Exploring the UAV-Based Ground-Penetrating Radar for Historical Site Detection: A WWII Hiding Place Case Study near Bornerbroekseweg

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ABSTRACT

This study evaluates the potential of Unmanned Aerial Vehicle-based Ground-Penetrating Radar (UAV-GPR) for identifying buried features related to a suspected World War II (WWII) hiding place near Bornerbroekseweg, the Netherlands. The survey area is an active farmland field with limited surface indicators and partially documented historical significance. A total of six UAV flight lines and four ground-based GPR paths were conducted to cover the site. Subsurface anomalies were identified at depths between approximately 0.2 and 1.5 m. In particular, Flight 6 revealed a near-surface reflection at 0.2–0.4 m, whereas Flight 4 showed a deeper horizontal anomaly at around 1.2–1.5 m. Ground-based Path 3 supported these findings with continuous horizontal reflections distinct from natural stratigraphy. The integration of UAV and ground-based data enabled full-site coverage and localized resolution, supporting the identification of areas warranting further archaeological investigation. The results demonstrate the applicability of UAV-GPR for non-invasive prospection in rural historical sites with uncertain spatial records and suggest its value for informing targeted excavations.

Keywords-Ground-Penetrating Radar (GPR); UAV-based sensors; remote sensing; cultural heritage preservation; anomaly detection; radargram; non-invasive prospection

I. INTRODUCTION

Non-invasive geophysical techniques have transformed historical research by making it possible to detect and characterize subsurface features without tampering with sensitive or protected areas. Ground-Penetrating Radar (GPR) is a versatile and widely used method of historical prospection within these techniques. GPR operates by transmitting electromagnetic waves into the ground and recording reflections from subsurface structures with contrasting dielectric properties. This makes GPR a valuable method for the determination of buried walls (archaeological structures, unknown objects, graves, foundations, voids, and stratigraphic discontinuities) [1-3].

Traditionally, GPR surveys have been performed manually with handheld or cart-mounted units, with researchers systematically walking across survey areas. While effective, there are several drawbacks to such a method: physical access to the site, time constraints for larger survey areas, and possible interference with delicate surfaces [4]. Additionally, on densely vegetated, marshy, or otherwise hazardous ground, ground-based GPR surveys can be infeasible.

The combination of GPR technology with Unmanned Aerial Vehicles (UAVs) provides a viable alternative to existing practices. UAV-mounted GPR technology can cover extensive areas using a minimally ground-disturbing approach at high speed, yielding new opportunities for the detection of archaeologically significant features within demanding topography [5-7]. New challenges are, however, introduced with the technology, including the need for a stable flight altitude to produce high-quality data, signal loss due to variations in the soil, as well as a reduced spatial resolution compared with ground-based technology [8-10].

Despite these challenges, UAV-based GPR is proving to be a valuable tool for remote sensing archaeology, especially for reconnaissance surveys, risk assessments, and the identification of areas for more extensive excavation. Nonetheless, there are few documented uses of UAV-GPR systems for real historical case studies, and more work is necessary to test their performance under a wide range of field conditions [11].

The subject of the current research is the application of UAV-based GPR for detecting historical sites by means of a case study of locating a World War II (WWII) hiding place, the "Onderduikhol", situated near Bornerbroekseweg, Wierden municipality, the Netherlands. Several Jewish families hid during WWII under the German occupation inside such improvised shelters as the Onderduikhol. Many of these locations were hidden purposely, and their exact positions have now been lost to history.

During the German occupation of the Netherlands in WWII, numerous Jewish families and members of the resistance went into hiding in improvised shelters known as onderduikholen, camouflaged underground bunkers or pits. These hiding places were often constructed in remote fields, forests, or on farmland, designed to be invisible from aerial surveillance and unknown even to neighbors. After the war, many of these shelters were either destroyed, repurposed, or forgotten due to landscape changes, lack of documentation, or the sensitive nature of the events. The Wierden municipality, and specifically the rural area near Bornerbroekseweg, is historically noted for several such wartime shelters. Local testimonies and historical narratives point to the presence of a concealed chicken coop that served as a refuge for multiple families, though its precise location was never formally documented. Given the historical significance and humanitarian value of such sites, locating and preserving them is an important step toward understanding civilian resistance and survival during WWII.

Based on historical records and testimonies, the suspected hiding place was believed to be located in agricultural fields bordered by Bornerbroekseweg, Huttemansweg, and Entelerweg. The structure, a buried chicken coop modified for camouflage, was estimated to have a size of around 4 × 7 m with a depth of around 60 cm. Although local accounts helped restrict the general area, the exact location of the hiding place had been lost over time. This necessitated the use of systematic UAV-GPR survey paths to help identify more precise anomaly zones. A historical topographic map from 1901 with the suspected search area outlined in blue is shown in Figure 1 to provide geographical and historical context.

To identify possible remnants of the Onderduikhol, a comprehensive geophysical survey was conducted with a drone-mounted Compact Broadband Detector (CBD) [12] GPR system combined with a DJI Matrice 600 Pro [13] UAV, supplemented by a handheld ground-based survey for validation. This article outlines the methodology, results, and reflections from the survey, as well as considers the wider implications of the application of UAV-based GPR for historical and heritage contexts.

