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DETERMINATION OF LOCATION OF HISTORICAL AND CULTURAL HERITAGE OBJECTS USING PHOTOGRAMMETRIC AND GEOPHYSICAL METHODS

Borys CHETVERIKOV[1], Ihor TREVOHO[2], Lyubov BABIY[1], Mariia MALANCHUK[3]✉

[1]*Department of Photogrammetry and Geoinformatics, Lviv Polytechnic National University, Lviv, Ukraine*
[2]*Department of Geodesy, Lviv Polytechnic National University, Lviv, Ukraine*
[3]*Department of Cadastre of Territory, Lviv Polytechnic National University, Lviv, Ukraine*

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Abstract. Two central problems related to the study of historical fortification systems are apparent. First, there are high labour costs for the excavation of defensive structures. Therefore, studying each line of defence along its entire length by traditional archaeological methods is practically impossible. That's probably why special studies of the fortification system are the exception rather than the rule, and information about defensive structures is given in single sections. The second problem is related to the fact that some lines of fortifications were destroyed in ancient times or were practically destroyed due to later economic activity. The specified circumstances determine the need to use photogrammetric and geophysical methods for the preliminary search of the infrastructure of defence structures. This work provides an example of deciding mass graves during the Second World War using the interpretative properties of German aerial photographs of 1944, archival cartographic data on the territory of the Lviv Citadel, where the Nazi concentration camp for prisoners of war Stalag-328 was located during the war. After predetermining the places of mass graves by photogrammetric methods, geophysical surveys were carried out with the help of ground-penetrating radar (GPR) for the exact localisation of the graves. 13 locations of mass burials and mass executions and burning of bodies of prisoners of war were discovered.

Keywords: historical and cultural heritage, space images, archival aerial photographs, photogrammetry, Ground Penetrating Radar survey.

✉Corresponding author. E-mail: ***malanchuk.mari@gmail.com***

1. Introduction

In the practice of applying photogrammetric and geophysical methods to objects of historical and cultural heritage, precise results have been obtained in the detection of buried remains of stone structures: the foundations of towers and walls, underground passages and other elements of fortification structures. Considering the high contrast of the physical properties of stone in relation to the soil, almost all geophysical methods can be used for this: electrical surveying, magnetic surveying, seismic surveying, GPR surveying, etc. Investigations of ground defense structures in most cases are aimed at identifying lines of fortifications that could be more visually traceable, for example, filled-in ditches and ramparts smoothed by plowing. In some cases, the use of various modifications of electric exploration allows the restoration of the shape of the preserved part of the fortifications and their structure and the assessment of the composition of the soils. The analysis of the geophysical map allows us to preliminarily determine the boundaries of the settlement and its structural parts, in general, to restore the planning and to reveal "hidden" defensive structures, or, in our case, mass graves of various forms. Method of electrotomography – "stratigraphic" geophysical surveying is used to clarify the geometric parameters of studied objects. The effectiveness of this approach has been proven for medieval settlements. From the point of view of identifying the boundaries of mass graves and assessing their structure, the most interesting results are obtained when solving the following tasks: 1) identifying and assessing the configuration of graves that were destroyed (levelled) earlier and are not visually fixed now; 2) restoring the location of burial sites, which are currently not fixed on the ground. Usually, such objects are expressed in relief fragmentarily and ambiguously; 3) assessment of the shape, size and structure of mass graves.

An urgent task is not only the search for various objects of historical and cultural heritage but also their detailed study. The methods of photogrammetry and electron tomography fundamentally allow us to restore the shape and geometric parameters of graves, reveal their structure (layering-homogeneity) and assess the composition of soils. In particular, during interdisciplinary studies of mass graves, the structure of all objects was restored.

The issue of preserving historical and cultural heritage for future generations is critical. With the development of new methods and techniques for the study of cultural objects, more and more scientific works on this issue are appearing both among scientists from Ukraine and from all over the world.

In this work, two methods of study of objects of historical and cultural heritage are considered: photogrammetric and GPR methods (Chetverikov et al., 2017). From the analysis of the literature on this topic, the following facts have been identified. Ground-penetrating radar (GPR) is a safe, non-destructive and non-invasive surveying method that can be effectively used for advanced investigation of composite structures and diagnostics affecting the entire life cycle of building structures. GPR can also be successfully used in archaeological exploration and cultural heritage diagnostics. In many countries where archaeological heritage is an outstanding value, ground-penetrating radar is commonly used as a diagnostic tool for the preventive detection of archaeological structures and as the most advanced tool, able to determine the geometry and shape of the underground values of the sites (Chen et al., 2022; Himi et al., 2016; Ji et al., 2021; Rial et al., 2009).

