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HOW TO FIND THE UNDISCOVERED? ANTHROPOGENIC OBJECTS IN FOREST AREAS: A CRITICAL ASSESSMENT OF CURRENT METHODS

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Abstract

Landscape archaeology (archaeogeography) is a multidisciplinary study used by pre-historical, classic, and historical archaeologists. Archaeogeography deals with the study of how people have shaped and used their environment throughout history. It focuses on the relationship between the material culture of a given community and the changes it introduces in its spatial environment. Traditionally search for archaeological sites is mainly carried out using surface research, i.e., observation of ploughed fields in spring and autumn. However, the percentage ratio of the area covered by forests to the total area of the countries can reach up to even several dozen per cent. This is where archaeogeography aided with modern remote sensing data and processing techniques can be most useful. In this article, the authors describe the problems occurring while searching for anthropological objects in forest areas. In this first part of the two-part series, the authors present a non-invasive method based on widely available remote sensing and historical data that can be used for remote prospection or archaeological sides. The authors also present methods of field verification and critically describe the limitations and advantages of this method.

***Keywords**: Archaeology; LiDAR; Spectrometry; Thermal images*

Introduction

This project aimed to propose a method of using airborne LIDAR data for non-destructive recognition and documentation of archaeological heritage sites located in areas of difficult access. These areas, in particular, include heavily wooded areas and areas partly covered by woods and partly by agricultural lands.

During this project, documentation of the proposed method was produced, and the results were verified during field inspections that included geophysical methods. The results met the need for the reconnaissance of archaeological heritage in forest areas.

This field of study has not been fully discussed and is becoming more prominent in Polish archaeology. Currently, conducting this type of research seems to be one of the key challenges for both scientists and conservation services. The archaeological heritage in forests has so far remained elusive due to the widespread use of traditional methods of prospection that do not

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allow for such works to be done in a timely manner or would require significant human resources. This paper contains a description of the methodology, data set, and study area; the detailed results can be viewed in the 2nd part of this paper. Part 1 is divided into a description of the history and localization of the study area, methods used for identifying potential heritage sites, processing of the airborne laser scanning (ALS) data, and field and geomorphologic analyses of the discovered sites.

Background

Increasing availability and advancements in processing of aerial Light Detection and Ranging (LiDAR) data have become a handy tool for various engineering, science, and documentation applications, including archaeological surveys. Digital terrain model (DTM)-LiDAR data are a powerful instrument for detecting macro- and micro-ground changes, surface discontinuities, and identifying existing heritage landforms [1]. An interesting example of this type of research is an analysis of the nature of land-use/land-cover change throughout the ages where current LiDAR-based models are compared to existing data. It allows to locate research, catalogue, and demarcate the features and their material sources and impact [2] or provides means to generate a standardized GIS workflow [3]. For such analyses often, the bone-mapping method is used, named after the color-mapping used in its original development. This method combines LiDAR datasets to create a record of near-surface features with SMRF (Simple Morphological Filter) algorithm and produce a visualization called PSSM (Perceptually Shaded Slope Map). These elements were tested empirically [4, 5]. Despite advances in technology and methodology, the main problem with archaeological research using LiDAR data is vegetation land cover, which might create hard to interpret artefacts [6, 7]. There has also been an analysis of improvements in the efficiency of the aerial LiDAR data [8, 9]. Analysis of usage and quality of results study of the ALS (Airborne Laser Scanners) data mounted on the satellites for archaeological investigation was provided by the I [10]. Data obtained using UAVs (unmanned aerial vehicles) were described by [11, 12]. The main advantage of such data is extensive and often readily available large-scale data sources for archaeological, forest or biodiversity monitoring. The majority of the research proposes new methods for the creation of appropriate models for the prospection of the archaeological objects such as mounds [13, 14], graves [15] or walls [16, 17].

A deep analysis of the visualization techniques for the model created from ALS gives an insight into the strengths and weaknesses of this data. Moreover, this technique differs in terms of feature visibility and accuracy [18]. The most frequently used visualization model for archaeological analysis using LiDAR data is hill-shading [19–21], a relief visualization [22]. In this paper, the authors examine airborne LiDAR data for an object from the Medieval period. Such analyses were already conducted but differently - using only raw DTM models [23] or DTM/DSM (digital surface model) [24].

Study area

Chełmno region covers several physical and geographic mesoregions. These include *Grudziadz Basemen* from the north [25]. There is a *podwieski* microregion, characterized by sandy formations with forest patches and *Łunawa* - lying at the foot of a forested slope [26]. In the central part, there is the *Chełmno Lakeland*, while from the west, the research area is limited by the *Fordońska Valley* [25]. The *Toruń Basin* marks the southern border of the research areas, while to the east - is the *Drwęca Valley* mesoregion. These mesoregions were used to establish the project range (Fig. 1).