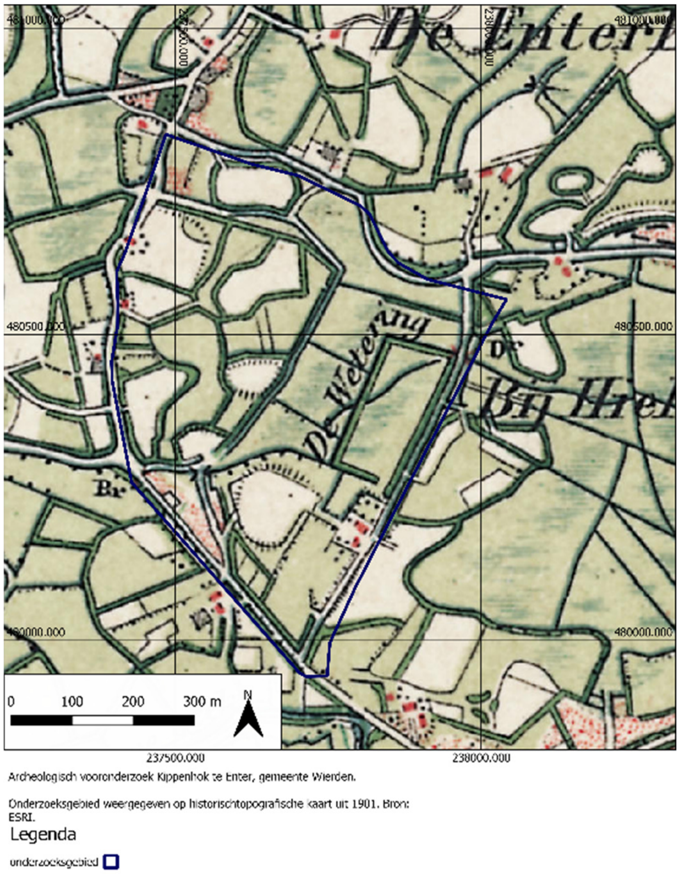


Fig. 1. Study area highlighted on a 1901 historical topographic map of the Wierden municipality, showing the agricultural field believed to contain the WWII hiding place. The marked field lies between Bornerbroekseweg, Huttemansweg, and Entelerweg.

By bringing actual field data and insights to bear, the research strives to improve the knowledge of UAV-GPR applications within historical prospection as well as identify its strengths and weaknesses when applied to sensitive historical investigations. The study's key contributions are:

- Scientific contribution: The research validates UAV-based GPR for heritage archaeology, with a strong focus on identifying small-scale historic structures in complex soils. It presents a critical examination of the performance and interpretation constraints of operating a UAV-GPR system within real-life heritage applications.
- Practical contribution: The research supports cultural heritage preservation efforts by proposing efficient, non-invasive methods that can help historians, archaeologists, and municipalities identify hidden or lost history sites without actual excavation.

Recent research has explored the integration of UAV-based GPR systems in a range of domains, including archaeological prospection, infrastructure inspection, geotechnical analysis, and environmental monitoring. These applications have demonstrated the technical feasibility and practical advantages of deploying GPR from aerial platforms, such as rapid data acquisition, access to hard-to-reach areas, and reduced ground disturbance [14, 15]. In archaeological and historical contexts, UAV-GPR has been used to detect subsurface walls, foundations, burial chambers, and former road networks, often with promising results when survey areas are well-defined or supported by previous excavation records. Similarly, in civil and environmental engineering, UAV-mounted GPR has shown utility in locating pipelines, sinkholes, and voids beneath roads or open terrain.

However, the majority of these studies are conducted in settings where the approximate location, depth, or geometry of the buried features is already known or at least hypothesized based on prior knowledge. This allows survey planning and data interpretation to be optimized around known targets. While useful, such contexts differ substantially from real-world historical or forensic scenarios where surface indicators are absent, documentation is sparse, and terrain conditions may have changed over time. In these more ambiguous cases, the applicability of UAV-GPR remains underexplored, particularly as a first-pass tool for identifying areas of interest that justify further investigation or excavation.

In contrast, the present study applies UAV-GPR to a historically relevant location where no visible surface traces exist and the precise location of the suspected feature is unknown. The investigation was informed only by oral testimony and historical accounts, without the benefit of previous excavation or structural data. This context reflects a growing need for non-invasive methods that can be used in preliminary surveys of undocumented or sensitive sites. By combining UAV-based and ground-based GPR surveys, this work illustrates a flexible approach to data collection and anomaly detection across terrain that has been transformed by decades of agricultural use. The study thus contributes to the growing field of UAV-GPR by demonstrating its practical use in uncertain real-world scenarios and offering insights into its methodological value for heritage-related investigations, with relevance not only for archaeology but also for other fields such as crime investigations [16-18].

II. MATERIALS AND METHODS

A. *Overview of Ground-Penetrating Radar Technology*

GPR is a geophysical method that relies on the propagation of electromagnetic waves to image and detect subsurface features. GPR works by emitting short bursts of high-frequency radio waves into the ground and measuring the reflections from subsurface structures due to contrasting dielectric properties [19]. Radargrams resulting from these reflections exhibit layering, voids, buried structures, and other anomalies, making GPR a proven method of archaeological and historical prospection [20].

The penetration depth and the level of detail of GPR data are governed by a number of controlling factors, such as the frequency of the antenna, the composition of the ground, the groundwater content, and the electrophysical characteristics of the surveyed material [1]. Low-frequency antennas (e.g., 100–400 MHz) can provide deep penetration but lose detail, whereas high-frequency antennas (e.g., 500–1000 MHz) can offer more detail but less penetration. A trade-off between penetration depth and detail is desirable for archaeological and historical applications, particularly when buried small-scale structures are at relatively shallow levels.

The application of GPR-based platforms using UAVs was recently designed to address constraints inherent in conventional surveys, including restricted access to sensitive zones, surveyor fatigue, and the need to cover extensive ground areas [21]. The installation of GPR equipment on a UAV allows for fast, regular, and non-intrusive surveying, challenges such as maintaining a constant flight height and signal attenuation due to ground conductivity must be addressed for effective application [22].

B. Equipment and Data Collection

1) Unmanned Aerial Vehicle Platform

An aerial survey was performed using a DJI Matrice 600 Pro (M600 Pro) [13] UAV, a heavy-lifting professional hexacopter designed for high-stability flight with heavy payloads. The M600 Pro incorporates a six-rotor platform, a GNSS/RTK positioning system for true precision positioning, and the A3 Pro flight controller for repeatable, accurate flight trajectories even under moderate wind speeds. M600 Pro can carry a maximum payload of around 6 kg with a standard flight duration of 16–30 min, depending on payload and battery configurations.

