Journal homepage: https://jmr.uaic.ro/

JOURNAL OF MULTIDISCIPLINARY RESEARCH
NEW APPROACHES AND DATA

Volume 1, Issue 1 (2024): 35 – 49

"Hic requiescit…": Localisation of a Baroque Crypt through a Combination of Ground-Penetrating Radar and Structure-from-Motion

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Abstract

For Archaeological Prospection a multitude of geophysical methods is commonly applied, as each of them is suitable for different tasks. Out of these, Ground-Penetrating Radar (GPR) depicts an ideal tool for the detection and mapping of stone constructions and air-filled cavities. As crypts are examples of both types of subsurface structures and, furthermore, are often located within existing buildings, in most cases, GPR is chosen as best approach. The presented results of the crypt of Baron Franz Hermann Anselm Christoph Augustin von Benzel-Sternau in the catholic Parish church St. Margareta at Kahl am Main (Northwestern Bavaria) document the advantages of the method, as even construction details like the ribbed vault and the internal layout can be identified in high detailed quality. Often, the pure geophysical results are not very comprehensible for the non-scientific public. For this purpose, further visualization methods are needed. We present a Structure-from-Motion (SfM) survey of the interior of the new baroque church to integrate the GPR data and to explain and show the results to the public.

Keywords: Archaeological Prospection, Ground-Penetrating Radar, GPR, Structure-from-Motion, SfM, Crypt, Ribbed Vault

1. Introduction

Non-destructive survey methods have become more and more important for archaeological research in the last decades. Especially for archaeological studies related to heritage protection, destructive excavation campaigns are either not possible or very limited. Hence, geophysical surveys play an indispensable role in this field. First attempts in the Bavarian governmental heritage protection were already made more than 40 years ago using aerial archaeology and magnetometry (Fassbinder et al. 2019; Linck et al. 2021b). In the meantime, Ground-Penetrating Radar (GPR) has been established as another important survey method, mainly for mapping stone constructions in the subsurface. Contrary to magnetometry, GPR can also be applied inside of buildings and on sealed ground. Therefore, stone-built crypts, partly being even air-filled, are ideal targets for the application of GPR. Corresponding results of such studies, revealing tombs and ribbed vaults detected by GPR, sometimes even combined with other methods like gravimetry or resistivity, are published in many countries. A lot of work on this topic was executed in Italy (e.g. Barilaro et al. 2007; Imposa and Mele 2011; Calia et al. 2012; Cataldo et al. 2012; Leucci et al. 2021; Cooper et al. 2023); but also, projects in other countries like e.g. Slovakia (Panisova et al. 2013), Portugal (Correia 2019), Germany (Zickgraf and Riese 2009; Riese and Schäfer 2014; Hofmann and Linck 2023; Linck 2023) or France (Tabbagh et al. 2002; Bully et al. 2011) are documented. All of them have proven the suitability of GPR for mapping the corresponding remains with varying antenna frequencies.

In the last few years, the principle of photogrammetry or Structure-from-Motion (SfM) has become more and more widespread due to the increasing ability to acquire such data by drones and high-pole tripods. Hence, the number of historical buildings documented in 3D by these methods, or Terrestrial Laserscanning (TLS) increased significantly. As a result, also the number of research projects combining 3D point clouds and geophysical data has increased. Published projects can be found from Italy (Cooper et al. 2023; Pomar et al. 2023), Nepal (Schmidt et al. 2023), Sweden (Viberg et al. 2011), Germany (Linck et al. 2023) or UK (Gaffney et al. 2018). Some of the above-mentioned examples even deal with the same approach we want to present for our case study: the combination of 3D-data with GPR results to visualize subsurface crypts (e.g. Pieraccini et al. 2020; Cooper et al. 2023).

2. Site description

Kahl am Main is located in Lower Franconia approximately 14 km northwest of Aschaffenburg in the northwesternmost corner of Bavaria, directly at the frontier to Hessen (Fig 1). One of the most famous inhabitants had been Baron Franz Hermann Anselm Christoph Augustin von Benzel-Sternau (* 28. August 1738 in Mainz; † 07. March 1786 near Palace Emmerichshofen), who was chancellor in Electoral Mainz and reorganised the Old University Mainz. In 1766, he constructed the Palace Emmerichshofen north of Kahl am Main, nearby the frontier between Bavaria and Hessen (PZP 2020). After his death, the Baron was buried in a vaulted crypt between the altar and the pews inside the former Baroque church.