GPR data obtained during the investigation of historic buildings is often difficult to interpret. GPR assessment of historic structures and cultural heritage is usually inferior to sophisticated radar imagery due to the inherent complexity of these landmark structures. A large number of different elements and structural parts can cause recorded anomalies. In addition, unknown restorations and changes made during the structure's existence introduce important uncertainties in the interpretation of the data. To reduce uncertainty in GPR assessments of historic structures and buildings, experimental measurements are carried out in controlled laboratory conditions. Experimental data provide valuable information about the behaviour of GPR antennas (Filzwieser et al., 2021; Kanli et al., 2015; Gilmutdinov et al., 2022).

Historical buildings undergo important changes during their existence. Many of these changes are structural modifications, usually undocumented or poorly documented. Despite this difficulty, in this type of research, it is necessary to obtain subsurface images with sufficient resolution. Accurate interpretation of radar data and correct information analysis require extensive knowledge of radar behaviour (Pérez-Gracia et al., 2012; Perez-Gracia et al., 2019; Masini & Soldovieri, 2011).

Three following main areas in the field of GPR can be identified that need to be considered to facilitate the use of this technology in archaeological exploration and diagnostics of cultural heritage:

- increasing the sensitivity of the system to ensure the possibility of use in a broader range of conditions; archaeological sites are often located in impervious and critical environments;
- research of new data processing algorithms/analysis tools for the interpretation of GPR results;
- contribute to developing new standards and guidelines, as well as end-user education, which will also help raise operator awareness. It is important to conduct further research and promote the combined use of GPR with other non-invasive advanced methods (e.g. satellite radar interferometry) commonly used in archaeological research (Pajewski et al., 2013; Keay et al., 2009, 2014).

Also, in our opinion, the groups of authors (Martinho & Dionísio, 2014; Morris et al., 2019; Pisz et al., 2020; Trinks et al., 2018) made a significant contribution to the analysis and research of objects of historical and cultural heritage using ground-penetrating radar surveying and other geophysical non-invasive methods in their scientific works.

Geophysical studies for objects of historical and cultural heritage that have not been preserved have a local, clarifying character. To determine the areas subject to geophysical research, cartometric or photogrammetric research methods are usually used beforehand.

In the paper of Ukrainian scientists (Chetverikov & Babiy, 2016) considered the problem of the destruction of ancient Jewish cemeteries over time and the method of determining their boundaries using archival aerial and cartographic data was proposed. The software, which is appropriate to use for this kind of task was recommended. The legal aspects of using remote sensing data to study objects of historical and cultural heritage and granting the appropriate status to the lands of the historical and cultural fund in Ukraine are presented in the work of a group of authors (Malolitneva & Hurova, 2021).

In our opinion, among the latest studies of the use of remote sensing data of the Earth for the study of objects of historical and cultural heritage and lands of the corresponding purpose (both archival data of aerial photography and modern aerial survey, including UAV, and space images), the following scientific works are worthy of attention (Morgan et al., 2017; Piekielek, 2019; Themistocleous, 2020).

Our research aims to develop a method of combining the photogrammetric method of processing archival aerial photographs with GPR data to determine the boundaries and areas of mass graves from the Second World War, which are objects of historical and cultural heritage.

2. Material and methods

The historical and architectural ensemble "Citadel" is one of the best examples of Austrian fortifications of the mid-19th century. It is the only such example in Ukraine (Figure 1). During the Second World War, the Germans Nazis used the Citadel for the concentration camp "Stalag-328", the existence of which corresponds to 1941–1944. According to the number of prisoners who passed through the camp (about 280 thousand people) and died there as a result of the following actions of the camp administration: executions, deliberate spread of epidemic diseases, artificial starvation and torture (about 142 thousand people were killed), it is among the ten largest in the military history of that time, such as Auschwitz, Buchenwald, Dachau.

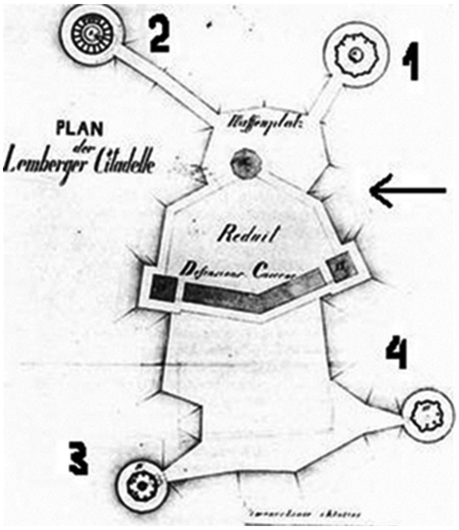

Figure 1. Austrian plan of the Citadel objects location of the 19th century (from the Lviv Regional State Archive)

To realise the aim of the work, a workflow of research is proposed, which includes two blocks: photogrammetric and GPR (see Figure 2).