The UAV was operated at around 2 m above ground level for this research. This altitude was chosen to maximize the trade-off between signal penetration and resolution. Small altitude variations occurred during flight due to ground effects and environmental factors, a common challenge for UAV-based GPR applications [23, 24]. Future development could include real-time altitude control devices, such as laser rangefinders or downward-pointing radar altimeters, to improve data consistency.

2) Ground-Penetrating Radar Sensor

The GPR device utilized was the CBD GPR produced by Radarteam Sweden AB [12]. This lightweight, UAV-mounted GPR device is optimized for geophysical imaging in hard-to-reach areas.

Operating within a wide frequency range of around 400–800 MHz, the CBD GPR provides a reasonable compromise between penetration depth and resolution for detecting historical objects within the top 2–3 m of the subsurface.

Key specifications of the CBD GPR include:

- Antenna frequency range: 400–800 MHz.
- Penetration depth: up to ~3 m, depending on soil conditions.
- Weight: approximately 3–4 kg.
- Data acquisition: high-speed radargram collection with GNSS-tagged coordinates.
- Software compatibility: Prism2 platform for data processing and visualization.

The CBD GPR unit was mounted beneath the UAV using a custom suspension system designed to minimize vibrations and mechanical interference during flight.

3) Data Collection Protocol

Data collection was conducted during two dedicated field campaigns:

- March 31, 2025: Initial UAV-based survey covering both left and right sections of the test field.
- April 9, 2025: Ground-based survey of the right section of the test field using the same GPR sensor mounted on a wheeled cart for comparative analysis.

The UAV survey employed predetermined flight lines with overlapping passes to obtain complete coverage of the area of concern. Eight individual flights (Flight 1–8) were conducted with attention to both extensive field coverage as well as specific high-probability areas derived from preliminary results. Each radargram was geotagged with GNSS data to allow spatial correlation with aerial imagery and ground features. The narrow and repetitive survey routes reflect the strategy of methodically covering a historically identified high-likelihood zone where testimonies had suggested presence but no exact coordinates were available.

At the same time, a ground-based survey was conducted using the same GPR mounted on a manually operated cart. Three paths (Path 1–3) were surveyed, with a focus on the right half of the field, which was recognized as the most likely place for the Onderduikhol due to records. All the GPR data were captured as binary data and later processed with Prism2 software for visualization, filtering, and interpretation.

4) Data Processing and Analysis

Preprocessing and interpretation were performed using Prism2 [25], a specialized software suite designed for GPR data handling. The following standard preprocessing steps were applied:

- Time-zero correction: Aligning the start of each radargram to a common reference point to ensure consistent depth scaling.
- Background removal: Eliminating constant reflections from the surface and background noise to enhance subsurface anomaly visibility.
- Gain adjustment: Applying signal amplification functions to compensate for attenuation with depth, allowing clearer visualization of deeper layers.
- Migration (where necessary): Correcting hyperbolic reflections to better localize point targets.

Analysis was targeted towards the identification of planar reflections, hyperbolic signatures, and localized anomalies that are indicative of possible anthropogenic structures. Special attention was directed towards depths within the range of 0.2 to 3 m, consistent with the predicted burial depth of the Onderduikhol and associated features.

Interpretation of data was performed with careful consideration of the known GPR constraints, which encompassed effects of soil conductivity, environmental conditions (e.g., water content), as well as spurious positive effects from agricultural operations like ploughing [26-29].

III. RESULTS

A. Drone-based Survey Results

1) Flights 1–3: Left Field Survey

The first three flights focused on the left portion of the field, which was initially considered less likely to contain structural remains based on historical accounts.

a) Flights 1 and 2 (Near-Wall Passes)

The radargrams generated from Flights 1 and 2 displayed continuous, uniform horizontal layering throughout the upper ~2.5 m of the subsurface. A prominent planar reflection was consistently observed at approximately 1.5–1.7 m depth across both flights, suggesting a natural soil boundary or a denser geological layer.

Importantly, no hyperbolic reflections, which could indicate discrete buried objects such as voids, stones, or constructed features, were detected. The consistency between Flights 1 and 2, presented in Figures 2 and 3, suggests the subsurface conditions in this area are stable and relatively undisturbed.

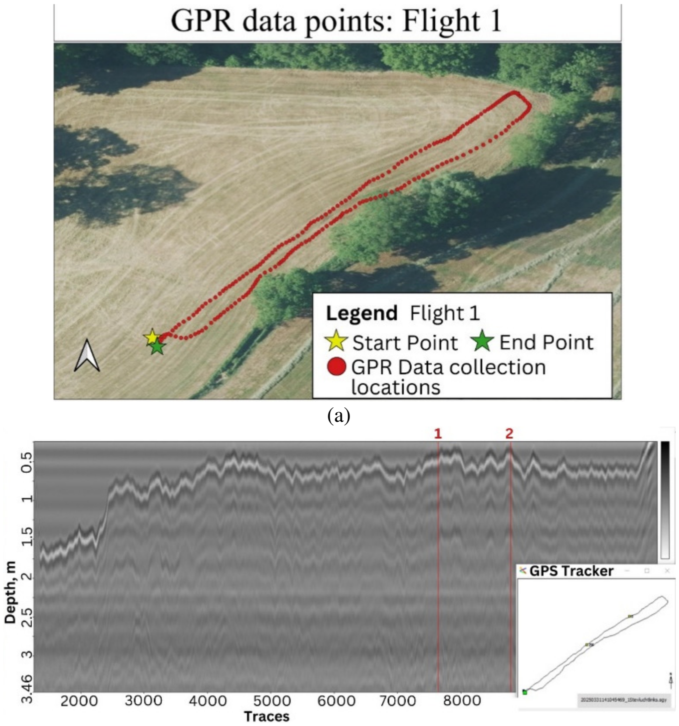


Fig. 2. (a) Flight path and GPR data points for Flight 1, (b) radargram of Flight 1 showing planar reflections between traces 7,641 and 8,786.

