

# Non-Invasive Investigation with a Combination of GPR and SfM in a Former Baroque Garden at Memmingen, Germany

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## Abstract

In archaeological geophysics, ground-penetrating radar (GPR) has developed into one of the standard methods over the past decades. In particular, the method is the preferred choice for the detection of stone structures and air-filled cavities. The project from Memmingen (Bavaria, Germany) presented here starts by addressing the investigation of a former Baroque garden for any remaining subsurface remnants such as paths, flowerbed borders and fountain installations. Based on the results, it is hoped that the former appearance can be rendered visible again. In addition, a presumed cellar structure was documented underneath the preserved garden pavilion, the exact extent and shape of which were previously unknown. A brick barrel vault was identified below the entire pavilion. From a geophysical perspective, the results from the latter area also show that, even for small grids, medium-frequency antennas are often preferable despite their lower resolution, as the penetration depth of high-frequency antennas is often too shallow. To create a 2.5D overview on the pavilion layout, the GPR data is additionally combined with a Structure-from-Motion (SfM) documentation of the pavilion's outer walls.

## Keywords

Ground-penetrating radar (GPR), Structure-from-Motion (SfM), vaulted cellar, Baroque garden, pavilion

## Zusammenfassung – Nicht-invasive Untersuchungen mittels Kombination aus GPR und SfM in einem ehemaligen Barockgarten in Memmingen, Deutschland

Im Bereich der archäologischen Geophysik hat sich in den vergangenen Jahrzehnten das Bodenradar (GPR) zu einem der Standardverfahren entwickelt. Insbesondere zur Detektion von Steinbefunden und luftgefüllten Hohlräumen ist die Methode das Mittel der Wahl. Das hier vorgestellte Projekt aus Memmingen (Bayern, Deutschland) behandelt zum einen die Untersuchung eines ehemaligen Barockgartens auf etwaige noch im Untergrund vorhandene Überreste, wie beispielsweise Wege, Blumenbeeteinfassungen und Brunnenanlagen. Basierend auf den Resultaten soll nun das ehemalige Aussehen wieder sichtbar gemacht werden. Zum anderen wurde unterhalb des erhaltenen Gartenpavillons eine mutmaßliche Kelleranlage dokumentiert, deren genaue Ausdehnung und Form bisher unbekannt war. Hier ließ sich ein gezieltes Tonnengewölbe unterhalb des

gesamten Pavillons identifizieren. Aus geophysikalischer Sicht zeigen die Ergebnisse aus letzterer Untersuchungsfläche zudem, dass teilweise auch bei kleinen Arealen mittelfrequente Antennen trotz ihrer geringeren Auflösung zu bevorzugen sind, da oft die Eindringtiefe hochfrequenter Antennen zu gering ist. Um einen vollständigen Überblick über das Zusammenspiel zwischen Pavillon und seinem neu entdeckten Keller zu gewinnen, wurde die Außenseite des Pavillons zudem in 2,5D mittels Structure-from-Motion (SfM) vermessen.

## Schlüsselbegriffe

Bodenradar (GPR), Structure-from-Motion (SfM), Gewölbekeller, Barockgarten, Pavillon

## 1. Introduction

Non-invasive methods have become crucial instruments of heritage protection during the last few decades, because excavating sites to study them always means a certain amount of destruction of the corresponding remains. Besides geophysical methods, surface modelling using Structure-from-Motion (SfM) is important here. The combination of the two approaches often provides a comprehensive overview of heritage sites.

The presented monument represents a former Baroque garden, of which almost nothing is preserved nowadays. In investigating such buried garden architecture, ground-penetrating radar (GPR) has proven its value in several case studies (e.g. Schmidt 2009; Alexander et al. 2013; Coolen, Eßer 2020; Linck 2021; Linford et al. 2023). The reason is that GPR is sensitive to differences in the material or density in the subsurface (von der Osten 2003; Conyers 2004; David, Linford, Linford 2008; Linck 2013). Transferred to Baroque gardens, this means that both paved and/or compacted paths and stone-framed flowerbeds and fountains can be resolved in high detail. Other geophysical methods, like magnetometry, often fail under such circumstances due

