on complementary surveying technologies. The resulting dataset provides an objective record of the site's morphology, preserved architectural remains, terrain configuration, and defensive landscape, while creating a scientific baseline for future archaeological, architectural, geological, and environmental investigations.

This work intentionally focuses on documenting the site rather than interpreting it. Establishing a reliable spatial reference framework represents the necessary first step before archaeological excavation, architectural analysis, geophysical investigation, environmental reconstruction, or archaeoastronomical evaluation can be undertaken.

Recent work has demonstrated that GIS can be applied not only to conventional archaeological mapping but also to the quantitative evaluation of geometric relationships, constrained spatial hypotheses, and network organization within complex archaeological landscapes [11]-[13].

2. Materials and Methods

2.1. Study Area

The Kolun Hillfort is situated on Kolunsko Brdo near the village of Mrežica, Municipality of Foča, in southeastern Bosnia and Herzegovina. The fortified summit reaches approximately 1190 m above sea level within the Dinaric mountain system (survey-derived elevations within the fortified enclosure range from 1158 to 1191 m). The locality occupies a naturally defended limestone plateau bounded by steep escarpments on several sides, while gentler approaches occur along the northeastern sector. The topographic position provides extensive visual control over the surrounding valleys and mountain passes, characteristics typical of prehistoric, fortified settlements throughout the western Balkans.

The visible archaeological remains consist primarily of dry-stone wall segments preserved along the margins of the plateau together with prominent natural limestone cliffs that formed an integral part of the defensive system. At present, no excavated architectural remains or stratigraphically documented archaeological deposits have been reported from the site. The survey therefore focused exclusively on non-destructive documentation of the visible landscape and terrain morphology.

The current study extends previously developed GIS methodologies by applying high-resolution RTK-GNSS surveying, UAV photogrammetry, airborne LiDAR, and integrated spatial analysis to a newly documented archaeological site [11]-[13].

2.2. Survey Strategy

The survey was designed to produce a complete high-resolution geospatial record of the hillfort using complementary surveying methods. Each technique documented a different aspect of the archaeological landscape while all datasets were integrated within a common coordinate reference framework.

Field documentation included:

- RTK-GNSS measurements for establishing precise ground control.
- Total Station observations for detailed mapping of visible archaeological and topographic features.
- UAV photogrammetry for high-resolution aerial imagery and surface recon-

struction.

- Airborne LiDAR acquisition for generation of terrain models independent of vegetation cover.
- GIS integration of all spatial datasets into a unified geodatabase.

The combination of these techniques minimized positional uncertainty while allowing direct comparison between independently acquired datasets.

2.3. Geodetic Survey

Figure 2. DJI Matrice 350 RTK unmanned aerial vehicle equipped with the DJI Zenmuse L2 LiDAR/RGB sensor, used during the integrated geospatial survey of the Kolun Hillfort. The platform was employed for simultaneous airborne laser scanning and UAV photogrammetric data acquisition. Photograph taken during the field campaign, 10 July 2026.

Field data collection employed the UAV/LiDAR platform shown in Figure 2 and was carried out between 10 and 21 July 2026 by GeoGIS Studio d.o.o. (Sarajevo), covering a surveyed extent of approximately 14.1 ha across the hillfort and its immediate surroundings (elevation range of the surveyed extent: 1082 - 1248 m a.s.l.). Ground control was established using real-time kinematic (RTK) GNSS positioning, referenced to the national geodetic coordinate system, in order to secure high absolute positional accuracy for all collected data; GNSS receivers (Leica GS14 and South G1+) and Total Stations (FOIF RTS362 and Trimble S6) were used for detail surveying. Five ground-control/orientation points (GG1-GG5), used to orient and check the LiDAR point cloud, were measured by RTK-GNSS across the site; their coordinates are listed in Table 1. A network of nine pre-existing national trigonometric points was used to compute the datum transformation parameters for the survey area, and the official transformation parameters published for the Foča area were applied during coordinate processing.

All spatial data are referenced to the Bosnia-Herzegovina State Coordinate System, using the Bessel 1841 ellipsoid on a Gauss-Krüger (Transverse Mercator) projection, central meridian 18˚E—equivalent to EPSG:3908 ("MGI 1901/Balkans zone 6"). Transformation between WGS84/GRS80 and the Bessel 1841 datum was performed using a seven-parameter Helmert transformation, whose parameters (as computed for the project area from the national trigonometric network) are given in Table 2. Real-time GNSS corrections were obtained from the permanent reference stations of the Federal Geodetic Administration of Bosnia and Herzegovina via RTCM correction messages; residuals at the ground-control points, measured with a Leica GNSS receiver, were approximately 2 cm. Comparison of the LiDAR-derived terrain model against the five RTK-GNSS check points (GG1-GG5) indicated a horizontal RMSE of 0.031 m and a vertical RMSE of 0.019 m.

