Geophysics for architecture: non-invasive inventory of the buried relicts of a medieval monastery in Poland with application of the Amplitude Data Comparison Method (ADCM)

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EDITOR'S NOTE

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1. Introduction

The use of archaeological methods to study sites with architectural remains has a longstanding tradition, exemplified by the early adoption of the Harris matrix. This method is employed to establish the chronology of stone and brick walls in historic buildings uncovered during archaeological excavations, a practice also known as vertical archaeology. Since the 1970s, this approach in research has been called the archaeology of architecture and more recently, as the archaeoarchitecture or building archaeology. According to A.T. Cirigliano and R.A. Tirello (2015), archaeology of
architecture uses methods and tools of archaeological nature for the temporal recognition of historical buildings and to obtain the information about construction techniques, useful for further conservation and restoration projects. Thus, the historical building is considered a multi-layered object, constructed according to the temporal and diachronic processes. The methodology of archaeoarchitecture includes microstratigraphy – based on the Harris matrix method –, chronotypology and material analysis – radiocarbon dating, dendrochronology and geochemical analysis. When possible, this approach is also used in combination with the stratigraphic excavations to link the occupation layers to the successive architectural phases.

2 The pattern of architectural and archaeological investigations mentioned above applies mainly to buildings or architectural complexes that have been largely preserved. The situation changes drastically when we are dealing with a dilapidated building where only the foundations, hidden underground, have survived. In these cases, archaeological excavations become the primary method of the research. It should be stressed that the excavations usually expose masonry and other architectural elements, which must be subjected to costly conservation treatments; otherwise, they will slowly deteriorate. For these reasons, the best way to protect architectural remains preserved underground is to leave them in their natural environment, which implies reducing archaeological investigations to the bare minimum.

3 Thanks to the very dynamic technological progress, buried archaeological relics can be successfully inventoried and comprehensively studied using non-invasive methods such as magnetometry, ground penetrating radar (GPR) and geoelectric method, supplemented recently by aerial surveys – photogrammetry, LIDAR, infrared thermography and other techniques, using drones (UFV - unmanned flying vehicles). The use of GPR is particularly well-suited for the purpose of locating underground structures. In addition, GPR complemented by geomagnetic measurements, can provide valuable information not only on vertical and horizontal stratigraphy, but also on material properties of the buried structures. This became possible by implementing the innovative Amplitude Data Comparison Method (ADCM), which aids in interpreting the acquired geophysical data. In the next stage of data processing, geophysical results can be used to visualize underground relics, for example through 3D graphics, which are more understandable to viewers who are not specialists in geophysics. These graphic images can also serve as a valuable tool for promoting both the outcomes of geophysical survey and architectural heritage. This aligns well with the current trend of restoring and promoting lost architectural heritage in Poland through non-invasive detection and 3D visualization. It should be noted here that Poland is among those European countries whose history is marked by numerous invasions and wars. These events have significantly contributed to the extensive destruction of cultural assets, particularly architectural heritage. Below, the author outlines successive stages of non-invasive research of the buried remains of the medieval Dominican monastery located in Sandomierz, south-central Poland (fig. 1, A-C). These stages are complemented by the application of the ADCM, and the subsequent proposal of graphical 3D visualization of the subterranean remnants identified through GPR survey.

4 The monastery in Sandomierz has long attracted the interest of researchers, leading to a wealth of literature and numerous architectural and archaeological studies (fig. 1).
According to available historical data, the first Order of the Rule of St. Dominic was founded in Krakow in 1223, and by 1226, the Dominicans had settled at the Church of St. James in Sandomierz, promptly beginning the construction of a monastery. In the first phase, the church was built, followed by the construction of the eastern wing of the monastery, which is preserved to the present day. Around the middle of the 13th century, the southern wing was constructed independently of the eastern part of the complex. In 14th century, the western wing of the monastery was added, and the cloisters were likely built during the same period. The early Gothic bell tower, located to the west of the northern aisle, dates back to the transition between the 13th and 14th centuries. The 13th century Church and Monastery of St. James thus form an ensemble consisting of two elements: the church and two separate monastery wings. The entire complex was constructed using bricks, featuring particularly rich wall decorations on the northern elevation of the church, especially evident in the main portal (cf. fig. 1, D-F).