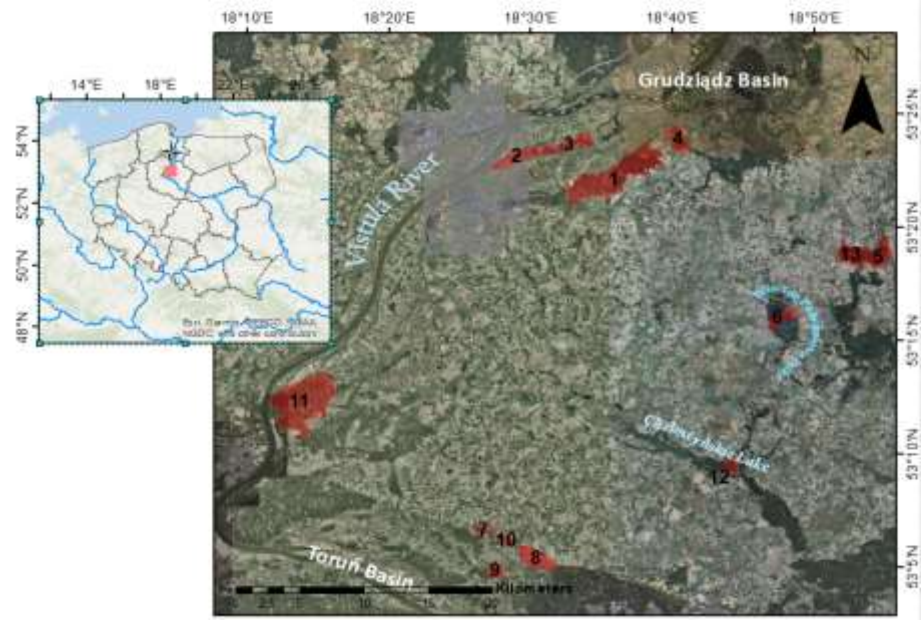

Fig. 1. On the left, study areas (light red rectangle) with admin borders in black (source: https://www.geoportal.gov.pl/ access date: 01.02.2022) and main rivers in blue (source: http://ihp-wins.unesco.org access date: 01.02.2022) on the background ESRI base map (source: ESRI access date: 01.02.2022). On the right archaeological test sides (red polygons) on the background of the Orthophoto Map (source: geoportal.gov.pl access date: 01.02.2022), with borders of the physical and geographic mesoregions (source: geoportal.gov.pl, access date: 01.02.2022)

In this study, only wooded areas with older stands were considered since data for at least the past 100 years of this land use was available. The source of such information is the Numerical Forest Map, which allows reviewing the contents of the forest database in terms of stand characteristics such as age, species, and habitat type of forest (Fig. 2).

Fig. 2. Selected study area (boundary of areas red colour) - "Katarzynki" on the background of the Forest Numerical Map in the composition of the stand map (source: https://www.bdl.lasy.gov.pl/portal/mapy access date: 15.07.2019)

The beginnings of archaeological field prospecting in the *Chełmno Region* should be associated with accidental discoveries that occurred in the 19th century. At this time, archaeology, as a scientific discipline, became more prominent and defined. This is why the accidental discoveries of monuments were recorded and catalogued. The research from this period consisted of a field inspection of monuments and recording their unique form and shape by employing pictures and sketches. An example of this kind of activity was the works of the German Scientific Society Copernicus-Verain, whose members, in 1866, inspected the megalithic complex in *Dźwierzno* [27]. Toruń Scientific Society, established in 1875, and the works of G. Ossowski are associated with the discovery of many megalithic objects and the first excavation type research [28]. *J. Kostrzewski* [29], together with students, carried out the first series of successful, well-documented archaeological field surveys in the *Chełmno Region* from 1926 to 1928. The interwar period brought a keen interest in settlement and cultural heritage discovery in the area of *Pomerania*, including the *Chełmno Land*. Both Polish researchers Delekta or Łęga and German researchers Baume and Langenhaim took part in those works. The Second World War caused huge losses, especially in museum inventories and archives, making it impossible to carry out thorough field verifications for lost archaeological sites [30]. Field prospection in the post-war period was closely related to uncovering the remains of settlements. Hence the researchers' interest was mainly focused on areas associated with more extensive river valleys, which could potentially be suitable areas for prehistoric settlements. The areas outside the valleys were not subject to prospecting and detailed research unless they were discovered by chance or had a uniquely visible form. This state of affairs lasted until the 1970s, when comprehensive surface surveys started in connection with the planned civil engineering investments in the Chełmno area. These works were related to large investment projects such as: "Wisła Program" (Vistula Project) or the construction of the Trans-European North-South Highway. This had a mobilizing effect on the researchers in the region, who started planned surface works in the second half of the 1970s [31]. Starting from the 1980s, there was a significant development of prospective research, which was associated with the popularization of the AZP (Pl. Arechologiczne Zdjęcie Polski, Eng. Polish Archaeological Record) [32,33]. In this period, planned field research began in the *Chełmno region*, the results of which significantly enriched the knowledge about prehistoric, especially Neolithic settlements of this area [34]. In the second half of the 1990s, many interesting discoveries were also made in the *Chełmno region*. They were usually related to strongholds visible aboveground [35]. Many research expeditions also identified settlement structures in the area with features similar to castle-type objects dated to the early Middle Ages. Such objects were presumed to have existed in that region for a long time [36]. Along with the construction of the A1 motorway, which crosses the *Chełmno lands* from north to south, large-scale prospective research and archaeological rescue research were carried out, which resulted in interesting discoveries on an unprecedented scale for this region [37]. Current research is carried out using modern remote sensing-based recognition of areas of interest and field verification of small numbers of sites or small area of larger identified sites. The most interesting results of this kind of novel approach include the discovery of the relics of the megalithic tomb in *Dźwierzno* [27, 38]. The recent discovery of relics of two monumental objects such as rondelas (circular enclosures) in *Łysomice* and *Tylice* [39] proves that this area is rich in archaeological remains.

Methods

This section starts with a flowchart (Fig. 3.) that describes the proposed method's, general steps and the analysis strategy.

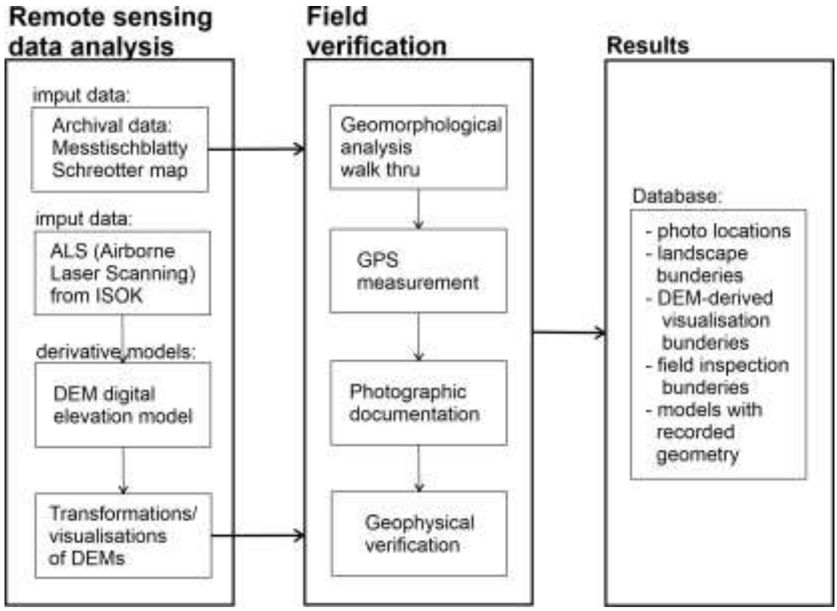

Fig. 3. Flowchart of the performed works

ALS based DEM data analysis – general workflow

The research methodology adopted in this study followed the non-invasive archaeology trends based on data from historical cartographic sources (HGIS - Historical Geographic Information System). Current topographic, thematic data and DEMs [40] derived from ALS (Airborne Laser Scanning) point clouds from the ISOK program (Informatyczny System Osłony Kraju eng: The IT Country Protection System [41]) was used.

