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Remote Sensing of American Revolutionary War Fortification at Butts Hill (Portsmouth, Rhode Island)

James G. Keppeler [1], Marcus Rodriguez [2], Samuel Koontz [1], Alexander Wise [3], Philip Mink [2], George Crothers [2], Paul R. Murphy [4], John K. Robertson [5], Hugo Reyes-Centeno [1,2,6,7,*] and Alexandra Uhl [8,*]

1 Department of Anthropology, University of Kentucky, 211 Lafferty Hall, Lexington, KY 40506, USA; james.keppeler@uky.edu (J.G.K.); samuel.koontz@uky.edu (S.K.)
2 William S. Webb Museum of Anthropology, 1020 Export St., Lexington, KY 40504, USA; marcus.rodriguez@uky.edu (M.R.); pbmink2@uky.edu (P.M.); george.crothers@uky.edu (G.C.)
3 Department of Computer Science, University of Kentucky, Davis Marksbury Building, 329 Rose St., Lexington, KY 40506, USA; alex.wise@uky.edu
4 Independent Researcher, Battle of Rhode Island Association, P.O. Box 626, Portsmouth, RI 02871, USA; foothalls17@icloud.com
5 Independent Researcher, Emeritus, United States Military Academy, West Point, NY 10996, USA; jkrobertson6@outlook.com
6 Swedish Collegium for Advanced Study, Linneanum, Villavägen 6c, SE-752 36 Uppsala, Sweden
7 Center for the Human Past—Uppsala & Stockholm Universities, Evolutionary Biology Centre, Norbyvägen 18A, 752 36 Uppsala, Sweden
8 Department of Sociology and Anthropology, Stonehill College, 320 Washington Street, Easton, MA 02357, USA
* Correspondence: hugo.reyes-centeno@uky.edu (H.R.-C.); auhl@stonehill.edu (A.U.)

Abstract

The Battle of Rhode Island in 1778 was an important event in the revolutionary war leading to the international recognition of U.S. American independence following the 1776 declaration. It culminated in a month-long campaign against British forces occupying Aquidneck Island, serving as the first combined operation of the newly formed Franco-American alliance. The military fortification at Butts Hill in Portsmouth, Rhode Island, served as a strategic point during the conflict and remains well-conserved today. While LiDAR has assisted in the geospatial surface reconstruction of the site's earthwork fortifications, it is unknown whether other historically documented buildings within the fort remain preserved underground. We therefore conducted a ground-penetrating radar (GPR) survey to ascertain the presence or absence of architectural features, hypothesizing that GPR imaging could reveal structural remnants from the military barracks constructed in 1777. To test this hypothesis, we used public satellite and LiDAR imagery alongside historical maps to target the location of the historical barracks, creating a grid to survey the area with a GPR module in 0.5 m transects. Our results, superimposing remote sensing imagery with historical maps, indicate that the remains of a barracks building are likely present between circa 5–50 cm beneath today's surface, warranting future investigations.

Keywords: GPR; LiDAR; American independence; semiquincentennial; Battle of Rhode Island; First Rhode Island Regiment; historical archaeology; heritage preservation; heritage science

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1. Introduction

1.1. Butts Hill Fort in the American Revolution

Butts Hill Fort (BHF), or Fort Butts, is a historical site in the town of Portsmouth in the northern part of Aquidneck Island in the U.S state of Rhode Island, recognized

for its importance as a military fortification during the American Revolution leading to independence from Britain. Initially referred to as Windmill Hill as early as 1667 [1] and later as Butts or Butt's Hill in reference to the landowner John Butts [2,3], the area's topography offered a strategic view of the landscape, with Bristol Ferry to the northwest and Howland's Ferry to the east (Figure 1), thus facilitating inspection of the movement of troops and ships during wartime. The American Continental Army initially built an artillery emplacement, or battery, in Butts Hill at the start of the revolution, but British forces occupied the area following the 1776 Declaration of Independence by the thirteen colonies [4,5]. George Washington, as Commander-in-Chief of the Continental Army, assigned Major General Spencer to assume command of the American forces in Rhode Island in the winter of 1777. Historical maps during this time show a dynamic re-configuration of the fort (see Waller [6] for a list of maps), associated with alternating American or British occupation throughout the duration of the Rhode Island Campaign and the Battle of Rhode Island, which refer, respectively, to the French intervention attempting to free Rhode Island from British occupation and the conflict that ensued in 1778.

