Virtual GeoRadar Model of Archaeological Memorials

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Abstract. 3D modeling of archaeological memorials and historical objects based on undestructive methods of shallow-depth geophysics permits their projected study by traditional archaeological methods and facilitates a development of methodologies for their preservation in the museums or in natural buried state for future investigators.
Observations and approach of 3D model development including geophysical and geological interpretations are considered in this paper.
A detailed georadar survey was conducted on a site of outstanding Russian architectural assemble of the XIV-XIX – the Holy Trinity St. Sergius Lavra, the centre of Russian Orthodox religion (Sergiev Posad, Moscow region). The level-by-level details of 3D georadar model of the historical area are correlated with data of archaeological excavations of past years and records of historical documents.

Development of 3D model of an archeological memorial, as well as any buried object within the limits of historical or cultural sites is clearly the most up-to-date approach to detection, analysis and preservation of heritage objects. Degree of approximation of such model to actual appearance of the buried object is determined by data quality of non-destructive remote examination.

Georadar approach provides a detailed and accurate result of remote examination and permits a precise 3D localization of objects and integrated reflection of the subsurface area characteristics - archeological layering, engineering-geology features and etc.

Methodology of GPR model development

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

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

1. Analysis of geological environment: recognition of natural and man-made heterogeneities of subsurface structure, which includes, if necessary - solution of geological, geomorphologic, and engineering geology problems.
2. Diagnostics of buried archeological objects, reconstruction of the layout, borders and layering of archeological objects, creation of geophysical anomaly libraries related to various archeological objects, development of 3D models of archeological objects, and development of super-3D project (association of 3D project series) for large areas with intricate layout of the surface.
3. Adaptation of geophysical data for archaeological application: development of the procedures for remote access to geophysical databases for users without any special software products, development of multimedia 3D model versions of archeological objects, and integration of geophysical and geodesic data in GIS-projects.

A virtual 3D model is supplemented by the historical data and interpretation materials: archeological reports, sketches of memorial constitution, description of known objects, historical documents etc.

The key methodology problem of archaeological application of GPR data is its reliability and correlation with the geological cross-sections of the studied area. This aspect of archaeological georadar study is considered on the basis of detailed investigation of subsurface structure at one of the sites of the Russian architectural assemble of Holy Trinity St. Sergius Lavra. This assemble is a world heritage UNESCO site, the centre of Russian Orthodoxy as well as historical and cultural monument.

Georadar investigations on a site of Holy Trinity St. Sergius Lavra

The Holy Trinity St. Sergius Lavra has a unique and structurally diverse cultural layer as observed by GPR survey. Here at relatively small area, during six and a half centuries the numerous ecclesiastical and household buildings have been constructed, renovated, and occasionally disassembled. During the above period the Lavra has been a burial place for monks, hierarches of the Russian Orthodox Church and glorified people of the time. The restricted size of the area has forced to bury more tightly, sometimes even in several layers.

The aged tombs have been often replaced under recurring restructuring of the area, and during which, in many instances, the burial sites were lost.
The multiple fires resulted in the incompleteness of the Lavra history records and fragmentariness of the historic annals of grandiose and honored Necropolis. During the Soviet time the Lavra was seized from the Church, and some of structures and tombs were demolished.

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

Problems of mapping of lost structural elements, renovation of foundations, contouring of the Necropolis, and prospecting for individual burial sites and crypts, are very common and currently are of significant importance for church archaeology, in particular, for the Russian practice of reconstruction and renovation of the church and monastery architectural ensembles.
The georadar examination of the Lavra has started at a small experimental site in order to determine the characteristic buried objects for this historical area. The site is located in a historical core of the architectural ensemble, between the most ancient cathedrals of the Lavra – the Holy Trinity Cathedral (1422) and the Holy Spirit Church (1476). The inspected site extends from the altar wall (eastern) of the Holy Trinity Cathedral along the southern facade of the Holy Spirit Church up to a level of its apse part.
The areal GPR survey was conducted with the antenna with a center frequency of 400 MHz, on an array of parallel profiles oriented westward. The tile cover of the site was used as a natural delimitation of the area, so that the spacing interval between profiles was 40 sm. Such density of georadar survey provides for almost solid sounding of the upper cross-section, considering width of the most beaming antenna (about 40 м) and flare distributional pattern of a signal (about 600). GPR data of such a high quality guarantee a high resolution and a high degree of fidelity for 3D model of the area.
Data processing and interpretation of georadar survey were based on the program Radan-6 and special geophysical 3D modules. Quality of the field georadar survey allowed for archaeological interpretation without any or minimal post-processing.
Analysis of the upper geological cross-section of the area is made by development of digital 3D model on the basis of georadar survey data. In this paper 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, demonstrating localization of the miscellaneous buried objects or heterogeneities of soil variable depth horizons, or by examples of georadar profile fragments, where the anomalies are found and interpreted as hidden objects. None of the above-mentioned ways of visualization separately provides a complete picture a subsurface area structures.