The present-day church St. Margareta at Kahl am Main is a later new baroque construction that was erected in 1910 by Karl Marschall from Ludwigshafen on top of its predecessor (Fig. 2a). Due to the shifted position, nowadays the crypt of Baron Franz Hermann Anselm Christoph Augustin von Benzel-Sternau is located in the rear part of the nave. It was opened for the last time in 1910 during the church’s construction and afterwards refilled with sand. Unfortunately, the exact position was not documented, and a tomb slab at one of the outer walls of the church is the sole evidence (Fig 2b). The GPR survey aimed to map the detailed location and to acquire further information about the construction itself.

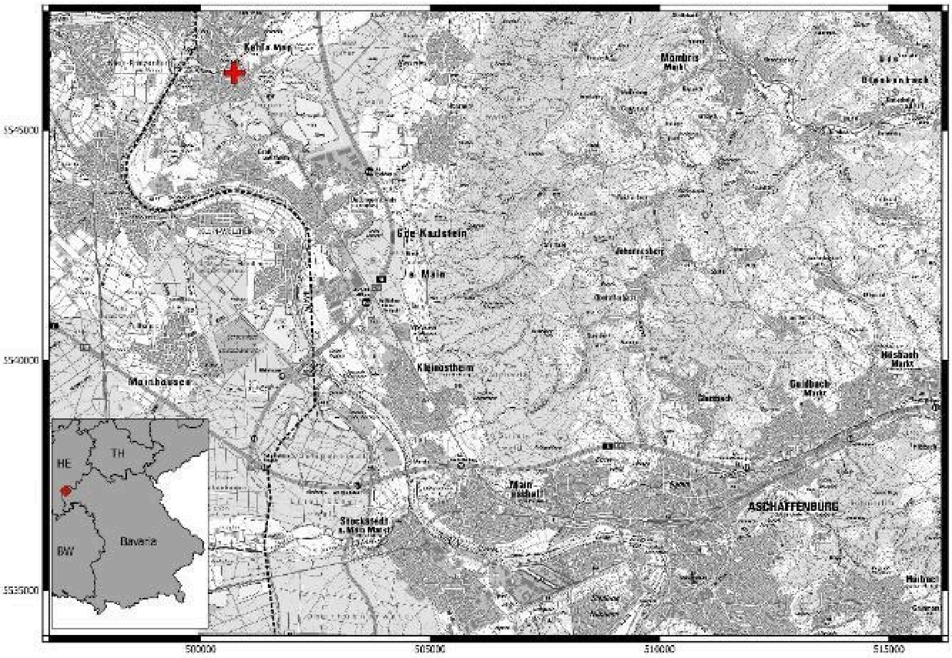

Fig 1. Topographical map illustrating the location of St. Margareta at Kahl am Main (marked with red cross). The dashed line depicts the frontier between Bavaria and Hessen. Coordinate system WGS84/UTM32N (© Bayerische Vermessungsverwaltung – www.geodaten.bayern.de). The bottom left corner marks the location within Germany with a red rectangle (© Bundesamt für Kartographie und Geodäsie, Frankfurt am Main, 2011).

Fig 2. (a) Photo of the church St. Margareta at Kahl am Main from southwest (Photo by Tatjana Gericke, BLfD), (b) Photo of tomb slab of Baron Franz Hermann Anselm Christoph Augustin von Benzel-Sternau at the outer walls of St. Margareta (Photo: Karl Becker, Heimat- und Geschichtsverein Kahl a. Main).

