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The Potential of Aerial Reconnaissance in the Detection, Mapping and 3D Reconstruction Modelling of Crop-Marked Military Components of Bohemia's Postmedieval and Early Industrial Landscape

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Abstract: From the 17th to the 19th century, a score of military events, campaigns and battles took place in the Czech lands, leaving numerous traces and distinctly changing the appearance of the cultural landscape in some regions. The results of long-term aerial-archeological surveys in the Czech lands have demonstrated that this detection method is advantageous in identifying buried sites built in the past in the context of military conflicts. Experience hitherto has made it possible to label archeological remote sensing as a collection of the potentially most effective methods for uncovering sites of field fortifications dated to the modern period and the beginning of the industrial era. This includes finds of both solitary sites and segments of strategically built fortification lines. This paper is an attempt to critically evaluate these hitherto recorded landmarks which have been discovered and documented via aerial prospection from the 1990s to the present. At the same time, this study reflects on the possibilities offered by the modern methods of remote sensing which have played a significant role in the discovery, mapping, documentation, digital terrain modelling, and the 3D virtual reconstructions of these sites.

Keywords: field fortifications; aerial prospection; cropmarks; spaceborne data; aerial lidar scanning; 3D reconstructions; 17th–19th centuries

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1. Introduction

This paper reports the results of the research on postmedieval (early-modern) military field fortifications discovered and documented in Bohemia by the author from the 1990s to the present using aerial reconnaissance. At the same time, this study reflects on the possibilities offered by the modern methods of remote sensing which have played a decisive role in the mapping, digital terrain modelling and 3D reconstructions of this kind of archaeological heritage.

One of the most characteristic components of the postmedieval (i.e. early-modern and the Baroque to Industrial period) landscape in Bohemia (the largest historical part of the Czech Republic, a country situated in the geographical center of Europe, naturally enclosed by frontier mountain ranges (Figure 1)) used to be its temporary defensive military installations—camps, forts, strongholds and redoubts. They were constructed in response to the frequent military attacks launched by enemies of the Habsburg (Austrian) Empire (Czech Lands, i.e., Bohemia, Moravia and Silesia, belonged to its territory between 1526 and 1918) since the Thirty Year´s War (1618–1648) until the 1866 Prussian–Austrian War. Military campaigns, organized in those times mostly by the armies of Prussian kings, resulted in the construction of several hundred defensive bases. Some of them remain preserved as ruined (semi-buried) structures covered by trees or bushes, usually as rectilinear polygonal enclosures (Figure 2); however, in the past, once they became needless, most of them were dismantled, ploughed out, levelled off, or disappeared completely from the surface as a result of natural processes of transformation. In these cases, the remains are buried under the surface. They can be found when the surface layer of the ground is disrupted in the places where they are buried; however, the most productive method of identifying them is undoubtedly by remote sensing from the air and/or from outer space. As such, they are classified as invisible constituents of the national archaeological heritage which can be most easily detected, documented and mapped via remote sensing—both from the air, and from outer space.

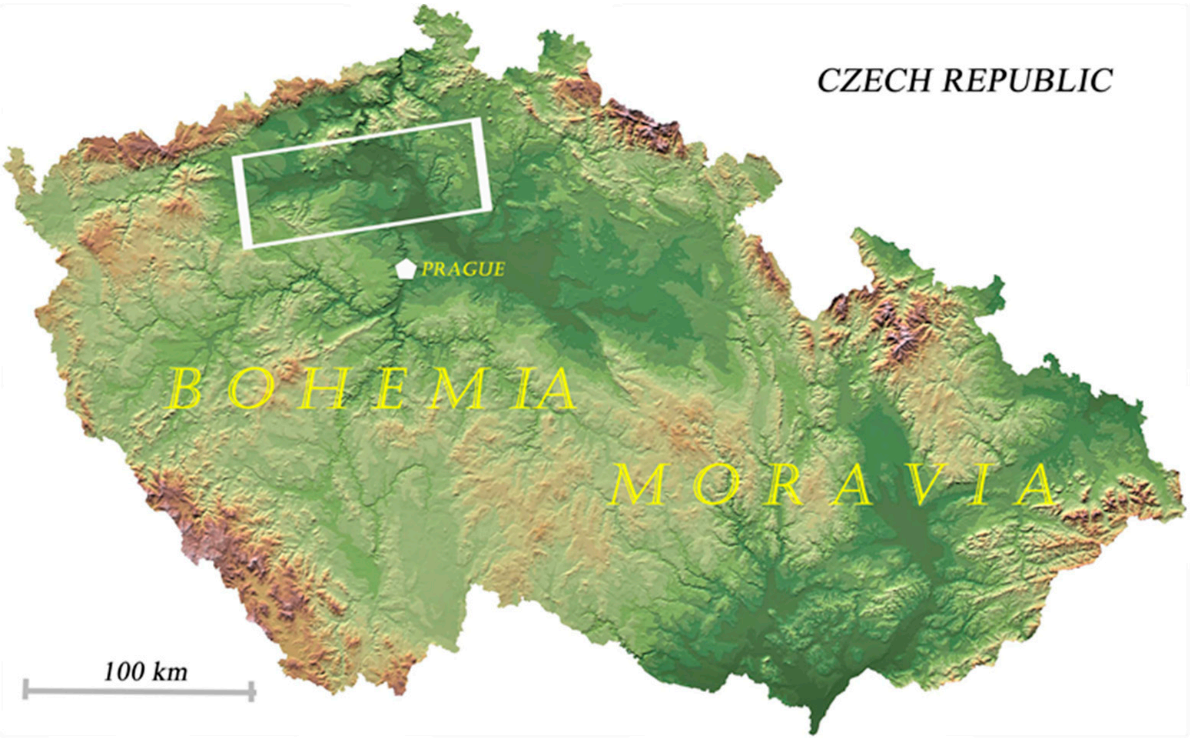

Figure 1. Map of the Czech Republic with the marked area representing NW Bohemia. All sites described in this paper are situated there. This is one of the two areas in Bohemia which used to be most frequently threatened by military campaigns from the Prussian Kingdom in the 17th–19th centuries (map source: www.cuzk.cz, accessed on 1 March 2023).

Experience has made it possible to label archeological remote sensing (ARS) as a set of the most effective methods for uncovering buried ancient and historical features/sites of any kind [1–15]. The position of remote sensing in current archaeology is supported by sophisticated technologies, innovative hardware and software instruments able to operate both in the heuristic (data gathering) process (such as the prospection/detection of new sites and monuments from a low-flying aircraft, or the visual analysis and interpretation or air- and spaceborne images), and in data processing. Obviously, the non-invasive characteristics of remote sensing also correspond to the current general trends in archaeological practice which stress a more careful—i.e., non-invasive—approach to, and manipulation of archaeological sources, making this approach highly useful, meaningful and attractive. Recently raised themes in this field include the analysis of historical/archival aerial photographs through modern methods [16], data gathering via crowdsourcing and artificial intelligence/automatic classification [17–25], the mapping and monitoring of endangered heritage [26–31], and the methods used for detecting and enhancing buried remains of archaeological heritage [32–37].

