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Virtual Georadar Modelling of Significant Archaeological Sites

Abstract: 3D modelling of archaeological sites and historical objects with non-destructive methods of shallow-depth geophysics assists future investigations using traditional archaeological methods and facilitates the development of methods for their preservation in museums or in their natural buried state for the next generation of investigators. This paper outlines some observations on and an approach to 3D model development including geophysical and geological interpretations. Detailed georadar prospection was conducted on the site of an outstanding Russian architectural ensemble from the 14th to the 19th centuries – the Holy Trinity St. Sergius Lavra, the centre of Russian Orthodox religion, in Sergiev Posad, Moscow region. Details from a 3D georadar model of the historical area are correlated level-by-level with data from previous archaeological excavations and historical records. The development of a 3D model of an archaeological site, or any object buried within historical or cultural sites, is clearly the most up-to-date approach to detecting, analyzing and preserving heritage objects. The degree to which such a model resembles the actual appearance of the buried object is determined by the quality of data obtained by non-destructive remote examination. A georadar approach provides a detailed and accurate result using remote examination, permits the precise 3D localization of objects and can produce an integrated representation of the subsurface area characteristics – archaeological layering, engineering geological features and so on.

Methodology of GPR Model Development

The key elements of a virtual model are the 3D georadar model of the subsurface area and the 3D model of micro-relief surface features obtained with high-resolution GPS (for large areas with a dissected topography).

Our methodology of georadar data interpretation and reconstruction of subsurface area includes the following:

1. Analysis of geological environment: division of natural and man-made anomalies in subsurface structure, if necessary; solution of geological, geomorphologic, and engineering geological problems.
2. Diagnostics of buried archaeological objects, reconstruction of design, borders and layering of archaeological objects, creation of geophysical anomaly libraries related to various archaeological objects, development of 3D models for archaeological objects, and development of a super-3D project (combining several 3D projects) for large areas with intricate design of the surface.
3. Adaptation of geophysical data for archaeological application: development of remote access to geophysical databases for users without special software, development of multimedia 3D models of archaeological objects, and integration of geophysical and geodesic data in GIS projects.

A virtual 3D model is supplemented by material to aid interpretation: archaeological reports, oral recollections, descriptions of famous objects, historical documents, etc. The chief methodological problem in the archaeological application of GPR data is its reliability and correspondence with the geological cross-sections of the area in question. This aspect of archaeological georadar studies is considered in the following detailed investigation of subsurface structures at one of the sites of the Russian architectural ensemble of Holy Trinity St. Sergius Lavra *(Fig. 1)*. This ensemble is a UNESCO world heritage site, the centre of Russian Orthodoxy, as well as an historical and cultural monument.

Georadar Prospection at Holy Trinity St. Sergius Lavra

The Holy Trinity St. Sergius Lavra has a unique and structurally diverse cultural layer as shown by the GPR prospection. Here, within a relatively small area, numerous ecclesiastical and domestic buildings have been constructed, renovated, and occasionally demolished over six-and-a-half centuries. During this entire period, the Lavra has been a burial place for monks, hierarchs of the Russian Orthodox Church and honourable people. The restricted size of the area has meant the graves are very closely

Fig. 1. Area of georadar prospection between the Holy Trinity Cathedral and the Holy Spirit Church in the Holy Trinity St. Sergius Lavra in Sergiev Posad, Moscow Region.

dug, sometimes even in layers. The aged tombs have been often replaced during repeated rebuilding in the area, and very often, the burial sites were lost. Multiple fires explain the incompleteness of the Lavra historical testimonies and fragmentary state of the annals of the grandiose and red necropolis. During the Soviet era, the Lavra was separated from the Church, and some of the constructions and tombs were demolished.

Difficulties are often encountered when mapping lost design elements, renovating foundations, contouring the Necropolis, and prospecting for individual burial sites and crypts, and this is now a very real concern for church archaeology, in particular because of the Russian practice of reconstruction and renovation of the church and monastery architectural ensembles.

Georadar prospection of the Lavra was started at a small experimental site in order to determine the buried objects characteristic of this historical area *(Fig. 1)*. The site is located in the historical core of the architectural ensemble, between the oldest cathedrals in the Lavra – the Holy Trinity Cathedral (1422) and the Church of the Holy Spirit (1476). The site prospected extends from the eastern altar wall of the Cathedral along the southern façade of the Church up to one of its apses *(Fig. 1)*.