The input data for photogrammetric studies were:

- archival German aerial photograph from 1944 obtained from the US National Archives;
- modern topographical plan of the ensemble of defensive structures "Citadel" on a scale of 1:5000;
- Soviet schematic plan of the Stalag-328 concentration camp, created after the de-occupation of Lviv from the Nazis.

Geometric correction of the German archival aerial photograph and cartographic data. The archive photograph is relatively high quality, but it was not transformed, as there was no data about the elements of orientation. For the determination of objects that have remained since the war and were depicted in the archive photograph, their coordinates were measured by GPS. Then, the geometric correction of the image has been completed using a second-degree polynomial model.

Nine points identified on archival aerial images were used for the correction. It was impossible to find more contour points. After solving the equations, the errors in the plane coordinates were obtained, and the mean square errors were calculated.

Since the cartographic data, both archival and modern, are orthogonal, an affine transformation was used for their referencing. To do this, five object points were used, which were preserved since 1944 and were maximally spread over the cartographic products.

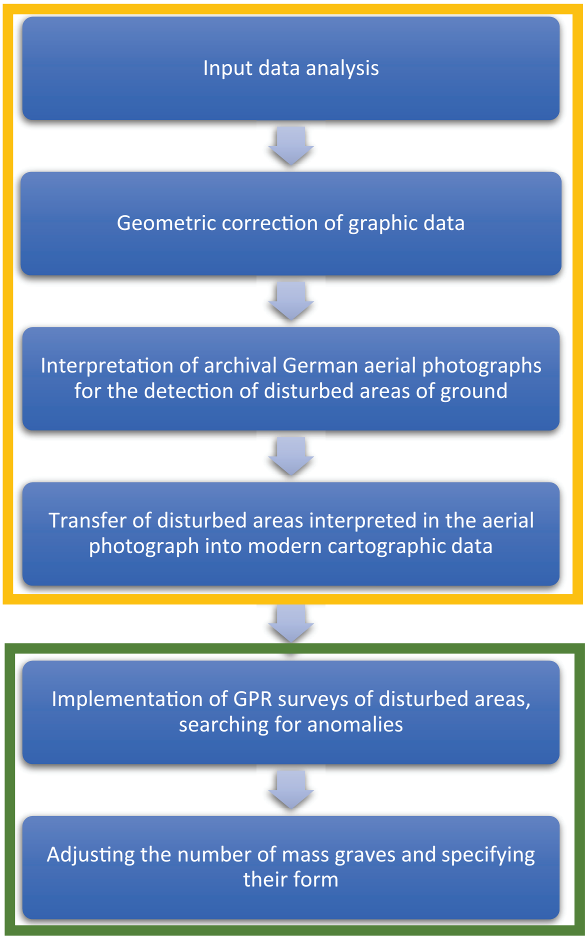

Figure 2. Workflow for determining mass graves using photogrammetric and GPR methods

Table 1 shows the root mean square errors of the geometric correction of each graphical input data.

Table 1. Results of geometric correction of aerial and cartographic data

Incoming data	RMSE (m_x), m	RMSE (m_y), m
Archival German aerial photograph from 1944	4.0	2.7
Modern topographical plan of the ensemble of defensive structures "Citadel" on a scale of 1:5000	0.5	0.4
Soviet schematic plan of the Stalag-328 concentration camp	0.9	0.7

As can be seen from Table 1, the root mean square errors of cartographic data are within tolerance. Let's consider the RMSE of the geometric correction of the archival aerial photograph. The errors are quite gross, but the lack of exterior orientation elements in the photograph explains this. Since further research is envisaged to refine the photogrammetric studies by the ground-penetrating radar method, such accuracy is acceptable.

During the interpretation of the archival German aerial photograph, 16 disturbed sites were discovered on the territory of the "Citadel" defensive complex, which may have previously contained mass graves of prisoners of war in the concentration camp. The interpreted archival aerial photograph of the concentration camp territory, as well as the biolocation implemented in 2001 and repeated in 2010, confirmed the presence of human remains at the sites of mass executions and within their borders (as of 1944). Numerous mass graves are located practically within the entire area of the former concentration camp. Separate pit burials alternate with burials of the "trench" type. In the post-war period (1970s), there is evidence of people finding human bones, partially covered with a layer of white-red mixture, gold crowns from teeth, etc., in the pits of the subterrene under the small eastern tower. Remains in the form of human bones are still found on the earth's surface to this day.