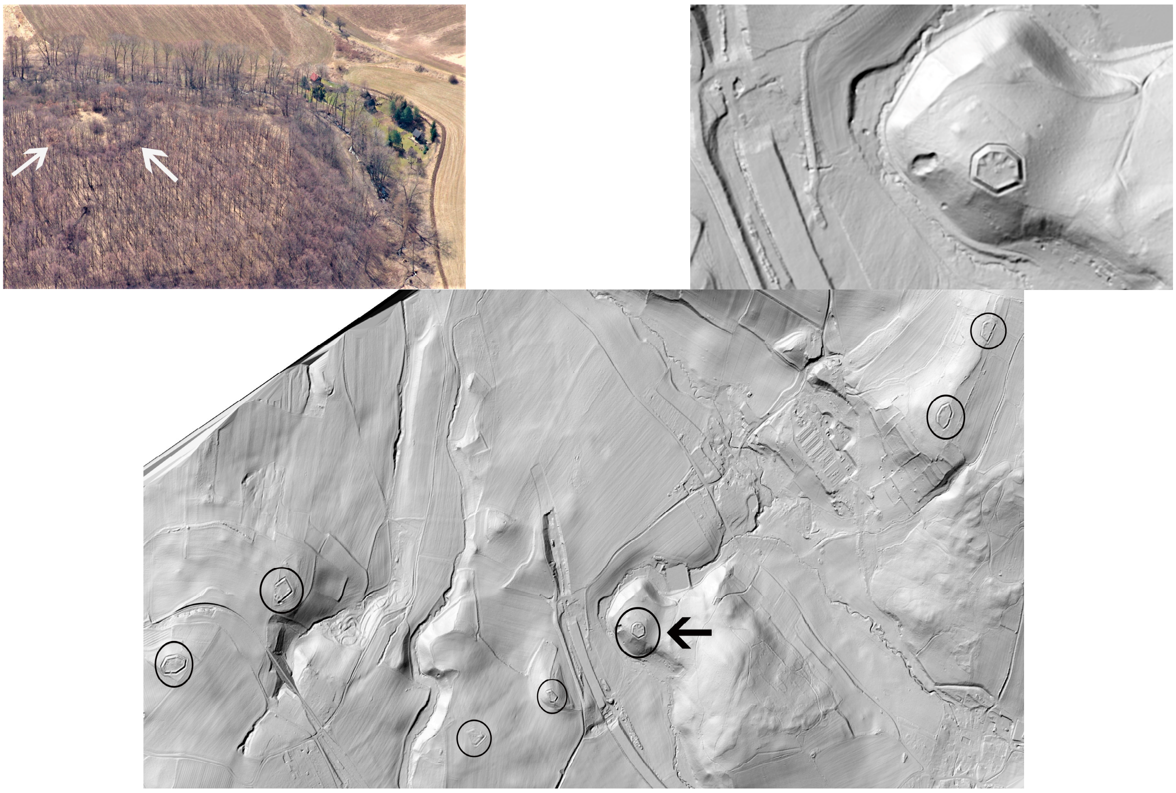

Figure 2. Habrovany (distr. Ústí nad Labem), Czech Central Highland. **Top left**—polygonal semi-ruined fortified artillery fort dated to the late 1770s hidden in local leaf forest (indicated by white arrows). Due to the fact that the oblique image was taken in the late winter season (no leaves on trees), the military structure is well recognizable on this oblique photograph; **top right**—the same base on DTM; **bottom**—the fortified linear system in which the base was included (see the black arrow). The author of all aerial images in this paper is M. Gojda; all DTMs produced from lidar data come from the present author´s project and are in the possession of the University of West Bohemia in Plzeň.

2. Materials and Methods

2.1. Visible and Hidden Fragments of Military Conflicts in Bohemia

Bohemia belongs to a region with some of the most diverse types of landscape in Europe, and this fact is reflected in the varying intensity of presence of ancient and modern settlements in individual areas of this geographically closed country, as mountain ranges surround its perimeter. This diversity, which is characteristic of the Czech landscape in terms of its natural conditions and the exploitation of these conditions by man, is also reflected in the level of preservation of immovable features and monuments of all kinds. In the classic settlement zone of fertile lowlands cultivated almost continuously since the late Stone Age via ploughing, most prehistoric, medieval and modern constructions have been destroyed or have had their above-ground elements removed. These are much more frequently preserved in forested environments, where the ditches and walls of prehistoric hillforts, the embankments of tumuli, or abandoned villages and roads or sites linked to production are not subject to such radical processes as in the open landscape. We observe them on the ground surface as elevations and depressions of various size, which are often overgrown with specific types of plants. Their groupings on the ground's surface form a characteristically shaped relief, the study of which has been the subject of surface geodetic-topographic surveys and airborne laser scanning [38].

Consequently, the history of abandoned fortified bases built in the terrain outside large, sophistically constructed fortresses reflects the impact of natural processes, which consists primarily of soil erosion in the hilly terrains. At the same time, it reflects processes linked to the human use of the natural environment's resources. Terrain obstructions have either been completely removed by man (for example, by transporting soil from the mounds/walls to fields, or to the beds of former river meanders, or to ditches of these fortifications to level the terrain for agricultural purposes) or have been subjected to long-term terrain levelling as an effect of the climate or repeated plowing. As field fortifications were usually built ad hoc, i.e., due to the specific threat of a military invasion of the land from a previously assumed direction or, on the contrary, to defend conquered positions, the positioning of its individual elements was subject to strategic needs. For this reason, it was necessary to be perfectly acquainted with the morphology of the landscape in which these structures were to be built. Therefore, the creation of maps begun in the 18th century, and the oldest large-scale maps were the result of work by military land surveyors and cartographers (in the Czech lands, these were the "First Military Maps" from the 1760s to 1780s, 1:28.800; http://oldmaps.geolab.cz/map_root.pl?&map_root=1vm&lang=en; accessed on 1 March 2023). These maps are even proof of the fact that field fortifications—primarily in regions with a heightened risk of military conflicts—were a characteristic part of the Czech landscape in the Baroque epoch (Figure 3). This is often forgotten by studies synthesizing this phenomenon; however, it is discussed with increasing frequency [39,40].

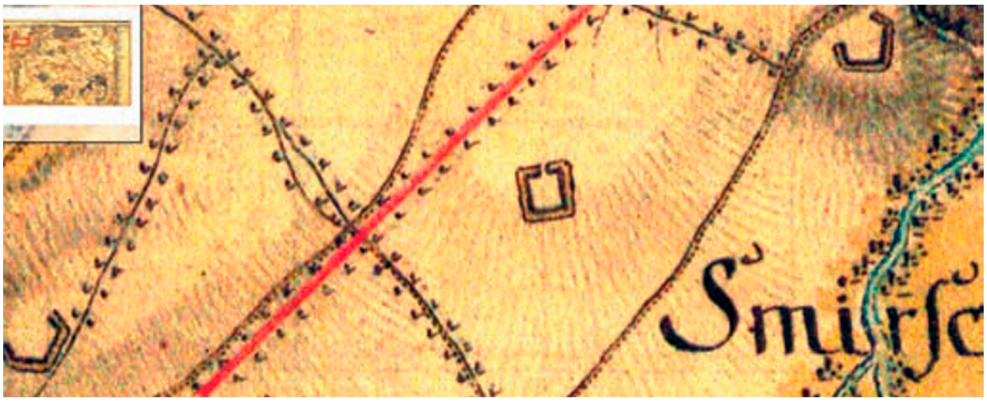

Figure 3. Linear setting of two lunettes and one redoubt near Eastern Bohemian Smiřice on the map of the 1st Military Mapping (freely available at http://oldmaps.geolab.cz/map_root.pl?&map_root=1vm&lang=en, accessed on 1 January 2023). Example of how the installation of a fortification structure affected the character of the 18th century post-medieval landscape.

The majority of field fortifications from the 17th to the 19th century are physically preserved in the forested environment (i.e., in the terrain relief), where these sites were exposed to less intensive human pressure after their abandonment and were located in agriculturally less fertile positions of uplands, highlands and hilly regions, suitable for cattle grazing rather than the cultivation of arable land. The process of gradually levelling the walls and ditches of fortifications did not follow the same pattern as the one observed in fortresses located in lowland, open landscapes. One of the best-mapped and most thoroughly studied areas using landscape archeology methods showed a heightened presence of field fortifications is the Tachov region (wider surroundings of Planá) in West Bohemia. This landscape is linked to the clashes between the Imperial and Swedish armies at Třebel at the very end of the Thirty Years' War [41]. The application of ARS methods in the type of environment described above is linked to the combined use of aerial laser (lidar) data, old maps and the results of surface (topographic) surveys. A number of similar projects in the Czech Republic and abroad have shown the potential that the integration of these aforementioned resources offers [42–45]. Refer to [46] for a study of military sites in the context of the Thirty Years' War; to [47,48] for studies of the period from the 17th to the 19th century; and [34] for general information on the aforementioned integration, including three examples of studies dealing with two prehistoric and one modern monuments.

An example of the integration of aerial lidar data with archive maps is the comparison of the evidence of DTM derived from lidar data (Figure 4) with that listed in the 1st and 2nd military mapping (1MM, 2MM) regarding the appearance of redoubts (ground plan) situated south of Ústí nad Labem, near the villages of Habrovany and Žim, which were in all likelihood built during the War of the Bavarian Succession (1778–1779) or shortly before. The visual comparison of both types of sources has shown a differently drawn ground plan of one of the redoubts in 1MM compared with what was found in reality (a rectangular ground plan in place of a pentagonal one, documented in DTM) and the absence of this site (it is not sketched) in the 2MM created more than half-a-century later. The reason for this may have been the loss of this redoubt's military significance due to its poor state, the impenetrability of the terrain in which it was located (even today it is overgrown with thick bushes, making it inaccessible in the winter), or negligence by the military land surveyors mapping the area [43].