The survival of a plan depicting the section of the monastery, drafted before its destruction in 1865, greatly facilitated the implementation of non-invasive research in Sandomierz. Subsequent archaeological investigations carried out in the last decades have further contributed to our understanding of the stratigraphy of the buried remains (fig. 2).
As restoration and modernisation work is currently underway in the monastery area, a non-invasive inventory of the destroyed southern wing of the complex was necessary. To determine the state of preservation of the underground relics, a geophysical survey was carried out in 2022, implementing GPR and magnetometry. The results of this survey were interpreted applying the ADCM.

2. Methodology

The GPR method is based on the emission of electromagnetic waves into the ground by a transmitting antenna. At the boundary between two layers with significantly different physical and chemical properties, the electromagnetic waves are reflected and then recorded by the receiving antenna. The GPR method is ideal for searching for voids (crypts) or tracing the course of buried walls. However, it should be noted that the depth of GPR penetration is strongly dependent on the local lithological composition of the soil. The results of GPR measurements are called radargrams, or reflection profiles, which show the amplitude of the recorded signals using a colour palette. Additionally, if the GPR profiles have been conducted in parallel measurement lines, it is possible to interpolate the amplitude values by converting the time (ns) to distance (m) using the known speed of the electromagnetic wave in the ground. This allows for the creation of horizontal maps of the GPR signal amplitude values, known as GPR time slices, which provide an insight into the structure of the investigated site.
archaeological site at certain depths. Finally, it is also possible to superimpose the time slices, allowing for a 3D view of the detected underground remains9.

9 During the survey of the Sandomierz Monastery, the ABEM/MALA-GX Groundexplorer GPR system, equipped with a bimodal antenna with a nominal frequency of 450 MHz, was used. This provided an effective depth range, which can be estimated ca. up to 3 meters – again, this factor is strongly depended on soil lithological composition, see above. The individual profiles were spaced 0,50 m apart and covered the entire area of the now defunct southern wing of the monastery. The data was processed using the GPR Slice software (https://www.gpr-survey.com).

Magnetometry was the second geophysical method applied during non-invasive survey in Sandomierz, especially for further ADCM analysis. Typical magnetometer measure spatial variations in the Earth’s magnetic field18. On field, the total intensity values and components of the geomagnetic field are measured using different types of magnetometers – e.g. proton precession, optically pumped, cryogenic – or magnetic gradiometers. The latter are more commonly used in archaeological prospection. In this case horizontal or vertical derivatives of the total magnetic intensity are obtained by measuring and comparing two values of the geomagnetic field (or its components) at two closely situated points, up to 1,5 meters apart. The results of measurements taken with gradiometers are expressed in nanoteslas per meter (nT/m). Geomagnetic measurements that yield maps depicting the local distribution of the Earth’s magnetic field strength in a specific area, proves to be ideal for detecting traces of hearths, ditches, pits, burials, destructions layers, and other relevant features19. During the survey in Sandomierz a Bartington Grad 601 gradiometer was used, and the field data was processed using Terra Surveyor software. For the ADCM analysis, the geomagnetic measurements were conducted in the same area as the GPR profiling, following the same lines within measurement grids.