Table 1. Ground-control/orientation points (GG1-GG5), measured by RTK-GNSS, used to orient and check the LiDAR point cloud.

Point	Y (m)	X (m)	H (m)
GG1	6551764.567	4826539.883	1119.734
GG2	6551717.244	4826564.270	1117.852
GG3	6551627.656	4826624.762	1113.416
GG4	6551753.036	4826572.540	1125.780
GG5	6551807.261	4826568.902	1135.782

Table 2. Seven-parameter datum transformation (WGS84/GRS80 → Bessel 1841) applied to the survey area.

Parameter	Value	Unit
Translation ΔX	−198.110713	m
Translation ΔY	33.886804	m
Translation ΔZ	−517.365630	m
Rotation RX	1.944726	arc-seconds
Rotation RY	11.130053	arc-seconds
Rotation RZ	−9.019356	arc-seconds
Scale factor ΔS	−42.433074	ppm

2.4. UAV Photogrammetry

UAV photogrammetric data were acquired using a DJI Matrice 350 RTK platform on 10 July 2026 between 12:59 and 13:30 local time, yielding 580 overlapping aerial photographs georeferenced directly from the platform's onboard RTK-GNSS positioning. The platform was flown at a constant altitude of 45 m above the terrain surface, with 70% along-track and 40% cross-track image overlap. Camera exposure settings were controlled automatically by the platform. The photographs were processed together with the LiDAR data in DJI Terra, which generated a digital orthophoto in TIFF format. UAV imagery provided detailed visual documentation of preserved dry-stone walls, natural cliffs, vegetation cover, and the overall configuration of the fortified plateau (**Figures 3-6**).

Figure 3. Location and general view of the Kolun Hillfort obtained from UAV photogrammetry. The photograph illustrates the elevated plateau, surrounding cliffs, and the strategic topographic position of the fortified settlement.

Figure 4. Natural limestone cliffs forming the western defensive sector of the hillfort. These steep escarpments significantly reduced access to the settlement and formed part of its natural defensive system.

Figure 5. Aerial view of the central plateau showing preserved dry-stone wall remains and the principal occupation area enclosed within the fortification.

Figure 6. UAV photograph of the central plateau showing the preserved dry-stone wall and the principal interior area of the hillfort.

2.5. Airborne LiDAR

The locality presents markedly complex morphology, with substantial elevation differences across the fortified enclosure and dense vegetation and low undergrowth covering much of the site. This required careful UAV flight-path planning to maintain a constant sensor height above the ground surface and ensure uniform point-cloud density across the variable terrain. The site's karstic character further motivated the choice of airborne LiDAR: multiple-return laser scanning allowed elimination of vegetation returns during post-processing and recovery of precise ground elevations in areas that were not visible to photogrammetric reconstruction alone. The combined LiDAR/RGB sensor package also allowed simultaneous acquisition of laser returns for terrain definition and high-resolution RGB imagery for photogrammetric processing within a single flight.

Airborne laser scanning was performed at a constant flight altitude of 45 m above the terrain surface, using a DJI Zenmuse L2 sensor mounted on the DJI Matrice 350 RTK platform (**Figure 2**), capable of registering up to five returns per laser pulse. Compared with earlier UAV-mounted LiDAR systems, the Zenmuse L2 provides higher point density, improved ranging accuracy, and multi-return capability, making it particularly suitable for documenting archaeological landscapes beneath dense vegetation. This configuration achieved a point density exceeding 150 points/m^2, enabling penetration through vegetation cover on the karstic terrain and recovery of ground elevations not visible to photogrammetry alone. LiDAR and photogrammetric data were fused, and the resulting point cloud was ground-classified in DJI Terra to separate terrain returns from vegetation and other above-ground objects. Ground-classified points were then used in ArcGIS Pro to generate raster terrain models at a spatial resolution of 0.3 m × 0.3 m (per the DEM product specification; a directly confirmed value for the DSM was not available, though it was generated by the same processing pipeline). The principal products used in this study include:

- Hillshade model (light source azimuth 315˚, altitude 45˚ above the horizon).
- Digital Elevation Model (DEM).
- Slope model (expressed in degrees).

These products significantly enhanced the visibility of subtle terrain features, preserved wall alignments, scarps, and geomorphological structures that are difficult to identify through conventional aerial photography alone (**Figures 8-11**).