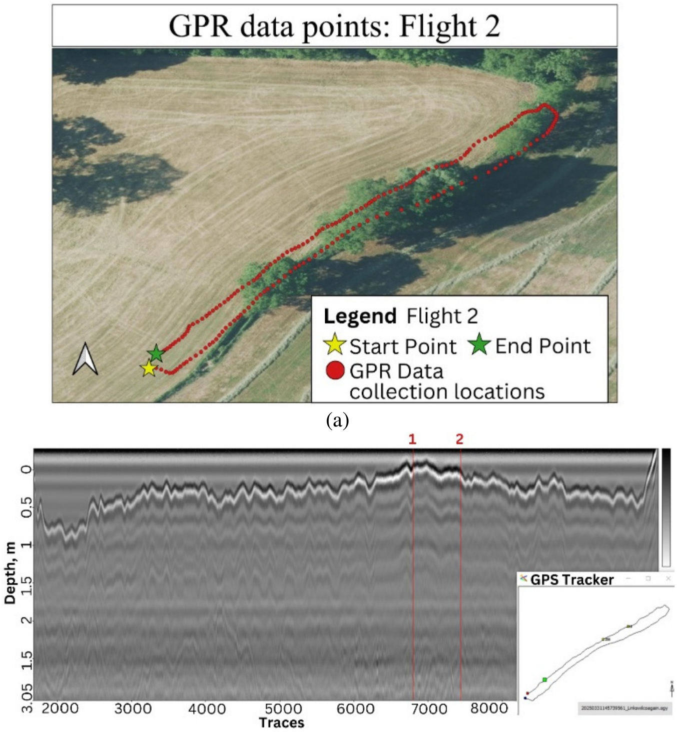


Fig. 3. (a) Flight path and GPR data points for Flight 3, (b) radargram of Flight 3 with highlighted planar reflections.

Figures 2(a) and 3(a) show the spatial layout of the drone's survey paths over the left field section, visualized on an aerial orthoimage. Red dots represent individual GPR data collection points, with a clear linear trajectory indicating a stable flight path. The yellow star marks the starting point, and the green star indicates the endpoint of the flight. The two parallel lines represent the outbound and return passes of the drone during the near-wall survey, ensuring data consistency through repeated coverage of the same area.

b) Flight 3 (Offset Survey 2 m / 6 m from Wall)

Flight 3, shown in Figure 4, expanded the survey coverage outward from the wall. The radargram again revealed mostly uniform stratigraphy, with a slight increase in reflection amplitude between traces 4,934 and 5,525 at around 1.5 m depth. This localized planar reflection may indicate subtle subsurface heterogeneity but showed no clear evidence of human-made structures.

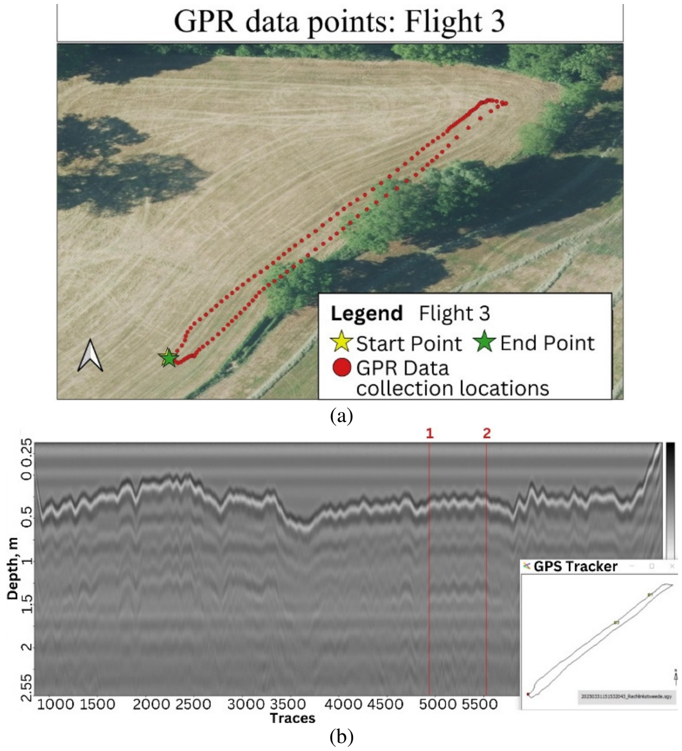
Overall, the left field surveys indicated a geologically homogeneous area with no strong indications of buried historical features.

2) Flights 4–8: Right Field and Targeted Zones

Based on historical information suggesting a higher probability for the hiding place location on the right side of the field, Flights 4–8 concentrated efforts in this area.

a) Flight 4 (Right Field Near-Wall Pass)

As presented in Figure 5, two distinct planar reflection zones were detected between traces 7,247 and 7,842 within a shallow depth range of 0.2–0.6 m. These strong, coherent reflections stand out against the surrounding stratigraphy and suggest localized subsurface anomalies potentially related to past disturbances or buried materials.



(a)

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Fig. 4. (a) Flight path and GPR data points for Flight 3, (b) radargram of Flight 3 with highlighted planar reflections.