3. Survey details

3.1 Ground-Penetrating Radar

The GPR survey area is located in the southern part of the church's nave, between the entrance gate and the last row of wooden pews, and covers an area of 48 m². The rectangular grid is disturbed in the southeastern corner by a life-sized statue of Maria and a metal mesh covering a modern heating system in the subsurface. Luckily, the latter did not reach further into the survey grid. Flat earthenware tiles cover the church's floor. Silty, sandy, or gravelly fluviatile sediments of the Holocene characterise the geological subsoil (LfU 2023). Thus, the outer circumstances are quite favourable for a successful GPR prospection. As the theory and methodology of GPR surveys can be found in a multitude of text books, e.g. Reynolds 1997, Milsom 2003 or Conyers 2004, we will not cover this topic in more detail. The survey at Kahl am Main was executed with a GSSI SIR-3000 equipped with a 400 MHz shielded antenna (Fig. 3a). An odometer was attached to the system to guarantee an evenly spaced inline sample interval of 0.025 m. As the spatial resolution should be as high as possible, a dense raster of 25 cm profile spacing in crossgrid mode, i.e. two perpendicular survey directions, was chosen. The profiles were exactly oriented in North-South and East-West direction. The reflection amplitude of the electromagnetic signal was recorded over an 80 ns time window with 512 samples at 16-bit resolution. These parameters were determined based on the geological circumstances, the requested penetration depth, and the necessary vertical resolution. For data processing, all standard steps, like e.g. bandpass-filter, stacking, signal gain, time offset removal, and migration were applied. Furthermore, a Hilbert-transformation was executed after the migration of the data to calculate the absolute value from the positive and negative reflection amplitudes via a hull curve. For data visualisation, depth slices between 2 ns and 12 ns two-way-travel time were calculated for each survey direction and the addition of both. The results were resampled to a spatial resolution of 5 x 5 cm afterwards.

3.2 Structure-from-Motion

For a high-resolution, three-dimensional mapping of the interior of the church St. Margareta, we chose an approach with a manual SfM by a standard system camera mounted to a high-pole tripod of maximum 7 m length (Fig. 3b). Utilizing an Unmanned-Aerial-Vehicle (UAV), as commonly applied for outdoor surveys like the ones cited above, was not possible in this case study due to the huge amount of lamps, hanging at thin ropes from the ceiling, that endanger operating an UAV. Similar surveys using ground-based high-poles instead of UAVs are published e.g. in Abate et al. (2023). The advantage of a high-pole tripod with several meters length compared to such used for normal photography is that higher parts of the walls can be recorded easier and in shallower camera angles. This results in a higher quality of the model without gaps in areas of complex geometry and undercuts (Linck & Sahler 2023). Our camera was a Panasonic GX800 with a lens of fixed 20 mm focal length. The latter guarantees that all photos have the same focal length, a precondition for successful photogrammetric data processing. The photo acquisition was triggered with a WiFi remote switch controlled with a tablet PC. Furthermore, several floodlights were installed in the church's nave to ensure a constant illumination of all areas. To ascertain an overlap of more than 70% in all directions, a regular grid was set up by measuring tapes on the church's floor. Mapping each facade in different camera angles and heights guarantees a minimum of seven parallel and overlapping rows of single photos. This results in a total amount of 1140 photos, generating an overlap of minimum nine photos for all parts of the church. After data processing, the resulting accuracy at fixed control points is calculated as better than 3.5 mm. Further details on the theory of SfM and the data processing can be found, e.g. in Torres et al. (2012) or Luhmann (2010).

Fig 3. (a) Photo of the GPR-instrument GSSI SIR-3000 with 400 MHz antenna and odometer mounted onto a sled during a survey at the Monastery Eberbach im Rheingau (Photo: Jan Bosch, PZP), (b) Panasonic GX-800 camera mounted to the high-pole during the SfM survey inside St. Margareta Kahl am Main (Photo: Tatjana Gericke, BLfD).

4. Survey results and discussion

4.1 Ground-Penetrating Radar

The results of the GPR survey (Fig. 4, 5) show modern structures and remains of the crypt of Baron Franz Hermann Anselm Christoph Augustin von Benzel-Sternau. The modern ones are mainly located in the upper to medium depth range, but some also extend into deeper regions. These modern sources of interference restrict the localization of the crypt only marginally. Primarily, the strong reflections of the heating duct or shaft at the eastern edge of the investigation area should be mentioned here, which somewhat obscure the boundary to the adjoining crypt in the west. Other structures found in the vicinity presumably also belong to the heating system, but cannot easily be attributed to a specific origin. These include wide lineaments in the deeper depth range, as well as a faint one recognisable just below the surface, which are supposedly channels or pipes. A larger single reflector in the medium depth range, lying directly to the west of the heating shaft, might also be connected to the heating system; however, it is not possible to recognise exactly what type of modern installation it depicts. In the upper to medium depth range, in the northeast quarter of the grid, a large rectangular area with increased reflection energy can be identified, which is probably due to the floor substructure, e.g. a levelling layer.

