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SHORT REPORT

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Evaluation of the benefits for mapping faint archaeological features by using an ultra-dense ground-penetrating-radar antenna array

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Abstract

Modern archaeo-geophysical radar surveys are often executed with multichannel antenna arrays, which allows a much faster survey progress combined with a denser profile spacing. Furthermore, from a methodological point of view, a full 3D dataset is necessary to resolve small targets of a few decimetre diameter. However, only a few test surveys deal with the evaluation of the real improvement in data quality by applying such multichannel arrays. In this paper, a test survey with the IDS Stream-C 600-MHz radar device on a small area covering the Roman Bath of Kempten-*Cambodunum* is presented. The aim of the study is to figure out whether faint archaeological remains like hypocaust pillars, that is, the pillars of a Roman floor heating system, that are missed by single-channel devices, are detectable in an ultra-dense antenna array. Thus, the same area was simultaneously mapped with both GPR configurations. The results of this case study demonstrate the benefit of such antenna arrays for the archaeological prospection of small subsurface features with a diameter of 25 cm or less. For ground-truthing of the results, a comparison with old excavation maps was executed.

KEYWORDS
GPR, ground-penetrating radar, hypocaust pillars, multichannel antenna array, Roman bath

1 | INTRODUCTION

Ground-penetrating radar (GPR) is one of the most common geophysical methods in archaeological prospection. In the first decades, mainly single antenna devices were used to generate a 2.5D data set, whereas modern surveys often take advantage of antenna arrays consisting of several single antennas that are aligned parallel to each other to simultaneously transmit and record with multiple radar sources. The advantage of such multichannel systems is, on the one hand, a much faster data acquisition while leaving the profile spacing the same. On the other hand, the profile spacing can be reduced dramatically and therefore the resolution of the data can be improved. The choice of a profile spacing as dense as possible is one of the crucial points for GPR prospection. However, in most case studies, a compromise has to be found between resolution and field expenditure. The effect of a too coarse profile spacing on the data is treated in several publications: For example, Linck (2013) or Neubauer et al. (2002) synthetically simulated a coarser profile spacing in real data by skipping profile lines in-between during data processing. For a 400-MHz antenna, these attempts led to the result of a maximum profile distance of 50 cm, whereas in case of a transect spacing of 1 m, some archaeological remains can be missed.

First attempts using GPR antenna arrays have already been reported by Birken et al. (2002) and Leckebusch (2005) nearly

20 years ago. Today, there is a multitude of publications on this topic from different countries; hence, only some recent ones can be mentioned here: Similar surveys were made in, for example, Austria (Gamon et al., 2021; Neubauer et al., 2014), France (Baret, 2021), Northern Germany (Coolen et al., 2021), Norway (Stamnes & Kiersnowski, 2021) and the United Kingdom (Gaffney et al., 2018).

2 | SURVEY EQUIPMENT

Whereas most of the above-mentioned case studies use single-polarized multichannel GPR arrays with an antenna spacing of 8 cm—for MALÅ Mira (Gamon et al., 2021) and 3D-radar Mark IV (Stamnes & Kiersnowski, 2021)—or 12 cm—for IDS Stream-X (Baret, 2021; Novo et al., 2012), in our test survey, the IDS Stream-C system with an even denser antenna spacing (see below) was applied. In contrary to the Stream-X system that has an antenna frequency of 200 MHz, this newer IDS multichannel array uses 600-MHz antennas providing a much better resolution for archaeological purposes.

Standard single-channel GPR surveys often cannot exploit the full 3D nature of the data, as in crossline direction a severe interpolation is applied due to a much coarser spacing. From a theoretical point of view, the Nyquist interval for unaliased sampling that should not be exceeded for recording the full three-dimensional GPR wave field describes this (Novo et al., 2008):

$$\Delta x \leq \frac{c}{4f\sin\left(\frac{\theta}{2}\right)\sqrt{\varepsilon_r}}$$

with Δx = profile spacing, c = velocity of light, f = antenna frequency, Θ = antenna beamwidth and ε_r = dielectric value of the soil.

Under the simplified assumption of a soil with a dielectric value $\varepsilon_r = 9$ and a beamwidth of 120°, the Nyquist interval for the 600-MHz antenna would be 4.8 cm. Based on this, the IDS Stream-C consists of 23 antenna dipoles in vertical configuration (VV) and a spacing of 4.4 cm (Figure 1a, Table 1). Besides, practical tests revealed that a simpler ratio of $\lambda/4$ is often sufficient (e.g., Janaschek et al., 1985). For a 600-MHz antenna, this would give a comparable value of 4.1 cm.