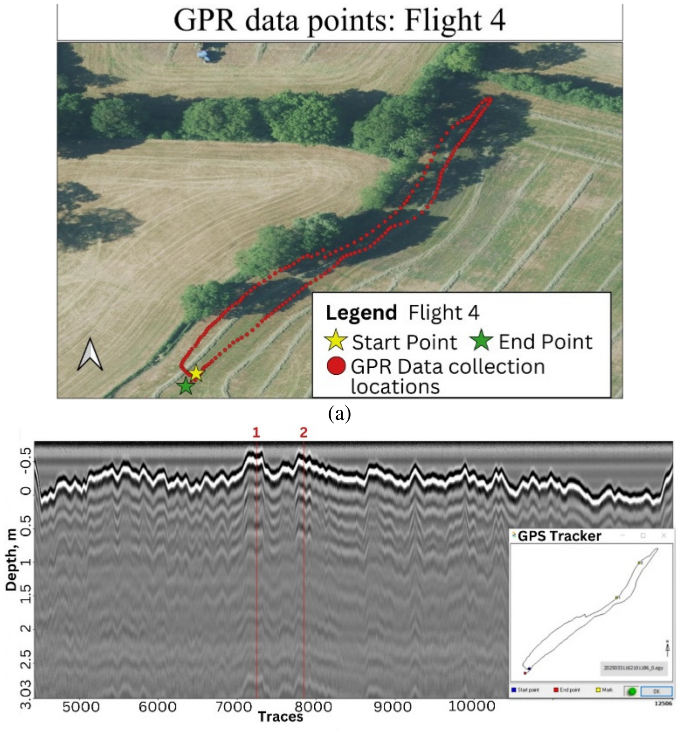

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Fig. 5. (a) Flight path and GPR data points for Flight 4, (b) radargram of Flight 4 highlighting planar reflections at marks 1 and 2.

b) Flight 5 (Repeated Flight 4)

A second flight over the same trajectory, as shown in Figure 6, produced radargrams that lacked the clear anomalies observed in Flight 4. The data primarily exhibited regular stratification without distinct localized features. This discrepancy could be due to slight lateral shifts in flight path, variable soil moisture content, or natural subsurface variability.

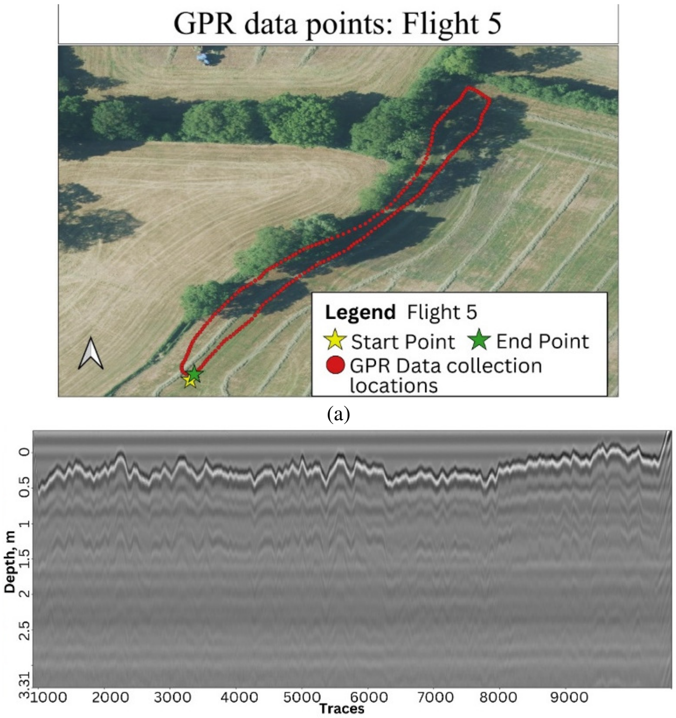

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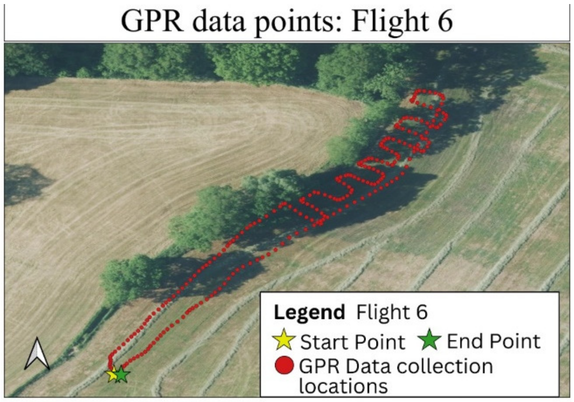
Fig. 6. (a) Flight path and GPR data points for Flight 5, (b) radargram of Flight 5 showing general stratification.

c) Flight 6 (Offset 2 m / 6 m Right Field)

Offset passes, shown in Figure 7, aimed at expanding the search perimeter revealed no significant anomalies. The resulting radargrams displayed continuous stratified layers, reinforcing the localized nature of the disturbances observed in Flight 4.



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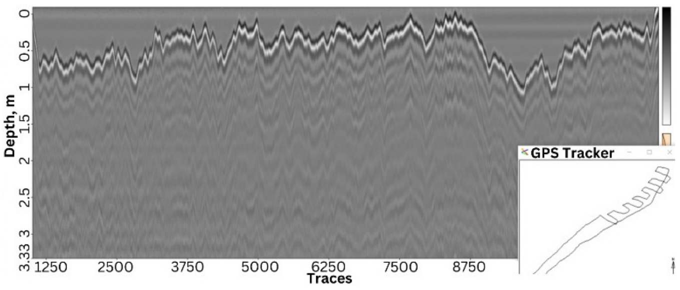

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Fig. 7. (a) Flight path and GPR data points for Flight 6, (b) radargram of Flight 6 with GPS overlay.

d) *Flight 7 (Targeted High-Probability Zone 1)*

Flight 7, presented in Figure 8, focused on a previously identified area of interest, revealed shallow linear reflection anomalies between traces 7,000 and 10,500. Although these anomalies lacked the parabolic geometry typical of voids or compact buried structures, they may indicate subtle soil disturbances or slight changes in material composition.