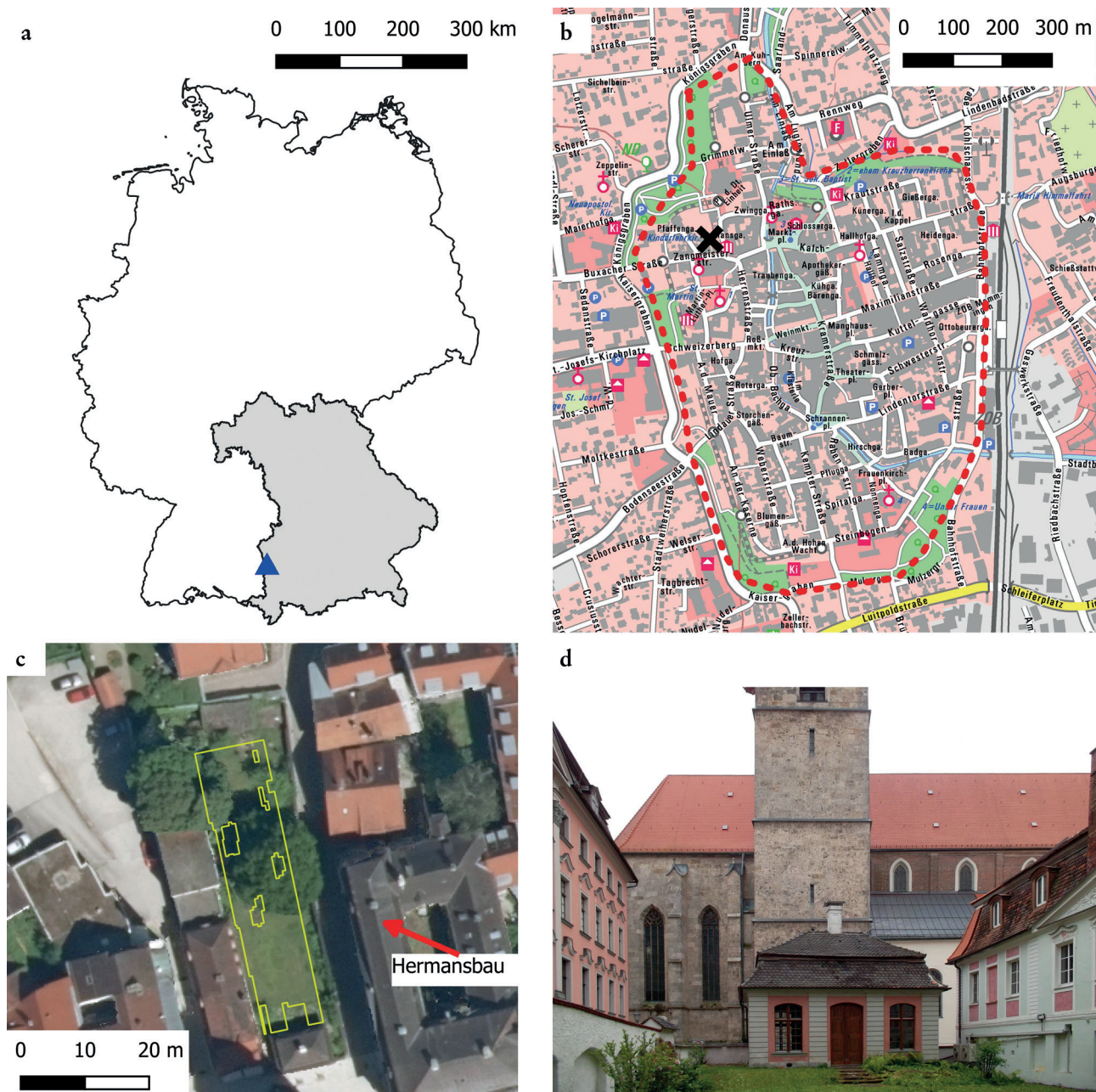


Fig. 1. – a. Topographical map of Germany with the outline of Bavaria shown in grey. The blue triangle marks the location of Memmingen (© Bundesamt für Kartographie und Geodäsie, Frankfurt am Main, 2011); b. Map of the historic city centre of Memmingen (= red dashed line) that is still visible nowadays in the layout of streets and parks. The black cross marks the location of the study site; c. Modern orthophoto of the site (Both: © Bayerische Vermessungsverwaltung – [www.geodaten.bayern.de](http://www.geodaten.bayern.de)). For all geodata, north is at the top; d. Photo of the garden with pavilion during the survey, view from the north. The *Hermansbau* is the apricot-coloured building on the left (Photo: R. Linck, Bavarian State Department for Monuments and Sites [BLfD]).

to strong ferrous disturbances in urban areas. In addition, the physical contrast in magnetisation is very low for garden architecture.

Considering the potential cellar underneath the preserved Baroque pavilion, GPR is again the best choice to investigate similar air-filled structures, as there is a strong reflection contrast between soil/stone and air (von der Osten

2003; Conyers 2004; David, Linford, Linford 2008; Linck 2013). The value of GPR for detecting archaeologically relevant cavities has been demonstrated in publications on sites in Italy (Barilaro et al. 2007; Imposa, Mele 2011; Calia et al. 2012; Cataldo, D'Agostino, Leucci 2012; Leucci et al. 2021; Cooper, Kay, Pomar 2023), Slovakia (Panisova et al. 2013), Portugal (Correia 2019), Germany (Zickgraf, Riese 2009;

Riese, Schäfer 2014; Hofmann, Linck 2023; Linck, Zickgraf 2024) and France (Tabbagh et al. 2002; Bully et al. 2011), for example. All of these projects have proven the suitability of GPR for mapping the corresponding remains with varying antenna frequencies.

Especially within the last few years, the principle of SfM has become common due to the increasing ability to acquire such data through the use of drones or high-pole tripods. Therefore, detailed documentation of historical buildings using these methods or, in addition, terrestrial laser scanning (TLS) has increased the number of research projects combining 2.5D datasets with geophysical survey data (e.g. Viberg, Schultzen, Wikström 2013; Gaffney et al. 2018; Cooper, Kay, Pomar 2023; Pomar et al. 2023; Schmidt et al. 2023; Fauchard et al. 2025).

This project had three main research aims: firstly, a non-invasive, detailed map of the different building phases of the Baroque garden in Memmingen was to be drawn and analysed to determine whether and to what extent the structures are preserved in the ground. Previously, the layout was only known from historic maps of uncertain reliability. Secondly, an approach to data integration was to be presented, as we combine GPR and SfM to achieve a better understanding of the results and for easier interpretation and public dissemination. Thirdly, it tackled a geophysical question, investigating the influence of profile spacing and antenna frequency in narrow grid environments like inside the pavilion and for detecting air-filled cavities.

## 2. Description of the Site

Memmingen, a small town in the Allgäu region (southwestern Bavaria, Germany), is located approximately 105 km west of Munich near the border to Baden-Württemberg (Fig. 1a). The area of the Baroque garden investigated within this study is situated in the northwestern corner of the historic city centre of Memmingen. Its extent can still be traced today in the layout of streets and parks that mark the former city walls with gate towers and a moat system (Fig. 1b). The Baroque garden is related to the so-called *Hermansbau*, a palace erected in 1766 for the baron Benedikt von Herman which constitutes the most important testimony to the aristocratic upper middle class of Memmingen (Breuer 1959). Nowadays, there is only little left of the former Baroque garden architecture: its location is marked by the old enclosure wall, and a garden pavilion (also built around 1766) is preserved in the southern part (Fig. 1c–d). The pavilion is a single-storey construction with a mansard roof and segmental arch windows, and its interior is decorated with stucco frames depicting landscapes in brown painting as well as rocailles and putti above the windows and ceiling paintings (Breuer 1959). The layout of the garden is only known from

two historic maps that reveal that there were a minimum of two construction phases (Fig. 5a–b). A renovation of the design could perhaps be associated with the construction of the previously mentioned pavilion.

## 3. Survey Equipment

### 3.1. Ground-Penetrating Radar

GPR is an active geophysical survey method based on the transmission and reflection of electromagnetic waves in the subsurface. The theoretical background of GPR and the corresponding methodology applied to archaeological geophysics have been comprehensively described in several textbooks (e.g. Reynolds 1997, 681–749; Conyers 2004; Milsom 2011). Hence, this section will mainly focus on the methodological insights relevant for our research questions in Memmingen: the choice of antenna frequency and profile spacing.