According to contemporaries, during the construction and engineering works of the former "Electron Bank", in the 1990th–2000th and the hotel-restaurant "CitadelInn" in 2007–2009, workers, employees and random witnesses found human remains in large quantities in both places, namely in pits near the eastern square tower (part of the main building of the barracks), on the part of the length of the earthen shaft of the trench dug on the territory of the Citadel, as well as around the circumference of the large eastern tower ("Tower of Death"). Part of the remains (near the east square tower) was filled with concrete.

After interpreting all disturbed sites, they were transferred to cartographic data. Considering the RMSE of geometric correction of graphic data, the boundaries of predefined mass graves displayed on a modern topographic plan 1:5000 could be shown with a maximum error of up to 4.5 m and on an archival schematic plan up to 4.9 m.

Ground-penetrating radar studies of disturbed sites identified from the archival aerial photograph of 1944 were carried out by order of the American representation of the Committees for the Jews of the former Soviet Union in Ukraine and with the support of geophysicists from Great Britain Tim Fletcher and Charlie Enright.

The research was carried out by ground-penetrating radar GROUNDVUE 3_1 by Utsi Electronics. The size of the coordinate grid varied depending on the characteristics of each site, but all surveys were carried out at an antenna frequency of 400 MHz with a reading step of 0.015 m. Dielectric properties were evaluated separately for each site. Considering that the territory of the study is a vast and complex area, two sites were selected for preliminary research.

There are two tennis courts, which naturally create conditions for the design of two grids for the survey, almost defined by the fence's boundaries. The north side court and its survey grid are designated as the AOI1 site and the south side court as the AOI2 site. AOI1: Site size 15×30 m surveyed by GPR. AOI2: Site size 15×27 m surveyed by GPR.

3. Results and discussion

The result of photogrammetric studies is the interpretation of 16 disturbed sites on the territory of the former concentration camp for prisoners of war Stalag-328 from an archival German aerial photograph. These sites are cross-referenced to all graphic data that were used as input data and were all referenced to a single WGS-84 coordinate system and projection.

Figure 3 presents an archival aerial photograph of the Citadel area with interpreted disturbed sites of the area, which most likely represent the sites of mass burials and mass POW incineration.

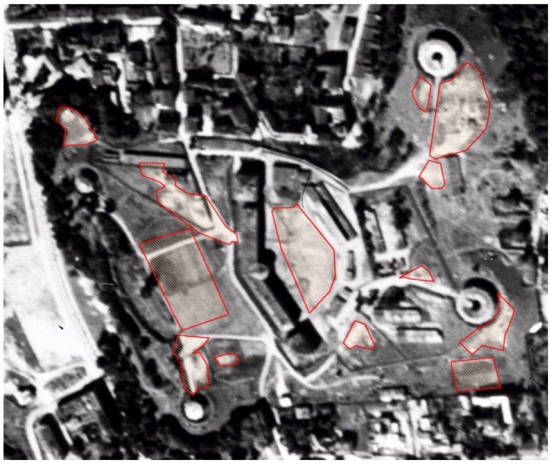

Figure 3. German aerial photograph of the Citadel area in 1944, with the interpreted disturbed sites marked (in red)

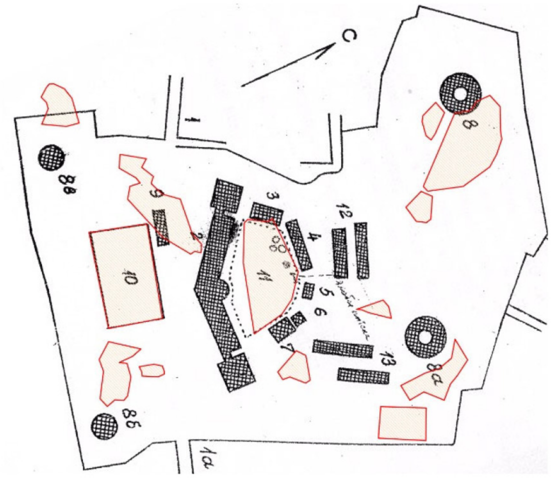

Figure 4. Disturbed sites interpreted from an aerial photograph of 1944 (marked in red), plotted on an archival Soviet schematic plan

Additionally, these sites were plotted on the Soviet schematic plan of the study area. The plan was created by the Soviet military immediately after the deoccupation of Lviv. This plan was used because it is dated to almost the same period as the aerial photograph but does not contain extraneous elements (Figure 4).