2.6. Geographic Information System (GIS)

Vectorization of visible fortification and terrain features was performed directly on the classified LiDAR point cloud, first in AutoCAD and subsequently refined as three-dimensional polylines in Autodesk Civil 3D, so that each digitized line retained its true elevation. Vectorized elements were assigned unique feature codes by category: BW (bedemi/walls), EN (ulazi/entrances), PT (karakteristične tačke/characteristic points), CL (litice/cliffs), TR (terase/terraces), and RK (izdvojene stijene/isolated rocks). Digitized features were cross-checked against the orthophoto and the digital terrain model during vectorization to reduce misinterpretation, particularly where stone walls were partially obscured by vegetation. The resulting CAD dataset (DWG format) was then converted into a File Geodatabase in ArcGIS Pro, preserving the original feature codes and attributes, to produce the first comprehensive digital archive of the Kolun Hillfort and provide the spatial framework for future site management and conservation planning.

2.7. Research Limitations

This study documents only the visible morphology and topography of the site. Since no archaeological excavations, geophysical surveys, or stratigraphic investigations have yet been conducted, the paper intentionally avoids chronological or cultural interpretations beyond those supported by visible surface evidence. The geospatial documentation presented here is intended as a baseline dataset for future excavation planning and site conservation.

The chronological attribution of the hillfort to the Illyrian period, with probable reuse during the Middle Ages, follows the preliminary field assessment of the Foundation "Čuvari baštine-Bassania" and the general typological similarity of the preserved dry-stone construction to other Illyrian hillforts documented in the western Balkans [1]-[3]. This attribution is provisional, based on surface morphology and regional comparison rather than on stratigraphic or artifactual evidence; confirmation will require future excavation and absolute dating.

3. Results

3.1. General Morphology of the Hillfort

The integrated geospatial survey demonstrates that the Kolun Hillfort occupies a naturally defended limestone hilltop overlooking the surrounding mountainous landscape of southeastern Bosnia and Herzegovina (**Figure 1**). The site is positioned on the summit of Kolunsko Brdo (approximately 1,190 m above sea level), where steep escarpments form substantial natural obstacles along much of the perimeter. Only a limited number of approaches provide relatively easy access to the plateau, explaining the strategic value of the locality as a prehistoric, fortified settlement.

UAV photogrammetry clearly illustrates the relationship between the central plateau, surrounding cliffs, and adjacent terrain (**Figure 3** and **Figure 4**). The plateau occupies the highest part of the hill, while abrupt limestone outcrops define several sectors of the site's perimeter. These natural landforms significantly reduced the need for continuous artificial fortifications and probably influenced the overall layout of the settlement.

3.2. Preserved Architectural Features

The aerial imagery documents several preserved segments of dry-stone construction distributed along the margins of the central plateau (**Figure 5** and **Figure 6**). Although no archaeological excavation has yet been undertaken, the visible remains are consistent with defensive wall construction traditionally associated with prehistoric hillforts in the western Balkans. The preserved structures follow the natural configuration of the terrain rather than imposing a regular geometric plan.

A ground photograph obtained during the initial field reconnaissance by the Foundation "Čuvari baštine - Bassania" provides additional documentation of one of the principal limestone escarpments forming the hillfort's natural defensive system (**Figure 7**). The image records the condition of the site before the commencement of systematic geospatial documentation and complements the UAV observations by illustrating the vertical character of the exposed rock face.

Figure 7. Principal limestone escarpment at the Kolun Hillfort photographed during the initial field reconnaissance by the Foundation "Čuvari baštine-Bassania" (https://fondacijabassania.org/blog/kolun-mrezica-foca/). The steep natural cliff forms one of the site's principal defensive features and illustrates the geomorphological setting prior to systematic geospatial documentation.

In addition to the dry-stone walls and cliffs, the detailed geodetic vectorization (§2.6) identified two further surface features within the fortified enclosure: a linear channel or ditch, and the remains of a wooden construction, both digitized directly from the classified point cloud together with the wall segments, terraces, and isolated rocks described above. As with the wall remains, these features are documented here strictly as visible surface morphology, without distinguishing construction phase or period.

3.3. Geodetic Documentation

The RTK-GNSS and Total Station survey established the first high-precision geodetic reference framework for the Kolun Hillfort. The survey accurately recorded the visible archaeological structures, cliff edges, terrain breaks, pathways, and other significant topographic features. The resulting geodetic dataset provides the spatial control necessary for integrating all subsequent photogrammetric and LiDAR products within a common coordinate system.

Unlike conventional archaeological site plans, which often rely on manual field sketches or simplified topographic surveys, the present dataset offers centimeter-level positional accuracy suitable for future archaeological excavation planning, architectural reconstruction, and GIS-based spatial analyses.