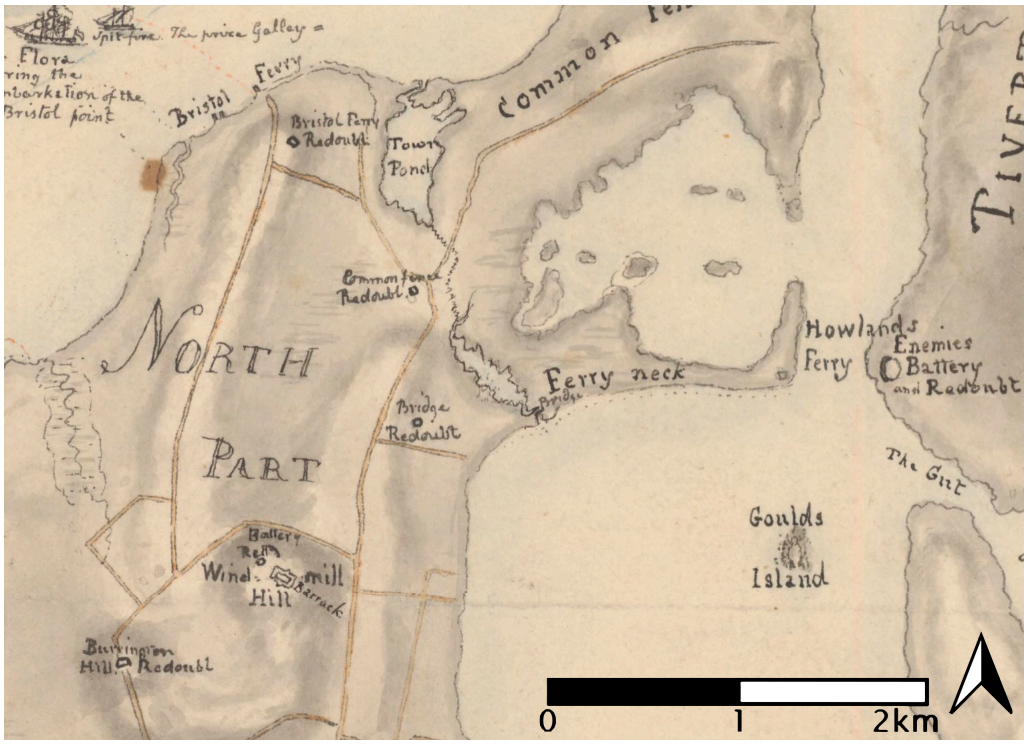


Figure 1. Historical Map of the North Part of Aquidneck Island, Rhode Island, USA. Portion of the 1778 Fage Map, modified from Ref. [7], showing Windmill (Butts) Hill fortifications (lower left), Howlands Ferry (East), and Bristol Ferry (Northwest), with lighter shading indicating higher elevation. Scale in kilometers is translated from original map scale in miles. Digital map courtesy of University of Michigan Library.

The events surrounding BHF are notable in U.S. American history because they mark the first official allied military cooperation between French and U.S. American forces. At the same time, the conflict at Butts Hill also involved German-Hessian forces and their civilian families operating under British command, including the Landgrave, von Wutgenau, and Ditfurth regiments [5,8]. In addition, the Battle of Rhode Island involved the first Black and Native American military unit in American history—the First Rhode Island Regiment, the creation of which was the result of a February 1778 Act passed by the Rhode Island General Assembly which stipulated that "...every able-bodied Negro, Mulatto, or Indian Man Slave...may inlist...to serve during the Continuance of the present War with

Great-Britain. . .” and “. . .upon his passing Muster before Col. Christopher Greene, be immediately discharged from the Service of his Master or Mistress; and be absolutely FREE, as though he had never been incumbered with any Kind of Servitude or Slavery” [9,10]. The regiment was directly involved in the construction activities of BHF between 1780 and 1781, as documented in Revolutionary War pension accounts (see, e.g., Refs. [11–13]).