The GPR surveys inside the garden and the pavilion were executed with a GSSI SIR-4000 and two single channel antennas with different centre frequencies (Tab. 1 and Fig. 2a–b). Higher central frequencies mean better resolution but a shallower penetration depth. For the task of detecting the former Baroque garden installations such as paths, flowerbeds and fountains, a 400 MHz antenna seemed to be the best choice, as the remains were believed to lay at a depth of up to 150 cm and have a size in the decimetre range. By contrast, for the detection of the air-filled cellar underneath the pavilion, both a 400 MHz and a 900 MHz antenna were chosen, as the latter is smaller and can be operated more easily inside the narrow pavilion of only  $7.5 \times 4.8$  m in size. Furthermore, a denser profile spacing can be chosen for higher frequency antennas (see next paragraph). However, the 400 MHz antenna data was also acquired, as this antenna has a higher penetration depth. This ensured that the cellar's floor could be mapped from at least one dataset. Furthermore, due to the higher signal penetration, this frequency guaranteed that the assumed air-filled space underneath the modern floor was imaged.

Similarly to other geophysical prospecting methods, it is extremely important to achieve a high measurement point density when using GPR in archaeology in order to detect even faint archaeological features in the decimetre range. However, a higher measurement point density also means significantly slower measurement progress, so a trade-off must be made between the two factors. Overall, it should be noted that, theoretically, the profile distance should not be greater than the antenna footprint (Conyers 2004; Luo et al. 2019). Therefore, for the 400 MHz antenna, a profile distance of 50 cm is generally sufficient (see Tab. 1). Due to the small size of the survey areas within this case study, we nevertheless chose 25 cm in order to gather a higher resolution.



Fig. 2. Survey equipment utilised. – a. GSSI SIR-4000 with 400 MHz antenna for the survey of the Baroque garden; b. GSSI SIR-4000 with 900 MHz antenna for the survey of the cellar underneath the pavilion; c. SfM survey with Panasonic GX800 mounted on a high monopole (Photos: BLfD).

|                       | 400 MHz<br>(Model 5103) | 900 MHz<br>(Model 3103) |
|-----------------------|-------------------------|-------------------------|
| Horizontal resolution | 15.2 cm                 | 7.6 cm                  |
| Vertical resolution   | 10.2 cm                 | 5.1 cm                  |
| Size of footprint     | 61.0 cm                 | 10.2 cm                 |

Tab. 1. Specification of the GSSI antennas that were utilised (GSSI 2017).

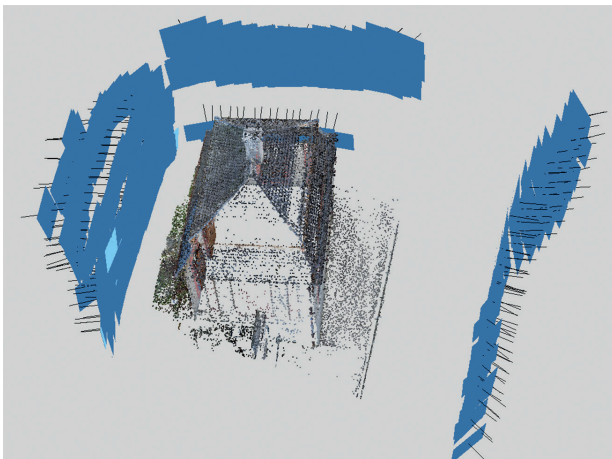


Fig. 3. Acquisition layout for the 2.5D documentation of the Baroque pavilion showing the position of the single photos.

By contrast, for 900 MHz antennas, the profile spacing needs to be smaller than 11 cm (see Tab. 1). For the present study, we chose a profile spacing of 10 cm. As this value is small for both surveys, it offers the possibility to execute

cross-cuts orthogonal to the profile orientation. This enables an analysis of the subsurface features in all directions without the need to use a GPR antenna array. Additionally, the in-line sample interval should be as small as possible for a continuous survey at normal walking speed. Therefore, we chose a value of 1 cm for the 900 MHz antenna and 2 cm for the 400 MHz antenna. To improve the signal-to-noise ratio, both datasets were stacked by a factor of three. This results in effective sample intervals of 3 cm (for the 900 MHz antenna) and 6 cm (for the 400 MHz antenna).

### 3.2. Structure-from-Motion

SfM is a common method for 2.5D surveying based on standard RGB photos. It uses the fact that the distance between two images changes due to the movement of the camera, allowing this distance to be used as a parameter for reconstructing the photographed object. It assumes a fixed object geometry, which is captured from different perspectives and locations (Torres et al. 2012). Therefore, a very high overlap between individual shots of at least 70–80 % in all directions is necessary. Again, the methodological details of SfM are described comprehensively in several textbooks such as Luhmann 2018 or Wiggenghagen, Steensen 2021 and, therefore, will not be discussed further here.

For creating the 2.5D model of the Baroque pavilion in Memmingen, the Panasonic Lumix GX800, a standard system camera with a Live MOS sensor and a resolution of 16 megapixels, was used (Fig. 2c). Furthermore, we attached a Panasonic Lumix lens with a focal length of 20 mm,

corresponding to a 35 mm equivalent focal length of 40 mm. This lens ensures that all the images obtained have the same focal length, as this is necessary for processing using SfM. To guarantee a constant and high overlap between the single photos, a measuring tape was placed on the ground and images were taken every 0.5 m and at 4–7 different heights (Fig. 3). Due to another nearby building, this was only possible for three of the pavilion's facades; inclined photos from the other sides were used to map the fourth. In total, 411 single photos were acquired to generate the detailed 2.5D model. As the SfM survey was executed later than the acquisition of GPR data for the cellar, only the outer walls could be mapped, and the interior was no longer accessible.

#### 4. Results and Discussion

##### 4.1. Baroque Garden

The survey area within the former Baroque garden has a size of  $11 \times 45$  m; the gaps in the data are caused by modern trees, flowerbeds, etc. Due to this small size, we decided to increase the resolution of the data by executing the GPR acquisition with a 25 cm profile spacing. The structures of

the Baroque garden can be detected at a depth of 20–90 cm below the modern surface (Fig. 4). The time-to-depth conversion for this task was executed using a hyperbola-picking function in the processing software. As the signal floor (i.e. the depth at which the signal/noise ratio gets too low) is calculated as 175 cm according to RADAN 7, the data-processing software that was used, it can be stated that all archaeological features associated with the garden architecture could be mapped. Analysing the above-mentioned depth range reveals that all features are quite shallow. This fact can be explained by their recent dating, as the garden still existed just 200 years ago (see Fig. 5b). The topmost depth slices are mainly dominated by modern disturbances such as former ponds, gravel areas and a rectangular concrete flowerbed.