3.4. LiDAR-Based Terrain Analysis

The airborne LiDAR survey produced a detailed representation of the hillfort independent of vegetation cover. The hillshade model (**Figure 8**) enhances subtle variations in surface morphology and reveals terrain features that are only partially visible in aerial photographs. Linear embankments, preserved wall alignments, abrupt scarps, and natural limestone ridges become considerably more distinct through hillshade visualization.

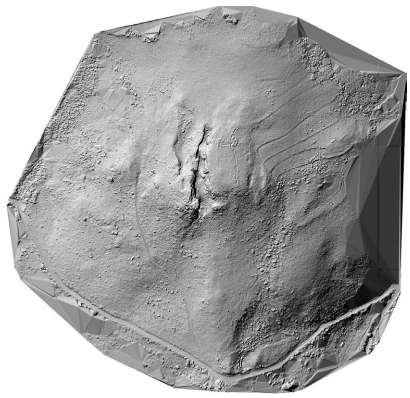

Figure 8. LiDAR-derived hillshade model of the Kolun Hillfort, revealing topographic discontinuities, cliff edges, and linear surface features interpreted as probable components of the hillfort's defensive system that are difficult to recognize in conventional aerial imagery.

The hillshade model with coordinate grid (**Figure 9**) provides an accurate spatial framework for future mapping and archaeological interpretation. It also facilitates comparison with other spatial datasets by preserving the precise location of individual terrain features.

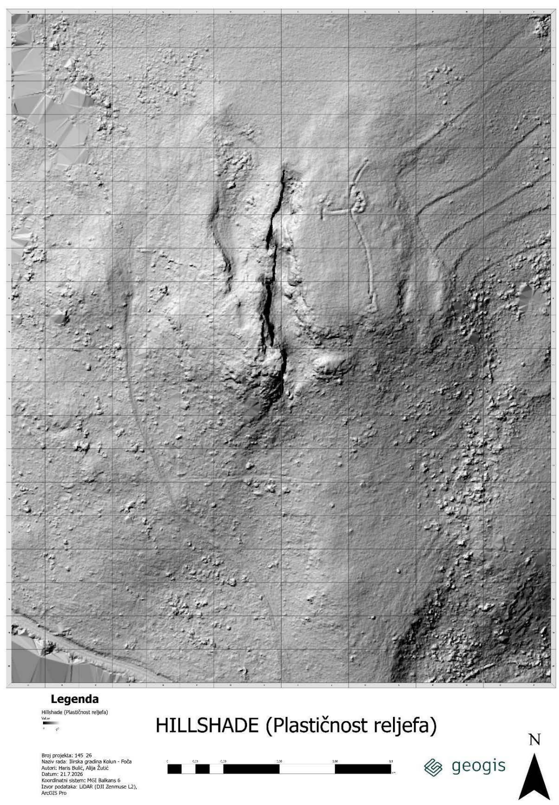

Figure 9. Hillshade model with coordinate grid, used to spatially reference the terrain features visible in **Figure 9** for subsequent GIS analysis and site-management planning.

The Digital Elevation Model (**Figure 10**) illustrates the relative elevation of the fortified plateau and the surrounding landscape. The highest elevations correspond to the central occupation area, while pronounced elevation differences occur along the natural defensive escarpments.