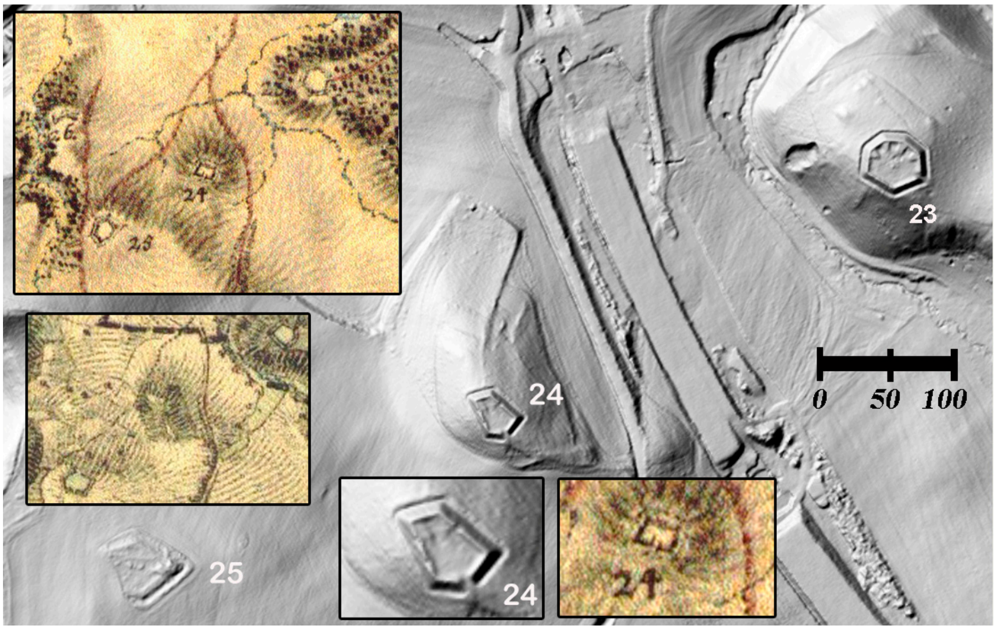

Figure 4. Central part of the Habrovany–Žim area. Comparison of the present state of redoubts in the area of interest via DTM derived from lidar data and their depiction on maps from the 1st and 2nd Military Mapping. The numbers of each redoubt are original part of the Map and served to find their descriptions in a supplemented catalogue. After: [43].

With regard to the physical preservation of field fortification sites, the situation is different in the open landscape of the most fertile regions of the so-called "old settlement territory/first settlement zone" (flat lowlands in the basins of central and lower Labe/Elbe, lower Vltava and Ohře/Egger rivers). The abandoned sites in these regions, which were utilized primarily for grain production, were hindrances in two senses: firstly, they took up a fairly large area of the field tracts in which they were located (leaving such an area agriculturally unused); secondly, they made maneuvering with agricultural tools (primarily horse-drawn ploughs) more difficult. Therefore, they were destroyed by the levelling of convex structures (earthworks) and the filling-in of concave features (ditches, palisade trenches) by soil from the levelled earthworks (Figure 5). In relation to the research of field fortifications, the author's completed aerial-archeological survey focused on the first settlement zone and was based on a targeted search of the buried relicts of military sites using vegetation marks—also known as cropmarks—to detect them. For more details see [37,49–51].

Figure 5. Semi-ruined earthworks of an artillery fort, part of the Třeboutice linear defensive system constructed near the district town Litoměřice. Part of its former rectilinear perimeter ditch (the dark-green zig-zag line) is now filled in and is visible through cropmarks produced by barley growing above it) and 7 this fort is marked by white arrows. In the original plan made in 1860 this fort is labeled Werk III.

2.2. Views from Above and the Discovery of the Hidden Military Dimension of Past Landscapes

Beyond the recent involvement of aerial-archeological surveys in the search for sites, mapping and the documentation of relicts of past military activities has a relatively long tradition abroad [52–55] which began developing to a larger degree in the Czech Republic only at the turn of the 20th and 21st centuries. [56,57]. In the first phase of this period, aerial archeology was almost completely focused on visual surveys practiced during a flight on a small sports plane by an archeologist familiar with the basics and equipped with knowledge of the morphology of field fortifications. The dynamic development of cutting-edge technological equipment opened new opportunities for the search of immovable military landmarks from the air. The onset of digital photography, the global navigation satellite system (GNSS), drones, high-resolution satellite images, aerial laser (lidar) scanning, or freely available orthophoto maps and the digital hypsographic model of the Czech Republic on geoportals and map servers (namely https://geoportal.cuzk.cz; www.mapy.cz; Google Earth; https://ags.cuzk.cz/dmr/, all links have been accessed in 1 January 2023), have unprecedentedly expanded the potential of aerial archeology to such a degree that it is considered today to be only one of several ARS methods. Experience has demonstrated the clear benefits of remote-sensing data for recording, documenting and mapping both specific categories of the cultural landscape and larger regional units.

ARS thus has the potential to have a significant impact on our knowledge of the topography of physically extinct (i.e., unpreserved in the terrain relief) modern field fortifications in the open landscape of the most fertile regions of the Czech lands. Practice focused hitherto on identifying field fortifications via vegetation marks (cropmarks) has shown that the abandoned earth–wood constructions in these areas (sometimes stone was also used as a building material) are located in relatively distinct concentrations. This primarily concerns northwest Bohemia, next to eastern Bohemia (for existing results of modern archeological and historical-cartographic research of relicts of military activities in these areas, see [58,59]), which was the territory of Bohemia most militarily exposed to the threat of invasion by the Prussian army. The vast majority of these sites have been identified in the Ohře (Egger) river basin, namely, along the course of this river, between the towns of Louny, Budyně nad Ohří and Roudnice nad Labem. As the processing of this north–west sector of the Bohemian basin has shown, a spatially structured system of defensive lines was constructed (such as in the period of the Napoleonic Wars), which stretches from below the Ore Mountains to Central Bohemia, and at least to the Mělník region (directly to the confluence of the Labe and Vltava, the two most important of three Bohemian rivers), but may have continued on to Prague. We know from written reports that most of the military facilities built on this territory arose—similar to large bastion fortresses—in the time of military conflicts between Austria and Prussia during the reign of Maria Theresa (Silesian Wars, Seven Years' War, the War of the Bavarian Succession) and the period of the Napoleonic Wars. The last military clashes occurred in the mid-19th century, when conflict flared up between the two monarchies and culminated in the Austro–Prussian War in 1866 (on the archeology of these war battles, see most recently [60,61]).

In spite of the high potential of ARS for detecting field fortification sites it is necessary to keep in mind that the knowledge acquired via ARS on fortifications stems from the specific environmental (soil and subsoil, or quaternary geological) conditions, and that it is therefore geographically focused on landscapes with a permeable gravel–sand subsoil, where arable land continually erodes due to plowing and the slant of the terrain, which positively influences the creation of cropmarks above the sunken features. It is thus wholly legitimate to assume that other sites that are no longer discernable in the terrain can be also discovered in greater or lesser concentrations elsewhere. However, these sites can be found in other ways, primarily by surface survey in connection to reports of diplomatic and narrative origins in historical documents, as well as evidence in the oldest military maps, but also via modern remote-sensing methods. This includes the use of multispectral and thermal sensors placed on drones in order to record field surfaces in which sunken features appear in the form of visibly developed vegetation marks. However, this takes place at irregular intervals: sometimes annually, sometimes only once in many years [62–65].

As the number of newly identified field-fortification sites began to increase and knowledge of them grew (as a result of repeated flights over some sites and the acquisition of photographs with features visualized on various types of arable crops in variable contrasts), questions whose answers might significantly contribute to aerial survey began to arise. These questions deal with the morphology of field-fortification structures, their positioning in the landscape relief, their numbers in militarily important regions threatened by a potential enemy attack, their inclusion into a more permanent defensive system based on a combination of bastion fortresses with a high concentration of soldiers and munitions on one side and a chain of field fortifications (infantry or artillery) on the other. In terms of monitoring the influence of the (agricultural) use of the landscape on the transformation processes that accompanied the single or gradual/long-term demise of these immovable landmarks, it is important to study the ratio between completely abandoned (buried) sites and those whose relicts have been physically preserved in varying levels of destruction in the terrain relief.

The reason for the author's gradually increasing interest in the aerial survey of modern field fortifications was the fact that their area of occurrence is to a large degree linked to the most fertile regions of the Bohemian basin, i.e., with the lower courses of large rivers (the Labe, Ohře, Jizera, Vltava), where aerial-archeological survey was most often carried out since the end of the previous century. There were at least two reasons for selecting these areas. Firstly, they possess the most favorable geological soil conditions for the creation of cropmarks; secondly, as the most fertile regions of the Czech landscape, they are home to the largest accumulation of prehistoric and early-medieval remains of the settlement activities of our ancestors. However, it is already known that vegetation marks can indicate human interventions into the terrain relief regardless of when the intervention took place, i.e., from agricultural prehistory to the modern period. The wide alluvial valley of the Ohře river (still regulated today to a small degree only) between Louny—and, to a lesser degree, even farther west, i.e., Žatec—and its confluence with the Labe near Litoměřice, with its large accumulation of modern field fortifications, has been one of the primary areas of interest during the survey campaigns carried out by the author, and the goal of repeated survey campaigns in the most productive months of the year (i.e., roughly from mid-May to the end of July in terms of the cropmarks' appearance).