However, below this level, the layout of the Baroque garden can be identified very well (Figs. 4, 5c). In particular, the circular areas of former fountains that are mapped in the *Uraufnahme* (Fig. 5b) generate strong reflection anomalies. The southern one (Fig. 5c/1) has a diameter of 6 m and, hence, is much bigger than the northern one (Fig. 5c/2) with

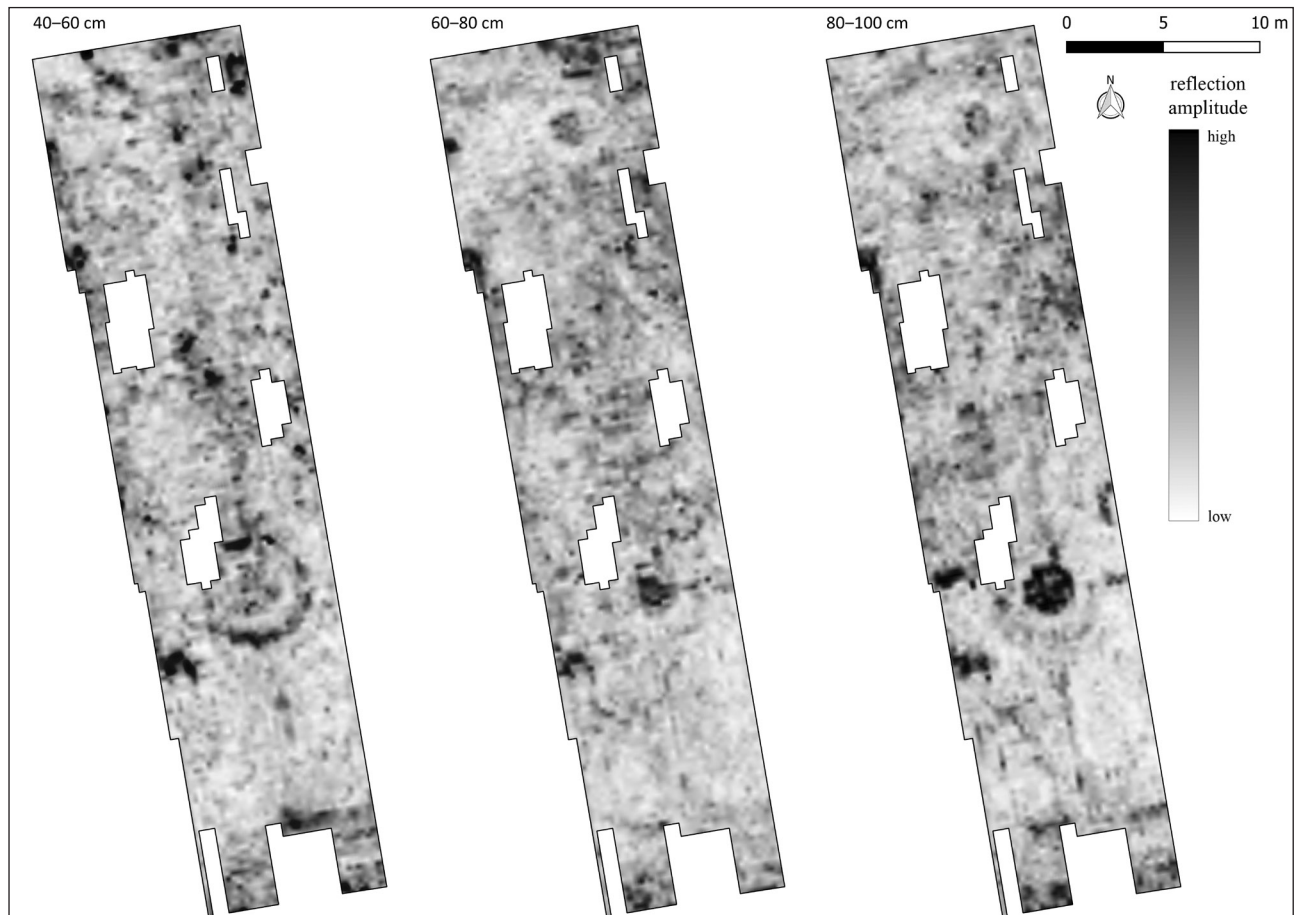


Fig. 4. Selection of GPR depth slices of the Baroque garden between 40 cm and 100 cm below the modern surface. GSSI SIR-4000 with 400 MHz antenna, sample interval  $6 \times 50$  cm.



Fig. 5. Representation of the Baroque garden of the *Hermansbau*. – a. Map from 1737 displayed in the municipality of Memmingen; b. Map from 1819 (= *Uraufnahme*). Black lines mark the outline of the GPR survey grid; c. GIS-based interpretation of the anomalies detected during the GPR survey.

its 3.5 m diameter. This is quite unusual, as corresponding Baroque installations in Bavaria were normally symmetrical and of the same size. Inside the round plazas, the remnants of the actual fountains have still been preserved. The southern one (Fig. 5c/1) is still in good condition and shows a waterlogged infill at a greater depth of 80–100 cm. By contrast, the northern fountain's foundations (Fig. 5c/2) are in worse condition. Overall, the preservation of the northern half of the Baroque garden is much worse, and it can be assumed that the terrain may have ascended slightly in this direction and, therefore, was levelled during the last two centuries. This would also explain why structures which are actually deeper lying appear closer to the surface (see below).

The north-south-oriented main path (Fig. 5c/3) of the Baroque garden starts in the south at the staircase of the preserved pavilion and leads towards the two fountains. At the round plazas, further paths branch off towards the east and the west (Fig. 5c/4–5). The third orthogonal path that is mapped in the *Uraufnahme* (Fig. 5b) cannot be detected in

the GPR data. There are two potential explanations for this: either it was never constructed and represents an error in the map, or it was destroyed in the meantime. It is remarkable that the northernmost 11 m of the main path rapidly become nearly invisible in the depth slice of 20–40 cm, whereas the southern part can be identified in detail as a high reflective band. This could be proof for the theory that levelling has occurred in the northern area. In the south, the Baroque garden does not reach the preserved pavilion. The same fact is visible in the *Uraufnahme*, which seems to be quite accurate, and, therefore, the hypothesis of destruction of the third orthogonal path is likely. Between the garden and the pavilion, the GPR data shows three small, transverse walls (Fig. 5c/6) that lay underneath the hill with the staircase (see Fig. 1d for orientation). This means that already in Baroque times, the pavilion was elevated and the small walls represent retaining walls of the artificial embankment. Northwest of the northern fountain, two linear features are visible that possibly can be interpreted as remains of water pipes associated with the



Fig. 6. Photo of a small excavation trench below the pavilion's floor showing parts of the vaulted cellar roof. The folding ruler shows the estimated depth below the modern floor (Photo: Prof. Dr. Dr. von Wachter).

fountains (Fig. 5c/7). Due to the above-mentioned assumed levelling, these pipes appear shallower than expected.