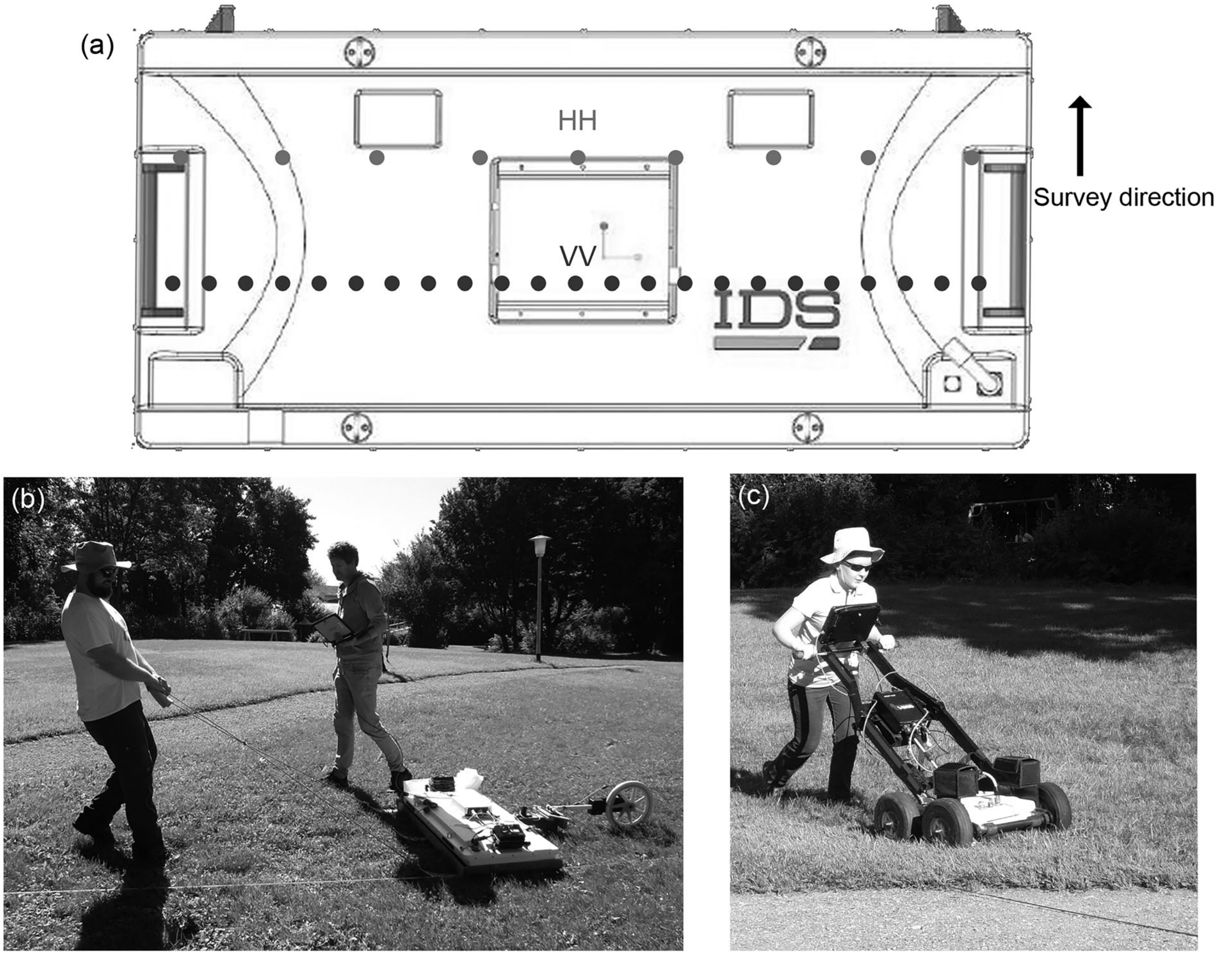

FIGURE 1 (a) Schematic view of the IDS Stream-C multichannel system. The lower dots mark the position of the 23 VV polarized antennas with 4.4-cm spacing; the upper dots the 9 HH polarized ones with 10 cm spacing (© IDS). (b) Photo of the survey equipment used in Kempten. The Stream-C is mounted on a self-built sled and an odometer wheel triggers the sampling interval (photo: BLfD, Roland Linck). (c) IDS Duo single-antenna cart in Kempten (photo: BLfD, Roland Linck).

TABLE 1 Survey parameters of the two GPR systems used for this case study

Type of system	Antenna frequency	Acquisition configuration	Antenna separation	Calculated resolution[a]
IDS Stream-C	600 MHz	VV and HH	4.4 cm for VV 10 cm for HH	8 cm
IDS Duo	200 and 600 MHz	VV	50-cm transect interval	25 and 8 cm

[a] Calculation with rule of thumb formulated by Milsom (2003): $d = 150/f\sqrt{\varepsilon_r}$ with $\varepsilon_r = 9$ and f in MHz.

Furthermore, there is also the unique chance of the IDS Stream-C radar to simultaneously acquire data by nine channels in horizontal configuration (HH) and 10-cm spacing (Table 1). This leads to an effective coverage of 96 cm by one survey swath. Due to the resulting antenna weight of 20 kg, it is normally mounted to a motorized vehicle. However, for our small-scale test site, we simply put the module onto a self-built sled (Figure 1b).