The final stage of the results of photogrammetric studies is a modern topographical plan of the studied territory on a scale of 1:5000, with disturbed sites as of 1944, interpreted from an archival aerial photograph (Figure 5).

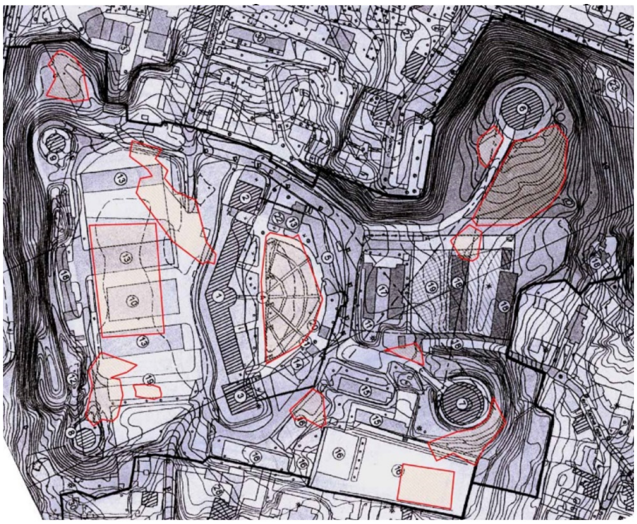

Figure 5. Disturbed sites interpreted from an aerial photograph of 1944 (marked in red), plotted on a modern topographical plan of the territory at a scale of 1:5000

As a result of GPR research on the site AOI1 (it is the northern tennis court closest to the two smaller barracks) at a depth of approx.0.3 m (t = 11.88 ns), an underground object 20×3 m was detected, which is located diagonally through the tennis court and is first shown on GPR scans at a depth of 0.3 m. This object coincides with the site of disturbed soil interpreted in the 1944 aerial photograph, and the results are consistent with well-determined historical excavations. The object's edges are especially clearly defined closest to the southwestern corner of the tennis court and go beyond the boundaries of the studied area to the northwestern corner of the site of AOI2. The central section of the object has less defined edges throughout the entire depth, which may result from ground disturbance during the period of tennis court construction. At a depth of about 0.7 m (t = 14.38 ns), the clarity of the sides decreases, and additional features appear in the middle of the main object. These are possibly reflections from objects within the excavation, but they are not observed along the entire length of the object and are absent where excavations may have been. Reflections from the northern edge of the object begin to lose clarity at about 0.8 m (t = 15.63 ns) in contrast to the southern side, where it remains clear at a depth of about 0.93m (t = 18.44 ns). The object is not visible at depths over 1.1 m (t = 22.1 ns).

The time intervals shown in Figure 6 represent the dimensions of the object. Figure 7 shows the interval of the object at a depth of about 0.68 m (t = 13.75 ns). Particular attention should be paid to the darker reflections (higher amplitude) to the left of the object's centre, which marks the place of a possible disturbance that could have occurred during the construction of the tennis courts.

Section AOI2 is the southern tennis court, which is located above the site, showing soil disturbance interpreted on the aerial photograph of 1944. At the southern edge of the studied territory, a very well-defined object is located at an angle to the survey grid. The soil on the south side of this object shows markedly different properties. A comparison with the 1944 image shows the presence of a fence line located directly above this object. On the northern edge of the court, you can see the end of a large object, which becomes more apparent when combining the results of both surveys. From the central western edge