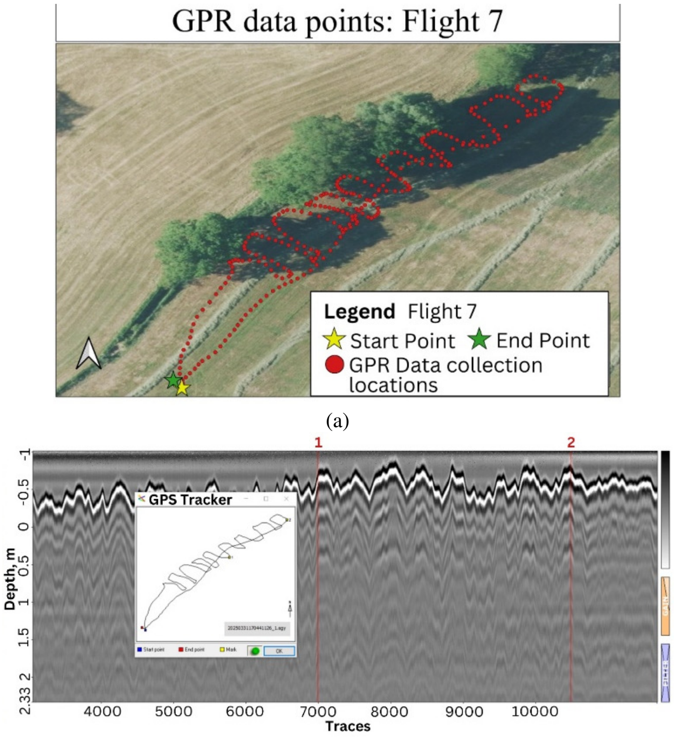

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Fig. 8. (a) Flight path and GPR data points for Flight 7, (b) radargram of Flight 7 showing localized planar reflections.

e) *Flight 8 (Targeted High-Probability Zone 2)*

Radargrams from Flight 8 (Figure 9) exhibited significant attenuation, with signal strength diminishing rapidly with depth. The blurry and noisy data strongly suggest elevated soil conductivity or moisture saturation, which likely masked weaker reflections and severely limited the ability to detect or interpret any meaningful subsurface features.

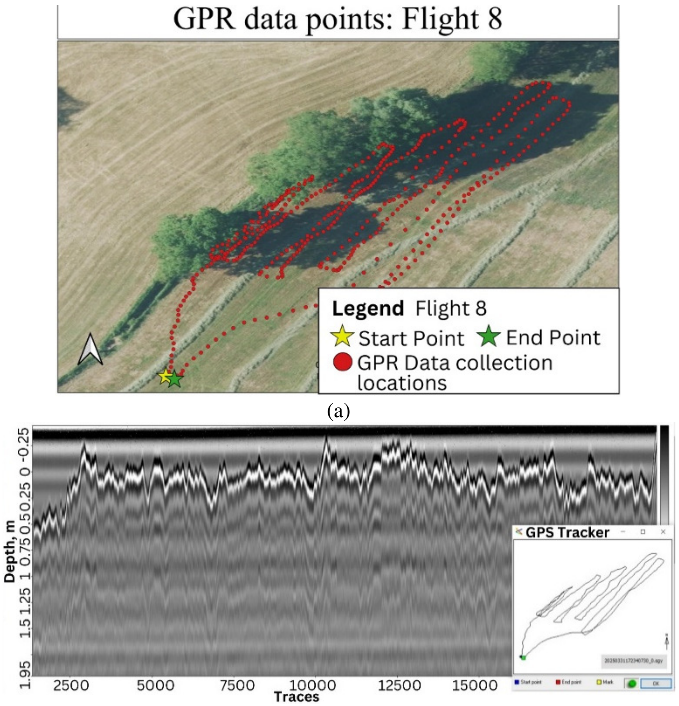

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Fig. 9. (a) Flight path and GPR data points for Flight 8, (b) radargram of Flight 8 showing heavy signal attenuation.

3) *Summary of Drone-based Survey Observations*

The drone-based survey findings revealed several important observations. The surveys conducted over the left side of the field confirmed a homogeneous and undisturbed subsurface, with no significant anomalies detected throughout the investigated area. In contrast, the right side of the field produced more promising results. In particular, Flights 4 and 7 identified localized shallow planar anomalies that warrant further attention, as they may correspond to zones of historical subsurface disturbance or potential anthropogenic features. Additionally, environmental conditions significantly impacted data quality during certain flights. Flight 8, in particular, exhibited heavy signal attenuation likely due to elevated soil moisture or conductivity, highlighting the sensitivity of UAV-GPR surveys to environmental variability.

B. *Ground-based Survey Results*

Ground-based GPR surveys were conducted to complement the UAV data and achieve higher resolution, especially in zones where anomalies had been detected.

1) *Path 1: Far Right Side*

Radargrams from Path 1 (Figure 10) indicated relatively high background noise, horizontal stratification, and periodic data loss at turning points. No clear anomalies or hyperbolic reflections were detected. This suggests that, at least in this sector, the subsurface remains undisturbed.

2) *Path 2: Middle Section*

Path 2 radargrams (Figure 11) revealed multiple repetitive shallow hyperbolas, reaching depths of approximately 0.75 m. The uniformity and distribution of these features strongly suggest they are associated with historical agricultural ploughing activities rather than buried man-made structures.

3) Path 3: Tree Line Area

Surveying near the tree line in Path 3 revealed two concentrated zones of stronger reflections:

- Between traces 14,572 and 15,024.
- Between traces 17,689 and 18,130.

Both reflection zones were found at a depth of approximately 1 m and appeared more localized and coherent than the surrounding stratigraphy. These anomalies may indicate buried objects, soil disturbances, or remnants of anthropogenic features, although confirmation would require additional methods such as coring or targeted excavation. This can be observed in Figure 12.