Regarding data processing, the standard steps for GPR surveys like a bandpass-filter (between 200 and 1000 MHZ with a Butterworth Taper of order 3), time-zero, background removal (over the whole signal range) and 3D-fk-migration (with a velocity of 0.065 m/ns) were applied in ReflexW. Another important step for antenna array data is the channel balancing to set each antenna to the same energy level, as there are differences due to the single antenna characteristics and the different ground coupling conditions (Trinks et al., 2018). For the latter step, the "normalize profiles"-algorithm in ReflexW was applied for the amplitude balancing across the single transect lines (Sandmeier, 2022).

Although the IDS Stream-C provides data in VV- and HH-polarization, only the VV data will be presented in this paper, as the HH polarized one does not provide any additional information. This is due to the real 3D mapping based on the ultra-dense profile spacing, which minimizes the effect of stronger reflections from features orientated perpendicular to the profile direction described, for example, by Annan and Cosway (1992) and Pomfret (2006). To some degree, this effect can already be detected in even coarser profile spacing, for example, 25 cm for a 400-MHz antenna (Linck & Fassbinder, 2014).

For the evaluation of the improvement in resolution, the same area was simultaneously measured in 50-cm profile spacing with a single-channel IDS Duo GPR system using 200 and 600-MHz antennas (Figure 1c, Table 1). Only the latter will be compared with the Stream-C system, as it operates in the same frequency. The data processing steps were principally the same as for the Stream-C data.

3 | LOCATION AND HISTORICAL BACKGROUND

As a test site, we chose the Great Roman Bath at Kempten-*Cambodunum*. Kempten is located in Southwestern Bavaria in a region called Allgäu, approximately 80 km southwest of Augsburg (Figure 2). The Roman settlement concentrated on the top of the Lindenberg, approximately 30 m above the right bank of the river Iller.

Cambodunum was the first capital of the Roman province Rhaetia and was founded around 17 AD shortly after the Roman conquest of the alpine upland at the junction of the East–West running route from Bregenz-*Brigantium* to Salzburg-*Iuvavum* and the Northeastern one towards Augsburg-*Augusta Vindelicum* (Gottlieb & Weber, 1989; Kleiss, 1962). After a first phase in wooden constructions, the first public buildings were rebuilt in stone at the end of the 1st century AD due to their demolition during the civil war after Emperor Nero's death (Czysz, 1995; Gottlieb & Weber, 1989; Schleiermacher, 1972). In this time, the settlement covered an area of 700 × 500 m. The rise of *Cambodunum* abruptly ended at the begin of the 2nd century AD, when the Roman Empire reached the Limes region and the capital of Rhaetia was shifted to *Augusta Vindelicum* depicting the province's centre in this time (Czysz, 1995). The remaining settlement of *Cambodunum* was abandoned around 260 AD due to several Alemannic invasions and was rebuilt at the left riverbank of the Iller, where the new medieval and modern town developed (Kleiss, 1962; Schleiermacher, 1972). Since this time, the area on top of the Lindenberg remained unchanged in huge parts. Hence, *Cambodunum* offers the unique possibility to survey a whole Roman town with geophysical prospection. The results of this comprehensive survey executed in 2011 with a single-channel GSSI SIR-3000 equipped with a 400-MHz antenna are published in Linck and Kühne (2012) and Linck (2013).

Geologically, the Kempten area is characterized by sandstone and marl that was deposited since the Tertiary as molasse around 15–25 million years ago. These former river and sea rubbles had been compacted and partly folded before they were overlaid by loose glacier and meltwater deposits. The Lindenberg itself depicts the remains of a former delta of the meltwater influx (Scholz, 2000). Hence, the soil is mainly built by gravel that provides a good water drainage and low conductivity. However, in situ time-domain reflectometry (TDR) measurements before and during the GPR survey revealed a soil moisture of 39 vol%, resulting in a quite high dielectric value of $\varepsilon_r = 24$ for the topsoil. A more comprehensive description of the survey method can be found in Linck (2013) and Linck and Fassbinder (2014). As, in contrast, the soil conductivity is as low as 1.8 dS/m, the circumstances are still suitable for good GPR results.

4 | RESULTS AND DISCUSSION

The multichannel IDS Stream-C survey covered a grid of 40 × 40 m size in the area of the Great Roman Bath of *Cambodunum*. This building was chosen, as old excavations in 1911 by the "Königliches Generalkonservatorium der Kunstdenkmale and Alterthümer Bayerns," the predecessor institution of the "Bayerisches Landesamt für Denkmalpflege" (BLfD), revealed a multitude of small hypocaust