A digital terrain model used in this study was obtained using the Nearest Neighbour interpolation method for ALS point clouds [42, 43]. We used only points classified as 'ground' [44–46]. To perform the analyses, model parameters were adopted following generally used methods in non-invasive archaeology:

1. Shaded Relief Model (SRM) with parameters: A = 315, H = 35;
2. Multidirectional Shaded Relief (MSRM) with parameters: A = 315, H = 35, 16 directions;
3. PCA of multi-azimuth shaded relief maps and Slope Gradient of three first components;
4. Slope Model (Slope);
5. Sky-View Factor (SVF) - with parameters - directions = 16, r = 10;
6. Positive Topographic Openness (PTO) - with parameters - directions = 16, r = 10;
7. Negative Topographic Openness (NTO) - with parameters - directions = 16, r = 10;
8. Simple Local Relief Model (SLRM) - with parameter, r = 10.

The visualizations of the derived DEMs allowed for identifying the archaeological sites in the 13 research areas and a preliminary determination of their characteristics: area, form, function and a preliminary determination of the boundary (Fig. 4).

On this basis, it was possible to choose sites for field verification and determine anthropogenic threats to the sites. The analyses were also the basis for the delineation of areas designated for geophysical surveys. As a result, documentation was made for nine sites, eight of them were completely unknown, and the largest site covers an area of nearly 166 ha.

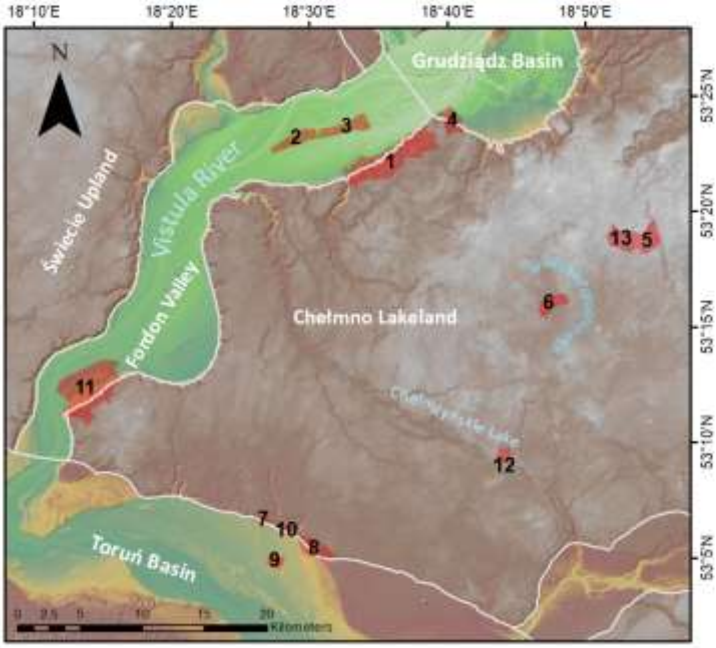

Fig. 4. Map of the ranges of research areas (red polygons) on the background of the Shaded hypsometry Map (source: geoportal.gov.pl access date: 01.02.2022), with borders of the physical and geographic mesoregions (source: geoportal.gov.pl, access date: 01.07.2019)

DEM visualization techniques – detailed description

This section details the DEM visualization methods used to identify the archaeological sites illustrated in

Fig. 5. The most basic produced model is the SRM, commonly known as a hill shade model. It is produced by giving each cell or pixel a value (shading) based on a hypothetical light source. The landform is directly illuminated, allowing for the intuitive recognition of features. Hillshaded visualizations are quite effective for earthworks with well-defined edges, where the detrimental effect of shading in one azimuth is largely overcome, and the character of earthworks is effectively represented. Hill shade has several disadvantages. The biggest drawback is its inability to represent linear objects that lie parallel to the direction of the light source and the saturation of shadow areas. One way to overcome the problem of direct illumination is to create multiple hill shade models with the sun at different angles, saving each as a separate layer in GIS software that can be turned on and off for comparison purposes or as a summed composition called Multidirectional Shaded Relief (MSRM). Another solution is to use Principal Components Analysis (PCA) to extract the most significant components explaining the largest percentage of the variation in land undulations [16].

Slope models (SLOPE) calculate the value of the degree of slope for each cell. This is interpreted as the slope angle at a given point in reference to the horizontal line. The visualization of the degree of slope is effective for earthworks with steep slopes and provides a correct visualization for them and reflects their nature. The disadvantage of this model is that it is much less effective in identifying gently sloping slopes and earthworks, for example, ridges and furrows and not large embankments.

