



The gradient structure tensor (GST): an efficient tool to analyze 3D GPR data for archaeological prospection

Philipp Koyan ^{1*}, Jens Tronicke ¹

¹ Institute of Geosciences, University of Potsdam, Potsdam, Germany

* Corresponding author: E-mail: koyan@uni-potsdam.de

Abstract

We present GPR data across remains in a Palace Garden at Paretz (Germany). We use the GST to highlight archaeological structures in the GPR data. We outline the flexibility and time-efficiency of a GST-based analysis strategy.

Keywords

archaeological prospection; attribute analysis; gradient structure tensor; ground penetrating radar; 3D imaging

Introduction

Ground penetrating radar (GPR) is a well-established near-surface geophysical tool commonly applied in archaeological prospection. Thanks to steady developments in system design and surveying strategies, the acquisition of 3D GPR datasets densely covering thousands of square meters has become common practice. However, developing GPR interpretation strategies has not kept pace with technological advances. Today, the ever-growing amount of GPR data is still typically interpreted in a manual fashion which makes interpretation a time-consuming and rather subjective process.

Amongst other techniques, the application of 3D attributes has shown to be a helpful strategy in GPR data analysis to concise the interpretation processes and make interpretation a less subjective and more reproducible task. Attributes enhancing and quantifying structure information such as dip and continuity are able to deliver reliable results when incorporated into the interpretation process (Koyan et al. 2021). The gradient structure tensor (GST) is well known as a tool to describe structure in 2D/3D/4D image and video processing including medical applications. GST-based strategies have also been successfully used to interpret reflection seismic data (e.g. Bakker 2002) but to our knowledge no examples for the application to 3D GPR datasets can be found in the literature.

Theory and method

In 3D, the gradient structure tensor N of an image I is defined by smoothed outer products of the image gradients:

$$N(x, y, z) = \begin{pmatrix} \langle I_x^2 \rangle & \langle I_x I_y \rangle & \langle I_x I_z \rangle \\ \langle I_y I_x \rangle & \langle I_y^2 \rangle & \langle I_y I_z \rangle \\ \langle I_z I_x \rangle & \langle I_z I_y \rangle & \langle I_z^2 \rangle \end{pmatrix}. \quad (1)$$

Here, the indices x, y, z denote the derivatives with respect to the three spatial dimensions and $\langle \cdot \rangle$ denotes a Gaussian smoothing operation applied to produce stable results at the target spatial scale characterized by a standard deviation $\sigma_T(x, y, z)$. Relevant information from this tensor can be obtained by calculating its three eigenvalues ($\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq 0$) and the corresponding eigenvectors \hat{e}_i with $i = 1, 2, 3$. From the orientation of the eigenvectors, local structure, for example, within locally stratified environments can be quantified by calculating the dip angle and dip azimuth. In contrast, to detect and map archaeological targets, we analyze the tensor eigenvalues in terms of planarity C_{plane} calculated by

$$C_{plane} = \frac{\lambda_1 - \lambda_2}{\lambda_1 + \lambda_2}. \quad (2)$$

In general, planarity describes the local structure in terms of continuous regions ($C_{plane} \approx 1$) such as layers in stratified sediments and discontinuous regions ($C_{plane} \ll 1$) such as