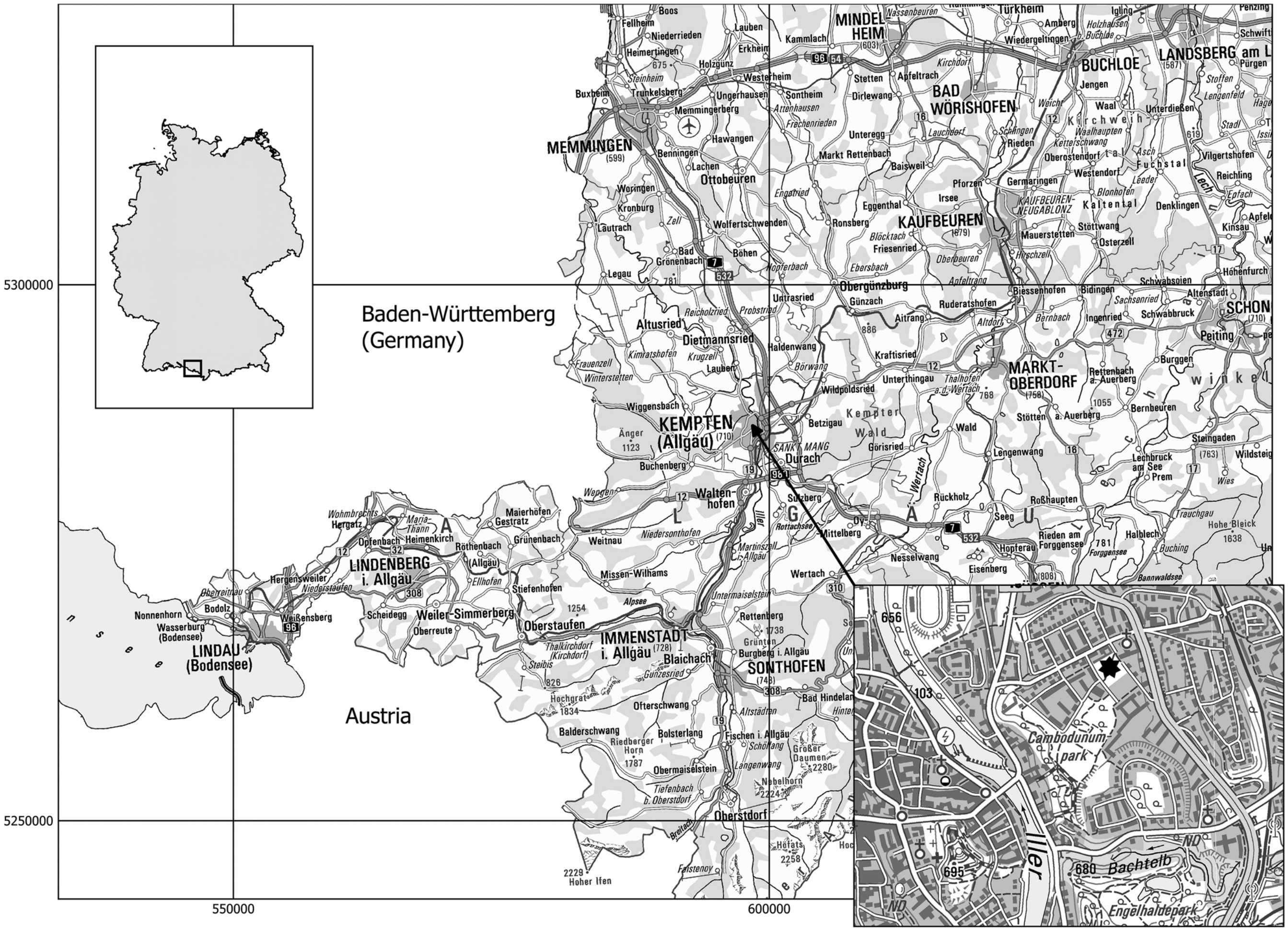

FIGURE 2 Topographical map showing the location of Kempten. The black star in the map in the lower right corner marks the exact position of the survey area. Coordinate system WGS84/UTM32N (© Bayerische Vermessungsverwaltung—www.geodaten.bayern.de). In the top left corner, the location within Germany is marked (© Bundesamt für Kartographie und Geodäsie, Frankfurt am Main, 2011).

pillars in the *caldarium* (i.e., the warm bath) of the second building phase (Figure 3). Hence, it offers the possibility to detect faint archaeological remains that might only be visible in real 3D GPR data.

The Great Roman Bath covered an area of 4000 m^2 and belonged to the largest complexes of this kind north of the Alps, comparable with those in Augst-*Augusta Raurica* (Switzerland) and Avenches-*Aventicum* (Switzerland) (Weber, 2000). It had two building phases with a slightly varying layout, which can also be distinguished in the GPR data by their different depth. The radar data show the Roman walls in a depth range from 45 to 150 cm below the modern surface. Schleiermacher (1972) reports the same depths for excavated walls in other parts of *Cambodunum*; hence, the depth estimation by the GPR survey seems to be quite accurate. By comparing the results of the IDS Stream-C with those of the IDS Duo, it can be noted that the Roman walls are detected by both systems (Figure 4a,c). Due to their width of 50–90 cm, already the profile spacing of 50 cm that was applied for the IDS Duo is dense enough to resolve them. However, they have a higher contrast to the background reflection and are more pronounced in the Stream-C depth slices due to the exploitation of the full resolution of the GPR data based on the equal sample interval in both directions. The layout and different building phases of the Great Roman Bath in *Cambodunum* have already been published in detail in Linck and Kühne (2012) and Linck (2013). Hence, these topics are not treated further, as they are not relevant for the approach to detect faint archaeological remains by an ultra-dense full 3D survey.