11 Along with significant advantages, the GPR and geomagnetic methods have also some limitations because they rely on different physical phenomena. Paradoxically, this makes them complementary in terms of the information they can provide. The author of this article, together with Professor L. B. Conyers, has proposed comparing the amplitude data obtained from measurements using both instruments20. The method, known as Amplitude Data Comparison (ADC), involves comparing specific GPR profiles – the records of signal amplitude captured by the GPR’s receiving antenna – with corresponding to them records of the ground magnetic field strength amplitude along the same measurement lines, recorded by a gradiometer. This provides information not only about the spatial structure of the architectural relics preserved underground, but also about the materials from which they are constructed21. The author of this article has also developed software, integrated into the Geographic Information System platform (QGIS), which fully automates the process of ADCM analysis.

3. Results of the non-invasive inventory of the southern wing of Sandomierz Monastery

Archaeological and historical data collected so far indicate that the monastery was built in several phases, interspersed with periods of destruction (fig. 3, A)22.
In the initial phase, a small church dedicated to St. James and the eastern wing, which remains intact today, were constructed. Further construction process was abruptly halted by the Mongol invasion in 1241. In the subsequent phase (1241-1264), the complex was rebuilt following the destruction caused by the Mongols. The church was enlarged by adding the nave and constructing narrow southern and western wings of the monastery. Finally, in the 14th century, tower was added to the nave of the church, and a Gothic-style cloister was built around the courtyard. The monastery complex was once again destroyed during the war between Poland and Sweden (1600-1611). After the war, the monastery was rebuilt in the Baroque style. At this time, the southern and western wings, as well as the cloister, were reconstructed as well (cf. fig. 3, A). The 19th century plan of the non-preserved southern part of the monastery, serves as documentation of this final phase. The key and most interesting question is to what extent the concept presented above regarding the architectural development of the southern part of the monastery is reflected in the resulting GPR images.

Selected GPR maps (time slices) for depth interval between 0.7-1.1 meters revealed the course of the wall foundations of the southern wing of the monastery in the form of characteristic linear anomalies characterised by a high signal amplitude (red colour). It is noteworthy that there are numerous discontinuities, suggesting the fragmentary state of preservation of these features (cf. fig. 3). First, an anomaly with a regular square outline draws special attention. It echoes the foundations of the cloister built around the courtyard of the monastery in the 14th century (cf. fig. 3, B1). The GPR images presented below suggest that while the northern and eastern foundations have...
survived in relatively good condition, the southern and western sections, in contrast, have been almost completely destroyed or demolished. Another area with relatively well-preserved foundation walls is located in the south-western part of the study area. The GPR profiling revealed a series of walls here, forming a large room obliquely oriented towards the monastery courtyard. In this case, there is a strong correspondence between the detected walls and the 19th century plan of the southern part of the monastery (cf. fig. 3, B2). Thus, it can be assumed that this room was constructed during the Baroque phase of the complex’s reconstruction.

The sequence of rooms in the southern and the oldest wing of the monastery, built in the 13th century is particularly challenging to interpret. (cf. fig. 3, B3). This is the result not only of demolition work but also of numerous archaeological surveys and excavations for underground installations, as demonstrated by the ADCM analysis below. The GPR profiling indicated that the western wing, also constructed in the 13th century, is preserved in a very fragmentary state (cf. fig. 3, B4).

To summarize, some of the rooms detected by GPR correspond with the layout of the southern wing as depicted in the 19th century plan, while others appear to be missing from it. The discrepancy between the wall arrangement shown in the old plan and their positions revealed by GPR profiling may result from the destruction during demolition or intentional alterations like levelling, excavations, or installation of underground infrastructure elements (cf. fig. 3).

Superimposing the selected time slice for the approximately one meter depth level with the location of the archaeological trenches leads to another interesting conclusion that traces of the previous excavations are not visible on the GPR images analysed here (fig. 4).
This is likely because the lithological properties of the infill within the trenches do not vary significantly from the surrounding ground, primarily composed of horizontally layered rubble of varying composition and diameter, as confirmed by excavation findings. In other words, the lack of contrast between the physical and chemical properties of the trench infill and the surrounding soil makes it initially invisible for the GPR. This observation is significant as it demonstrates that it may not always be feasible to trace old excavations applying the GPR method, especially on sites containing architectural relics.