At a distance of 4 m southwest of the northern fountain, another faint circular structure is vaguely detectable (Fig. 5c/8). It could represent a brim of a well dated to an earlier construction phase, as nothing is mapped in the *Urkataster* here. However, it is known from the map from 1737 (Fig. 5a) that the Baroque garden looked different in the 18<sup>th</sup> century. As the identified anomaly fits with the fountain mapped there, this can be taken as proof of a second building phase of the garden. Again, the shallow depth is remarkable and can be explained by the modern levelling of the terrain in the northern part.

#### 4.2. Pavilion

Due to the bad state of preservation of the Baroque pavilion, a restoration campaign started in 2022. Right from the beginning, indications of a bricked vaulted cellar underneath the floor were found during the opening of a small trench in the floor (Fig. 6). Nothing is known about this construction, as the position of the former entrance is uncertain and only some ventilation openings in the pavilion's foundations hinted at a potential vault. Consequently, the aim of the study was to gain further insights into the layout of this

cellar, and the GPR survey therefore covered the complete accessible area of 4 × 6 m.

##### 4.2.1. Results of the 900 MHz Antenna Survey

First, the data from the 900 MHz survey will be discussed, as they have a higher resolution and the archaeological features can be mapped in more detail. Due to the dense spacing of 10 cm, it is possible to generate cross-sections perpendicular to the actual profile. They indicate that the detected structure represents a typical vault, as it shows up as a curved anomaly in a north-south direction (Fig. 7a). Combining the results from the x and y directions, the shape of the cellar seems to be a barrel vault (Fig. 7b). Hence, even the lower signal strength of the 900 MHz antenna was sufficient to penetrate through the air-filled space underneath the modern wooden floor of the pavilion.

The analysis of the wiggle-trace plot of the single profiles reveals that the cellar is an air-filled cavity, as the signal's first peak is negative (Fig. 8a). Such reversed polarities in GPR data indicate a strong material contrast such as stone/soil to air, as buried walls/debris have normal polarisation (Fig. 8b as a comparison). To give an example, Qawesmeh, al-Hameedawi, Conyers 2021 or Linck, Zickgraf 2024 already described such a typical signal behaviour for air-filled cavities.

Approximately 60 cm below the vault's ceiling, another parallel, slightly curved anomaly is identifiable in the cross-sections running parallel to the one described above (Fig. 9a). Interpretation as the floor of the cellar is possible, as the signal's polarity changes again, indicating a further transition from air back to solid material. The apparent narrow height of the cellar of only 60 cm is caused by the problem that for the data processing, the GPR wave velocity was determined by hyperbola fitting to be 0.1 m/ns. This underestimates the real conditions within the air (having a velocity of 0.3 m/ns), and the distances within the cavity are compressed (see Qawesmeh, al-Hameedawi, Conyers 2021; Linck, Zickgraf 2024). Executing the Kirchhoff migration with an average velocity of 0.2 m/ns reveals a more realistic, but still shallow, height for the vault of 1.2 m (Fig. 9b). Therefore, all depth information in this case study has to be regarded with caution, as the electromagnetic wave velocity varies greatly depending on whether it is passing through soil or an air-filled cavity. The faint uparching of the supposed floor that is not as prominent as that of the ceiling could also be due to the variations in the signal transmission velocity compared to the surrounding undisturbed soil: the air-filled area has a higher velocity  $v$  and the depth  $d$  is calculated as

$$v = \frac{d}{t} \rightarrow d = v \cdot t$$

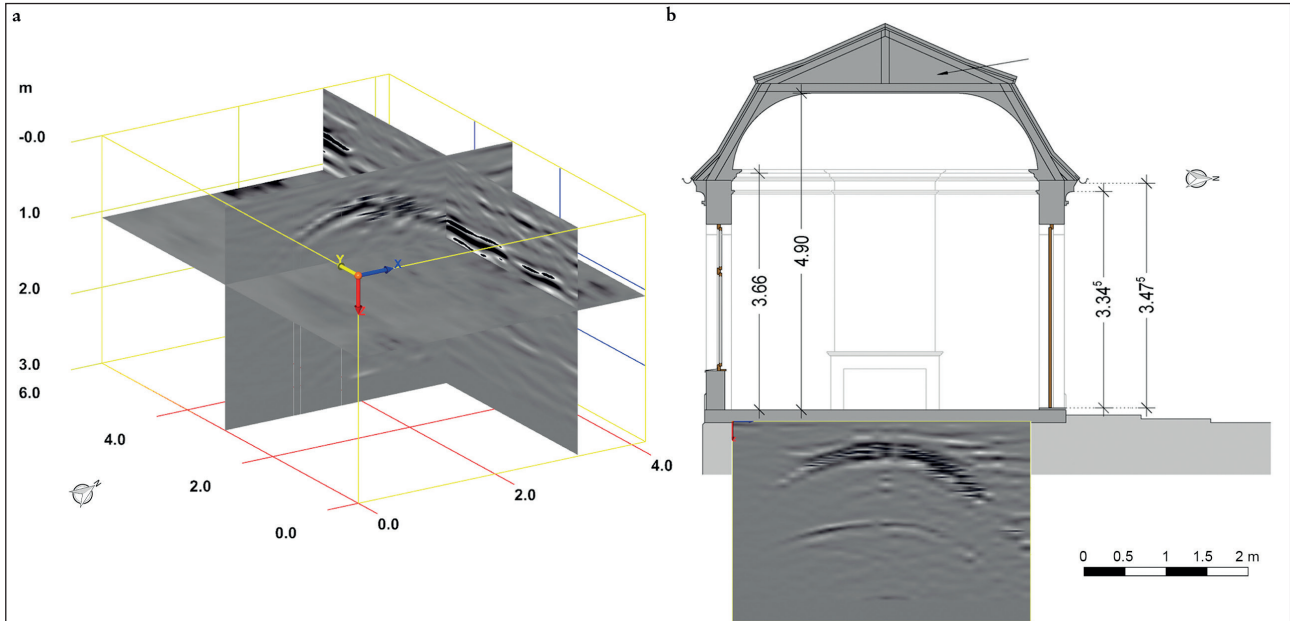


Fig. 7. – a. 3D visualisation of 900 MHz data in the profile direction and cross-line reveals that the structure is a barrel vault; b. Cross-section at 2.2 m profile distance to visualise the layout of the vault. Overlay with a lateral cut through the pavilion. For migration, an average velocity of 0.2 m/ns was used (GPR data: R. Linck, BLfD; pavilion section: Zettler Bau Memmingen).