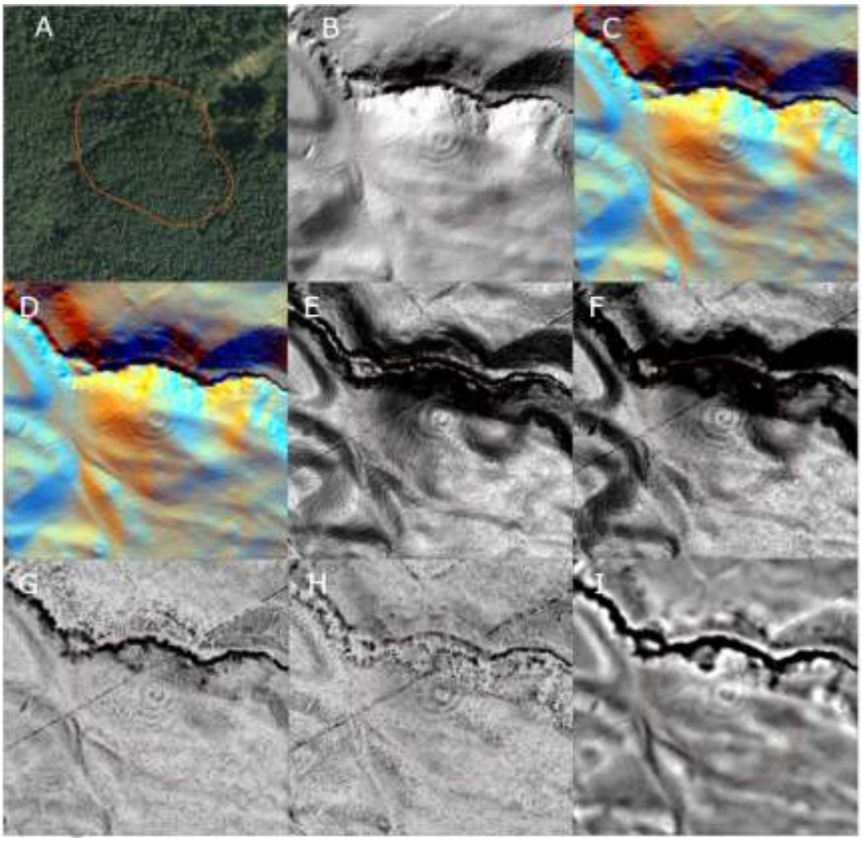

Fig. 5. Results of the DEM analyses for the Paparzyn site from left:
A - High-Resolution Ortho (source: geoportal.gov.pl);
B - Shaded Relief Model (SRM); C - Multidirectional Shaded Relief (MSRM);
D - PCA of multi-azimuth shaded relief maps and Slope Gradient of 3 first components;
E - Slope Model (Slope); F - Sky-View Factor (SVF); G - Positive Topographic Openness (PTO);
H - Negative Topographic Openness (NTO); I - Simple Local Relief Model (SLRM)

Sky-View Factor (SVF) is a lighting technique based on calculating sky visibility from any position [20], used in geomorphological mapping and detection of archaeological remains. Positive and Negative Openness (PTO and NTO) are also illumination techniques based on the degree of openness of the landform at one point, used successfully in geomorphology and archaeology [47]. These illumination techniques have the main advantage of being independent of the illumination direction and not distorting the relief.

The Local Relief Model (LRM), developed by *R. Hesse* [48], attempt to mitigate the masking effect of natural topographic variability by creating a differential model. The result is a new relief representation containing only differential values. It is particularly effective for landscapes with lowland characteristics and single elevation variations. This technique clearly distinguishes local minima and maxima with a quite significant variation and allows for identifying features above and below the Simple Local Relief Model (SLRM). It also allows for large scale morphological elements larger than the fitted kernel to be shrouded from the data so that only small scale elements remain [20]. We used a simplified process; the trend is calculated using a simple mean filter. The trend-free model is created directly by subtracting the filtered model from the original model. A more complex method can be found in [48, 49].

Archival data analysis

Archival data analysis was based on two maps. First, a German topographic map (*Messtischblatty*) was used at a scale of 1:25.000, characterized by a very high level of detail and high accuracy in representing the topography of the terrain [50–52]. *Messtischblatty* was issued from the end of the 19th century until 1944. They are one of the best sources of information on spatial transformations that have taken place in nature over the last 120 years. By 1876 more than 3.000 sheets of maps of this type, known today as *Ur-Messtischblatts*, had been published. The relevant *Messtischblatt* map sheets were downloaded from Archiwum Map Zachodniej Polski [53] and Kujawsko-Pomorskiej Bilioteki Cyfrowej [54]. Archival maps, with one exception, did not require manual calibration. This analysis aimed to determine the historical use of the selected sides. This included the functioning of the settlement network, economic activity and the identification of terrain forms marked as anthropogenic [52]. Using an innovative method, super-positioning of historical maps, and a derivative shading model allowed obtaining unambiguous answers to the research questions.

The second archival data source was the Schreotter map from 1803, downloaded from David Rumsey Map Collection [55]. Schroetter's maps involved manual comparative analysis using the tool [56]. This solution was chosen because there was no sufficient amount of initial data for correct map calibration. The query for this source consisted of manual displaying images depicting the research areas on topographic map bases. It processed NMT derivative models while comparing their location with the content of the archival map. The aim of these analyses was first to determine the occurrence of the settlement network, including roads concerning the current state. The second objective was to determine the late 18th century land cover for specific locations of selected potential archaeological sites.

Fig. 6. Fragments of Schroetter's map from 1803 and
the German topographic map (Messtischblatt) from Orlowo village
(source: https://rcin.org.pl/, access date: 01.07.2019)

In both cases, the quality of information recognition varied. Some data were highly legible forms associated with the functioning of communication routes, roads, or forest separation boundaries. Others had a more discrete form, such as traces of forest management, e.g., forest ploughing. Therefore, it is crucial in this case to look at the problem of an archaeological landscape in the context of gradual deconstruction based on available archival sources.

Field verification

Field verification was carried out on the areas identified by analyzing digital derivatives of DTM and the results of consultations with geomorphology experts. It consisted of a walk-thru selected areas and individual objects and visual verification of detected objects' existence with their landscape form. It was performed in the early spring and late autumn of 2018 and

2019, and the availability of forest areas and vegetation growth were considered when choosing dates. When selecting the dates, the availability of forest areas and the state of vegetation of the forest were considered. At the chosen dates, the research area offered the best conditions in terms of a wide field of view, which was unlimited by the vegetation of the lower forest floors. It was carried out on nine sites with a total area of 85ha. The purpose of the verification was to determine the visibility of forms and, if possible, the registration of traces indicating the period of their erection or transformation. The aim of the observations was also to determine the state of preservation or to note any potential threats.

As part of the verification, a parallel archaeological surface study was carried out on selected areas and objects. A mobile GPS device was used to allow spatial registration of analyzed sites. At the same time, photographic documentation was made, which consisted of taking a photo of recognized archaeological landforms with geodetic signal poles for scale. A total of 425 geotagged photos were taken.