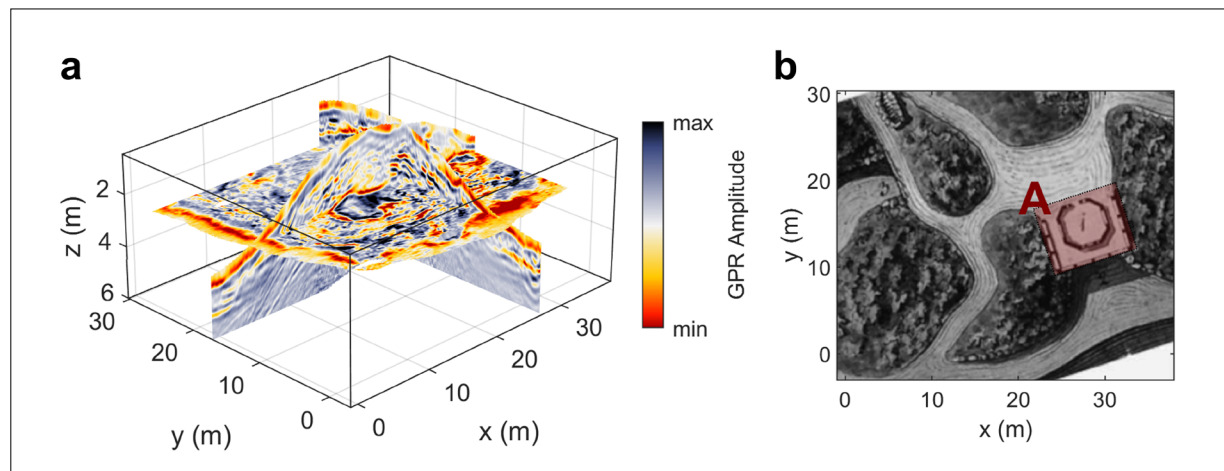


Fig. 1: a) Example slices of the processed dataset in terms of GPR amplitude (vertical exaggeration is 3). b) Historical sketch of the Paretz Palace Garden highlighting structure A, a historical grotto located beneath a teahouse (redrawn after Böniger and Tronicke 2010).

debris. Compared to other relevant attribute calculation strategies, the GST procedure (1) can be considered as computationally efficient (calculation times in the order of seconds for typical 3D datasets consisting of several 100.000 traces and more), (2) delivers a wide range of diverse attributes highlighting different structural characteristics, and (3) enables an intuitive parameter selection because its output mainly depends on the target-specific parameter $\sigma_T(x, y, z)$.

Results and discussion

To detect the remains of ancient architectural elements in the Palace Garden of Paretz, Brandenburg (Germany), Böniger and Tronicke (2010) collected densely-sampled 3D GPR data (with an in- and crossline spacing of approximately 0.05 m and 0.25 m, respectively) using a common-offset pair of unshielded 200 MHz antennas covering an area of approximately 35 m x 40 m. In Figure 1a, we show selected slices of the GPR amplitude volume after applying a typical 3D processing sequence including migration, topographic correction, and time-to-depth conversion. By performing extensive attribute-based analyses of this GPR volume also considering collocated magnetic and topographic surveys, the authors identified several anomalies that they interpret using a historical sketch of the garden from the early 19th century (Fig. 1b). To demonstrate the potential of our GST-based method, we focus on structure A, where the historical sketch reports an ancient grotto with rectangular walls underneath a teahouse.

To calculate the GST, we set $\sigma_T(x, y, z)$ to 0.35 m such that the Gaussian smoothing kernels operate in the order of a dominant GPR wavelength. In Figure 2a, we show a selected x-y slice of the GPR amplitude volume shown in Figure 1a at a depth of approximately 3 m. We observe mainly chaotic reflection patterns appearing to lack a preferential direction which makes it hard to interpret the GPR data alone in terms of archaeologically relevant structures. Mainly the same holds for GPR energy (here calculated as the averaged sum of squared amplitudes over a depth window of 0.35 m), a common attribute in archaeological GPR prospection, that we show along the same slice in Figure 2b. Here, we calculate planarity across the GPR amplitude volume following Equations 1 and 2, and show the result as transparent overlay on the corresponding GPR data slice shown in Figure 2a. Comparing Figures 1b and 2c reveals that discontinuous areas (highlighted by lower planarity values) nearly perfectly trace the apparently well-preserved walls of the grotto. Additionally, we calculate planarity for the GPR energy volume and show the result in Figure 2d as transparent overlay on the corresponding GPR energy slice shown in Figure 2b. Comparing Figure 2b and 2d shows that the energy-based planarity highlights the inner part of structure A and thus indirectly images the outer boundaries of the grotto. Taking also Figure 1b into consideration implies that the low energy-based planarity values in the central part of structure A are caused by discontinuous energy patterns that, in turn, indicate debris originating from the formerly overlying teahouse.