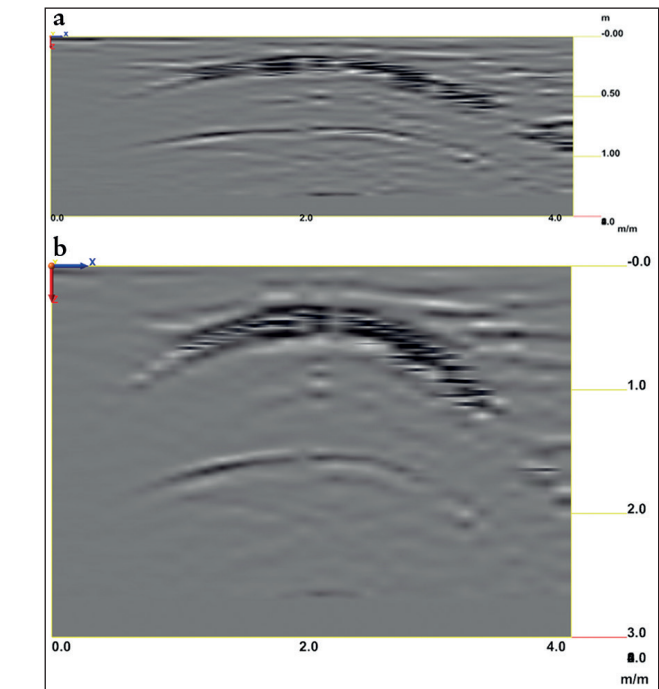
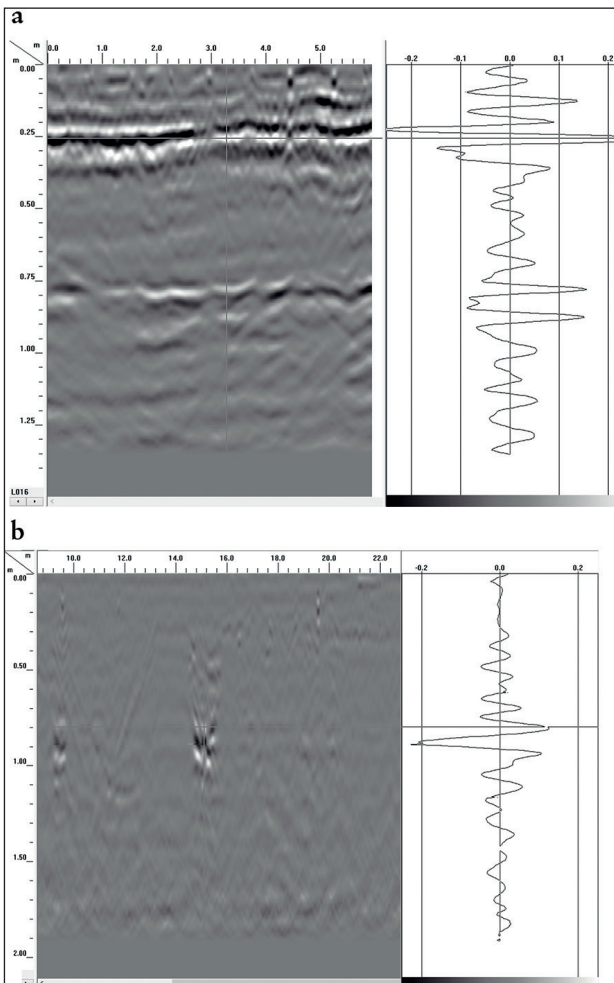


Fig. 9. Cross-section through 900 MHz data at 2.2 m distance in the survey direction. – a. Kirchhoff migration executed with a selected velocity of 0.1 m/ns; b. Kirchhoff migration executed with an average velocity of 0.2 m/ns.

Fig. 8. Wigggle-trace plot of – a. the pavilion in Memmingen with reverse polarity; b. the buried stone wall showing normal polarity.