Complementary geomagnetic measurements using a gradiometer were conducted in the same area as the GPR survey (fig. 5), namely to the south of the church. Individual profiles were measured at 0.50 meters intervals.
The resulting magnetic anomaly map has revealed numerous zones of high (darker areas) and low amplitude (lighter areas). Particularly noteworthy are the high-amplitude anomalies corresponding to the presence of water pipes, which are visible in the southern part of the polygon (cf. fig. 5). In between there are chaotically distributed anomalies with increasing amplitude values, which may be related to the accumulation of ash or destructs, just below the surface. There are also numerous point source anomalies of variable amplitude in the central part of the area. Some of these anomalies certainly indicate the position of metallic objects, especially those marked by dipoles (black-white dots). The anomalies marked with red arrows, are associated with the outlet of double gutters and lightning arrester installations (cf. fig. 5). The magnetic map presented here did not allow for tracing the course of the masonry, which was clearly visible in the GPR images. This is due to the presence of embankment layers rich in ferromagnetic material, as indicated by exceptionally high values of the magnetic field amplitude, reaching up to 100 nT.

To gather more information, the next step involved conducting an analysis applying ADCM. It should be noted that the presence of very high amplitude magnetic anomalies, generated by the elements of modern infrastructure, significantly reduces the applicability of ADCM. First, the GPR reflection profile no. 49 was combined with the corresponding gradiometer readings. This selected profile covered the central, previously unexplored part of the southern wing of the monastery (fig. 6).
Fig. 6 – ADCM analysis: GPR reflection profile no. 49 combined with the corresponding gradiometer readings. Time slice depth is marked by a horizontal white dotted line on the GPR profile (a). See detailed description in the text.

The profile revealed distinct zones of GPR high amplitude signals, which form the concentration of the diffraction hyperboles labelled as 1 and 2 (fig. 6, 1-2). These signals were, in fact, the reflections from the external stone and brick foundation walls of the southern wing of the monastery. Their magnetic signature (nT amplitude) is not substantially different from the surrounding area, indicating that the soil filling between the walls (cf. fig. 6, 3) has a similar lithological structure. Most likely it is dominated by stone and brick rubble embedded in a sandy matrix – these layers are visible on the GPR profile as numerous diffraction hyperboles and oblique and horizontal reflection surfaces. The significant increase in magnetic amplitude recorded at 12.5 meters on the x-axis (cf. fig. 6, 4) indicates the presence of an old and inactive water or sewage installation. In the lower part of the trench, a distinct hyperbolic reflection can be distinguished, likely an echo from a pipe, possibly made of cast iron. The detection of this pipe trench is significant for understanding the plan obtained using the GPR method, which depicts the layout of the former monastery walls. As noted earlier, the numerous discontinuities in the wall layout can now be precisely attributed to the presence of a wide and relatively deep trench. During its excavation, the foundations along its course were destroyed in the upper parts (cf. fig. 6, dashed line), making any analysis regarding the layout of the cellar rooms very difficult.

Another significant challenge in studying sites with remnants of the past architecture is that the valuable anomalies sought after are frequently obscured by anomalies generated by elements of modern road infrastructure, such as concrete pours or asphalted surfaces – e.g., car parks, access roads (this is also the case in our situation). Between 1 and 4 meters of the analysed profile no. 70 (x-axis), numerous anomalies in the form of horizontal reflection surfaces at a depth of 0 to 0.40 meters are visible
(cf. fig. 6, 4) echoing the embankment layers under the asphalt road. Below these, there are characteristic multiples, often referred to as such, which result from multiple reflections of electromagnetic waves between the layers comprising the road and the ground surface. In the northeast part of the analysed GPR profile, there is a zone of electromagnetic waves attenuation, characterized by low GPR signal amplitude and the absence of reflections. Additionally, this zone shows low magnetic readings (cf. fig. 6). This can be interpreted as a zone representing the interior of the monastery courtyard filled with sediments primarily composed of sand/clay fractions with the addition of fine rubble. It also suggests that the interior of the courtyard was gradually filled with various types of sediments due to natural and anthropogenic processes.