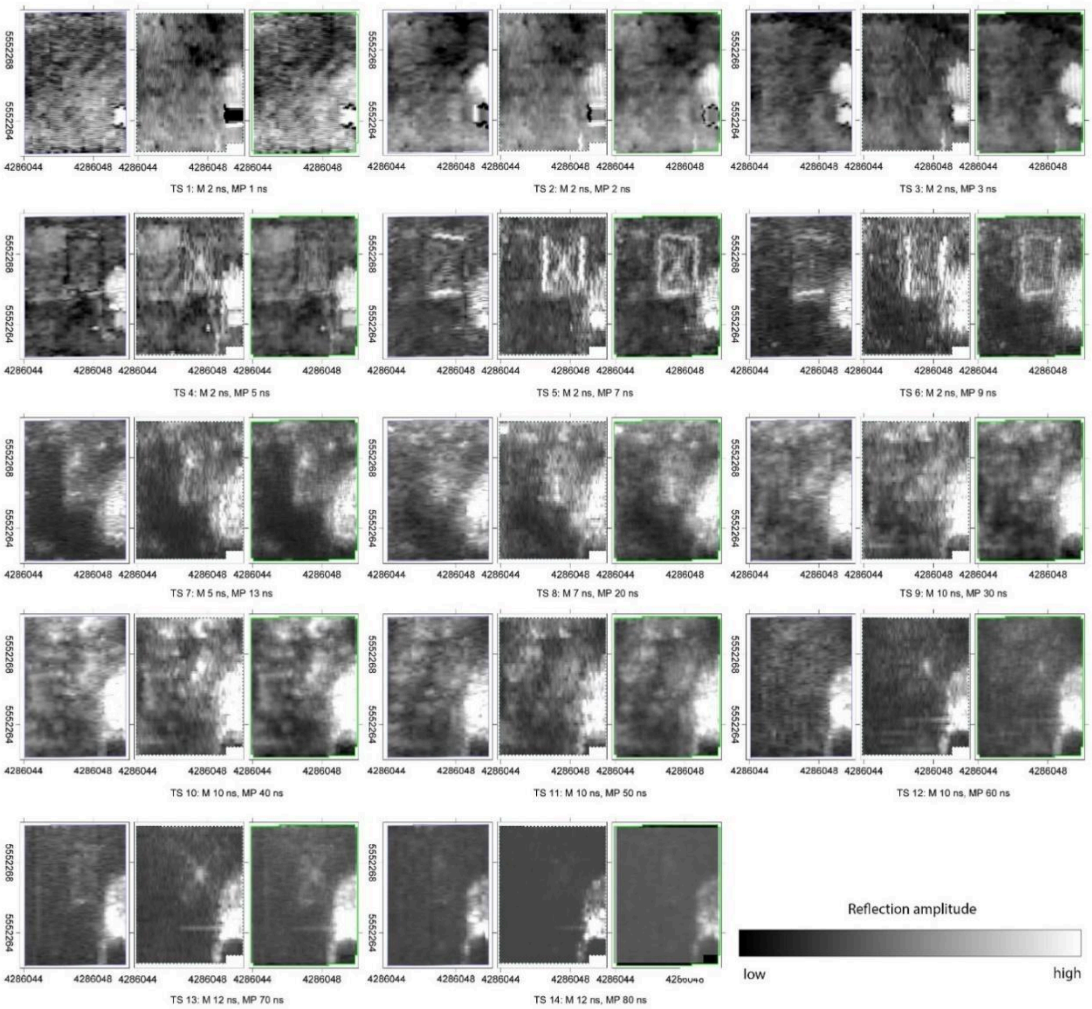

Fig 4. Depth slices of the GPR survey of the crypt. Legend: TS = number of depth slice, M = thickness of depth slice in nanoseconds (ns), MP = depth location of centre of depth slice in ns. All variations of results are shown: left = North-South survey direction, middle = East-West survey direction, right = combination of both directions. GSSI SIR-3000 with 400 MHz antenna, sample interval: 2.5 x 25 cm, resampled to 5 x 5 cm.