The visual prospection of the landscape from small aircrafts (referred to as aerial archaeological reconnaissance/survey) was the primary heuristic method through which most of the Czech post-medieval fortified sites have been detected/discovered and photographically recorded over the last 25 years. This is how ancient-landscape data from above have been acquired since the pioneering times of aerial archaeology in the 1920s when O.G.S. Crawford defined the principles by which buried and semi-buried prehistoric and medieval settlements, burials, ceremonial sites, fields, roads, etc., are to be visually detected when watched from aircrafts flying approximately 300 m above land surface [15]. The method is based on the fact that the chemical composition of secondary infill inside buried features produced by past digging and the removal of material (such as sunken dwelling, former ditch, palisade trench or posthole, storage pit/granary, grave pits, etc.) is different from the natural soil composition in their surroundings. Consequently, during the vegetation season (usually between May and July) plants growing over/above the past human structures have a different height, color and density compared to plants growing outside them. These effects are termed cropmarks. The so-called positive cropmarks indicate the features listed above, whilst negative cropmarks signify features that were erected (e.g., walls). It is important to bear in mind that positive cropmarks are also generated above pits and ditches of natural origin, such as past river basins, erosion wedges, frost wedges, etc. Cropmarks, as the name suggests, are best visible on cultural crops (although there are some examples which record a visible response of wild plants to the presence of buried features, it is more of an exception). The strongest response may be seen on cereals. Experience shows that the best indicator is barley (rye), followed by wheat and oats. Other important crops are sugar beet, rapeseed, garden peas, and, to a lesser extent, maize, sunflower and poppy plants [1,2,12,15,49,50].

Concerning the process of image data analysis and interpretation, most of the aerial photographs—both analogue and digital—have been edited using instruments available in common image editor software (the most frequently used were Photo Shop and Zoner Photo Studio) in order to improve their visual quality, including color saturation, hue, contrast, sharpness, etc.

In addition to the active aerial reconnaissance from low altitude—and photographs taken by a hand-held camera during flights—satellite panchromatic and multispectral data with very high spatial resolution was included from time to time to detect and/or enhance previously recorded crop-marked military installations spread over landscapes. Concretely, a set of QuickBird-2 archival images (taken May 2006) was applied in order to compare the ability of satellite and aerial imagery to make buried prehistoric-to-19th-century sites visible [66]. Using multispectral data and a number of procedures offered by special software (Geomatica and Idrisi) for the analysis enabled the highlighting of the contours of specific features (primarily vegetation indexes), which are also visible on a parallel panchromatic image. In no case was the chosen procedure able to identify an unknown feature that was not captured on a panchromatic image or that was not visually distinguishable. Concerning field fortifications, the site Třeboutice (see Section 3) was used as a case study; Figure 6 shows images presenting the range of enhancement in the cropmarks over this site in NIR, Red and NRVI [64,65].

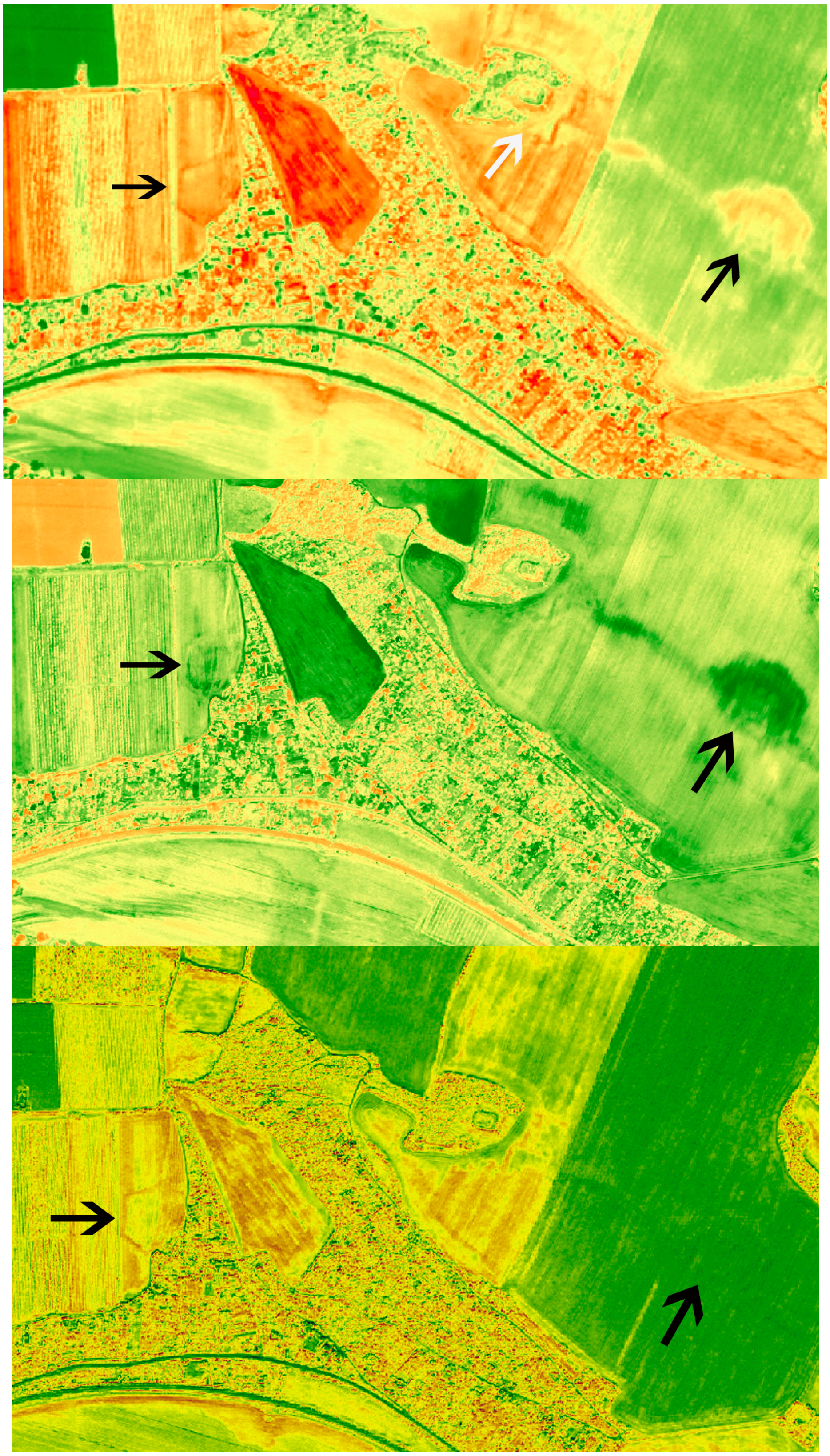

Figure 6. The linear defensive system composed of artillery forts in Třeboutice (district Litoměřice)—one semi-ruined (white arrow) and two completely buried (black arrows), as scanned on 3 May 2006 by QuickBird-2, displayed in the following spectral bands: **top**—NIR, **center**—Red, **bottom**—NRVI. The present author´s project, University of West Bohemia.

The potential of the normative ratio vegetation index (NRVI) for crop-marking over buried monuments is well illustrated on Figure 7. The images produced by using visible spectral bands show soil marks of the ploughed-out artillery fort placed in bottom right corner (A) (in different colors on the surface of the bare fields) are most discernible, while the application of NRVI via IDRISI GIS Analysis software resulted in very well enhanced cropmarks of the buried fort situated to the left which is indicated by a black arrow (B).

Figure 7. The Třeboutice linear defensive system on satellite images captured by QuickBird-2 on 3rd May 2006. (**A**) Combination of multispectral images (spatial resolution 0.61 m) in visible spectral band (R + G + B) adapted with pan sharpening; (**B**) result of the calculation of the normalized ratio vegetation index (NRVI) by the IDRISI software (also pan sharpened). After: [66].

The fact that the satellite images we had the opportunity to work with are sensitive enough to track larger linear features (former water streams, paths, fortifications, ancient field systems, etc.) makes them a valuable resource for studying the former appearance of the landscape as a whole.

2.3. Three-Dimensional Virtual Reconstructions of Crop-Marked Military Components in Past Landscapes

The transformation of analyzed and interpreted aerial photographs taken during active aerial survey (i.e., carried out by archaeologists from low-flying aircraft) into detailed plans/maps of individual sites can undoubtedly be considered the most important step in the process of their evaluation. This is meant both in terms of caring for archaeological heritage, and with regard to the application of data in research. It is this approach that increases the potential for discoveries made through active aerial survey, which the archive of aerial photographs (taken between 1992 and 2016 during annual aerial survey campaigns) of the Institute of Archaeology, Czech Academy of Sciences (IACAS), is now in the final stage of processing.

Recently, assorted prehistoric, medieval, postmedieval, and industrial sites revealed by cropmarks began to be rephotographed from drones in the high-vegetation season (in May–July each year since 2019). Large collections of images then make it possible to produce digital surface models (DSM) of these sites using Image-Based Modelling techniques with Structure from Motion photogrammetry, and to create video clips displaying virtual flights over the landscape with prehistoric villages, fortified sites, cemeteries, military-field installations, and other similar locations indicated by cropmarks [67]. Finally, these DSMs serve as the foundation for the production of digital 3D reconstruction models of buried sites and relics based exclusively on the evidence from cropmarks which are in some cases capable of displaying construction details that one would expect to be achievable only by means of excavation (Figure 8).