The areal GPR prospection was conducted with a centre frequency of 400 MHz on a number of parallel profiles oriented westward. The tiles covering the

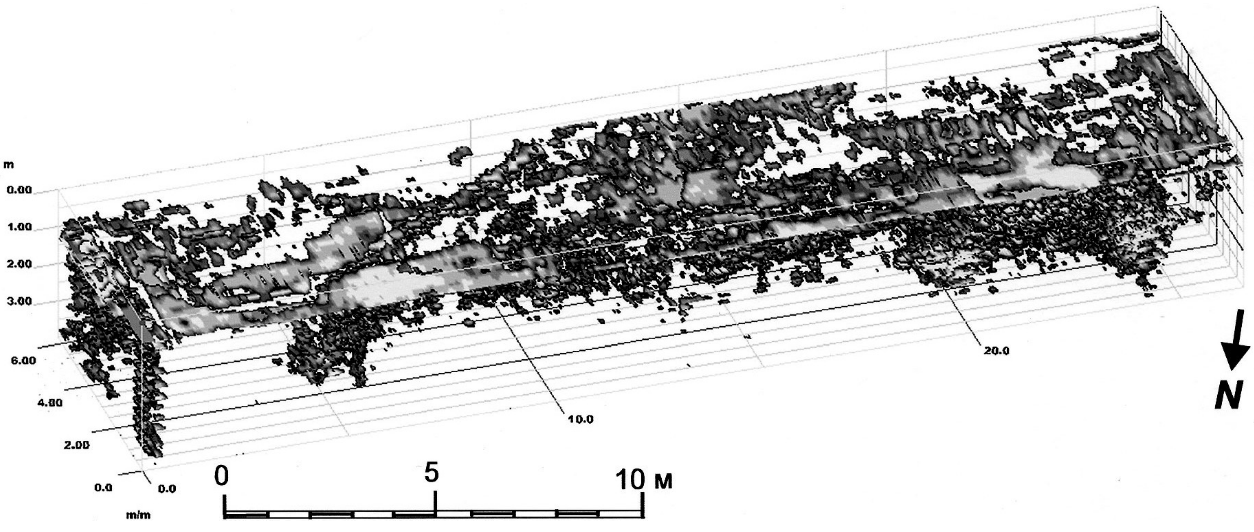

Fig. 2. 3D Georadar model of the Holy Trinity St. Sergius Lavra site. Excerpt of visualization showing objects from all stratigraphic levels: streak tile pattern paving the area, some tomb stones in the second layer, evidence of earlier archaeological excavations, and the compound foundations.