As described at the beginning, these modern disturbances fortunately have little effect on the visibility of the archaeological remains and the exact localization of the crypt. Quite clearly, starting at an average depth of approximately 30 cm below the present surface, lineaments of strongly increased reflection energy appear which form a rectangular ground plan of ca. 2.5 x 3.5 m outer diameter and 1.7 x 2.8 m inner diameter. These are probably the masonry walls of the crypt. However, they are only identifiable within a limited depth range (Fig. 4, depth slices 4-6).

In the deeper lying depth slices, compacted material, the backfill material, or the floor of the crypt probably generate areas of increased reflection energy. The exact spatial extent of the crypt, marked by the enclosing wall, can no longer be clearly identified at this depth. However, the backfill along the western and southern walls seems to be more compact, or a more reflective material was used there. No other structures, e.g., indications of an access staircase to the crypt, can be recognised in the surrounding areas.

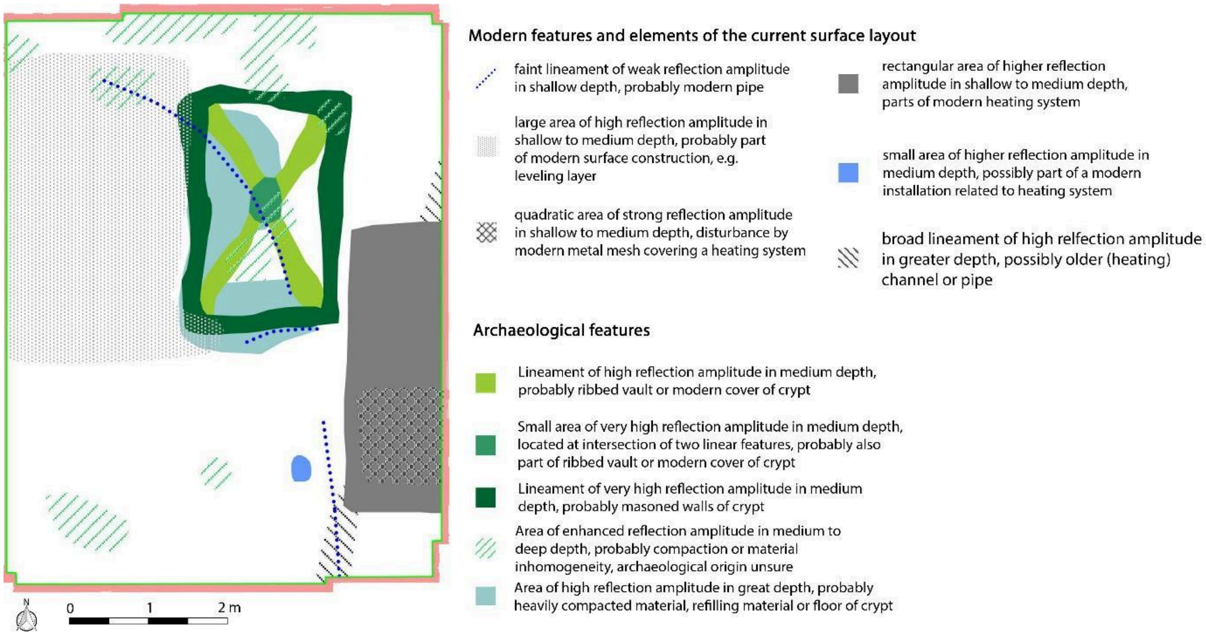

Fig 5. Interpretation map of the modern and archaeological features detected in the GPR depth slices. The results are based on the depth slices of the combined crossgrid data.

Striking is a cross-shaped structure leading to the four corners of the crypt. It is formed from two lineaments that intersect approximately at the centre, where the reflections are more pronounced. To assess this structure, it is helpful to look at selected profiles (Fig. 6a, e.g. profiles 22 and 24 at W-E-direction and Fig. 6b no. 2 and 3). Due to the above-mentioned arguments, these structures are of real archaeological relevance and no measurement artefacts. They are presumably elements of the ceiling construction of the crypt that seemed to have a ribbed vault. However, a modern origin in context with the opening in 1910 cannot be completely excluded, but is unlikely.