1.2. History of Butts Hill Fort Architecture

The presence of military or defensive structures prior to 1776 on Butts Hill is contentious, with multiple poorly cited sources giving conflicting accounts (reviewed in Robertson [4]). The first confirmed defensive structures on Butts Hill were built by the British upon taking possession of Aquidneck Island in December 1776 [4,5]. By early 1777, historical maps and records show that a guardhouse and powder magazine were constructed at the site alongside a barracks structure for 200–300 men [7,14–16] (Figure 2a). The area was abandoned by British forces in 1778 in the prelude to the Battle of Rhode Island and subsequently occupied by Americans, who constructed earthworks around the battery and magazine and separately around the barracks [14] (Figure 1). Between August and September 1778 during the Battle of Rhode Island, US American troops retreated from Aquidneck Island, once again abandoning the fort to the British, who occupied the area for 15 months.

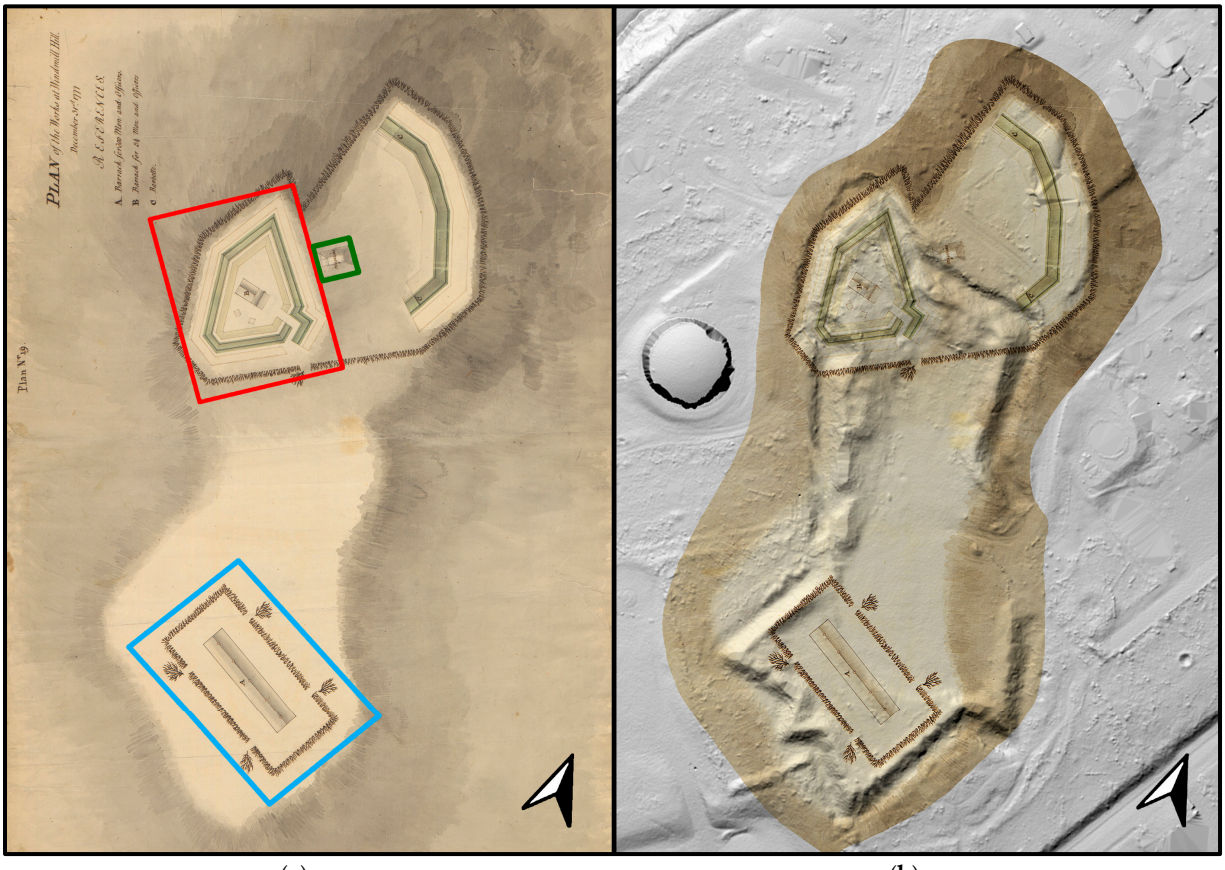
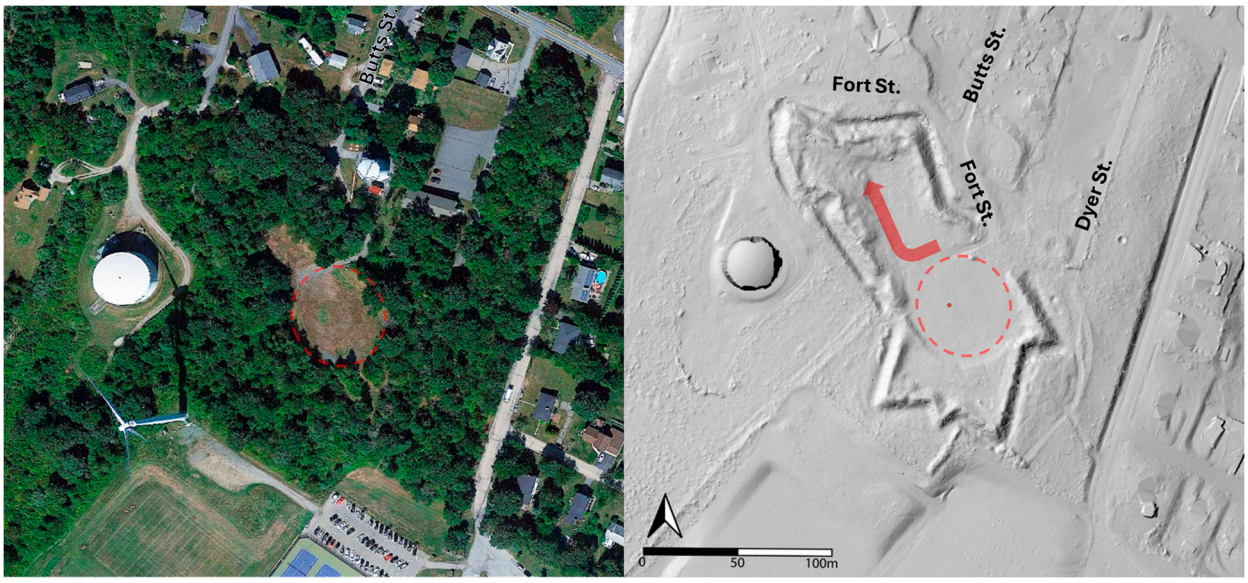