24 As demonstrated above, the ADCM analysis conducted enabled us to non-invasively identify the vertical stratigraphy in the central area of the southern wing of the monastery, which has not been explored through archaeological investigations before. Moreover, this analysis facilitated the characterization of the material composition of the architectural relics situated underground and the assessment of their state of preservation (degree of deterioration). Increasing the number of analysed GPR profiles using ADCM will notably enhance the amount of information obtained.

4. Visualisation of GPR results data in 2D and 3D

25 As demonstrated, ADCM analysis offers valuable insights into both the degree of preservation and the material characteristics of architectural relics. The challenge lies in visualizing the GPR profiling results in a way that is not only useful for specialists in geophysics and archaeology but also understandable for non-specialists. Therefore, the question of appropriate graphic representation of the results becomes particularly significant. It ensures the usability of the data not only within the scientific community but also in various materials aimed at promoting architectural heritage or a specific archaeological site.

26 The author of this article visualized the outcomes of the conducted geophysical survey through graphics that depict underground structures (anomalies) in both 2D and 3D formats. These graphics are accompanied by a spatial model of the preserved section of the examined architectural complex, constructed to an appropriate scale. This approach is feasible due to the availability of modern GPR software that can generate anomaly images in 3D format. For instance, in GPR slice software, this capability is achieved through the utilization of the Isosurface Rendering function, which relies on the API/Open GL and generates surfaces of anomalies of the same amplitude in a spatial volumetric model format. In the case of Sandomierz, the Isosurface Rendering function was used to create a volumetric model (3D) of the detected anomalies. These models were then exported to 3D graphics generation software, such as AutoCAD. The exported models were integrated into the spatial model representing the preserved section of the monastery. The model of the monastery was obtained by capturing photogrammetric images from a drone. These images were then processed in applications specifically designed for generating models from point clouds, such as Blender. The result is the comprehensive graphics presented here, which distinctively depict the preserved underground foundations of the southern wing of the monastery integrated with a 3D model of the preserved northern part of the monastery.
The graphic representations presented below aim to clearly illustrate the remnants of the unpreserved section of the monastery in relation to what has survived to the present day. These graphics are designed to be easily understandable to readers who are not specialists in geophysics. As a result, they can be valuable for projects aimed at preserving ancient architectural heritage, including specialized tourism initiatives. They could be published on websites or information boards to enhance the visual communication of this message.

The first option proposed by the author suggests integrating the 3D spatial model of the preserved section of the Sandomierz monastery complex with the results of the GPR scanning (depth: 1 meter) in the form of a 2D raster graphic with a colour amplitude scale. Such graphics effectively illustrate the correlation between the non-preserved wing of the monastery – identified through GPR profiling – and the preserved part of the complex (fig. 7).

![Integration of the 3D spatial model of the preserved part of the monastery complex with the results of the GPR scanning (depth: 1 meter) in the form of a 2D raster graphic.](image-url)

The second option would suggest merging 3D model of the existing part of the monastery with the results of the GPR profiling in the form of a transparent 2D raster graphic, under which a volumetric model of the underground relics of the southern wing of the monastery appears (fig. 8).

![Integration of the 3D spatial model of the preserved part of the monastery complex with the results of the GPR scanning (depth: 1 meter) in the form of a 2D raster graphic.](image-url)
In the proposed third version, the 3D model of the existing part of the monastery is combined with the results of the GPR profiling to create a 3D volumetric model of the preserved underground relics of the southern wing. This approach provides considerable flexibility for integrating additional raster graphics, such as old plans or archaeological findings (fig. 9, A-B).
Fig. 9 – A: 3D model of the existing part of the monastery integrated with the results of the GPR profiling in the form of a volumetric 3D model of the preserved underground remnants of the southern wing; B: The same version supplemented with the 19th century plan of the southern wing in the form of a semi-transparent 2D raster graphic.