In addition, method-related factors are responsible for complicating the interpretation of the survey results. Due to the reported backfilling of the crypt with sand in 1910, one or more cavities of unknown extent have to be expected in the GPR data. However, since radar waves travel much faster in cavities than in solid bodies and since the depth determination for the reflectors is determined via the travel time, these influences have to be taken into account, when evaluating the results (Fig. 6b). For the survey grid, at least for the part above the presumed vault/cavity, different travel times of the radar waves must be expected. This can result in a deviation of the positions of the reflectors from the actual depths. Below the assumed cover of the crypt (Fig. 6b, no. 2, 3), a probably air-filled space appears due to the rather “low-reflection” region here (Fig. 6b, no. 8). Hence, based on the arguments described above, the void appears smaller than in reality. This means that the reflection horizon of the crypt’s floor or its backfill level must also be located at a greater depth (Fig. 6b, no. 4, 5 and blue arrows). While it can be assumed that the measured values for the position of the crypt’s walls are reliable, the floor and the backfill are probably imaged too shallow in the profiles due to the faster travelling radar wave in the air.

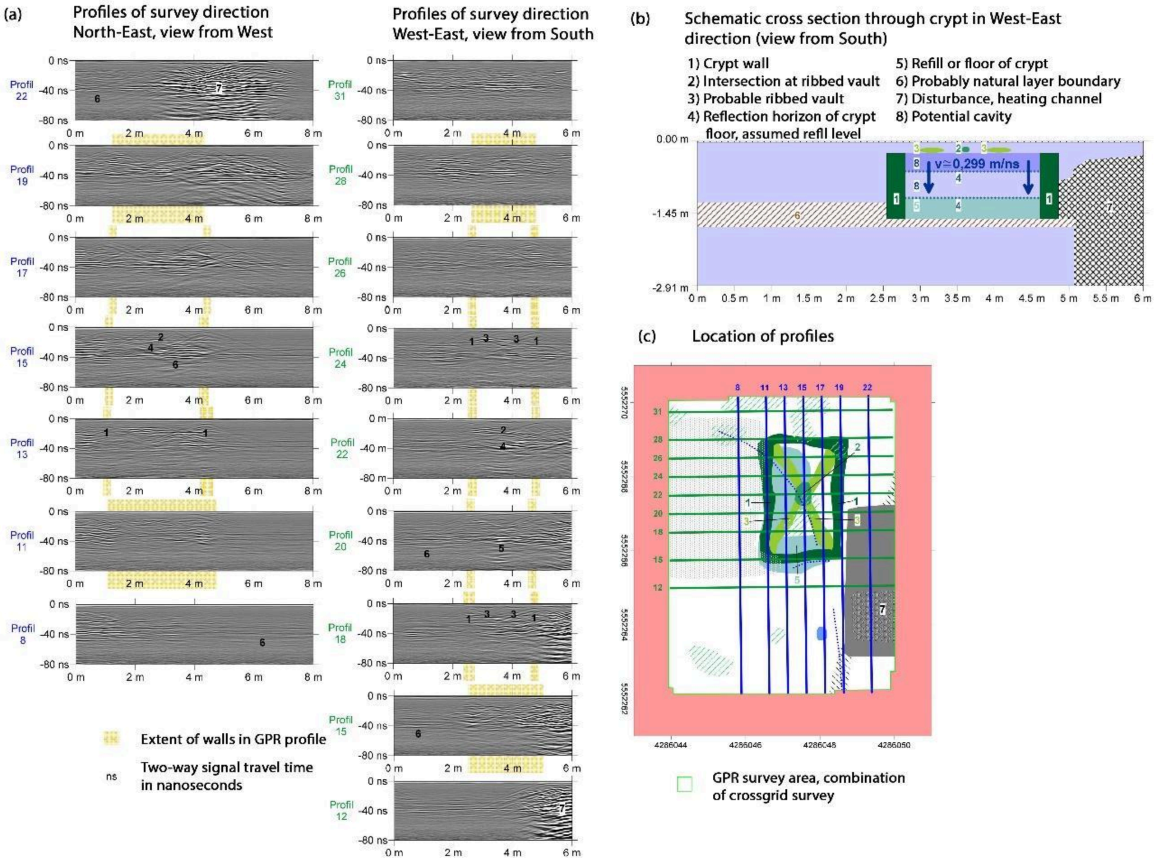

Fig. 6. Reconstruction of the layout and size of the crypt based on the GPR results. (a) Greyscale plot of selected profiles, (b) Schematic intersection through the crypt showing the relevant feature categories, (c) Localisation of the profiles shown in (a).