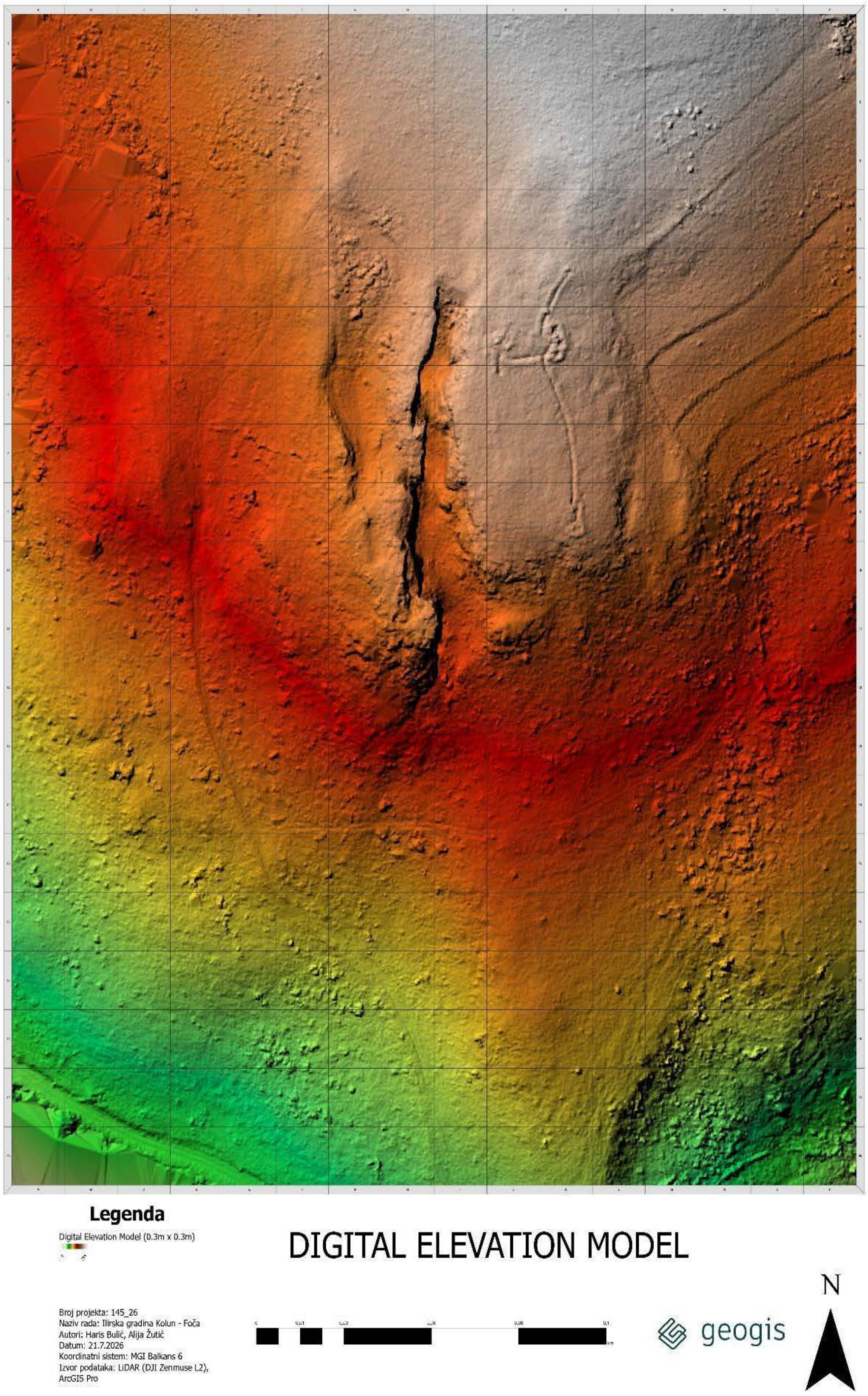

Figure 10. Digital Elevation Model (DEM) of the Kolun Hillfort and its immediate surroundings, showing the elevated central plateau and the escarpments that define its natural defensive perimeter.

The slope model (**Figure 11**) further emphasizes the defensive characteristics of the locality by distinguishing steep natural cliffs from the gently inclined surfaces of the central plateau. These terrain relationships explain why prehistoric builders selected the summit for fortification and demonstrate the close interaction between natural topography and defensive architecture.