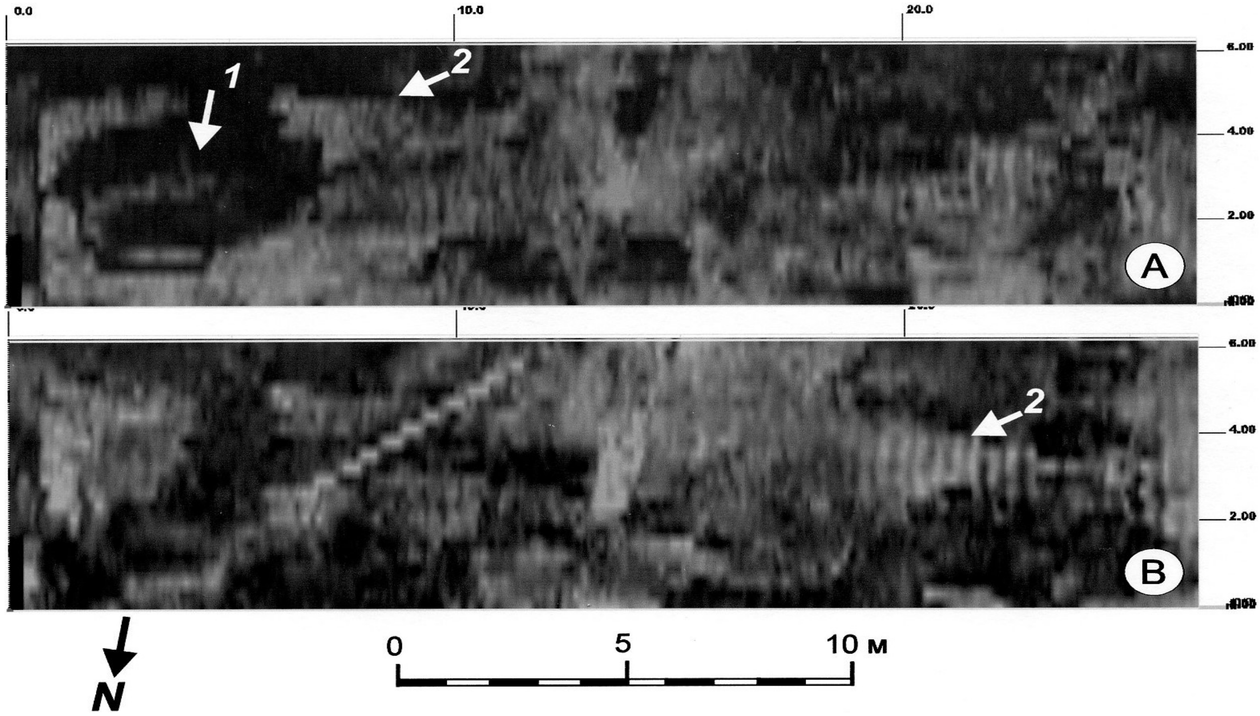

Fig. 3. Georadar image of the upper layers in the model — variable-depth 3D sections of the model. The cover of displaced burial sites is marked by light tone (2), dark areas mark the archaeological excavation (1).

site were used as a natural division of the area, so the interval between profiles was 40 cm. Such dense georadar prospection allows an almost complete sounding of the upper cross-section, considering the widest spread of the antenna beam (about 40 m) and the flare of the signal (about 60°). GPR data of such a high quality guarantee a reliability and high resolution for 3D model of the area.

The data processing and interpretation of the georadar prospection were done using the program Radan-6 and special geophysical 3D modules. The high quality of the field survey allowed archaeological interpretation with little to no post-processing (migration).

The upper geological cross-section of the area can be analyzed by developing a digital 3D model based on the georadar prospection data *(Fig. 2)*. In this paper, the 3D model of the object is visualized in two ways: either by a set of variable-depth cross-sections, i.e. georadar design of the area, showing the location of the miscellaneous buried objects or heterogeneity of the soil at a certain depth, or by examples of georadar profile fragments, where anomalies are found and interpreted as hidden objects *(Figs. 2–5)*. One of these means of visualization alone cannot provide complete information regarding subsurface area structure.

The GPR examination of the site and processing of prospection results were implemented before a review of archaeological and historical data. At the subsequent interpretation of the georadar data, historical documents (Baldin 1984) and descriptions of the numerous archaeological excavations conducted in the area were studied (Vishnevsky 2006; Vishnevsky 2007).

The 3D model of the site is distinguished by multi-layering – the subsurface structure is different at various depths. The georadar layering of the site is based on allocation of layers with a distinguishing wave pattern. By the term "wave pattern", we mean a combination of sounding electromagnetic signal features reflected from a soil layer of homogeneous structure. A specific wave pattern is characteristic of cultural deposits.

The upper layer of the site (0.15–0.2 m) is divided into a grid of thin stripes, marking the junctures between the tiles which pave the area between the churches. On this level, the georadar data does not contain any information of historical value; however, it can be used as a marking grid of a site surface.

A similar method is often followed during the detailed areal survey of solid or fragmentary slabs, block and other type of pavement. Visualization allows a set of parameters from the upper layer struc-