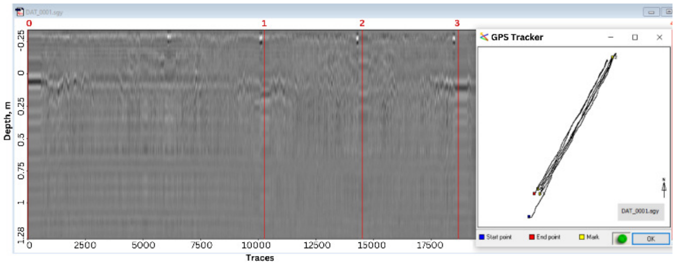

Fig. 10. Radargram of Path 1 showing background noise and data gaps.

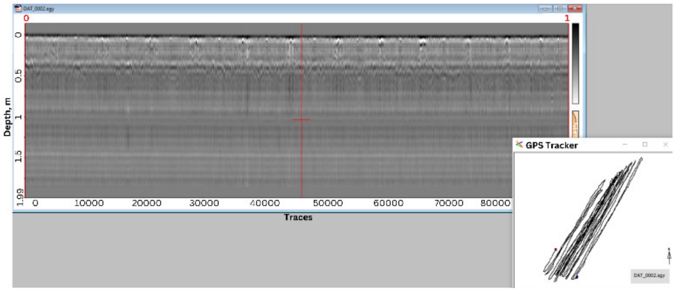

Fig. 11. Radargram of Path 2 showing hyperbolic patterns.

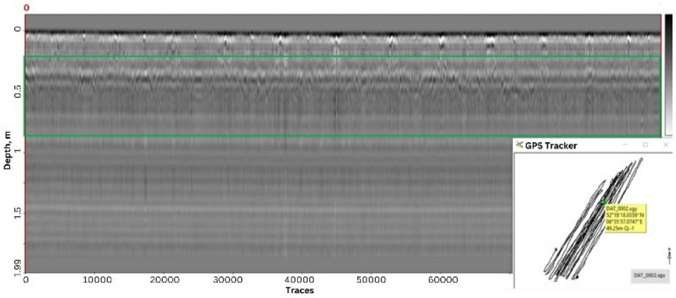

Fig. 12. Radargram of Path 3 highlighting localized reflection zones.

C. Summary of Findings

The combined analysis of UAV-based and ground-based GPR surveys yielded several key observations. In the left section of the field, covered by Flights 1–3 (Figures 2–4), the subsurface stratigraphy appeared continuous and undisturbed, with no evidence of anthropogenic features detected. In contrast, the right side of the field, investigated through Flights 4–8 (see Figures 5–9), revealed greater variability. Two shallow planar reflection zones detected during Flight 4, along with minor shallow anomalies observed in Flight 7, were identified as potential zones of interest for future investigation. Furthermore, Flight 8, highlighted significant limitations related to highly conductive or waterlogged soils, which caused strong signal attenuation and limited the depth of subsurface visibility.

The ground-based survey supported these findings. In the central part of the field, corresponding to Path 2 (Figure 11), characteristic agricultural disturbance patterns were confirmed, likely resulting from historical ploughing activities. Path 3 (Figure 12), adjacent to the tree line, revealed localized subsurface anomalies that differ from the surrounding stratigraphy, suggesting the presence of disturbed soil or buried features that may warrant further historical examination.

Although definitive evidence of the "Onderduikhol" hiding place was not found, the survey successfully delineated areas of interest for future, more invasive historical investigation.

IV. DISCUSSION

A. Interpretation of Findings

The UAV-based and ground-based GPR surveys conducted near Bornerbroekseweg provided important insights into the capabilities and challenges of applying aerial geophysics for historical prospection. Although no definitive structural remains of the "Onderduikhol" were detected, the surveys revealed several localized anomalies that merit further investigation.

Especially noteworthy are the planar reflections detected in Flight 4 at shallow depths (0.2–0.6 m), which are potential markers for buried features or disturbed soils. Localized, high-amplitude features are indicative of a material contrast or break in the natural stratigraphy, possibly due to remain of old structures. Likewise, the minor linear patterns of reflections evident in Flight 7, as well as the two concentrated reflection bands present in Path 3, suggest the likelihood of man-made disturbances around the area of suggested historical presence.

The lack of strong hyperbolic reflections, classically associated with buried objects or voids, suggest that if the hiding place structure still existed, it has collapsed, was severely degraded, or was constructed from materials (e.g., wood, organic material) that do not yield strong GPR responses. Another possibility is that post-war land use activities, such as ploughing or reforestation, may have altered or obscured subsurface evidence.

Left field surveys (Flights 1–3) revealed a stable, unperturbed subsurface with regular stratification. This finding aligns with previously recorded history, which indicated lower chances of finding remains there, underscoring the value of combining historical data with survey design.

Overall, the UAV-based GPR system proved capable of identifying subtle subsurface variation over a fairly extensive area with minimal ground disturbance. Its complementary integration with a ground-based GPR survey provided increased spatial resolution, especially around complicated boundaries like the tree line.

B. Broader Implications for Historical UAV-GPR Surveys

This case study makes a significant contribution to the new research area of UAV-based historical prospection. It proves that GPR can successfully be applied from a UAV to detect shallow subsurface anomalies under optimal circumstances, offering a fast, non-destructive preliminary assessment of potential historical locations.

However, the study also highlights that GPR signals captured from UAV platforms can be susceptible to several environmental and operational factors, including:

- Soil composition and moisture levels influence signal penetration and attenuation.
- Minor altitude fluctuations during flight affect data consistency.
- Vegetation density and surface irregularities limit survey access or cause signal scattering.

Therefore, although UAV-GPR can be a valuable reconnaissance tool, it must be considered as part of a comprehensive multi-method archaeological and historical toolkit, complementing conventional methods such as core sampling and excavation.

C. Connection to Prior Research and Practical Relevance

UAV-based GPR is increasingly explored as a non-invasive method for detecting buried cultural heritage and historical features, though most existing applications have focused on well-documented sites or areas where subsurface structures are already partially known. In such contexts, UAV-GPR is often evaluated under optimal or controlled field conditions [14, 15].