5. Conclusions

In this article the author outlines the successive stages of non-invasive research conducted on the buried remnants of the medieval Dominican monastery in Sandomierz, located in South-Central Poland. This research employs innovative Amplitude Data Comparison Method (ADCM), complemented by graphical visualizations of the underground remains identified through ground-penetrating radar in 3D mode.

For many years, GPR and geomagnetic methods have been effectively used to identify the extent and stratigraphy of archaeological sites. GPR relies on the emission of electromagnetic waves into the ground, whereas geomagnetic methods involve measuring the Earth’s magnetic field intensity using magnetometers and gradiometers. Due to their distinct operating principles and reliance on different physical phenomena, GPR excels at locating underground walls and voids. In contrast, magnetometers and gradiometers are highly effective for detecting debris, furnaces, metal objects, ditches, and moats. The widespread adoption of geophysics in archaeology facilitates the rapid and efficient identification of sites, eliminating the need for time-consuming and costly excavations. The main challenges often encountered with architectural remnants include thick layers of rubble, which significantly complicate the interpretation of geophysical profiling results, as well as the presence of tree stands or above-ground infrastructure elements. Despite these obstacles, when implemented and interpreted correctly, GPR and geomagnetic profiling can provide highly valuable data not only on vertical stratigraphy and preservation...
state but, most importantly, on the layout of surveyed architectural features, especially those preserved as relics like foundations.

The information obtained can be significantly enriched through the use of ADC method. This method entails conducting both GPR and geomagnetic profiling within the same survey area. Subsequently, the results of GPR measurements are integrated into specialized software alongside a record of the magnetic amplitude, referred to as the magnetic signature. This approach allows for precise insights into the layout of the surveyed structure, its preservation state, and facilitates the identification of its construction material. The ADC method also enables rapid and comprehensive inventoring of preserved architectural relics, which is undoubtedly its greatest advantage. Furthermore, integrating geophysical survey results with archival materials, particularly iconographic data, through close collaboration between geophysicists, archaeologists, and architects/art historians, facilitates the spatial visualization of a non-existing or fragmentarily preserved architectural object in the form of a 3D model. Such visualisation can be used in scientific publications, as well as in various projects aimed at promoting architectural heritage.

NOTES

5. X. M. A. VILA et alii, « Archaeotecture : seeking a new archaeological... », op. cit.


senatorial villa in the Santa Marina bay (Croatia, Istria) using the amplitude data comparison method (ADCM) », Studia Quaternaria, 37/2 (2020), p. 79-90.

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13. A. KADLUCZKA and K. STAŁA, « St James’ Church... », ibid.


15. L. B. CONYERS, Ground-Penetrating Radar for Archaeology..., op. cit., p. 20 sqq.


17. L. B. CONYERS, Ground-Penetrating Radar for Archaeology..., op. cit.


20. L. B. CONYERS, Ground-penetrating Radar and Magnetometry..., op. cit. ; F. WELC et alii, « The first Neolithic roundel discovered in Poland... », op. cit.

21. F. WELC et alii, « The first Neolithic roundel discovered in Poland... », ibid.

22. A. KADLUCZKA and K. STAŁA, « St James’ Church... », op. cit.

23. A. KADLUCZKA and K. STAŁA, « St James’ Church... », ibid.

24. A. KADLUCZKA and K. STAŁA, « St James’ Church... », ibid.

25. A. KADLUCZKA and K. STAŁA, « St James’ Church... », ibid.


29. F. WELC et alii, « From field survey to 3D model... », op. cit.

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