Field verification – geophysics methods

Various non-invasive geophysical methods have been employed in archaeology due to their significant potential in finding underground anomalies that can be interpreted as manmade. In this case, magnetometry, a commonly used method, was used [57, 58]. It is an entirely non-invasive, surface geophysical method in which the local strength of the Earth's magnetic field is being measured [59, 60]. Changes in its value indicate a change in the magnetic properties of the measured medium, thus signalizing an anomaly. In other words, the distribution of the magnetic field values is being measured. It allows to indicate the distribution of geophysical anomalies and to estimate the range and nature of the sites that are of interest to archaeology [61]. Magnetic anomalies that can be associated with classic archaeological objects (e.g., pits, trenches etc.) are usually manifested in the form of increases in the magnetic field. Relicts, artefacts or man-erected structures made of highly flammable materials, such as buildings, ovens etc. are most often recorded in the form of dipole anomalies.

However, this method is not without its flows. The limitation of the magnetic method is distortions of magnetic measurements resulting from the presence of modern metal objects and any infrastructure having its own high amplitude magnetic field (e.g. steel objects, modern installations, fences, reinforcements, building destruction etc.) [62, 63]. Disturbances often make it impossible to detect archaeological structures, which are usually of much lower amplitude. Sometimes this limits the possibility to allow defining the anomalies' age clearly. The nature of the works requires measurements to be made in uninterrupted profiles, which means that all terrain obstacles, such as trails, artificial structures etc., constitute a significant problem in conducting the works. Those obstacles make it either impossible or turn the interpretations of the results very difficult.

The geophysical survey was done using a high-resolution fluxgate gradiometer Bartington Grad601-2. It measures tiny variations in the magnetic field caused by hidden anomalies in the ground, such as archaeological and forensic features, pipes, cables, or unexploded ordnance [64-66]. The entire system includes single or dual sensors mounted on a rigid carrying bar, a data logger, and a battery cassette. Calibration is done via an automated procedure by the Grad601-2 magnetic gradiometer system. It is a high stability fluxgate gradient sensor, with a 1 m separation between the sensing elements and an effective sensitivity of 0.03nT/m. The temperature insensibility of this sensor ensures minimal drift during surveys and reduces the need for adjustment. Each sensor contains electronics and non-volatile memory for calibration data storage and can be operated independently over long cables if required. The setup used in the survey is as follows. Measurements were taken in parallel profiles at a sampling density of 0.25×1.00m for polygons with dimensions of 40×40m and at a sampling density of 0.12×1.00m for polygons with dimensions of 30×30m. The total area of 5.6ha was measured, and all results were later processed in TerraSurveyor [67] and Geoplot 3 [68] software.

Results

As a result of the conducted research, remote sensing and historical data analysis and field studies, a spatial database was created, which included:

- numerical terrain models in the form of DEM,
- archival maps,
- results of spatial analyses,
- data from geophysical measurements in the form of rasters,
- vector data,
- terrain geo-tagged photographs or verified archaeological sides (Fig. 7).

Fig. 7. Discovered Paparzyn site area

As part of the data optimization, it was decided to create individual thematic schemes for certain data ranges; this allows for better organization, acceleration and ordering of data. A Postgres/PostGIS database was created along with a spatial schema into which the vector data was imported through the appropriate QGIS commands. A number of data schemas have been created in the database.

Thus, raster data is characterized by large file sizes, approximately 23 GB in total. Exporting as a pgsql file will be similar in size, making such a file very difficult to manage. For this reason, importing raster models into the database can be done directly from a TiFF file. The data import is performed by the program raster2pgsql, a standard tool of the Postgres/PostGIS system. To make it easier, a script (models.bat) was created to load all the models, the duration of which depends on the computing power of the computer and can be quite long. As a result, the database consists of 261 raster models and 420 field photos with their location.

The range of geophysical survey results has been vectorized and moved into separate layers, which consists of the range coordinates of this survey and TIF files that hold the results of the surveys.

The result was 222 files with a total size more of than 19GB, which were stored in geoTIFF and PostgresSQL database with the PostGIS extension. This solution is flexible for use with different GIS software. Shaded Relief Model (SRM), Multidirectional Shaded Relief (MSRM) and Slope Model (SM) were calculated using the ArcGIS Pro 2.1. Sky-View Factor (SVF) and Positive and Negative Topographic Openness (PTO, NTO) were computed using the SAGA GIS software. Simple Local Relief Model (SLRM) and PCA of multi-azimuth shaded relief maps have been calculated using the Relief Visualization Toolbox 1.3 [20, 69].

Conclusions

The analyses carried out and described in this paper have revealed that non-destructive remote sensing methods allow recognizing of both single, potentially immovable heritage monuments and large-scale zones of archaeological sites. In some cases, the diversity of the occurring objects within individual zones is noticeable, indicating a spatially and chronologically complex structure that forms a homogeneous complex. The implementation of the project made it possible to register undiscovered archaeological landscapes. The preliminary classification of the discovered forms allowed us to distinguish among the objects those that reveal features of a defensive, sepulchral and probably settlement character. The project results illustrate the capabilities of modern non-invasive prospective methods as complementary research tools in previously recognized areas.

Magnetic geophysical surveys carried out as part of on-side validation of remote sensing analysis covered forested areas of very diverse terrain. In many cases, the regularity of the embankments does not align with the agricultural works, suggesting their direct connection with archaeological and historical objects. The low availability of these areas for archaeological research, resulting from afforestation, is a major research challenge.

The experience gained during the two years of the project is an important case study in building a methodology for conducting multidisciplinary research in such areas. This work shows that even analyses based on small and scattered samples carried out in a well-designed way allow the development of a complex methodology for integrated archaeological research.

References

[1] R. Lasaponara, R. Coluzzi, F.T. Gizzi, N. Masini, *On the LiDAR contribution for the archaeological and geomorphological study of a deserted medieval village in Southern Italy*, **Journal of Geophysics and Engineering**, **7**(2), 2010, pp. 155–163. https://doi.org/10.1088/1742-2132/7/2/S01.

[2] C. Witharana, W.B. Ouimet, K.M. Johnson, *Using LiDAR and GEOBIA for automated extraction of eighteenth–late nineteenth century relict charcoal hearths in southern New England*, **GIScience and Remote Sensing**, **55**(2), 2018, pp. 183–204. https://doi.org/10.1080/15481603.2018.1431356.