In contrast, this study applied UAV-GPR in a real-world setting with limited historical precision, where the suspected feature has been lost to time and landscape transformation. No surface indicators or previous excavations were available to guide data interpretation, making this case markedly different from most existing UAV-GPR investigations. This distinction highlights the practical value of UAV-GPR for investigating uncertain or sensitive heritage locations that are difficult to access using conventional methods.

The outcomes of this study support the growing recognition that UAV-GPR is a useful exploratory tool, particularly in preliminary investigations where excavation is not immediately feasible or desired. The identification of shallow anomalies in landscapes previously altered by agriculture and natural processes demonstrates UAV-GPR's potential to uncover meaningful signals in challenging environments.

Beyond its technical evaluation, this study contributes to the ongoing methodological discussion by demonstrating how UAV-GPR can complement historical analysis and ground-based validation in culturally significant investigations. It also demonstrates how non-invasive technologies can help narrow search zones in cases where oral history, testimonies, and sparse archival data are the only available sources. These findings are practically relevant not only to archaeological and historical prospection but also to broader heritage conservation, forensic research, and humanitarian recovery efforts, where similar conditions of uncertainty and limited access prevail.

D. Limitations

A number of constraints impacted the survey results and must be considered with caution when interpreting the results. Environmental conditions were the first of these. High conductivity and soil moisture, notably observed during Flight 8, generated significant signal loss and reduced subsurface visibility. It is generally known that waterlogged soils or clay-rich soils strongly absorb electromagnetic signals, which reduces the effectiveness and range of GPR surveys [30-33].

Secondly, inherent resolution constraints within the equipment limited detection. Although the broadband nature of the CBD GPR antenna provides a compromise between penetration depth and resolution, it may have been insufficient to resolve small-scale or deeply buried features, such as those typical of makeshift WWII hiding places.

Third, minor fluctuations in UAV altitude throughout data acquisition, even with rigorous flight planning, introduced heterogeneity in signal strength and resolution. These variations impacted inter-flight comparability and could affect the detectability of subtle subsurface anomalies.

Lastly, a degree of ambiguity is always present when interpreting GPR data. The detected anomalies cannot be conclusively attributed to historical structures or archaeological features without ground-truthing, such as soil coring or excavation. While GPR is highly effective at identifying subsurface contrasts, it cannot determine their historical significance without additional corroborative methods.

Looking forward, further work is already planned to address some of these limitations. More advanced signal processing techniques, including time-zero correction, background removal, stacking, bandpass filtering, and migration, will be applied to the existing dataset to improve resolution and feature characterization. Future field campaigns will also incorporate perpendicular flight paths and utilize a higher-frequency antenna to enhance spatial resolution. These follow-up activities will be accompanied by ground validation and, potentially, excavation, which are expected to provide deeper insight into the anomalies detected during this initial survey and further establish the value of UAV-GPR in similar historical investigations.

E. Future Work

Based on the results of this research, we offer several directions for future research that could improve the efficacy of UAV-based GPR for detecting historical sites. First, targeted high-resolution scanning should be the focus of future UAV-GPR surveys, with denser, smaller-scale flight grids over areas of interest, such as the Flight 4, Path 3 anomalies. Advanced altimeters or laser-based height control technology could help maintain a constant flight altitude, further enhancing quality and resolution of data.

Second, focused soil core sampling and stratigraphic examination of areas with detected anomalies would provide direct ground-truth validation, allowing proper correlation of GPR signals with physical subsurface features and improving the reliability of data interpretation.

Third, surveys repeated at various times of year may provide insight into the effects of seasonal variations in soil moisture content on GPR signal performance. Surveying under drier ground conditions could minimize signal attenuation and improve the detectability of minor anomalies.

Lastly, combining UAV-GPR surveys with other remote sensing technologies, such as magnetometry or Electrical Resistivity Tomography (ERT), could substantially enhance interpretative reliability. Multi-method approaches reduce the inherent constraints of single-method surveys and provide a more comprehensive understanding of the subsurface environment. Using these approaches, subsequent studies can improve the practicality and effectiveness of UAV-GPR for cultural heritage conservation and archaeology research.

V. CONCLUSION

This study presents a practical implementation of Unmanned Aerial Vehicles-based Ground-Penetrating Radar (UAV-GPR) technology to support the detection of historically significant subsurface features, focusing on locating a suspected World War II (WWII) hiding place ("Onderduikhol") in the Netherlands. Unlike many studies conducted under controlled or well-documented conditions, this research was carried out in a real-world environment with no visible surface markers and limited historical precision. The novelty of this work lies in applying UAV-GPR in such uncertain contexts, where traditional surveying or excavation would be either impractical or intrusive.

Although a definitive identification of the hiding site could not be made, several shallow subsurface anomalies were identified through both aerial and ground-based GPR surveys. Notably, anomalies detected during Flight 4 and ground Path 3 show characteristics consistent with artificial structures and have been marked as targets for follow-up investigation. These findings form a credible basis for planning upcoming core sampling and excavation activities, offering a valuable step forward in local heritage research.

In addition to highlighting potential buried features, the study outlines several technical and environmental limitations encountered during data collection, including soil conductivity, UAV altitude variation, and GPR resolution trade-offs. These insights help refine the understanding of UAV-GPR's strengths and weaknesses in heritage applications and underscore the importance of combining this technique with ground-truth validation and historical analysis.

The findings from this case contribute to a growing body of evidence supporting UAV-GPR as a flexible, non-invasive tool in cultural heritage and archaeological/historical investigations. Planned future work includes deployment of high-frequency antennas, perpendicular flight lines, improved signal filtering, and collaboration with local excavation teams to confirm the anomalies. This approach aims to strengthen UAV-GPR's role as a viable first-line exploration method in complex and historically sensitive landscapes.

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