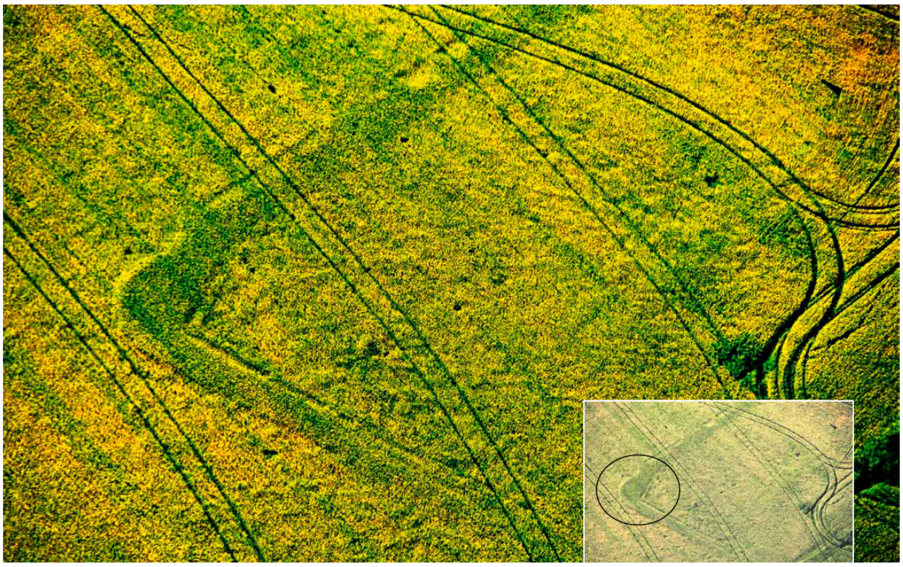

Figure 8. A crop-marked corner of the former defensive ditch and palisade trench of a buried Hornwerk near Poplze (district Litoměřice). The trench turning from the Hornwerk interior to the outside of the structure, in front of the ditch, is clearly visible.

The acquired photographs were processed using Agisoft Photoscan Professional software, long a mainstay in archaeology, using the usual workflow for processing aerial images. The resulting digital 3D model of the site was exported in one of the usual formats, including texture (OBJ, FBX, 3DS), thus allowing its further editing in 3D modelling software (Blender, Sketchup). Alternatively, another workflow was used in the rendering software Lumion 12, where additional data in the form of computer reconstruction models were added to the digital terrain model. It was also possible in the Lumion software environment to continue working with materials to highlight vegetation marks, while another significant advantage was the ability to simulate various lighting conditions. The final video post-processing was performed in Corel VideoStudio, which in addition to the usual functions such as editing or timing of the video, allows you to add additional graphic elements, including text.

The creation of computer-model-based reconstructions of individual crop-marked features was based primarily on the available information for a given period, whereby the appearance of the above-ground parts was based on interpretations of archaeological excavations of the same time period and region. If they were available, earlier drawing reconstructions of similar features by various authors were considered, a comparison with data from experimental archaeology was performed and available historical analogies were used [68,69]. In the majority of cases, the modelling took place directly into the orthophoto with visible vegetation marks, or into plans where the vegetation marks were converted into vector form in the GIS environment and the reconstruction models were subsequently set in the digital terrain model (the described technical workflow was processed by J. Unger, IACAS and M. Sýkora, Institute of Archaeological Heritage Management, Most).

3. Results

In terms of the types of components found in field fortifications, the existing aerial survey of the open landscape of the most fertile areas of the Bohemian basin provided proof of the use of two basic typological variations based on the detection of field fortifications from vegetation marks: closed and open structures. The first group includes redoubts, which were earth fortifications used by both infantry and artillery divisions with a ground plan that was either polygonal (most often pentagonal or hexagonal) or right angled (square, rectangular). It also includes batteries, which were artificially fortified artillery positions in which a tactical unit of between four and twelve cannons was deployed. The second group is represented primarily by lunettes and on rare occasions redans—refer to [53,70,71] for a typology of late modern/early-industrial field fortifications. The type of field fortification itself was created by a Hornwerk-type object which was recorded in two variations: as a site completely enclosed by a ditch, and as a site belonging to the terrain edge (followed by a steep slope) without signs of artificial fortification on the side adjacent to it. The final type is fortification made up of massive artillery forts (essentially sturdy redoubts/batteries), sometimes with mutually connected lines of ditches and communications.

What follows is the presentation of the morphological spectrum of field-fortification elements and the defensive systems linked to bastion fortresses created by their mutual integration, primarily using examples of sites that were constructed ad hoc in the summer of 1813 into a fortification line built as a solution to the impending invasion of French Emperor Napoleon I's armies (Figure 9) [72,73]. However, other sites have also been included in this paper.

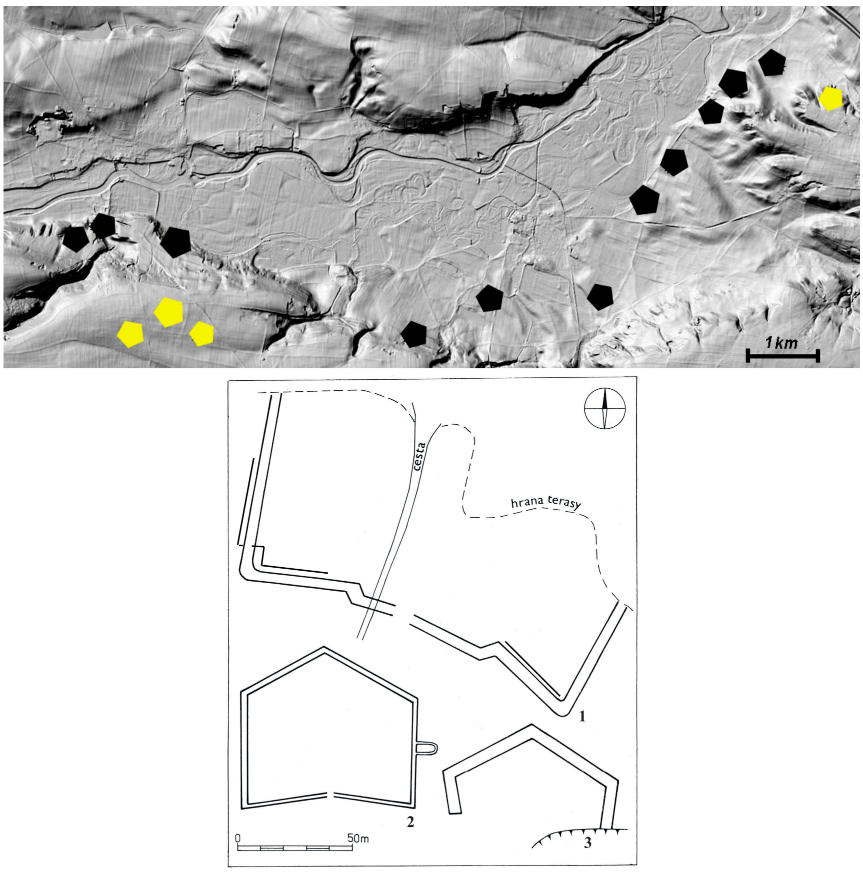

Figure 9. Top—defensive line from 1813 in the Ohře (Egger) river valley between Libochovice and Doksany based on a DTM 5G shaded digital elevation model (Land Survey Office—geoportal, freely available at https://ags.cuzk.cz/dmr/; accessed on 1 March 2023). Yellow marks: sites still preserved in the relief (as earthworks), black marks: field fortifications identified via aerial survey (modified according to [72]); **bellow**—variability in ground plans of field fortifications identified in the Ohře valley between Louny and Budyně nad Ohří according to type: 1. Hornwerk, 2. arrow-shaped redoubt, 3. lunette. Modified according to: [74].

REDANS and LUNETTES are field-fortification features that, in the case of redans, are created by a defensive ditch line that is angled once or several times. In the case of lunettes (Figure 9 bellow, and Figure 10–No. 3), the line is angled most often three times into the ground plan of a non-closed pentagonal redoubt. Throughout the whole modern period, they were used as components of a line system of light earth fortifications or to complement outlying artillery batteries (forts) together with redoubts, e.g., near passages over a watercourse. These are usually features formed by the angled line of one ditch (Figures 11 and 12) or of two parallel ditches on rare occasions (Figure 13).