[3] T.J. Pingel, K. Clarke, A. Ford, *Bonemapping: A LiDAR processing and visualization technique in support of archaeology under the canopy*, **Cartography and Geographic Information Science**, **42**(1), 2015, pp. 18–26. https://doi.org/10.1080/15230406.2015.1059171.

[4] T.J. Pingel, K.C. Clarke, W.A. McBride, *An improved simple morphological filter for the terrain classification of airborne LIDAR data*, **ISPRS Journal of Photogrammetry and Remote Sensing**, **77**, 2013, pp. 21–30. https://doi.org/10.1016/j.isprsjprs.2012.12.002.

[5] T. Pingel, K. Clarke, *Perceptually Shaded Slope Maps for the Visualization of Digital Surface Models*, **Cartographica: The International Journal for Geographic Information and Geovisualization**, **49**(4), 2014, pp. 225–240. https://doi.org/10.3138/carto.49.4.2141.

[6] P.L. Guth, *Incorporating vegetation in viewshed and line-of-sight algorithms*, **ASPRS 2009 Specialty Conference**, 2009.

[7] R. Seixas, M. Mediano, M. Gattass, *Efficient line-of-sight algorithms for real terrain data*, **III Simposio de Pesquisa Operacional e IV Simp ´ osio de ´ Log´ıstica da Marinha - SPOLM'99**, 1999.

[8] J.J. Murgoitio, R. Shrestha, N.F. Glenn, L.P. Spaete, *Improved visibility calculations with tree trunk obstruction modeling from aerial LiDAR*, **International Journal of Geographical Information Science**, **27**(10), 2013, pp. 1865–1883. https://doi.org/10.1080/13658816.2013.767460.

[9] A.F. Chase, D.Z. Chase, J.F. Weishampel, J.B. Drake, R.L. Shrestha, K.C. Slatton, J.J. Awe, W.E. Carter, *Airborne LiDAR, archaeology, and the ancient Maya landscape at Caracol, Belize*, **Journal of Archaeological Science**, **38**(2), 2011, pp. 387–398. https://doi.org/10.1016/j.jas.2010.09.018.

[10] Ž. Kokalj, J. Mast, *Space lidar for archaeology? Reanalyzing GEDI data for detection of ancient Maya buildings*, **Journal of Archaeological Science: Reports**, **36**, 2021, article number: 102811, https://doi.org/10.1016/j.jasrep.2021.102811.

[11] M. Balsi, S. Esposito, P. Fallavollita, M.G. Melis, M. Milanese, *Preliminary archeological site survey by UAV-borne lidar: A case study*, **Remote Sensing**, **13**(3), 2021, article number: 332. https://doi.org/10.3390/rs13030332.

[12] J.M. Vilbig, V. Sagan, C. Bodine, *Archaeological surveying with airborne LiDAR and UAV photogrammetry: A comparative analysis at Cahokia Mounds*, **Journal of Archaeological Science: Reports**, **33**, 2020, article number: 102509. https://doi.org/10.1016/j.jasrep.2020.102509.

[13] T.R. Cody, S.L. Anderson, *LiDAR predictive modeling of Pacific Northwest mound sites: A study of Willamette Valley Kalapuya Mounds, Oregon (USA)*, **Journal of Archaeological Science: Reports**, **38**, 2021, article number: 103008. https://doi.org/10.1016/j.jasrep.2021.103008.

[14] A.R. Randall, *LiDAR-aided reconnaissance and reconstruction of lost landscapes: An example of freshwater shell mounds (ca. 7500-500 CAL B.P.) in northeastern Florida*, **Journal of Field Archaeology**, **39**(2), 2014, pp. 162–179. https://doi.org/10.1179/0093469014Z.00000000080.

[15] T. Freeland, B. Heung, D. V. Burley, G. Clark, A. Knudby, *Automated feature extraction for prospection and analysis of monumental earthworks from aerial LiDAR in the Kingdom of Tonga*, **Journal of Archaeological Science**, **69**, 2016, pp. 64–74. https://doi.org/10.1016/j.jas.2016.04.011.

[16] K. Sadr, *A Comparison of Accuracy and Precision in Remote Sensing Stone-walled Structures with Google Earth, High Resolution Aerial Photography and LiDAR; a Case Study from the South African Iron Age*, **Archaeological Prospection**, **23**(2), 2016, pp. 95–104. https://doi.org/10.1002/arp.1532.

[17] K. Sadr, F. Mshuqwana, *Spatial analysis of a stone-walled compound using LiDAR and GIS*, **South African Archaeological Bulletin**, **75**(212), 2020, pp. 75–86.

[18] R. Bennett, K. Welham, R.A. Hill, A. Ford, *A comparison of visualization techniques for models created from airborne laser scanned data*, **Archaeological Prospection**, **19**(1), 2012, pp. 41–48. https://doi.org/10.1002/arp.1414.

[19] K. Challis, P. Forlin, M. Kincey, *A Generic Toolkit for the Visualization of Archaeological Features on Airborne LiDAR Elevation Data*, **Archaeological Prospection**, **18**(4), 2011, pp. 279–289. https://doi.org/10.1002/arp.421.

[20] K. Zakšek, K. Oštir, Ž. Kokalj, *Sky-View Factor as a Relief Visualization Technique*, **Remote Sensing**, **3**(2), 2011, article number: 398–415. https://doi.org/10.3390/rs3020398.

[21] K.M. Prufer, A.E. Thompson, D.J. Kennett, *Evaluating airborne LiDAR for detecting settlements and modified landscapes in disturbed tropical environments at Uxbenká, Belize*, **Journal of Archaeological Science**, **57**, 2015, pp. 1–13. https://doi.org/10.1016/j.jas.2015.02.013.

[22] A.E. Thompson, *Detecting Classic Maya Settlements with Lidar-Derived Relief Visualizations*, **Remote Sensing**, **12**(17), 2020, article number: 2838. https://doi.org/10.3390/rs12172838.

[23] R. Lasaponara, R. Coluzzi, N. Masini, *Flights into the past: Full-waveform airborne laser scanning data for archaeological investigation*, **Journal of Archaeological Science**, **38**(9), 2011, pp. 2061–2070. https://doi.org/10.1016/j.jas.2010.10.003.