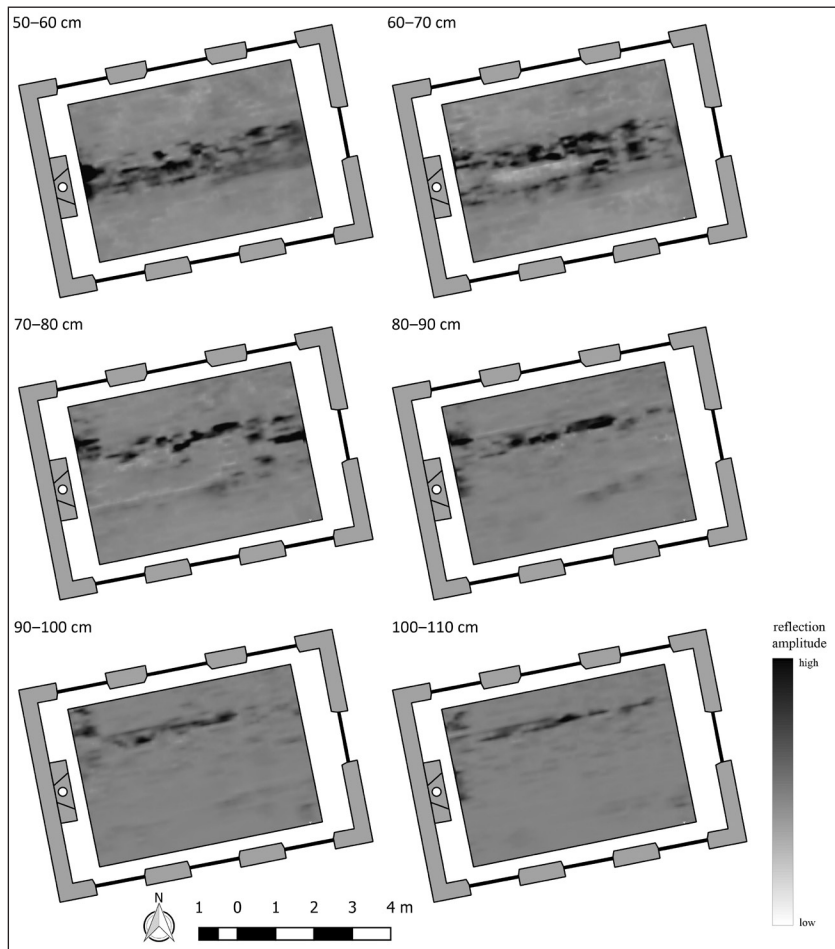


Fig. 10. Representative selection of depth slices inside the pavilion from the 900 MHz dataset. GSSI SIR-4000 with 900 MHz antenna, sample interval  $3 \times 10$  cm. Migration executed with an average velocity of 0.2 m/ns.

Hence, data with the similar recorded travel time  $t$  appears to be shallower in the processed data than in areas with undisturbed soil. However, an alternative interpretation of this feature as a reflection of a potential partial filling of the cellar with soil and rubble is possible. In this case, the high-frequency 900 MHz antenna and the corresponding shallow penetration depth would not allow mapping of the real floor level of the cellar.

In the following, an analysis of the GPR depth slices will be discussed (Fig. 10). As the Kirchhoff migration with an average velocity of 0.2 m/ns provided the most reliable results, these data are used. In the uppermost depth slice, the north-south-oriented braces of the wooden floor are visible due to the air-filled spaces in between. Furthermore, in the western part of the grid, a strong disturbance from a metal plate in front of the chimney occurs that can be traced to a great depth, as no signal can penetrate it and the radar waves are reverberating. In addition, an archaeologically relevant anomaly associated with the supposed cellar can be identified: a strong reflective anomaly appears in the centre of the grid 40 cm below the surface that dips to a depth of 140 cm towards the north and south (Figs. 7, 9). The burial depth

of the cellar's ceiling fits perfectly with that observed during excavation (Fig. 6). Again, the anomaly ranges over the whole length of the pavilion and an interpretation as a barrel vault is most likely. Towards the north and south, the anomaly starts to vanish and becomes less pronounced. For the southern part of the area, where the test trench was opened in 2022, the signal loss can possibly be attributed to an infill of loose material. In the northern part, the continuation of the vault towards the pavilion's foundations is at least partially detectable (Linck, Stele 2024). As the vault likely uses the same foundations as the pavilion above, no vertical wall features are visible, because a certain distance of the profiles from the upstanding pavilion's walls had to be maintained during data acquisition due to technical issues, for example the size of the antenna, the length of the odometer wheel, etc. Given the size of the mapped cellar, it is likely that the construction was already planned and executed during the erection of the pavilion. This is quite typical for Baroque garden installations.

For improved visualisation of the results and in order to show that the detected object really represents a barrel vault, the 2.5D datacube was visualised via isosurface rendering in



Fig. 11. Photogrammetric 2.5D model of the Baroque garden pavilion with isosurface rendering of the detected barrel vault displayed underneath. The blue lines illustrate the position of the bricked vault.

Voxler 4 (Fig. 11). This data can be projected beneath the 2.5D model of the pavilion generated by the SfM survey. In this combination, the specific layout is rendered clearly visible and the illustration can be used for public dissemination of the GPR data. Figure 11 furthermore illustrates the reason for the raised position of the pavilion compared to the garden itself and especially the adjacent road, which is separated from it by a high enclosure wall.

#### 4.2.2. Results of the 400 MHz Antenna Survey

In addition, we carried out another GPR survey with a 400 MHz antenna to analyse the differences between the two results and to evaluate which of the two frequencies is more suitable. Of course, the 900 MHz antenna provides a better resolution and can be operated more easily due to its smaller size. However, it was not clear in advance whether the penetration depth of the 900 MHz antenna would be sufficient to map fully the extent of the cellar. Moreover, as was known from the earlier excavation trench, the wooden floor inside the pavilion is not installed directly on the soil, but there is a certain amount of air underneath it. Therefore, it was also possible that we would encounter the problem that the signal penetration depth of the 900 MHz antenna was not sufficient to reach into the soil at all.

The depth slices of the 400 MHz data show approximately the same features as those previously described (Fig. 12). Due to the coarser profile spacing and the lower resolution of the antenna, the results appear significantly less clear.

Overall it can be concluded that the thesis of a barrel vault cellar underneath the Baroque pavilion is reasonable.

To analyse the interpretation of the lower reflector (i.e. the potential floor) in more detail and try to clarify the two hypotheses, cross-sections between the survey profiles were generated (Fig. 13). The topmost feature representing the ceiling again appears at approx. 40 cm below the surface with reversed polarity (Fig. 13b). Below, the proposed floor reflection of the 900 MHz data is detectable 160 cm below the surface. Corresponding to the previous dataset, the polarity changes back to normal. This indicates that there is a change from air to soil. In addition, a third reflector at 270 cm, still with normal polarity, is present. Therefore, it seems reasonable to interpret this structure as the real floor of the cellar and the central reflection anomaly could represent the top of a huge debris layer deposited during flooding events over the last two centuries.

## 5. Conclusions

The presented results once more show the potential of geophysical, non-invasive surveys in an archaeological context. In the field of garden archaeology, GPR data can be used to reconstruct the former layout of a Baroque garden, even if, after several centuries, nothing is visible on the surface. Detection of a predecessor building phase of the garden was only possible through the use of GPR. The results can be used to visualise the original layout and bring the garden architecture back to life for the public. In addition, the corresponding surveys can help to clarify the situation underneath existing historic buildings, irrespective of whether it is predecessor structures or cellar constructions that are supposed to be buried under the modern floor level.

From a geophysical point of view, the presented results also yield relevant information: often the penetration depth of high-frequency antennas (e.g. 900 MHz) is not sufficient to detect the relevant features right through to their bottom level. Therefore, sometimes it is advisable to favour medium-frequency antennas (e.g. 400–600 MHz) despite their lower resolution. However, as our project proves, even these data show all relevant information and, furthermore, over the whole depth range. Of course, the best solution would be to execute surveys with multiple antennas or multi-frequency systems, if time permits.