In a depth of 65–115 cm below the modern surface, the Stream-C data shows several hypocaust pillars of 25 cm lateral length. Figure 4b presents a sample hypocaust picked in the depth slice and the corresponding unmigrated profiles (i.e., inline and crossline). The reflection hyperbolas in the profiles mark the hypocaust's location very well. Furthermore, the cross-sections represent the correct depth of the pillars known from the excavation results quite well. However, not all pillars that were documented in the excavation plan of 1911 (Figure 3a) are identifiable in the GPR data. Some of them probably were destroyed or collapsed during excavation or the refill afterwards, as they consist of unstable layered burnt bricks. Another reason is that sometimes only the last stone layer is preserved (see excavation photo in Figure 3b), but the hand-drawn plan simply maps them without giving any information about their height, which leads to a reflection signal that cannot be distinguished from the natural background.

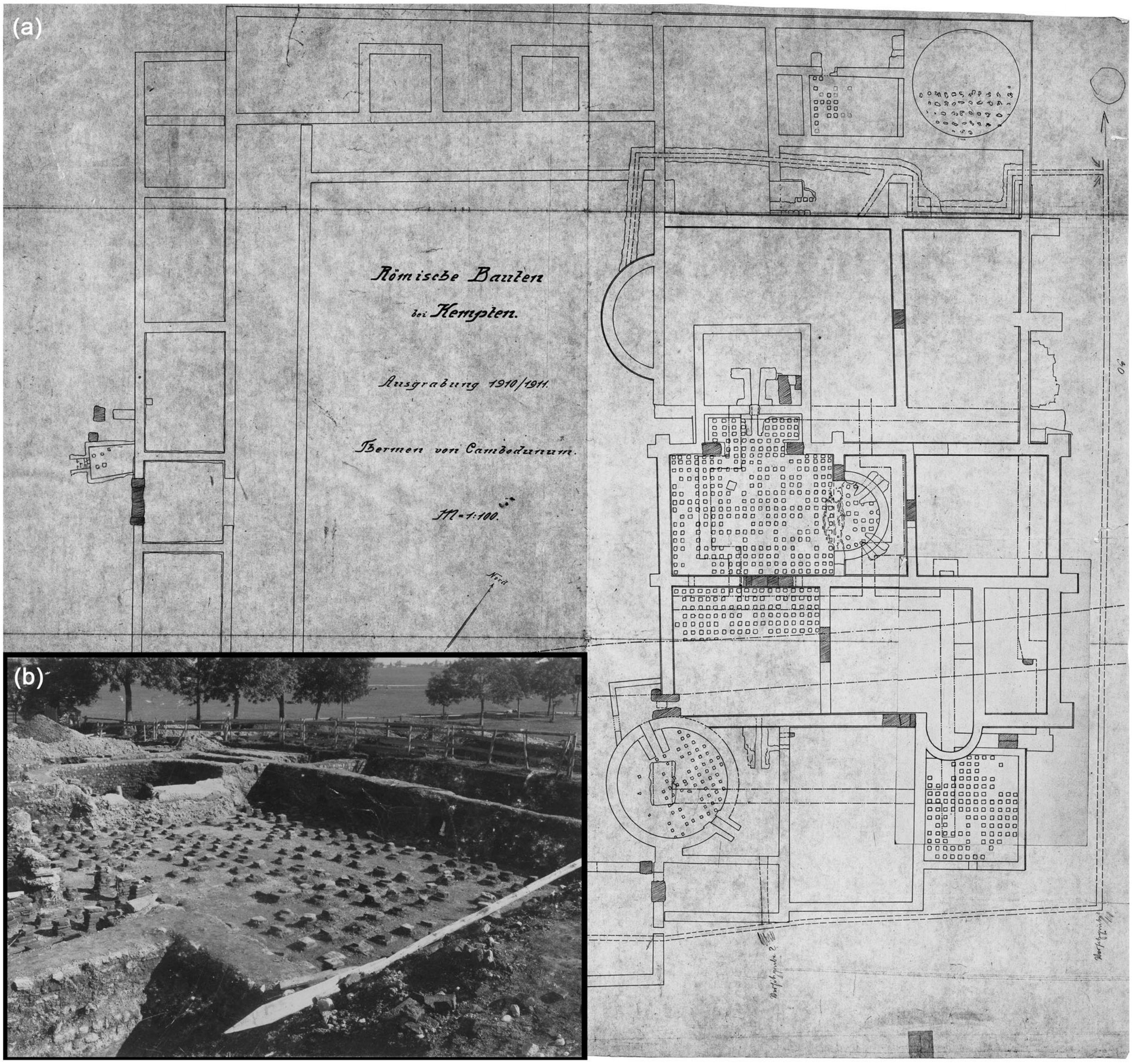

FIGURE 3 Excavation of the Roman Great Bath in 1911 by Paul Reinecke in Kempten-*Cambodunum*. (a) Hand-drawn plan of the unearthed remains including the walls and the hypocaust pillars in 1:100 scale. There is no distinction between the two construction phases. (b) Original photo of 1911 of the excavated *caldarium* (phase II) with the hypocaust pillars in different states of preservation. View from the west (© BLfD)

Thus, only 22% of the hypocaust pillars marked in the plan could be detected by the multichannel GPR survey.