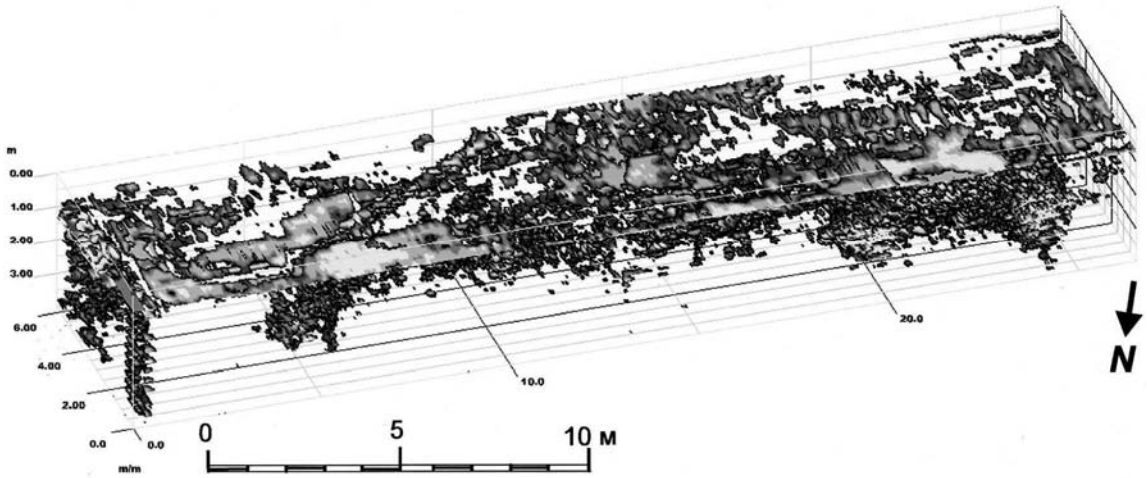

Fig.2. Georadar 3D model of the Holy Trinity St. Sergius Lavra site. Fragment of visualization. At the given parameters of visualization the objects of all stratigraphic levels are visible: streak tile pattern paving the area, some tomb stones of the second layer and track of archaeological excavation, and the compound foundation.