[24] A. Corns, R. Shaw, *High resolution 3-dimensional documentation of archaeological monuments & landscapes using airborne LiDAR*, **Journal of Cultural Heritage**, **10**(1), 2009, pp. e72–e77. https://doi.org/10.1016/j.culher.2009.09.003.

[25] J. Solon, J. Borzyszkowski, M. Bidłasik, A. Richling, K. Badora, J. Balon, T. Brzezińska-Wójcik, Ł. Chabudziński, R. Dobrowolski, I. Grzegorczyk, M. Jodłowski, M. Kistowski, R. Kot, P. Krąż, J. Lechnio, A. Macias, A. Majchrowska, E. Malinowska, P. Migoń, U. Myga-Piątek, J. Nita, E. Papińska, J. Rodzik, M. Strzyż, S. Terpiłowski, W. Ziaja, *Physico-geographical mesoregions of Poland: Verification and adjustment of boundaries on the basis of contemporary spatial data*, **Geographia Polonica**, **91**(2), 2018, pp. 143–170. https://doi.org/10.7163/GPol.0115.

[26] T. Gacki, J. Szukalski, *Morfostruktura krajobrazu i zróżnicowanie regionalne*, **Dol. Dolnej Wisły**, 1982, pp. 61–79.

[27] S. Kukawka, J. Kukawka-Małecka, B. Wawrzykowska, *O pomnikach przedhistorycznych Prus Królewskich*, **Idea Megal. w Obrządku Pogrzebowym Kult. Pucharów Lejkowatych**, 2006, pp. 131–133.

[28] G. Ossowski, **Grobowce kujawskie na ziemi chełmińskiej**, 1878.

[29] J. Kostrzewski, *Osada starszej ceramiki wstęgowej w Chełmży w pow. Toruńskim na Pomorzu*, **Rocz. Muz. Wielkop. w Pozn.**, 1928.

[30] B. Wawrzykowska, *Zarys historii badań nad neolitem i początkami epoki brązu na ziemi chełmińskiej*, **Neolit i Początki Epoki Brązu Na Ziemi Chełmińskie**, 1986, p. 21.

[31] W. Sosnowski, *Realizacja Archeologicznego Zdjęcia Polski na terenie województwa toruńskiego*, **Przegląd Regionalny**, **2**, 1992.

[32] K. Niedziółka, *The prospect of digitization of Polish Archaeological Record on an example of materials from the turn of Bronze and Iron Age from the area of Pomeranian Voivodeship (Northern Poland)*, **Sprawozdania Archeologiczne**, **68,** 2016, pp. 121–144. https://doi.org/10.23858/SA68.2016.007.

[33] S. Czerwiński, P. Guzowski, M. Lamentowicz, M. Gałka, M. Karpińska-Kołaczek, R. Poniat, E. Łokas, A.C. Diaconu, J. Schwarzer, M. Miecznik, P. Kołaczek, *Environmental implications of past socioeconomic events in Greater Poland during the last 1200 years. Synthesis of paleoecological and historical data*, **Quaternary Science Reviews**, **259**(1), 2021, article number: 106902. https://doi.org/10.1016/j.quascirev.2021.106902.

[34] J. Grześkowiak, S. Kukawka, *Badania weryfikacyjno-sondażowe na terenie województwa toruńskiego przeprowadzone w 1992 i 1993 r.: uwagi ogólne*, in: **Archeol. Badania Weryfikacyjno-Sondażowe Stanow. Neolit. Na Teren. Województwa Toruńskiego w Latach 1992 i 1993**, 1993, pp. 5–9.

[35] J. Sosnowska, *W. Sosnowski, Archeologiczne krajobrazy ziemi chełmińskiej i okolic*, in: **Kraj. Archetypowy**, 1999, pp. 70–78.

[36] J. Chudziakowa, **Wczesnośredniowieczne grodziska ziemi chełmińskiej. Katalog grodzisk**, 1994.

[37] M. Wiśniewski, L. Kotlewski, **Archeologia Autostrady. Badania archeologiczne w pasie autostrady A1 w granicach województwa kujawsko-pomorskiego. Katalog zabytków**, 2013.

[38] J. Czerniec, M. Kozicka, M. Przymorska-Sztuczka, M. Sosnowski, **Opracowanie wyników archeologicznych badań rozpoznawczych na stanowisku nr 60 w Dźwierznie gm. Chełmża. Maszynopis złożony w WUOZ w Toruniu**, 2019.

[39] S. Zdziebłowski, *Kujawsko-Pomorskie/ Dwie olbrzymie konstrukcje sprzed 7 tys. lat odkryto pod Łysomicami*, **Nauk. w Polsce**, 2020.

[40] * * *, GUGiK, *Geoportal*, 2022.

[41] Z. Kurczynski, *The selection of aerial laser scanning parameters for countrywide digital elevation model creation*, **Photogrammetry and Remote Sensing. 13th International Multidisciplinary Scientific GeoConference SGEM 2013**, 2013. https://doi.org/10.5593/SGEM2013/BB2.V2/S10.020.

[42] M. Keskin, A.O. Dogru, F.B. Balcik, C. Goksel, N. Ulugtekin, S. Sozen, *Comparing Spatial Interpolation Methods for Mapping Meteorological Data in Turkey*, **Energy Systems and Management**, (Editors A.N. Bilge, A.Ö. Toy, M.E. Gunay), 2015, pp. 33–42. https://doi.org/10.1007/978-3-319-16024-5_3.

[43] C.W. Bater, N.C. Coops, *Evaluating error associated with lidar-derived DEM interpolation*, **Computers & Geosciences**, **35**(2), 2009, pp. 289–300. https://doi.org/10.1016/j.cageo.2008.09.001.

[44] Ł. Banaszek, D. Cowley, M. Middleton, *Towards National Archaeological Mapping. Assessing Source Data and Methodology—A Case Study from Scotland*, **Geosciences**, **8**(8), 2018, article number: 272. https://doi.org/10.3390/geosciences8080272.

[45] D. Cowley, Ł. Banaszek, G. Geddes, A. Gannon, M. Middleton, K. Millican, *Making LiGHT Work of Large Area Survey? Developing Approaches to Rapid Archaeological Mapping and the Creation of Systematic National-scaled Heritage Data*, **Journal of Computer Applications in Archaeology**, **3**(1), 2020, pp. 109–121. https://doi.org/10.5334/jcaa.49.