REDOUBTS and BATTERIES are the most numerous types of field fortifications. They are made up of an area enclosed by a ditch on a polygonal ground plan (seen in the form of thick lines on photographs) and—as can be seen in several cases in the aerial images—by a narrower line made of the palisade's foundation trench, which usually copies the line made by the ditch on its inner side. Recorded examples of these sites differ from each other morphologically, and the singularly built lines in the Ohře basin give no proof of formally standardized shapes—most often, both closed and open features with a variable number of corners were found in one line (Figures 14 and 15). In sites of the kind documented hitherto, pentagonal and hexagonal redoubts with an arrow shape (Figures 16–19) were found most often; however, heptagonal redoubts were found in two cases (Figures 20 and 21).

Figure 10. Example of an open type of field fortification. Lunette, specifically one of the features of the defensive line from 1813 near Louny. In addition to the lunette, a whole palimpsest of lines and points, which are features of prehistoric origins, is visualized under the earth's surface via vegetation marks.

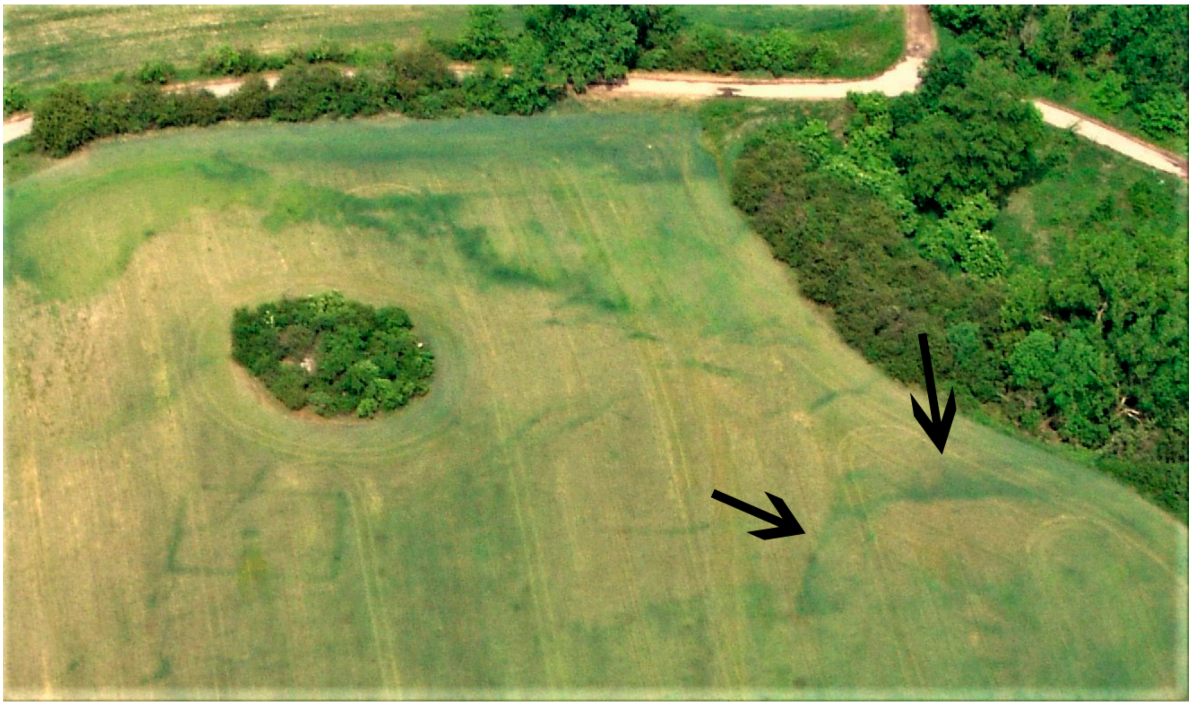

Figure 11. Redan-type field fortifications (indicated by black arrows) near Březno, district Louny. The right-angled enclosure to its left is the ditched enclosure of a prehistoric burial; above it, in the round area overgrown with vegetation, is an infantry bunker from the 1930s.

Figure 12. Interpretation of vegetation marks of a lunette (Písty, District Litoměřice). Parallel interpretation lines (bottom right) visualized via vegetation marks follow the ditch on both sides. After [72].

Figure 13. Lunette constructed by a double ditch (Poplze).

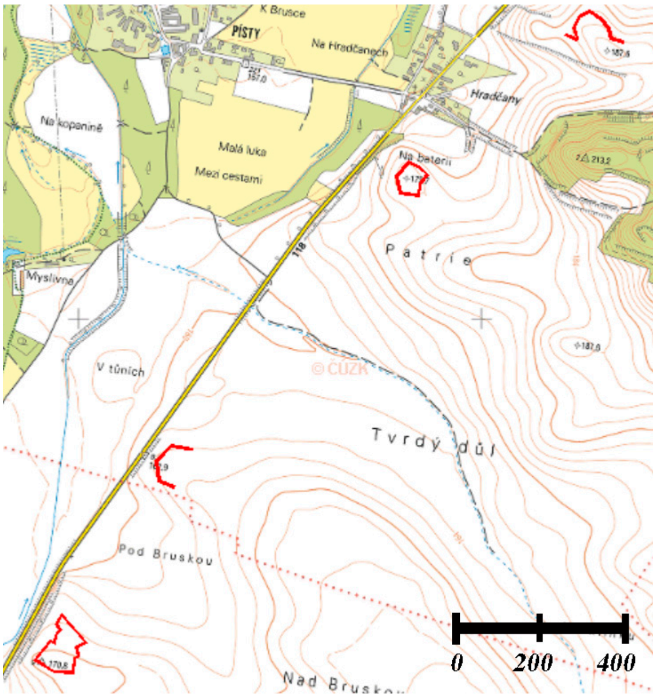

Figure 14. A linear arrangement of various types of field fortifications on the defensive line from 1813 between Budyně nad Ohří and Doksany (vectorization in ArcGIS by J. Dresler, IACAS).

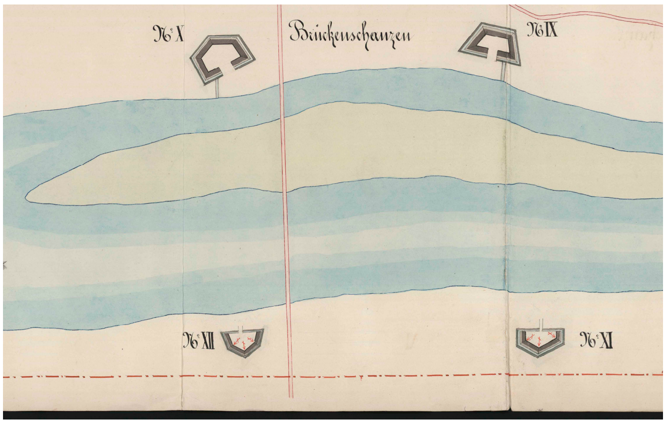

Figure 15. A grouping of polygonal redoubts in the Labe/Elbe alluvium on the northern bank of the river, east of Litoměřice, from the 1860´on the original plan (Kriegsarchiv Wien).

Figure 16. Budyně nad Ohří (district Litoměřice). A six-sided battery with a visible entryway in the middle of the slightly angled back (southern) side.

Figure 17. Most probably a pentagonal battery (as indicated by black arrows) situated near Roudníček (district Litoměřice), by the road to Kostelec nad Ohří.

Figure 18. Redoubt situated directly on the northern bank of the Labe as part of the fortification system east of Litoměřice from the 1860´. According to its placement, it corresponds to the redoubt on the original map (Figure 15 top left, labelled by Roman numeral X).

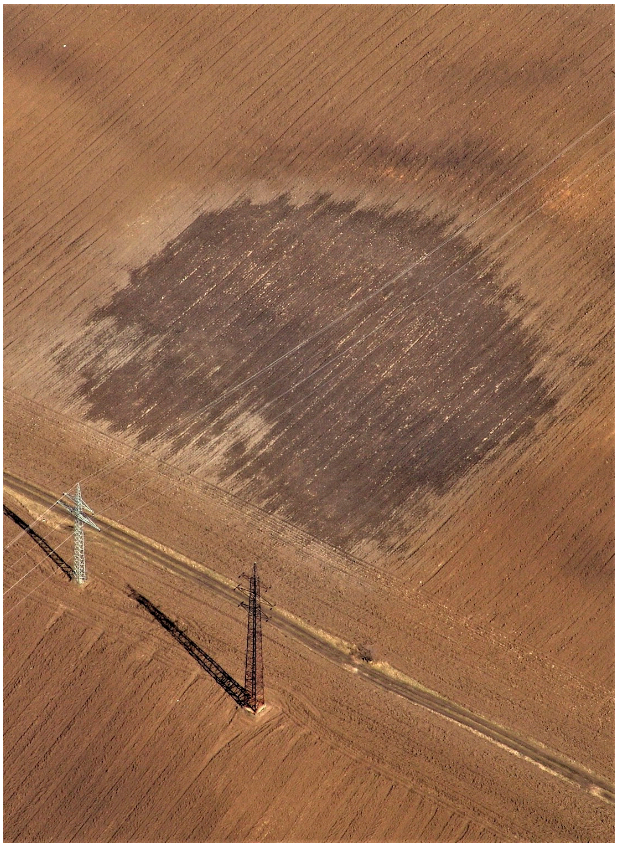

Figure 19. Ground plan of the site interpreted probably as a pentagonal redoubt visible via soil marks (Máslojedy, district Litoměřice).