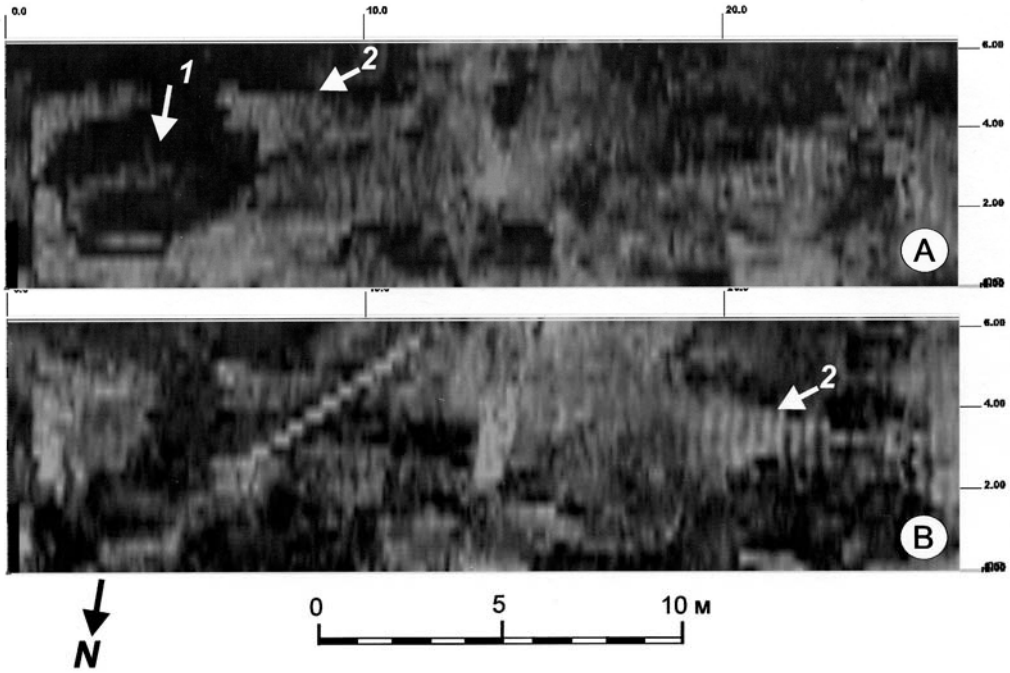

Fig. 3. Georadar picture of the upper layers in the model - variable-depths 3D sections of the model. The cover of displaced burial sites is marked by light tone (2); dark areas mark the archaeological excavation (1).

GPR examination of the site and survey data processing has been implemented before a review of archaeological and historical data. During the subsequent interpretation of the georadar data the historical documents (Baldin, 1984) and earlier description of the archeological excavations were systematically used (Vishnevsky, 2006; Vishnevsky, 2007). 3D model of the site is distinguished by multilayering - the subsurface structure is different from depth to depth. The georadar layering of the site is based on allocation of layers with a distinguishable wave pattern. By the term "wave pattern" we mean a combination of sounding electromagnetic signal features reflected from a soil layer of homogeneous structure. The specific wave pattern is characteristic for cultural deposits.