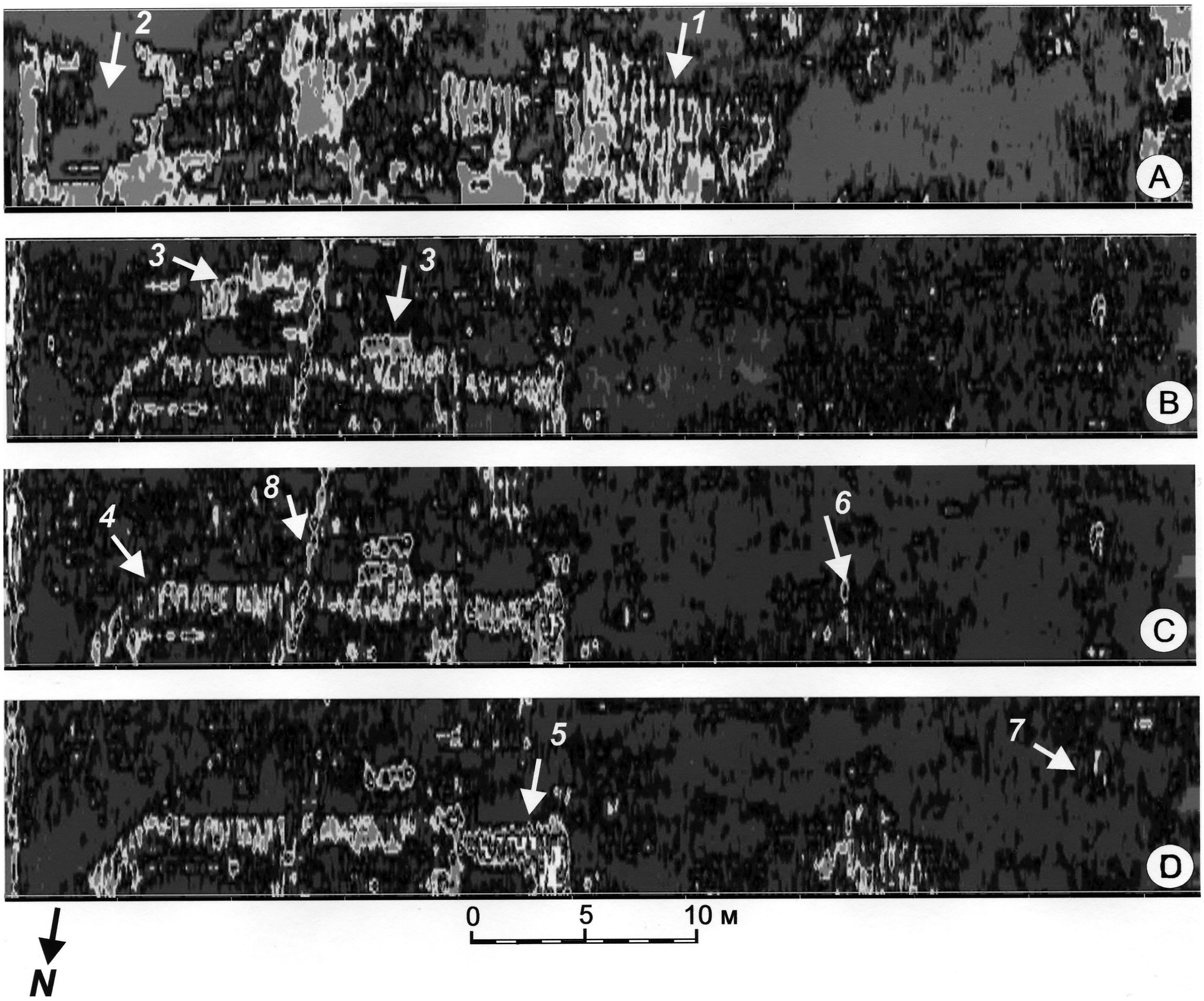

Fig. 4. 3D model of subsurface structure on a site south of the Holy Spirit Church. A: layer of marble tombs; B–D: subsequent layers with removed upper layer. Georadar anomalies: 2 – foundation of a destroyed free-standing bell, 4 – foundations of destroyed Filaret church, 4 – marble crypts, 5 – common burial sites, 6 – archaeological excavations, 8 – underground communications lines.

ture to be projected on all underlying objects, this being a natural means for precise localization of the whole area.

The next subsurface layer (up to 0.4–0.8 m) has a different wave pattern which reflects large buried slabs. The slabs are established at different depths by the analysis of variable-depth sections of the 3D model (*Fig. 3*; interval 10–20 cm), and a gentle surface tilt is exhibited by some of them (a difference in the first centimetre).

In the eastern part of the site, a dark contour is observed, which was interpreted as the remnant of an archaeological excavation when all tomb stones were removed (Vishnevsky 2007). In the same layer, various communication service lines are found, which have also disturbed the burials.

The third georadar layer, which includes most of the restructured volume of soil, occurs from a depth of about 1 m. The largest and the most contrasting georadar anomaly is located in this layer, having a clear straight-line contour at various depths on the 3D cross-sections *(Figs. 4, 5)*. This is the buried foundations of a small side-chapel constructed close to the southern wall of the Holy Spirit Cathedral for the tomb of the metropolitan Filaret in the mid-19th century. The side-chapel has already been destroyed during the Soviet era, since it distorted the original appearance of the ancient cathedral.

These foundations were well preserved: even small details of its internal design (internal walls) could be recognized, and one of the apse edges had kept its characteristic shape. The western, isometric