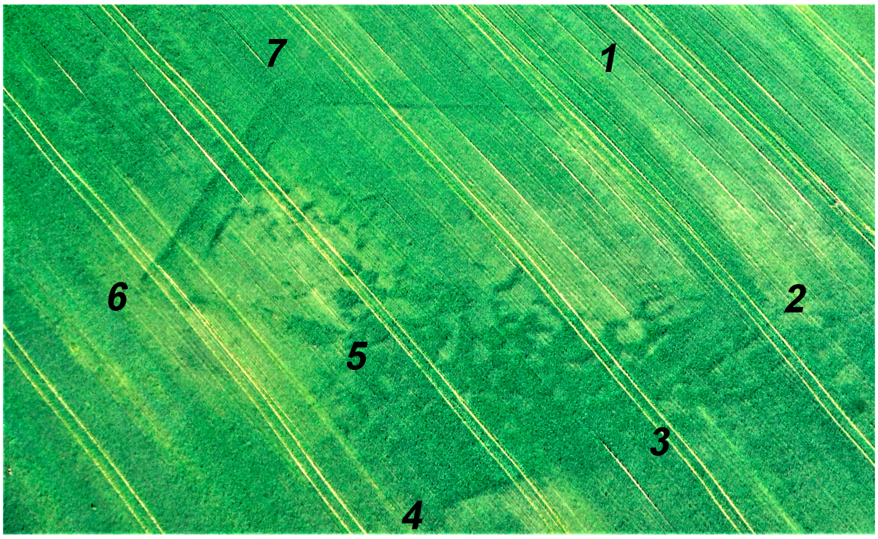

Figure 20. Polygonal battery with numbers marking the corners of the site's ditch enclosure. No. 1 belongs to the front side of the battery facing the potential enemy (Písty–Hradčany, district Litoměřice).

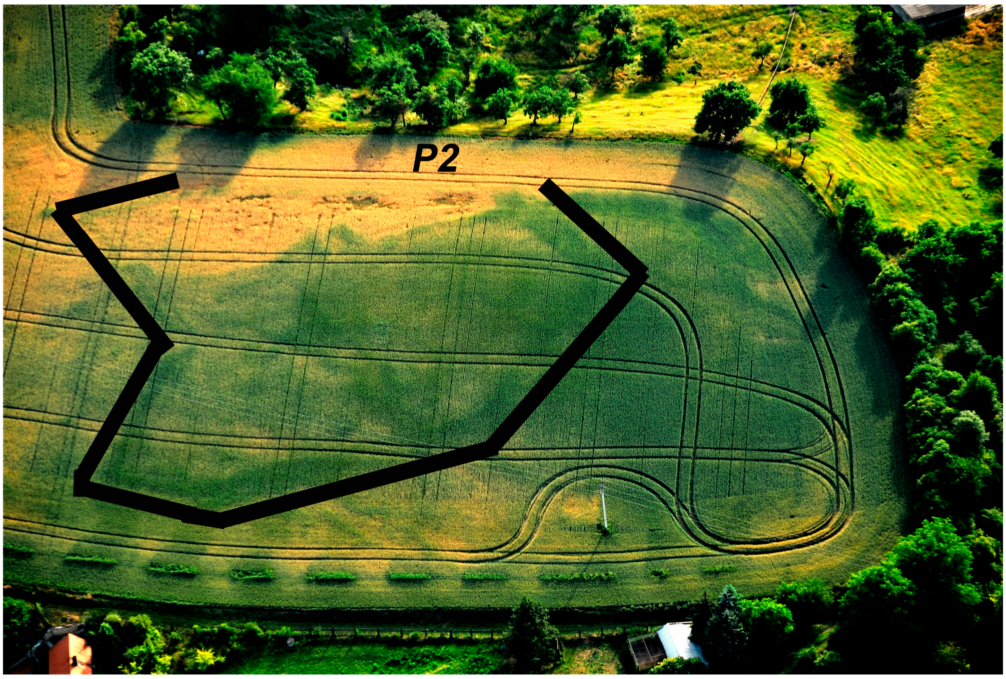

Figure 21. Ground-plan interpretation of crop-marked, seven- or eight-sided battery; dark interpretation line runs parallel to the line of the former ditch on its inner side (P2: Poplze, district Litoměřice, battery No. 2).

HORNWERK (a German term generally applied as terminus technicus in central European terminology; also referred to as crowns and/or corners) tends to be labelled as a sturdier variation of the redan-type fortification. This is because the angled line of the defensive ditch facing the expected enemy is extended only to its flanks and not its back side, as it made use of the natural defenses provided by the environment in which it was placed [74]. This was usually a place on the margin of the terrain's edge (mainly fluvial terraces) followed by a more-or-less steep slope. This is the case of the extensive site situated near Salomínka in Poplze (district Litoměřice; dimensions: 155 × 65–90 m; width of the ditch: 3.5–4 m, Figure 22) on the northern-facing slope of the distinct right-bank terrace of the Ohře, which stretches over the river at a distance of 10 km between Stradonice and Kostelec nad Ohří (in places where fortifications were located, the terrace is 30 m higher than the Ohře valley). On the north side of the site, no remains of a ditch have been preserved and it is not possible to determine whether the site on this side was open or closed by a ditch/wall which could have been destroyed as a result of colluvial erosion (for variations with artificial fortifications, see the attempt at reconstructing the site in Figure 22 bottom. It can be assumed that cannons for the defense of Libochovice's southern bridgehead were located on the right bank of the Ohře opposite Poplze. The aerial image from June 2011 provides an interesting detail: the palisade running along the inner edge of the ditch led outside of it from one of its corners, where it continued to run parallel to the ditch until its outer edge (see Figure 7; [72]).

Figure 22. Aerial picture of hornwerk/corners/crown-type fortification near Poplze (**top**); D reconstruction of the possible appearance of this object, created based on an analysis of aerial photographs (**bottom**). Technical processing by J. Unger, IACAS), see also Figure 8.

A site of similar dimensions and ground plan was identified on the local plain called Bruska in the cadaster of Budyně nad Ohří (Figure 23). It differs from the other site in that its back southeastern side is closed, meaning the whole site is enclosed by an irregular zigzag line of ditch, which complements the parallel lines of the palisade trench on the aforementioned side.

Figure 23. Top left—field fortifications (probably) of the Hornwerk type (Budyně nad Ohří, district Litoměřice); **top right**—clearly visible zigzag line of the ditch and the parallel palisade trench on the eastern side of the site (marked by arrows); **bottom**—ground plan of the site (vectorization in ArcGIS by J. Dresler, IACAS).

With a certain degree of uncertainty, the fortification located in the area of the early-medieval hillfort of Levousy could be labelled Hornwerk (District Litoměřice; Figure 24) and could have been another component of the anti-Napoleonic defensive line in the Ohře river basin. A part of it, i.e., the artificially modified terrain for an artillery firing position not far below the edge of the northwestern part of the hillfort area, is still well preserved today in the terrain relief. In previous years, thanks to vegetation marks, the inwardly angled wide line of a former ditch and the thin line of a palisade trench running parallel to it were recorded via aerial survey over the whole area of the older hillfort. Both lines are interrupted roughly in their middle by an entryway into the field fortifications demarcated in this manner. This design is reminiscent of the so-called "caponier", which was common in bastion fortresses since the end of the 18th century. The back side of such forts created "pincers" allowing for flanking fire from cannons and infantry and the mutual coverage of both wings [73].

Figure 24. Extensive surface of the former early-medieval hillfort of Levousy (district Litoměřice) traversed by parallel lines of a ditch and a palisade trench (Hornwerk?).

FORT LINES—OUTLYING MASSIVE ARTILLERY FORTIFICATIONS. Two sites of this type have been recorded in Bohemia. They represent a defensive system characterized by a concentration of several massive artillery and infantry redoubts (labelled in these cases by the term fort), which are either of the same ground-plan type and are not mutually connected by ditches/walls and communications parallel to them, or were each constructed on a different ground plan and a compact defensive base was built by connecting them via a ditch line. They were built either in the foreland of bastion fortresses or near important landscape components (e.g., at the confluence of larger rivers), and had strategic connections to important communications, cities, etc.

An example of the first-mentioned type of fort line is the site located on the confluence of the Labe and Vltava rivers below Mělník (cadastral village of Hořín), where the ground plans of four extensive forts of a specific shape were gradually detected over a period of twenty years (Figure 25). Their ground plans were formed by 5- to 7-m-wide ditches accompanied in at least one proven case by a palisade running parallel to its inner edge (Figure 25). It is highly probable that this defensive grouping was constructed as the easternmost part of the defensive line from the summer of 1813 mentioned in the previous chapter [75].