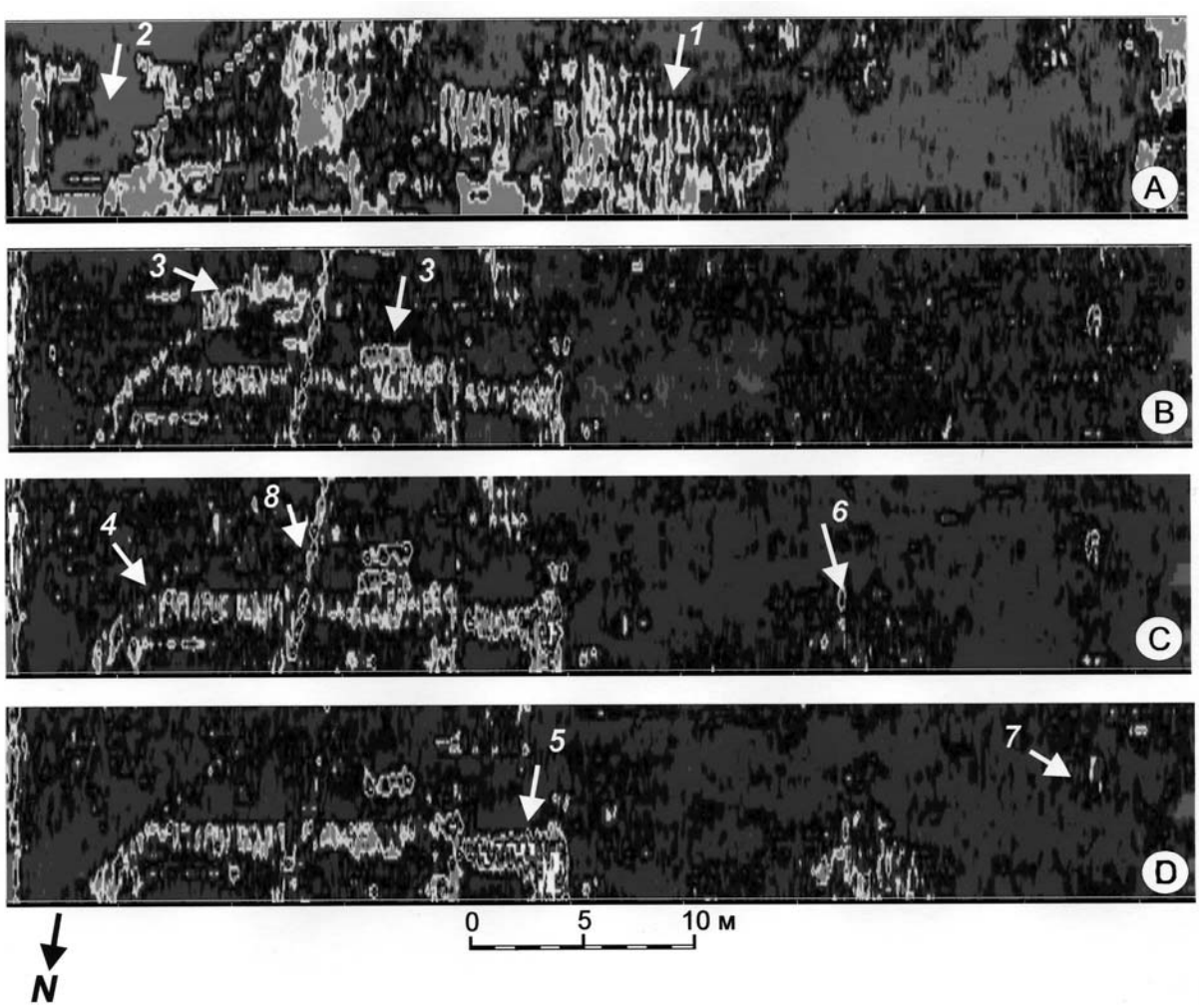

Fig. 4. 3D model of subsurface structure on a site south of the Holy Spirit Church.
A- layer of marble tombs; B-D - subsequent layers with removed upper layer. Georadar anomalies:
2- foundation of a destroyed free-bell, 4 - foundation of destroyed Filaret church, 4 - marble crypts,
5 – common burial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

The upper layer of the site (0.15 – 0.2 м) is divided by a grid of thin stripes, marking junctures between a tile, which paves the area between churches. The georadar data of this level does not contain any information of historical value, however, can be used as a marking grid of a site surface.

The similar observations were made previously during the detailed areal survey of continuous or fragmentary slabs, blocks and other type of pavement. Visualization of the subsurface projects provides basis for implementing such a set of parameters, at which the upper layer structure will be projected upon all the underlying objects, naturally outlining structures in the entire area.

The following subsurface layer at corresponding level of cross-sections (up to 0.4 – 0.8 m.) differs by wave pattern of reflecting large slabs. The slabs are established at different depth at the analysis of variable-depth sections of 3D model (interval 10-20 cm), and a gentle surface tilt is found for some of them (difference in the first cm).

In eastern part of the site the dark contour is observed which is interpreted as a track of previous archaeological excavation, t which point all tomb stones were extracted (Vishnevsky, 2007). In the same layer the different communication service lines lie, at the gasket of which the burials were also displaced.

The third georadar layer, to which the major part of the restructured volume of soil belongs, is isolated from surface by a horizon about 1 m thick. The largest and the most contrast georadar anomaly is localized in this layer having a clear straight-line contour at variable-depth of 3D cross-sections. This is a buried foundation of a small side-chapel constructed

closely to the southern wall of the Holy Spirit Cathedral for metropolitan Filaret burial place in the middle XIX century. Already in the Soviet time the side-chapel was destroyed since it was distorting the initial appearance of the ancient cathedral.