Furthermore, the location of the hypocaust pillars mapped by GPR does not completely fit to the corresponding ones in the original excavation plan. This can be explained by two facts: On the one hand, in 1911 certainly not all pillars were exactly levelled by hand, but more or less added in a regular raster with a defined distance in all directions. On the other hand, the hand-drawn plan is not completely true to scale, as modern excavations in other parts of the Roman town have revealed. Nevertheless, 89% of the probable hypocaust pillars detected by the Stream-C correspond to the excavation map. The remaining error is simply conditioned by the fact that the GPR data can also show bigger stones of the excavation infill.

For the single-channel IDS Duo data, the situation is even worse: Only 3% of the hypocaust pillars can be identified in these depth slices (Figure 4c,d). Especially Figure 4d shows impressively the problem of crossline interpolation in case of the single-channel surveys. Hence, such faint archaeological remains are only detectable by an ultra-dense multichannel array and the application of such a survey device is advisable for sites with expected small-scale structures in the subsurface. In addition, Figure 4d shows quite well the above-mentioned effect of strong interpolation in crossline direction that further blurs the detection of small features.

Similar archaeological remains of Roman hypocaust pillars were also mapped by Trinks et al. (2018) with a MÅLA Mira multichannel system in *Carnuntum* (Austria).

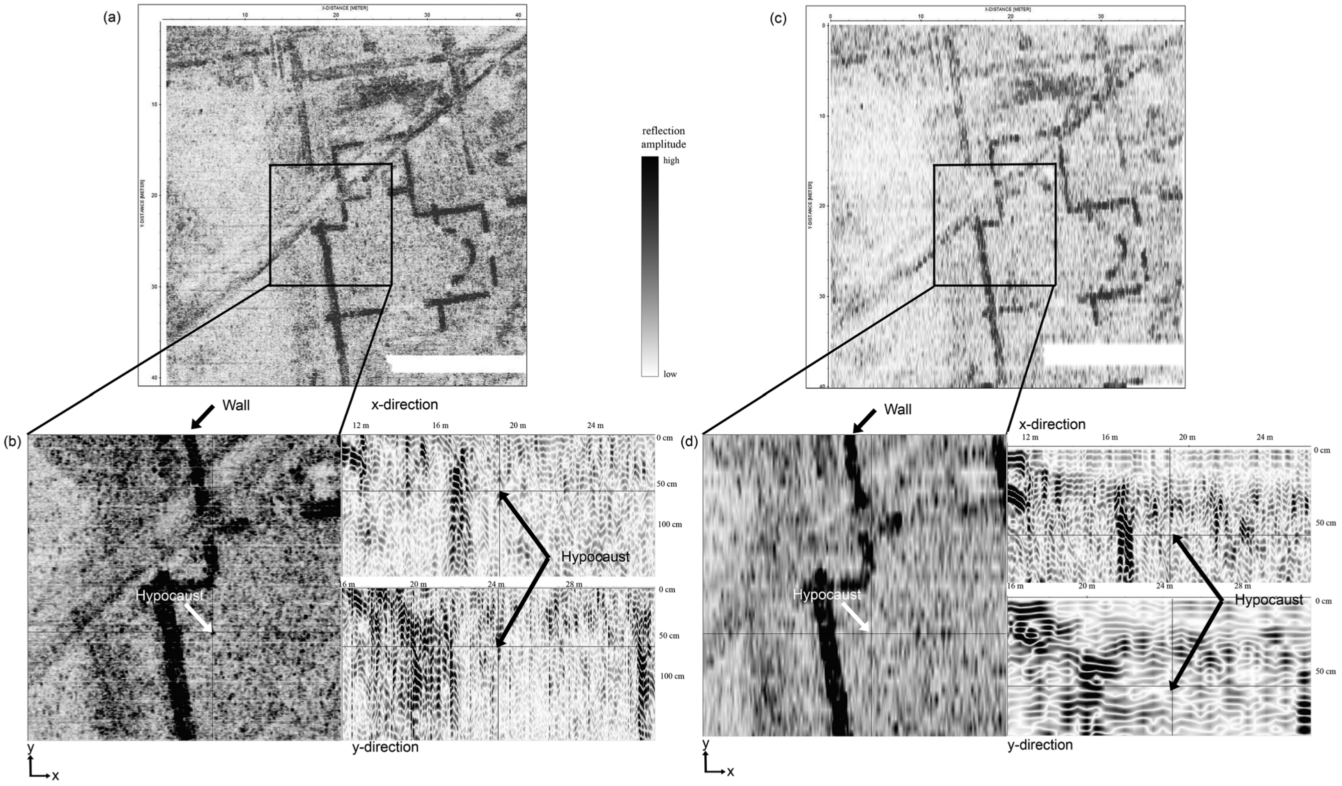

FIGURE 4 Comparison of the GPR depth slices of 10 cm thickness in 65–75 cm depth of the IDS Stream-C (a) and the IDS Duo (c). The black rectangle represents the zoomed area in the detailed view below. A sample hypocaust picked in the depth slice and the corresponding inline and crossline profiles, to present the visibility in the IDS Stream-C profile data (b) and no evidence at the same location in the IDS Duo data (d). Survey details: IDS Stream-C with 600-MHz antenna and sample interval 4 × 4 cm; IDS Duo with 600-MHz antenna and sample interval 4 × 50 cm. Grid size: 40 × 40 m; the no-data area is due to a table-tennis table. The broad feature that is running diagonal through the depth slices depicts a multiple reflection of a modern gritted footpath.

5 | CONCLUSION

The presented results of the test survey in Kempten show the advantage and benefit of ultra-dense GPR surveys with multichannel antenna arrays. Small archaeological remains can only be resolved by such full 3D datasets and are mainly missed by using a standard single-antenna configuration. The reason for this is that a single-channel survey normally uses a much higher crossline than inline spacing due to the fact that surveying the equivalent area with the same data density requires significantly more survey time. Another problem is that single-channel antenna cases are too big for such dense profile spacing, prohibiting the antenna centre being positioned exact enough. This results in a crossline interpolation of the data, which possibly eliminates the faint archaeological remains. A remediation for this fact would only be a bidirectional survey in inline and crossline direction that could fail due to the problem of exact positioning of the antenna. Hence, an antenna array should always be applied if such subsurface features are expected within the survey area.