In Netřebice near Nymburk, an aerial survey in 2011 recorded roughly half of an object that is to a certain degree reminiscent in size and partially in shape of the fort in Hořín, but its interpretation is uncertain without further research (Figure 26). If this was truly a field fortification, we would probably trace it to the military operations of the Seven Years' War (1756–1763) and most likely to the Battle of Kolín.

The second grouping of forts is a half-century younger than the complex near Hořín. It comes from the period of preparations for the invasion of the Prussian army in the 1860s and was built on the Labe's terrace east of Litoměřice as a bridgehead of Terezín after more than half a century of this bastion fortress's existence (Figure 27), when qualitative improvements to cannons made shortly after the mid-19th century (i.e., rifle-boring of barrels and cylindrical, pointed projectiles) posed an imminent threat of bombardment to the Terezín fortress from the high terrace on the northern bank of the Labe. The whole area was still fully preserved a half-century ago (as shown by black and white aerial surveying images and military maps), when its controlled demolition began. However, this destruction only affected one half of the site. Two wholly (and one partially) levelled forts have been continually and successfully recorded on aerial photographs, which show cropmarks with various intensity and in various quality of detail due to the annual alternation of agricultural crops (for more detail on this fort grouping, see [76]).

Figure 25. Top left—Arch-shaped line of four crop-marked massive forts built on mutually similar ground plans on the confluence of the Labe and Vltava (Hořín, district Mělník; vectorization in ArcGIS by J. Dresler, IACAS); **top right**—fort 2; **central image**—fort 3, arrows indicate the visible section of the palisade trench; **bottom image**—3D digital reconstruction of a probable design of the fort No. 1. (author: M. Sýkora, project of the IACAS).

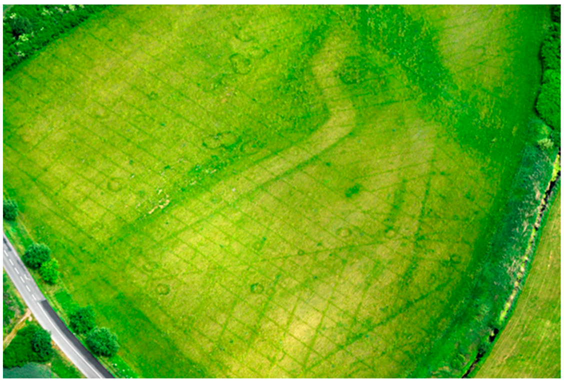

Figure 26. Probably part of a crop-marked fort near Netřebice (district Kolín).

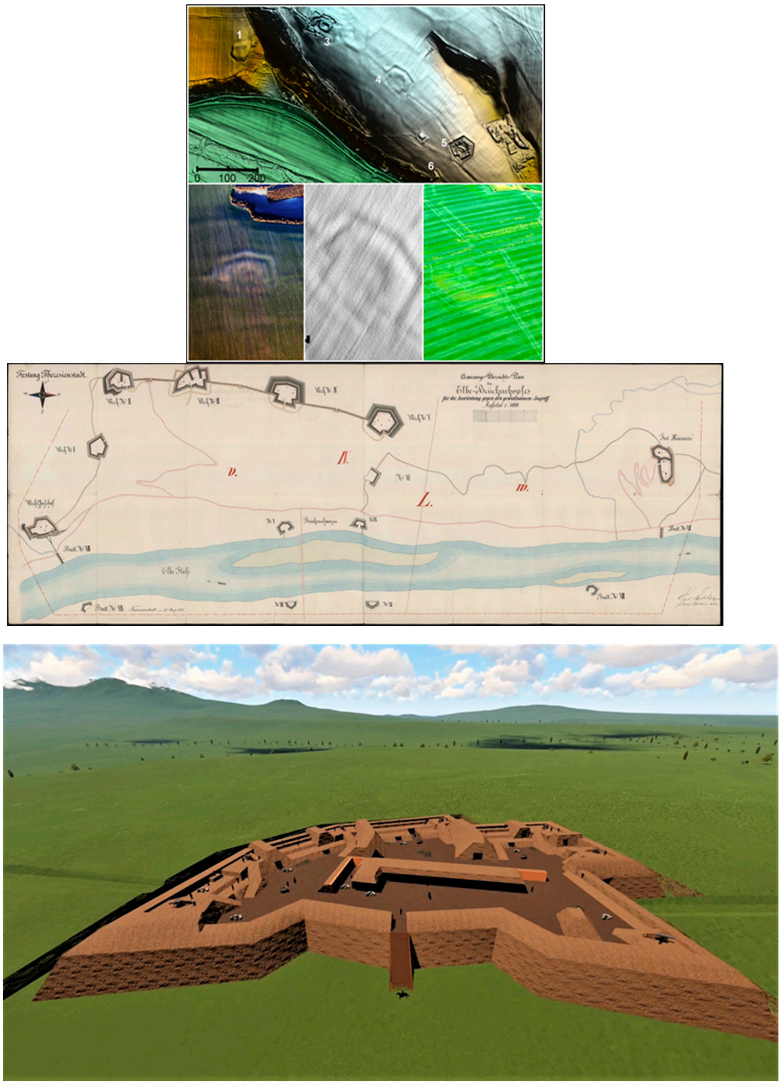

Figure 27. top image – visualization of the Třeboutice linear defensive system of artillery forts from the 1860s east of Litoměřice using various visualization methods. **Top**—forts 1,3,4,5,6 on DTM derived from aerial lidar data; **bottom**—fort No. 4: shadow marks on oblique aerial photograph on the left, shadow marks on DEM derived from lidar data in the center, aerial photo of cropmarks on the right; central image—Terezín bridgehead on the right-bank terrace of the Labe between Litoměřice, Trnovany and Třeboutice on the original plan from the mid-19th century (see also Figures 15 and 18); **bottom image**—3D digital reconstruction of a probable design of the fort labeled Werk III on the original plan, (author: M. Sýkora, project of the IACAS).

4. Discussion

For professional archaeologists, the 3D reconstruction models are an important format to illustrate the potential in remotely sensing/detecting archaeological remains which are completely hidden beneath the surface in a way that is non-invasive and which also has the ability to display the precise ground plans of a variety of buried sites of any age and complexity—under certain conditions. On the other hand, the processing of the gathered aerial photos (both oblique and vertical) into the animated 3D reconstruction models has the potential to offer non-professionals an idea of how to read the landscape memory exposed to current observers via clusters of points and lines of cropmarks in cultivated fields. Certainly, we still must keep in mind questions regarding the validity of remotely acquired data in terms of their archaeological interpretation, and, as a consequence, the final 3D reconstruction models obtained from them. Nevertheless, for the study of past societies, visualization allows us to see the invisible and offers science new and unexpected perspectives [77]. Moreover, if we operate with features that are too complex, incomprehensible, or exist only in our minds, it is extremely desirable to create visual models representing them as these will enable us to better understand their construction, organization, or transformation. Modelling thus creates analogies to realities that do not have an actual visual form, which mainly concerns multidimensional non-existent structures or objects that change over time.

Apart from the production of 3D reconstruction models, it should be stressed that the integrated remotely sensed data are an effective base for analyzing a variety of procedures concerning archaeological and architectural heritage, such as the diachronic evaluation of the processes of destruction traced on monuments, the documentation of sites and structures harmed by heritage looters, or the identification of buried structures, etc.

5. Conclusions

As the lines above have shown, the issues involved in identifying and recording sites labelled with the general term of field fortifications originating from the post-medieval to the industrial era is significantly dependent on both traditional and modern methods of remote sensing. Indeed, this is because the earth-and-wood constructions of batteries, redoubts, redans, lunettes, etc., were mostly only temporary structures built against an expected military attack and were thus quickly levelled after the end of the conflict so that their built-up area could be used again as soon as possible for economic purposes, primarily agriculture. This mainly concerned structures that were placed in agriculturally fertile lowland areas, while in higher positions (e.g., the Czech Central Mountains and the Ore Mountains) the opposite may have been true, as some fortifications were evidently preserved for future military needs. Thus, most of the fortifications found in mountainous areas, especially in the lowlands, have left little to no trace of their existence on the surface of the terrain relief. Considering their relatively large sizes, they are identifiable primarily using non-invasive survey techniques, which are methods that are primarily used in remote archeological surveys. As recent studies of field fortifications have shown, remote landscape survey—which is primarily based on visualizing buried features using vegetation marks—is one of the most important tools in the process of identifying and recording these sites.

Concerning the application of 3D-reconstruction virtual modelling to 'invisible' archaeological heritage, a double effect is obvious in terms of its potential. Firstly, it is a way of encouraging scholars to pay closer systematic attention to the analysis, processing and interpretation of remotely acquired data; secondly, it is a method with the ability to promote the general public's interest in the study and enjoyment of the human past—both ancient and recent.

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