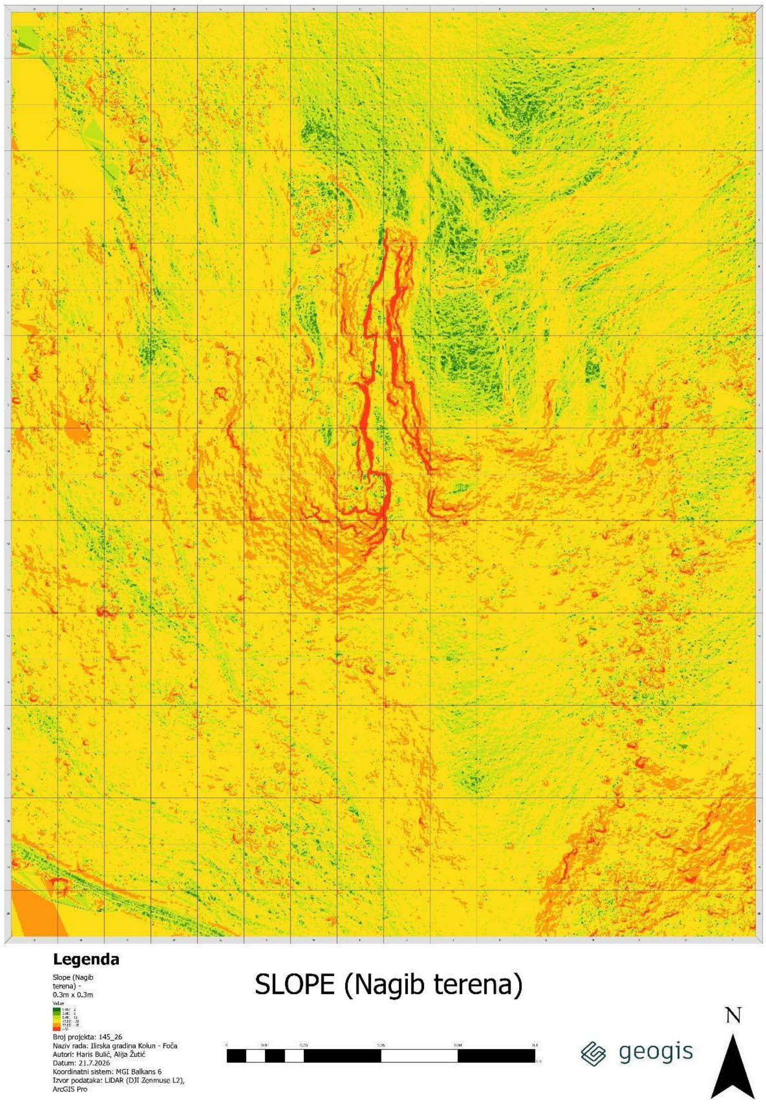

Figure 11. Slope model derived from the LiDAR dataset, distinguishing the steep natural cliffs that form the site's principal defensive barrier from the gently inclined surfaces of the occupied plateau.

3.5. Integrated Geospatial Dataset

One of the principal outcomes of the project is the creation of the first integrated geospatial database for the Kolun Hillfort. The database combines RTK-GNSS measurements, Total Station observations, UAV photogrammetry, airborne LiDAR products, orthophotography, and GIS layers within a single spatial framework. Such integration enables precise comparison of archaeological features, topography, and landscape morphology while preserving a permanent digital archive for future multidisciplinary investigations.

Rather than representing the final stage of research, this database establishes the foundation for subsequent archaeological excavation, architectural analysis, landscape modeling, environmental reconstruction, and spatial-statistical investigations. It also provides a reproducible reference dataset that can be expanded as new archaeological information becomes available.

The scale of the delivered dataset is unusually comprehensive for a newly documented archaeological site. The complete product set comprises approximately 36 GB of airborne LiDAR data, approximately 37 GB of UAV photogrammetric data, and an approximately 7 GB GIS geodatabase, together with a dedicated technical report, all produced by GeoGIS Studio d.o.o. (Sarajevo). This volume of centimeter-level digital documentation, assembled prior to any excavation, is not typical of first-season archaeological reconnaissance and instead reflects a level of geospatial investment more commonly associated with established, long-term research programs. To the authors' knowledge, this represents one of the most comprehensive integrated geospatial surveys conducted on a previously undocumented hillfort in Bosnia and Herzegovina prior to archaeological excavation.

Table 3 summarizes the principal parameters of the integrated survey and the resulting deliverable package.

Table 3. Summary of the integrated geospatial survey conducted at the Kolun Hillfort.

Parameter	Value	Source
Study area	Kolun Hillfort, Mrežica, Municipality of Foča, Bosnia and Herzegovina	Present study
Survey area	≈14.1 ha	GeoGIS Studio d.o.o.
Fortified enclosure elevation range	1158 - 1191 m a.s.l. (≈1,190 m at the highest preserved wall points)	Present study
Approximate hillfort summit coordinates	43.5949˚N, 18.6443˚E	Present study
Settlement coordinates	43˚34'48"N, 18˚39'22"E	Geographic reference
Survey dates	10 - 21 July 2026	GeoGIS Studio d.o.o.
Survey methods	RTK-GNSS, Total Station, UAV photogrammetry, airborne LiDAR	GeoGIS Studio d.o.o.
UAV/LiDAR platform	DJI Matrice 350 RTK with DJI Zenmuse L2 sensor	GeoGIS Studio d.o.o.
GNSS receivers	Leica GS14, South G1+	GeoGIS Studio d.o.o.
Total Stations	FOIF RTS362, Trimble S6	GeoGIS Studio d.o.o.
Coordinate reference system	MGI 1901/Balkans zone 6 (EPSG:3908); Bessel 1841 ellipsoid, Gauss-Krüger projection, central meridian 18˚E	GeoGIS Studio d.o.o.
UAV acquisition time	10 July 2026, 12:59 - 13:30 local time	Present study (UAV geotag log)
UAV photographs acquired	580	Present study (UAV geotag log)