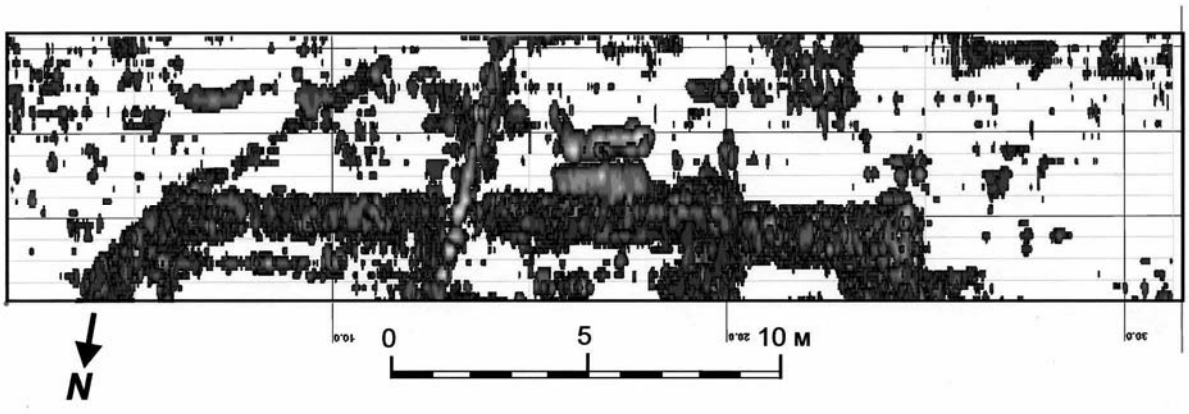

Fig. 5. Georadar 3D picture of the bottom layer

This foundation was well preserved: even the small details of its internal design (internal walls) are determined and a characteristic shape of an apse edge has been recognized. The western isometric part of the foundation differs in its georadar appearance: its reflection descends more intensively, which probably is related to the variable composition of massive and multilayer design of this part of the foundation. This element of the foundation is sunk deeply (up to depth of 60 ns and, probably, deeper). The eastern wall of this structure is a bearing support for the constructed upon it the lighter main foundation.

Thus, on the basis of the described georadar picture, it is possible to draw a conclusion, that this part of foundation structure is more massive and steep, and probably, more ancient. The historical interpretation of the georadar data revealed (Baldin,1984), that at the southwest corner of the Holy Spirit Church there was an ancient bell-tower dissembled in the middle XVIII century, at the construction of the present free-bell.

Two large rectangular objects are found closely to the central part of the foundation and are interpreted as massive tombs or crypts. They are arranged more deeply than the layer with displaced tombs and possibly are situated at their initial location. At the level-by-level analysis of 3D model, it is clearly visible, that the surface of slabs is located at various depths, and the southern slab is 15-20 sm deeper.

A series of poorly contrasted anomalies is observed in a cultural layer at the borders of the buried foundations, majority of which are the ancient burial sites (XIV-XVIII of century).

Conclusions.

Development of 3D model of a subsurface site structure at the historical area, rich in miscellaneous archaeological objects, permits the detailed reconstruction of its structure and subsequent in-depth historical interpretation.

Detection of extremely low-contrast georadar anomalies and changes of geological environment or properties of cultural layers which are not recorded by 2D consideration of the geophysical data is now possible with 3D models.

The GPR method is distinguished by high level of detailed visualization, permitting to conduct in-depth reconstructions in the context of complex geology and difficult engineering environment - in wet clayey soils, in littered and multilayered cross-sections.

The submission of 3D model as interactive multimedia project facilitates its application both at the stage of planning of archeological excavations, and during dissecting of buried objects.

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Figure captions

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Fig. 2 Georadar 3D model of the Holy Trinity St. Sergius Lavra site. Fragment of visualization. At the given parameters of visualization the following objects are observed in all layers: streak tile pattern paving the area, some tomb stones of the second layer and track of archaeological excavation, and the compound foundation.

Georadar picture of the upper layers in 3D model

Variable-depth 3D cross-sections of the model. The cover of displaced burial sites is of more light tone, dark area marks the archaeological excavation.

Archaeological excavations in the eastern part of the georadar survey site (Vishnevsky, 2007). The numerous Old Russian gravestones are found at depth to 0.4 m forming a solid layer. The contour of its archaeological excavation is well observed at the georadar site designs.

An example of a georadar profile with the main types of anomalies: foundation of old free-bell and the Filaret church, burial sites with immovable tombstones, ordinary burials and a geologic pit-hole.