However, there are some drawbacks of GPR antenna arrays that shall be mentioned: As already stated by Trinks et al. (2018), such systems are bulky and often have a width of 1 m or even more, which can cause some problems with ground coupling of the signal in case of rough terrain. Furthermore, these instruments create an enormous amount of data that have to be handled for data processing and are still quite expensive. Another crucial factor, especially in Bavaria, is that the farmers often do not permit access to their fields with motorized geophysical systems or that the survey areas are simply too small for operating such bulky arrays. In conclusion, it has always to be weighted, which configuration offers the best choice for the specific requirements of the case study, whereas for most archaeological remains, a coarser profile spacing offered already by single-channel GPR devices is often sufficient.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

Annan, A. P., & Cosway, S. (1992). Ground penetrating radar survey design. In *Proceedings of the Symposium on the Applications of Geophysics to Engineering and Environmental Problems*. Environmental and Engineering Geophysics Society.

Baret, F. (2021). GPR vs archaeological excavation: Comparison of the results obtained in the eastern district of the Roman small town of Bridiers (la Souterraine, Creuse, France). *ArchaeoSciences*, *45-1*, 17–22. https://doi.org/10.4000/archeosciences.8130

Birken, R., Miller, D. E., Burns, M., Albats, P., Casadonte, R., Deming, R., Derubeis, T., Hansen, T., & Oristaglio, M. (2002). Efficient large-scale underground utility mapping with a multi-channel ground-penetrating imaging radar system. In *Proceedings of 15th EEGS Symposium on the Application of Geophysics to Engineering and Environmental Problems*. Environmental & Engineering Geophysical Society. https://doi.org/10.3997/2214-4609-pdb.191.13IDA1

Coolen, J., Wallner, M., Trausmuth, T., & König, A. (2021). New insights into a Romanesque basilica church in the deserted town of Corvey, Germany, based on a high-resolution GPR survey. *ArcheoSciences*, *45-1*, 35–38. https://doi.org/10.4000/archeosciences.8275

Czysz, W. (1995). Das zivile Leben in der Provinz. In W. Czysz, K. Dietz, T. Fischer, & H.-J. Kellner (Eds.), *Die Römer in Bayern* (pp. 177–308). Konrad Theiss Verlag.

Gaffney, V., Neubauer, W., Garwood, P., Gaffney, C., Bates, C., Smedt, P., Baldwin, E., Chapman, H., Hinterleitner, A., Wallner, M., Nau, E., Filzwieser, R., Kainz, J., Trausmuth, T., Schneidhofer, P., Zotti, G., Lugmayer, A., Trinks, I., & Corkum, A. (2018). Durrington walls and the Stonehenge Hidden Landscape Project 2010–2016. *Archaeological Prospection*, *25*(3), 255–269. https://doi.org/10.1002/arp.1707

Gamon, M., Hinterleitner, A., Löcker, K., Tencer, T., Wallner, M., Neubauer, W., & Trinks, I. (2021). Clunia revisited—The inverse feedback case: Archaeological interpretation of high-resolution GPR data from the Roman site "uf dr Studa" in Altenstadt, Feldkirch, Austria, in comparison to archaeological excavation results from 1884. *ArcheoSciences*, *45-1*, 63–66. https://doi.org/10.4000/archeosciences.8513

Gottlieb, G., & Weber, G. (1989). Die Frühgeschichte Kemptens. In V. Dotterweich, K. Filser, P. Fried, G. Gottlieb, W. Haberl, & G. Weber (Eds.), *Geschichte der Stadt Kempten* (pp. 1–68). Verlag Tobias Dannheimer.