Another important finding is that sometimes the standard visualisation of GPR data as depth slices that is normally chosen for archaeological projects is not sufficient. The example of the barrel vault shows that it would not have been possible to extract the exact shape of the anomaly and its interpretation without the additional analysis of the survey profiles and even the cross-sections perpendicular to them. Similar statements are made by Conyers 2014 and

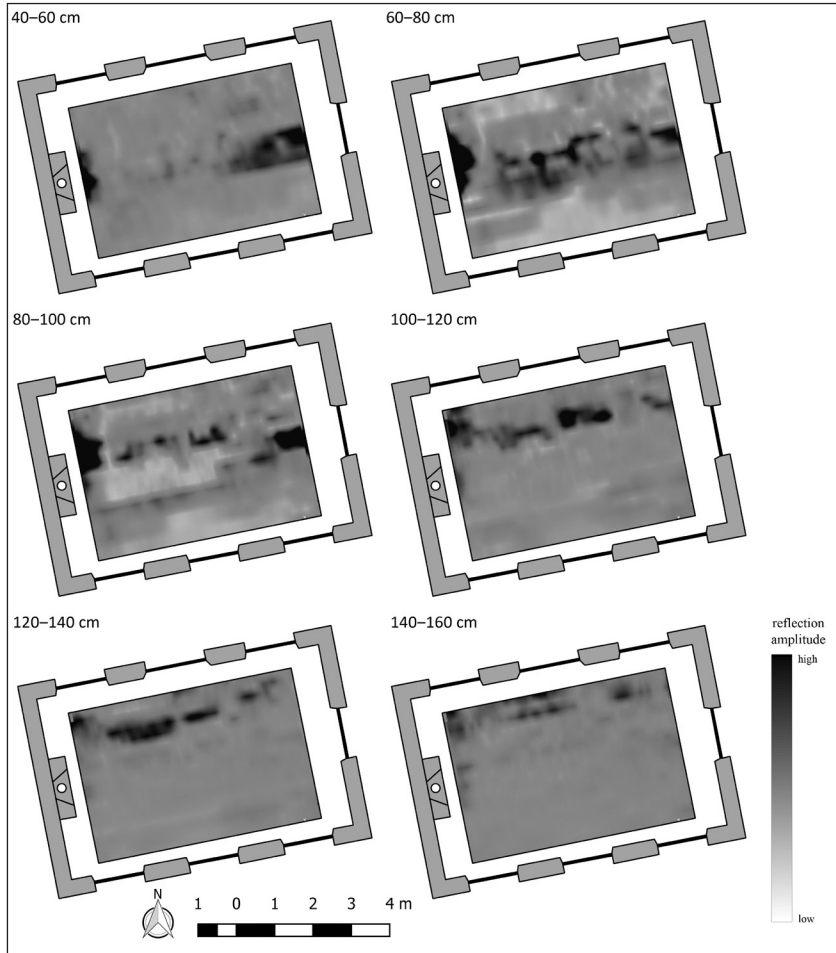


Fig. 12. Representative selection of depth slices inside the pavilion from the 400 MHz dataset. GSSI SIR-4000 with 400 MHz-antenna, sample interval  $6 \times 25$  cm. Migration executed with an average velocity of 0.2 m/ns.

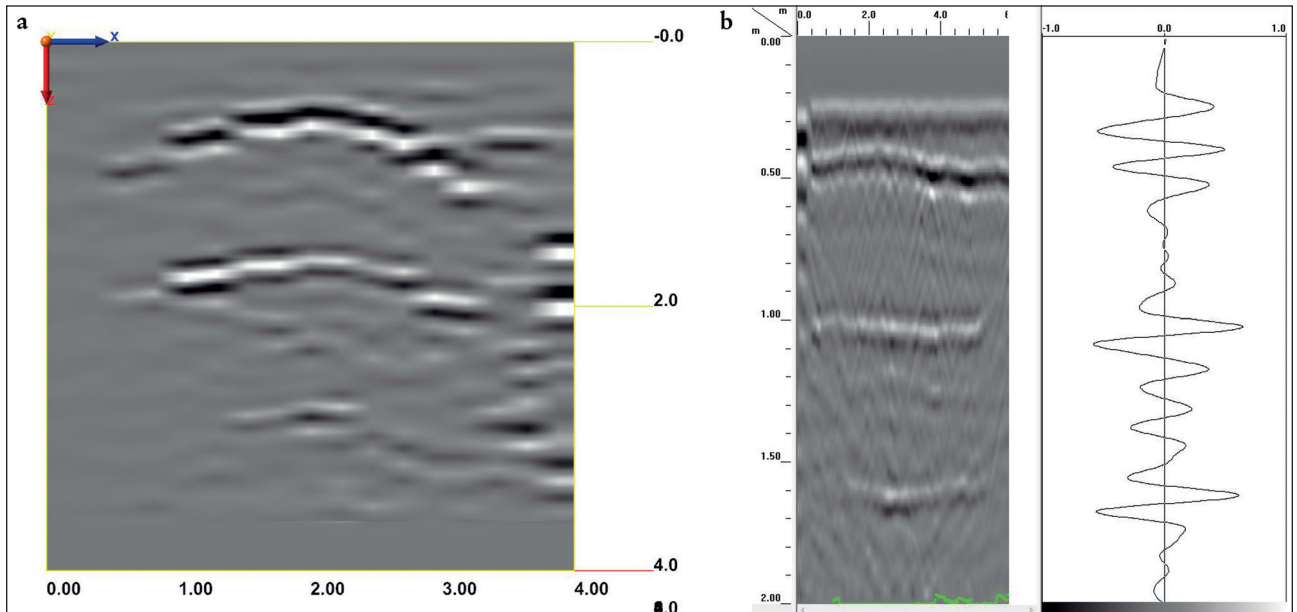


Fig. 13. – a. Cross-section through the 400 MHz data at a distance of 2.2 m in the direction of surveying. All three described reflectors are visible; b. Raw data profile directly above the apex of the vault showing all three reflectors and their polarity in wiggle view.

Conyers 2016, for example. The two deeper lying reflection anomalies in particular could not have been interpreted properly solely from the depth slices, as they do not create distinct features there.

### Acknowledgements

The authors want to thank Prof. Dr. Dr. Daniel von Wachter, the owner of the estate with the Baroque garden, for his permission to carry out the GPR surveys. Furthermore, we want to thank our colleagues Tatjana Gericke, Janina Moser and Florian Becker (all BLfD) for their assistance during fieldwork.

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