4.2 *Structure-from-Motion*

The processed SfM results of the interior of St. Margareta show a detailed three-dimensional model of the layout and decoration of walls and altars (Fig. 7).

Furthermore, distortion-free views even of larger parts like the walls or the ceiling (Fig. 7c) can be generated for the purpose of damage detection or historic construction research. Corresponding projects dealing with damage detection are published e.g. by Germinario et al. (2020), Linck et al. (2021a) and Karataş et al. (2022). Karachaliou et al. (2019), D'Amico et al., (2022), Angelini et al., (2023) or Linck & Sahler (2023) mention results of the use of SfM in historic building research. Most parts of the model are quite high-resolution and reliable, especially in the lower regions of the walls. However, even with a several metres long high-pole tripod, in huge buildings like churches, the limits for shallow-angle photos are reached quite soon. At St. Margareta, our 7 m high-pole extended until approximately the height of the gallery. All areas above could only be mapped with steeper angles. This results in several inaccuracies and model errors at these regions, e.g. leaning walls or deformed windows in Fig. 7b or "undulating" plastering at the ceiling (Fig. 7c). In addition, there are further problems in narrow areas that could not be mapped with the same overlap as open spaces. Similar problems are described in Fauchard et al. 2023, (under review) for a small chapel in Normandy (France).