[46] Ø.D. Trier, D.C. Cowley, A.U. Waldeland, *Using deep neural networks on airborne laser scanning data: Results from a case study of semi-automatic mapping of archaeological topography on Arran, Scotland*, **Archaeological Prospection**, **26**(2), 2019, pp. 165–175. https://doi.org/10.1002/arp.1731.

[47] T. Kato, Y. Terada, M. Kinoshita, H. Kakimoto, H. Isshiki, M. Matsuishi, A. Yokoyama, T. Tanno, *Real-time observation of tsunami by RTK-GPS*, **Earth, Planets and Space**, **52**, 2000, pp. 841–845. https://doi.org/10.1186/BF03352292.

[48] R. Hesse, *LiDAR-derived Local Relief Models - a new tool for archaeological prospection*, **Archaeological Prospection**, **17**(2), 2010, pp. 67-72. https://doi.org/10.1002/arp.374.

[49] Ž. Kokalj, R. Hesse, **Airborne Laser Scanning Raster Data Visualization. A Guide to Good Practice**, Založba ZRC, Ljubljana, 2017.

[50] D. Trepal, D. Lafreniere, T. Stone, *Mapping Historical Archaeology and Industrial Heritage: The Historical Spatial Data Infrastructure*, **Journal of Computer Applications in Archaeology**, **4**(1), 2021, pp. 202–213. https://doi.org/10.5334/jcaa.77.

[51] D. Trepal, D. Lafreniere, J. Gilliland, *Historical Spatial-Data Infrastructures for Archaeology: Towards a Spatiotemporal Big-Data Approach to Studying the Postindustrial City*, **Historical Archaeology**, **54**, 2020, pp. 424–452.

https://doi.org/10.1007/s41636-020-00245-5.
[52] M. Chorowska, P. Duma, M. Furmanek, M. Legut-Pintal, A. Łuczak, J. Piekalski, *Wleń/Lähn District in the Sudetes Foothills, Poland: A Case Study of Cultural Landscape Evolution of an East Central European Settlement Microregion From the Tenth to the Eighteenth Centuries*, **International Journal of Historical Archaeology**, **21**, 2017, pp. 66–106. https://doi.org/10.1007/s10761-016-0351-8.
[53] * * *, UAM Poznań, *Archiwum Map Zachodniej Polski*, 2009.
[54] * * *, UMK Toruń, *Kujawsko-Pomorska Bilioteka Cyfrowa*, 2021.
[55] * * *, Cartography Associates, *David Rumsey Map Collection*, 2022.
[56] * * *, Klokan Technologies GmbH, *Georeferencer*, **2019**, n.d.
[57] E. Achuoth Deng, K.O. Doro, C.-G. Bank, *Suitability of magnetometry to detect clandestine buried firearms from a controlled field site and numerical modeling*, **Forensic Science International**, **314**, 2020, Article Number: 110396. https://doi.org/10.1016/j.forsciint.2020.110396.
[58] J.W.E. Fassbinder, *Magnetometry for archaeology*, **Encyclopedia of Earth Sciences Series**, 2017, pp. 499–514. https://doi.org/10.1007/978-3-319-50518-3_10.
[59] S.H. Silliman, P. Farnsworth, K.G. Lightfoot, *Magnetometer prospecting in historical archaeology: Evaluating survey options at a 19th-century rancho site in California*, **Historical Archaeology**, **34**, 2000, pp. 89–109. https://doi.org/10.1007/BF03374315.
[60] J. Chilo, A. Jabor, L. Lizska, Å.J. Eide, T. Lindblad, *Obtaining "images" from iron objects using a 3-axis fluxgate magnetometer*, **Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment**, **580**, 2007, pp. 1105–1109. https://doi.org/10.1016/j.nima.2007.06.070.
[61] S. Ilinykh, N. Grafeeva, E. Mikhailova, O. Egorova, *Segmentation of Magnetic Anomalies in the Conduct of Archaeological Excavations*, **WorldCIST'19 2019: New Knowledge in Information Systems and Technologies**, pp. 58–67. https://doi.org/10.1007/978-3-030-16181-1_6.
[62] A. Schmidt, M. Dabas, A. Sarris, *Dreaming of Perfect Data: Characterizing Noise in Archaeo-Geophysical Measurements*, **Geosciences**, **10**(10), 2020, article number: 382. https://doi.org/10.3390/geosciences10100382.
[63] C.R. Bates, M. Bates, C. Gaffney, V. Gaffney, T.D. Raub, *Geophysical Investigation of the Neolithic Calanais Landscape*, **Remote Sensing**, **11**(24), 2019, article number: 2975. https://doi.org/10.3390/rs11242975.
[64] S.J. Keay, S.H. Parcak, K.D. Strutt, *High resolution space and ground-based remote sensing and implications for landscape archaeology: The case from Portus, Italy*, **Journal of Archaeological Science**, **52**, 2014, pp. 277–292. https://doi.org/10.1016/j.jas.2014.08.010.
[65] R. Cajigas, *An integrated approach to surveying an Early Agricultural period landscape: Magnetic gradiometry and satellite imagery at La Playa, Sonora, Mexico*, **Journal of Archaeological Science: Reports**, **15**, 2017, pp. 381–392. https://doi.org/10.1016/j.jasrep.2017.09.004.
[66] A. Cocean, V, Pelin, M.M. Cazacu, I. Cocean, I. Sandu, S. Gurlui, F. Iacomi, *Thermal effects induced by laser ablation in non-homogeneous limestone covered by an impurity layer*, **Applied Surface Science**, **424,** 2017**, pp.** 324-329, Special Issue SI, Part 3. DOI10.1016/j.apsusc.2017.03.172
[67] * * *, DW Consulting, *Terrasruveyot*, n.d.
[68] * * *, Geoscan Research, *Geoscan Research*, 2018.

[69] Ž. Kokalj, M. Somrak, *Why Not a Single Image? Combining Visualizations to Facilitate Fieldwork and On-Screen Mapping*, **Remote Sensing**, **11**(7), 2019, Article Number: 747. https://doi.org/10.3390/rs11070747.

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