Continued

Flight altitude (UAV/LiDAR platform)	45 m above terrain surface	GeoGIS Studio d.o.o.
Image overlap	70% along-track/40% cross-track	GeoGIS Studio d.o.o.
RTK correction source	Permanent GNSS reference stations, Federal Geodetic Administration of Bosnia and Herzegovina (RTCM correction messages)	GeoGIS Studio d.o.o.
GCP residuals	≈2 cm (Leica GNSS receiver)	GeoGIS Studio d.o.o.
LiDAR point density	>150 points/m^2	GeoGIS Studio d.o.o.
LiDAR terrain-model accuracy (vs. 5 GNSS check points)	Horizontal RMSE = 0.031 m; vertical RMSE = 0.019 m	GeoGIS Studio d.o.o.
DEM raster resolution	0.3 m × 0.3 m	GeoGIS Studio d.o.o. (DEM product legend)
Survey provider	GeoGIS Studio d.o.o., Sarajevo	Present study
Digital terrain products presented in this paper	Hillshade, DEM, slope models	GeoGIS Studio d.o.o.
Additional GIS/CAD deliverables in the full dataset	Orthophoto, DSM, CAD (DWG/DXF), point cloud, GIS geodatabase	GeoGIS Studio d.o.o.
Airborne LiDAR dataset volume	≈36 GB	GeoGIS Studio d.o.o.
UAV photogrammetric dataset volume	≈37 GB	GeoGIS Studio d.o.o.
GIS geodatabase volume	≈7 GB	GeoGIS Studio d.o.o.
Technical report	≈4 MB (PDF)	GeoGIS Studio d.o.o.

Camera exposure settings were controlled automatically by the UAV platform.

4. Discussion

This paper establishes the first comprehensive geospatial documentation of the Kolun Hillfort. It creates a permanent spatial framework that can support future archaeological excavation, architectural analysis, archaeoastronomical investigations, and spatial-statistical modeling.

4.1. Significance of Integrated Geospatial Documentation

The integrated geospatial survey carried out at the Kolun Hillfort represents the first comprehensive digital documentation of the site. Prior to this investigation, knowledge of the locality was limited to field observations and visual descriptions. No professional geodetic survey, UAV photogrammetry, airborne LiDAR acquisition, or GIS database had previously been produced. The present project therefore establishes the first objective spatial record of the monument and its surrounding landscape.

Unlike conventional archaeological plans based primarily on field sketches and selective measurements, integrated geospatial documentation records the entire landscape with a consistent level of positional accuracy. The combination of RTK-GNSS measurements, Total Station observations, UAV photogrammetry, and airborne LiDAR provides complementary information that cannot be obtained using a single surveying technique. The resulting digital products (**Figures 8-11**) document both visible archaeological features and the geomorphological characteristics of the surrounding terrain, creating a permanent digital archive that can be re-examined as new archaeological information becomes available.

The value of such documentation extends beyond simple mapping. High-resolution terrain models permit quantitative analyses of settlement morphology, defensive architecture, visibility, accessibility, and landscape organization that were previously difficult or impossible to perform. The digital dataset generated during this investigation therefore represents not only documentation of an archaeological site but also a reproducible scientific resource suitable for future multidisciplinary research.

4.2. Implications for Future Research

As noted in §2.7, this survey does not attempt archaeological interpretation. Establishing the chronology of individual wall segments, distinguishing separate construction phases, and determining the settlement's internal organization will require excavation supported by stratigraphic, chronological, and material analyses.

The geospatial framework established in this study provides the foundation for those future investigations. High-resolution orthophotography, LiDAR-derived terrain models, and precise geodetic measurements will facilitate the planning of excavation trenches, detailed architectural recording, volumetric analysis of preserved wall remains, and objective comparison with other prehistoric, fortified settlements in the western Balkans.

The integrated dataset also creates opportunities for future GIS-based investigations that extend beyond the scope of this study. These include viewshed analysis, least-cost path modeling, morphometric analysis of defensive architecture, spatial-statistical evaluation of settlement organization, and landscape archaeological investigations of the relationship between the hillfort and its surrounding environment. Because all datasets share a common spatial reference system, additional analytical layers can be incorporated without repeating the original field survey.

Finally, the methodology presented here demonstrates how modern geospatial technologies can be applied to poorly documented archaeological sites where little or no previous scientific documentation exists. The workflow developed for the Kolun Hillfort may therefore serve as a practical model for the documentation of similar fortified settlements throughout Bosnia and Herzegovina and the wider western Balkans.

4.3. Methodological Significance

The integrated workflow applied at Kolun addresses three recurring constraints in the documentation of hillfort archaeology: sites that are only recently identified and lack any prior survey record, terrain that is topographically inaccessible or hazardous for conventional ground-based mapping, and vegetation cover that obscures architectural remains from direct observation and from standard aerial photography. Each of these constraints has been addressed individually in earlier methodological literature; the present workflow combines the corresponding techniques within a single, centimeter-accurate spatial framework.