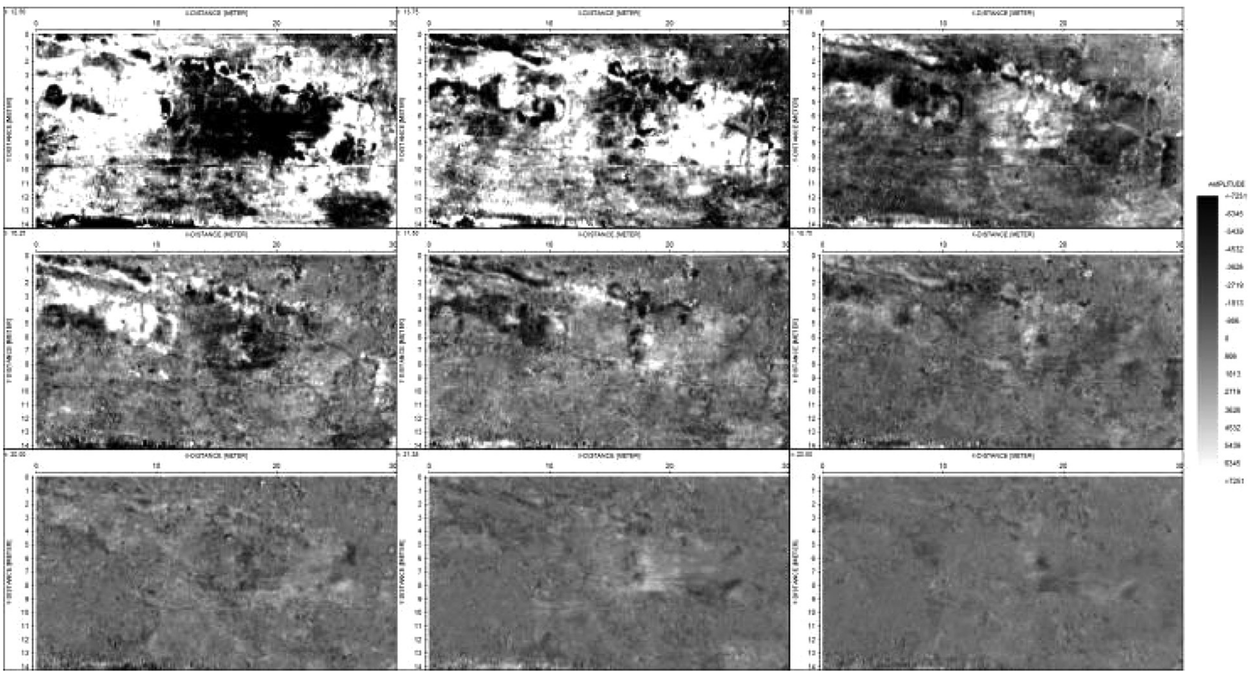

Figure 6. AOI1 research site – time intervals shown by GPR

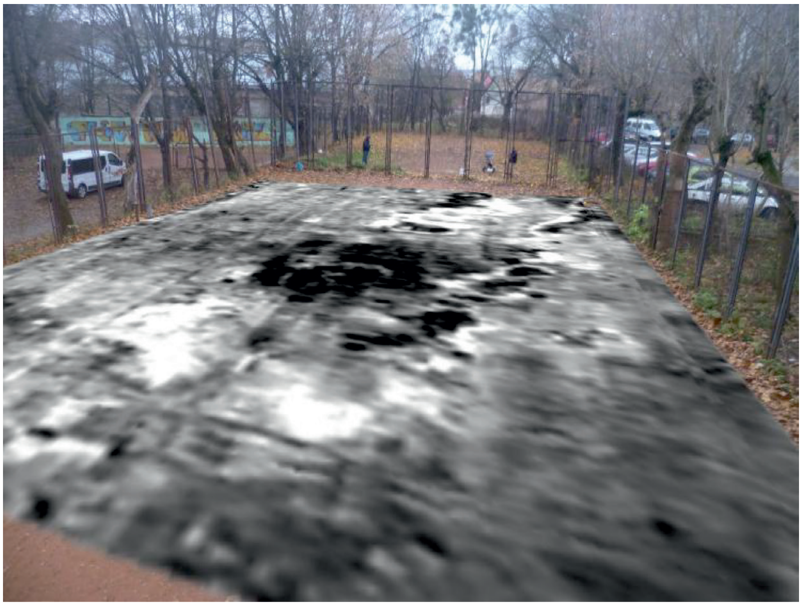

Figure 7. AOI1 research site – superposition of GPR intervals

of the site, you can see a rectangular object with a width of about 2.5 m, and its length is difficult to determine, it likely stretches for about 7 m to the centre of the site, but there is a possibility that it extends further and even beyond the eastern edge of the studied site, and the aerial photograph confirms this theory.

This object is similar in size to the one shown on the AOI1 site but is not so clearly defined. The first reflections of this object are detected at a depth of about 0.5 m (t = 10 ns), and at a depth of more than about 1 m (t = 20 ns), the reflections are not recorded.

The AOI2 site was surveyed with traverses in one direction, which were perpendicular to the edge of the object. Since the traverses at the AOI2 site intersect this object on the area of AOI1 at an acute angle, this may explain why the object at the AOI2 site is not so clearly defined. Alternatively, this particular object was more disturbed or the construction techniques were different.