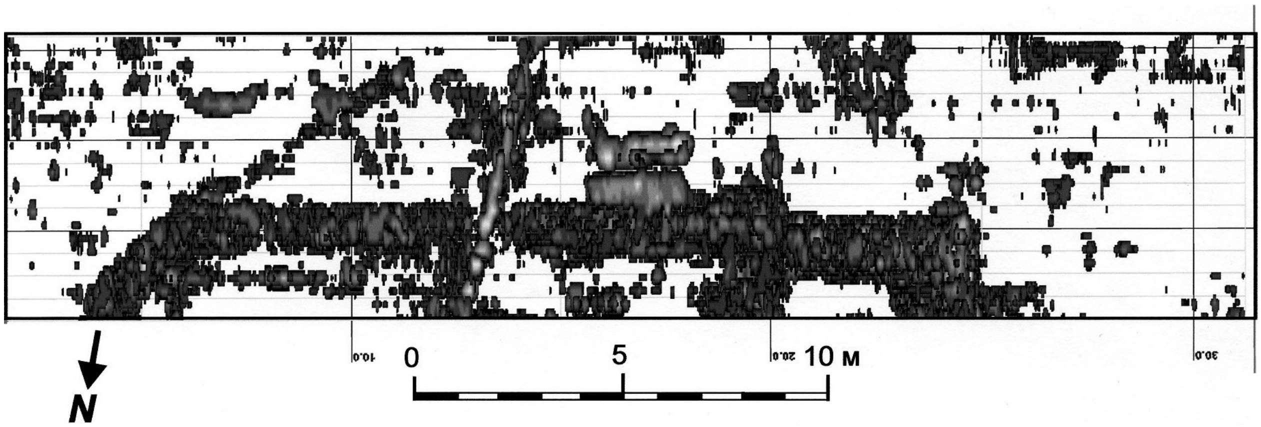

Fig. 5. 3D Georadar image of the lowest layer.

part of the foundations has a different georadar appearance, the signal descending more intensively there, which can be explained by the variable composition of massive and multilayer design of this part of the foundations. It is sunk to a considerable depth (corresponding to a 60 ns signal) and probably extends even deeper. The eastern wall of this design bears the load of the lighter foundations constructed upon it.

Therefore, on the basis of the described georadar picture, it is possible to reach the conclusion that this part of the foundation design is more massive and steep, and probably older. The historical interpretation of the georadar data revealed (Baldin 1984) that at the southwest corner of the Church of the Holy Spirit, there was an ancient bell-tower, demolished in the 18th century at the construction of the present free-standing bell.

Two large rectangular objects found near the central part of the foundations were interpreted as massive tombs or crypts. They are set deeper than the layer with displaced tombs and are possibly still situated at their original location. The level-by-level analysis of the 3D model shows clearly that the slab surface is located at various depths, and the southern slab is 15–20 cm deeper.

A series of poorly-contrasted anomalies can be observed in a cultural layer at the borders of the buried foundations, the majority of which are old burial sites from the 14th–19th century.

Conclusions

By developing a 3D model of the subsurface site structure in the historical area filled with miscellaneous archaeological objects, its structure can be reconstructed in depth and subsequently interpreted historically.

3D models make it possible to detect extremely low-contrast georadar anomalies and changes of geological environment or properties of cultural layers which are not recorded by a 2D consideration of the geophysical data.

The GPR method is distinguished by a high level of detailed visualization which allows in-depth reconstructions under complex engineering and geological conditions – e.g. in wet clayey soils, in littered and multilayered cross-sections.

The adaptation of the 3D model as an interactive multimedia project facilitates its application both in the planning of archaeological excavations, and during examination of buried objects.

References

Baldin 1984

V. I. Baldin, Zagorsk. Architectural-art monuments series (Moscow 1984).

Vishnevsky 2006

V. I. Vishnevsky, The Holy Trinity St. Sergius Lavra Necropolis. Discoveries of the last decades of XX century. In: L. A. Belyaev (ed.), Russian medieval tombstones, XIII–XVII century: data to the corpus. Institute of Archaeology RAS (Moscow 2006) 130–136.

Vishnevsky 2007

V. I. Vishnevsky, A water line and water drain of the Holy Trinity St. Sergius Lavra in XVI–XVIII century. In: Archaeology of Moscow Region: Data of a scientific seminar 3. Institute of Archaeology RAS (Moscow 2007) 349–359.

Klochko / Shishkov 2005
A. A. Klochko / D. L. Shishkov, Georadar research in analysis of historical and cultural heritage objects (by example of military and historical objects of the Borodino field). Ecological problems of historical and cultural heritage preservation. In: Data of the 9th All-Russia scientific conference, Borodino, November 2004 (Moscow 2005) 307–317.

Klochko / Shishkov 2006a
A. A. Klochko / D. L. Shishkov, Visualization of archaeological objects by the georadar data. Archaeology and geo-information science 3 (Moscow 2006).

Klochko / Shishkov 2006b
A. A. Klochko / D. L. Shishkov, Examination of historical and cultural heritage objects of Moscow Region. Problems of Moscow region history. In: Data of 5th applied scientific conference dedicated to 75 years of Moscow State University (Moscow 2006) 108–110.

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