Janaschek, H., Mauritsch, H., Rösler, R., & Steinhauser, P. (1985). Hochfrequenzmethoden. In H. Militzer & F. Weber (Eds.), *Angewandte Geophysik, Bd. 2: Geoelektrik - Geothermik - Radiometrie - Aerogeophysik*. Springer Verlag.

Kleiss, W. (1962). Die öffentlichen Bauten von Cambodunum. In *Baubeschreibung und Rekonstruktion*. Verlag Michael Lassleben.

Leckebusch, J. (2005). Use of antenna arrays for GPR surveying in archaeology. *Near Surface Geophysics*, *3*(2), 111–115. https://doi.org/10.3997/1873-0604.2005006

Linck, R. (2013). *Methodische Untersuchungen zur Weiterentwicklung der Boden- und Satellitenradarprospektion in der Archäologie*. Shaker Verlag.

Linck, R., & Fassbinder, J. W. E. (2014). Determination of the influence of soil parameters and sample density on ground-penetrating radar: A case study of a Roman picket in lower Bavaria. *Archaeological and Anthropological Sciences*, *6*(1), 93–106. https://doi.org/10.1007/s12520-013-0145-4

Linck, R., & Kühne, L. (2012). Römerstadt unterm Bodenradar: Prospektion für den "Archäologischen Park Cambodunum". *Das Archäologische Jahr in Bayern*, *2011*, 84–87.

Milsom, J. (2003). *Field geophysics*. John Wiley & Sons.

Neubauer, W., Eder-Hinterleitner, A., Seren, S., & Melichar, P. (2002). Georadar in the Roman civil town Carnuntum, Austria: An approach for archaeological interpretation of GPR data. *Archaeological Prospection*, *9*(3), 135–156. https://doi.org/10.1002/arp.183

Neubauer, W., Gugl, C., Scholz, M., Verhoeven, G., Trinks, I., Löcker, K., Doneus, M., Saey, T., & Van Meirvenne, M. (2014). The discovery of the school of gladiators at Carnuntum. *Austria. Antiquity*, *88*(339), 173–190. https://doi.org/10.1017/S0003598X00050298

Novo, A., Dabas, M., & Morelli, G. (2012). The STREAM X multichannel GPR system: First test at Vieil-Evreux (France) and comparison with other geophysical data. *Archaeological Prospection*, *19*(3), 179–189. https://doi.org/10.1002/arp.1426

Novo, A., Grasmueck, M., Viggiano, D.A., & Lorenzo H. (2008). 3D GPR in archaeology: what can be gained from dense data acquisition and processing?. In 12th International Conference on Ground Penetrating Radar (GPR 2008), Birmingham, UK, 5.

Pomfret, J. (2006). Ground-penetrating radar profile spacing and orientation for subsurface resolution of linear features. *Archaeological Prospection*, *13*(2), 151–153. https://doi.org/10.1002/arp.285

Sandmeier, K.J. (2022). ReflexW Handbook, Version 10.0.

Schleiermacher, W. (1972). *Cambodunum-Kempten*. Rudolf Habelt Verlag.

Scholz, H. (2000). Vom Werden der Landschaft. In G. Weber (Ed.), *Cambodunum - Kempten. Erste Hauptstadt der römischen Provinz Raetien?* Verlag Philipp von Zabern.

Stamnes, A., & Kiersnowski, K. (2021). Large-scale ground-penetrating radar surveys of the Iron Age site of Bodøsjøen, northern Norway. *ArcheoSciences*, *45-1*, 127–130. https://doi.org/10.4000/archeosciences.9014

Trinks, I., Hinterleitner, A., Neubauer, W., Nau, E., Löcker, K., Wallner, M., Gabler, M., Filzwieser, R., Wilding, J., Schiel, H., Jansa, V., Schneidhofer, P., Trausmuth, T., Sandici, V., Ruß, D., Flöry, S., Kainz, J., Kucera, M., Vonkilch, A., … Seren, S. (2018). Large-area high-resolution ground-penetrating radar measurements for archaeological prospection. *Archaeological Prospection*, *25*(3), 171–195. https://doi.org/10.1002/arp.1599

Weber, G. (2000). Bauboom in Stein - eine Stadt nach mediterranem Vorbild. In G. Weber (Ed.), *Cambodunum - Kempten. Erste Hauptstadt der römischen Provinz Raetien?* Verlag Philipp von Zabern.

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