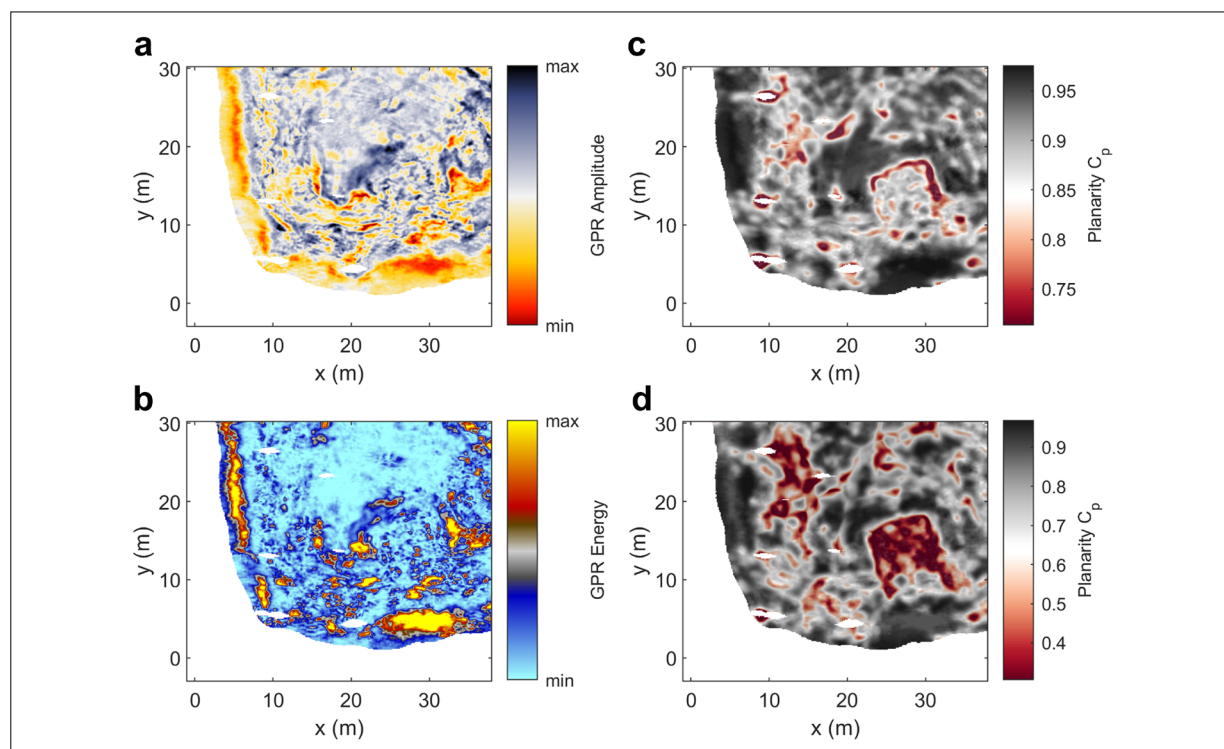


Fig 2: Example x-y slices at a depth of approximately 3 m of a) GPR amplitude, b) GPR energy, c) GST-based planarity calculated across GPR amplitude, and d) GST-based planarity calculated across GPR energy.

Conclusion

Analyzing GPR attributes aids the interpretation of the underlying datasets. However, calculating and selecting an appropriate set of attributes can be a cumbersome procedure. We apply the 3D gradient structure tensor (GST), a time-efficient, flexible, and comparatively objective tool that runs with only a few (target-specific) parameters. Additionally, applying the GST strategy delivers a selection of attributes to outline diverse structures in the underlying 3D datasets. Here, by calculating the planarity attribute based on the GST across a GPR amplitude and a GPR energy volume, we show that GST-based analysis is a useful means to detect and highlight a grotto and remains of an associated teahouse in the ancient Palace Garden in Paretz, Brandenburg (Germany). ■

References

Bakker P. Image structure analysis for seismic interpretation [dissertation]. Delft (The Netherlands): TU Delft, Delft University of Technology; 2002.

Böniger U, Tronicke J. Integrated data analysis at an archaeological site: A case study using GPR, magnetic, and high-resolution topographic data. *Geophysics* 2010;75(4):B169-B176. doi: [10.1190/1.3460432](https://doi.org/10.1190/1.3460432)

Koyan P, Tronicke J, Allroggen N. 3D ground-penetrating radar attributes to generate classified facies models: A case study from a dune island. *Geophysics* 2021;86(6):B335-B347. doi: [10.1190/geo2021-0204.1](https://doi.org/10.1190/geo2021-0204.1)

Open Access

This paper is published under the Creative Commons Attribution 4.0 International license (<https://creativecommons.org/licenses/by/4.0/deed.en>). Please note that individual, appropriately marked parts of the paper may be excluded from the license mentioned or may be subject to other copyright conditions. If such third party material is not under the Creative Commons license, any copying, editing or public reproduction is only permitted with the prior consent of the respective copyright owner or on the basis of relevant legal authorization regulations.