Figure 8 shows the time interval of the object at a depth of about 0.78 m (t = 15.63 ns). Termination of this object can be seen in the data of the AOI1 site RPG survey. A rectangular object can be seen below in the centre of

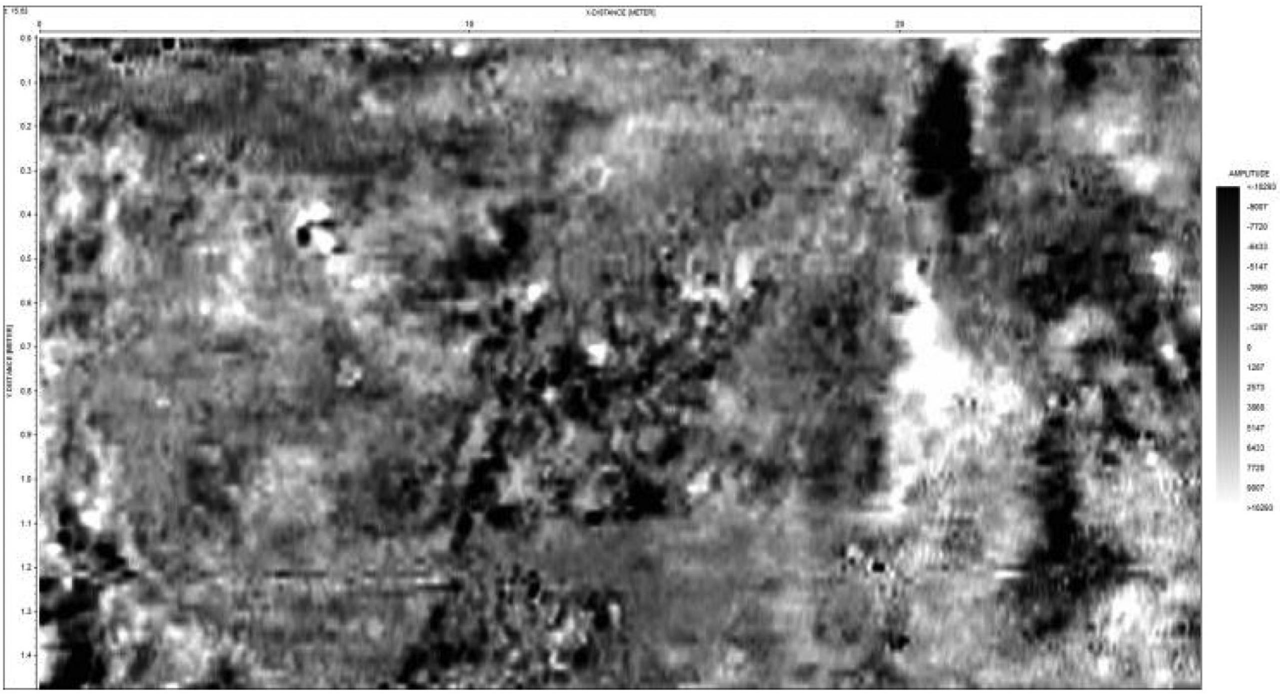

Figure 8. Research site AOI2-GPR scanogram at t = 15.63 ns

the image. The soil outside the fence of 1944 is located on the right.

In contrast to the horizontal time intervals, the vertical scan tracks show interpolated representations of the selected profiles. The four vertical scan profiles, as shown in Figure 9, show a break in the natural stratigraphy at the excavation area. The following four images show three selected sections, two from the AOI1 site and two from the AOI2 site.

Since the section from the AOI1 site intersects the object at an angle, it gives the appearance of a more comprehensive image of this object, which itself is, in reality, about 2.5–3 meters wide. You should also pay attention to how the studied area from the right side of section A-A goes across to the left side of section B-B, which usually corresponds to the diagonal orientation of this object relative to the survey grid.

The C-C profile passes through the middle part of the rectangular object of the AOI2 site. It ends a few meters from the eastern edge of the studied area. The D-D profile clearly shows much deeper, dense soil with undisturbed stratigraphy.