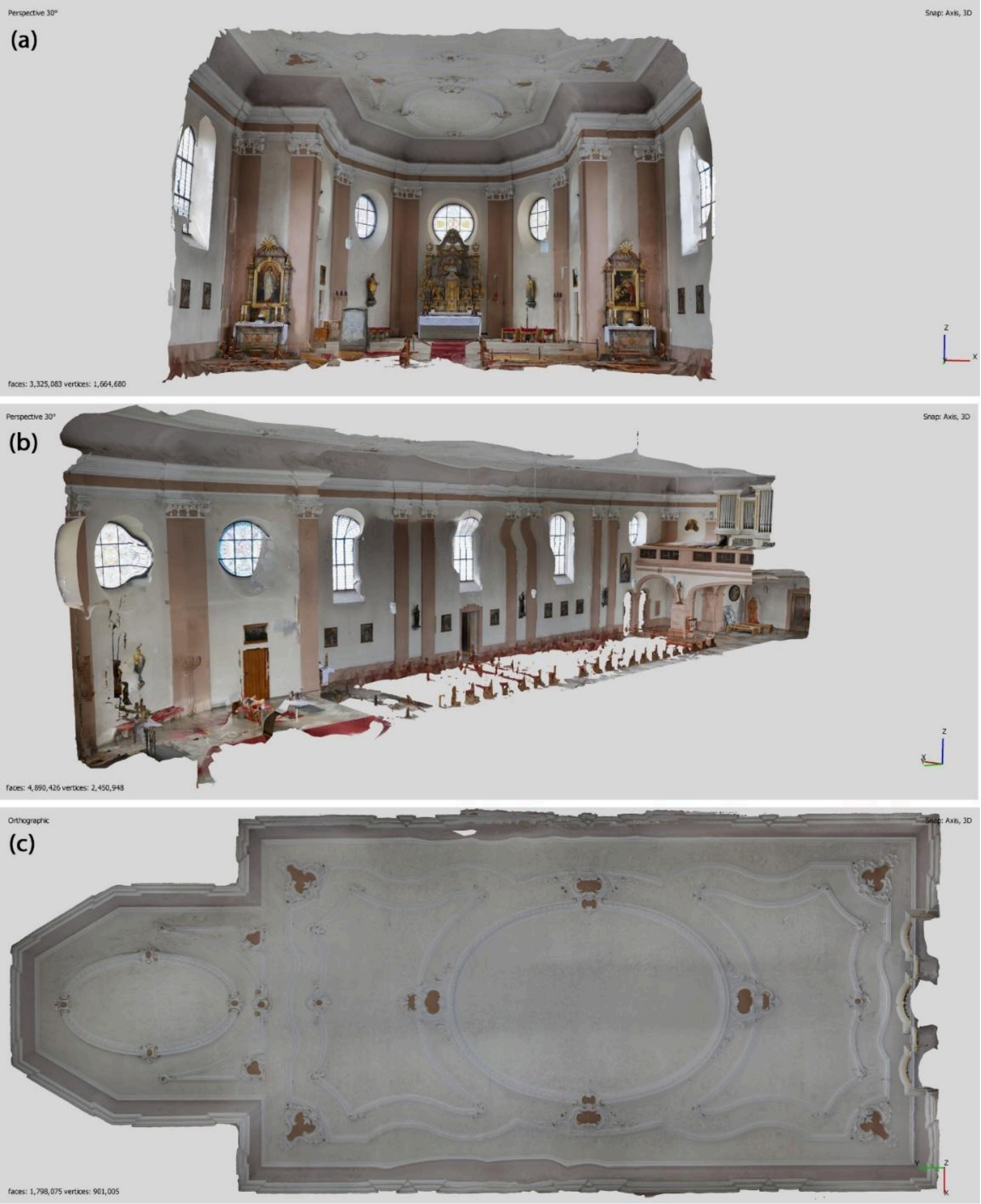

Fig 7. Three example views of the three-dimensional SfM model of the interior of St. Margareta in Kahl am Main showing the layout of the walls and the decoration as well as the mentioned problems. (a) Chancel, (b) Eastern half of the nave, view from Northwest, (c) Ceiling.

Despite these problems, the 3D-model of the interior of St. Margareta is more than sufficient for the requested task of a combination of the GPR data with the SfM model to better visualize the location of the Baroque crypt of Baron Franz Hermann Anselm Christoph Augustin von Benzel-Sternau. The overlay of the two different datasets could be easily executed, as both were georeferenced accurately in a projected world coordinate system via fixed points inside the church linked to ground control points outside the church. The latter were referenced by a Real-Time-Kinematic (RTK) Global Navigation Satellite System (GNSS) receiver with 1–2 cm spatial accuracy. The overlay of the two datasets in Fig. 8 illustrates the real location of the crypt in the middle between the entrance gates and the last row of pews inside the nave without the necessity of doing an invasive re-opening of the floor.

Fig 8. Overlay of 3D-model of the entrance area in the south of St. Margareta with the GPR depth slice of 7 ns depth showing the ribbed vault of crypt. View from North. White = high reflection amplitude, black = low reflection amplitude.

5. Conclusion and outlook

As shown above, the Baroque crypt could be precisely localised within the new baroque church by the GPR survey. The data allows to draw a clear floor plan of the construction. Even indications of the ceiling construction of the crypt have emerged, which presumably consists of a ribbed vault. However, also a modern origin of the cross-shaped construction in context with the opening in 1910 cannot be excluded. A detailed examination of the radar profiles suggests that the crypt partly forms a cavity and in the southern and western part, a partial backfill possibly has to be expected. The exact location of the burial itself cannot be recognised, nor could any evidence of further structural elements, such as e.g. a staircase, be found. The localisation of the crypt and its spatial extent now form the basis for further investigations regarding the final resting place of Baron Franz Hermann Anselm Christoph Augustin von Benzel-Sternau. The overlay of the geophysical data with a photorealistic 3D model of the church can be used for a virtual public dissemination that can be easily understood, also by non-scientists. The non-destructive manner of all applied survey techniques helps to preserve the archaeological remains for the future and allow investigating potential further research questions.

Acknowledgments

The authors want to thank the “Heimat- und Geschichtsverein Kahl am Main” and especially its manager Karl Becker for their help during the GPR data acquisition, as well as the Parish of St. Margareta in Kahl am Main for permitting the non-destructive surveys. Sebastian Pfnorr M.A. (PZP Marburg) gathered the GPR data. Tatjana Gericke and Florian Becker (both BLfD Munich) are thanked for their help during the SfM data acquisition.

Financial Support: The GPR survey was paid by the “Heimat- und Geschichtsverein Kahl am Main”.

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