Doneus and Briese [4] demonstrated that airborne laser scanning can recover ground-surface detail beneath forest canopy that is otherwise invisible to aerial photography, a limitation directly relevant to the densely vegetated karstic terrain at Kolun; the LiDAR point density and ground-classification results obtained here (§2.5, §3.4) are consistent with that earlier finding and extend it to a previously undocumented site. Campana [5], reviewing the state of the art in UAV-based archaeological prospection, highlighted the growing role of drone photogrammetry in documenting sites with limited prior investigation; the present survey's integration of UAV photogrammetry with airborne LiDAR, rather than treating the two as alternatives, responds to that trajectory by combining their complementary strengths. Verhoeven [9] showed that Structure-from-Motion photogrammetry can generate reliable three-dimensional reconstructions from aerial imagery without specialized survey-grade cameras; the UAV-derived orthophoto and surface products described in §2.4 follow the same principle within an RTK-georeferenced workflow. Opitz and Cowley [8] argued for treating airborne laser scanning, three-dimensional data, and ground observation as complementary rather than competing sources of topographic evidence, particularly for interpreting archaeological terrain; the combination of hillshade, DEM, and slope products presented here (**Figures 8-11**), cross-checked against ground-based Total Station and RTK-GNSS measurements, applies that same principle to a fortified hilltop landscape rather than to open or lowland terrain, where most prior LiDAR-based hillfort studies have been concentrated.

Taken together, these comparisons suggest that the principal contribution of the Kolun workflow is not any single technique in isolation, but the integration of RTK-GNSS, Total Station, UAV photogrammetry, and airborne LiDAR into one internally consistent spatial framework, applied from the outset to a site with no prior documentation. This integrated approach may be particularly transferable to other undocumented or inaccessible hillforts in mountainous, heavily vegetated landscapes of the western Balkans, where the individual constraints addressed by Doneus and Briese [4], Campana [5], Verhoeven [9], and Opitz and Cowley [8] frequently occur together rather than separately.

More broadly, the workflow presented here demonstrates that comprehensive digital documentation can precede excavation rather than follow it. Such an approach allows archaeological interventions to be planned using an objective spatial framework, while preserving a permanent digital archive of the site's initial condition.

5. Conclusions

The Kolun Hillfort represents one of the least documented fortified archaeological sites in southeastern Bosnia and Herzegovina. Prior to this project, no professional geodetic survey, UAV photogrammetric documentation, airborne LiDAR survey, or integrated GIS database had been produced. Consequently, the site's morphology, defensive configuration, and topographic setting had never been documented using modern geospatial methods.

The integrated survey presented in this paper combines RTK-GNSS measurements, Total Station observations, UAV photogrammetry, airborne LiDAR, digital terrain modeling, and Geographic Information Systems within a single spatial framework. The resulting dataset provides the first high-resolution digital documentation of the hillfort and establishes a reliable reference model for future excavation and archaeological documentation.

The generated geospatial products document the preserved dry-stone fortifications, natural limestone escarpments, central plateau, and surrounding terrain with a level of precision that substantially exceeds conventional archaeological mapping. These data provide an objective basis for future analyses of defensive architecture, settlement morphology, landscape organization, and environmental context.

Rather than presenting definitive archaeological interpretations, this study establishes the essential spatial infrastructure upon which future multidisciplinary investigations can be built. As archaeological excavations and additional analytical studies are undertaken, the geospatial database will provide a consistent framework for integrating new observations while preserving the integrity and reproducibility of the original survey.

The approach described in this paper demonstrates the scientific value of combining complementary geospatial technologies in the documentation of complex archaeological landscapes. Beyond the Kolun Hillfort itself, the workflow presented here demonstrates how integrated RTK-GNSS, Total Station surveying, UAV photogrammetry, airborne LiDAR, and GIS can establish a permanent, high-resolution spatial archive for archaeological sites before excavation. The approach is readily transferable to other hillforts and fortified landscapes throughout the western Balkans, and more broadly to comparable mountainous, vegetated, or otherwise inaccessible archaeological terrain elsewhere, providing an objective foundation for future multidisciplinary archaeological research.

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Data Availability

The geospatial datasets generated during this project, including RTK-GNSS measurements, Total Station survey, UAV photogrammetric products, LiDAR-derived terrain models, and GIS datasets, are maintained by the author. Selected datasets may be made available upon reasonable request for scientific research purposes, subject to the protection of the archaeological site and applicable data-sharing agreements. The complete LiDAR dataset is not made publicly available in order to protect the archaeological integrity of the site and to prevent unauthorized activity at the locality.

Author Contributions

Sam Osmanagich, Ph.D. conceived the project, designed the research methodology, interpreted the results, and wrote the manuscript.

Ethical Approval

The investigation consisted exclusively of non-destructive geospatial documentation and surface observations. No archaeological excavation, intervention, or testing involving human or animal subjects was undertaken. Ethical approval was therefore not required.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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