The combination of various non-invasive methods for identifying objects of historical and cultural heritage showed a positive result. In addition to combining the methods of archival aerial photograph processing with GPR studies, other remote methods can also be used, such as processing data from space optical-electronic imaging with different spatial resolution (depending on the studied objects), space radar imaging, aerial photography from UAV, and others. All these methods of aerospace research, in combination with the GPR method, enable a comprehensive study of objects of historical and cultural heritage, especially when it is impossible to apply archaeology due to various circumstances (for example, religious laws). One of the disadvantages of these complex studies is interpreting the results of GPR data because, at the moment, there is no technologically defined set of sample data that can be encountered during a GPR survey. Therefore, when performing these studies, one should rely entirely on the operator's experience. Also, GPR reacts differently to various objects found in the studied area. The ability of soil to transmit radio waves depends on several factors, including soil conductivity, soil density, porosity, temperature, physical structure of the soil, the frequency used, and the amount of salts contained in the soil. The most important factor is the electrical conductivity of the soil, which determines the speed of the radio wave and the penetration depth. Soils with high electrical conductivity cause signal loss. All this can be attributed to the disadvantages of the GPR method. Generally, the land and soils in the Lviv region are suitable for surveying using ground-penetrating radar.

All this objectively makes specific corrections in the possible reliability of the obtained results of the GPR survey. Therefore, in our opinion, a complex combination of remote research methods is necessary.

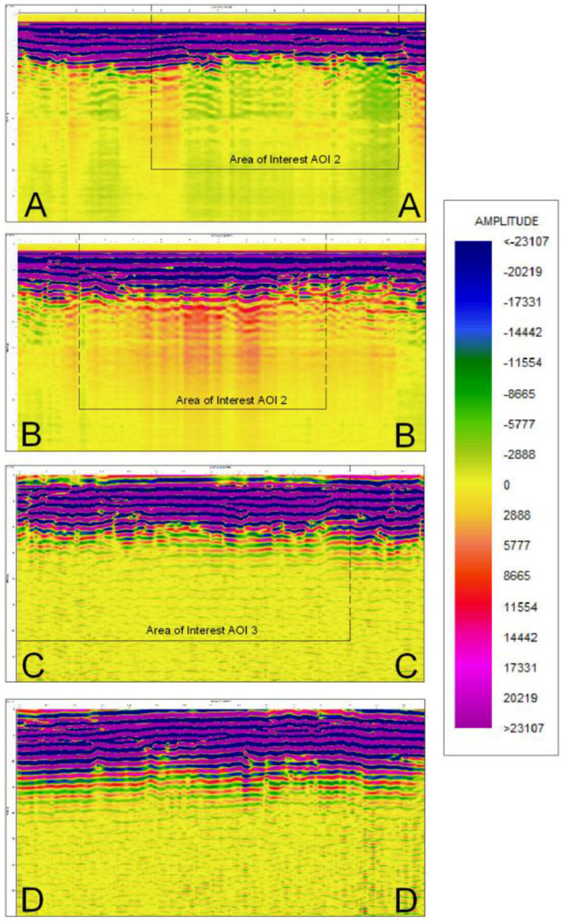

Figure 9. Research sites AOI1 and AOI2-GPR scanning profiles

4. Conclusions

The fragment of an archival aerial photograph of Lviv from the time of the Second World War (survey of 1944) was interpreted. Additionally, cartographic data and archival aerial images were jointly processed with the help of GIS tools. Using the photogrammetric research method, 16 disturbed sites of the study area were identified on the archival aerial photograph, which are most likely the places of mass graves and executions of prisoners of the Stalag-328 concentration camp. All disturbed sites overlapped with the modern topographic plan (with a maximum linear error of 4.5 m) and the archival Soviet schematic plan (with a maximum linear error of 4.9 m).

The next part of the work considered the second part of the complex technology of research of objects of historical and cultural heritage, namely ground-penetrating radar research of disturbed areas interpreted on a German aerial photograph. After the implementation of GPR surveying with the assistance of English scientists, identifying anomalies in the analysed areas and execution of additional ground surveys, the presence of historical objects was confirmed on 13 sites of study 16. Three sites interpreted from the archival aerial photo as disturbed areas were probably excavated for another purpose (perhaps by installing some engineering objects).

For the implementation of the ground-penetrating radar method to study the disturbed areas of the territory interpreted on the aerial photograph, two sites were chosen due to the general complexity of the territory. A significant object with a considerable disturbance was discovered, measuring about 20×3 m. Its depth is 0.3 m below the existing surface, and it deepens further to a depth of 0.8–0.9 m. Another object with a width of about 2.5 m was found in the southern section with a less visible length of about 7 m, possibly more. GPR successfully detected the position of the 1944 fence line and associated soil compaction outside the 1944 fenced site.

The proposed method of conducting a complex study of mass graves using non-invasive remote methods can be used to identify burials on the territory of modern Ukraine caused by Russian aggression. At the same time, instead of archival aerial photos, aerial photography data obtained from unmanned aerial vehicles or space images can be used.

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