Figure 2. Butts Hill Fort Historical Map and LiDAR Overlay. (**a**) Portion of the 1777 Clinton Plan Nr. 19 map, modified from Ref. [14], featuring the barracks (blue square; housing for soldiers and officers), the battery (red square; area for positioning artillery); and the magazine (green square; storage of munitions and arms). Digital map courtesy of University of Michigan Library. (**b**) Portion of (**a**) overlaid to-scale atop 2022 Rhode Island Geographic Information System (RIGIS) [17] LiDAR map processed using QGIS [18] and referenced in EPGS:32619. Arrow inset indicates cardinal north. See Figure 3b for scale.

In December of 1779 as the British evacuated, the fort came under the control of French allies, who, in July 1780, undertook the most comprehensive construction at the site. This construction connected the northern and southern portions of the hill, encompassing all architectural structures including the battery, magazine, and barracks, within an earthwork that is still conserved today (Figures 2b and 3) [14]. The earthwork includes multiple defensive redans forming V-shaped points at the fort's southern end, and a long, roughly 100 m long parade in a northwesterly direction that meets with the irregularly shaped battery in the northern end of the structure (Figure 3). While the consolidation of the fort was in anticipation of further attacks by the British, their defeat in other parts of the colonies ended the war. The Treaty of Paris was subsequently signed in 1783 to internationally recognize American Independence. In the same year, the site was briefly used as an almshouse [19], but the land was soon sold and the building structures were auctioned off [3]. The abandoned earthwork was rescued from a housing development project during the 1920s, with the land transferred to the Newport Historical Society [20,21]. In 1939, the Historical Society allowed a baseball diamond and playground for the local Boys and Girls Scouts organization to be constructed inside the earthwork, which involved substantial construction and soil removal, resulting in the leveling of the central parade of the fort [20–22]. In the 1960s, ownership of the site was transferred to the Town of Portsmouth [20,21].



(**a**) (**b**)

Figure 3. Satellite and LiDAR Imagery of Butts Hill Fort and Environs. (**a**) Satellite image from September 2019, sourced from Google Earth [23] (©2025 Google LLC, Mountain View, CA, USA). Dashed red circle indicates area inside the fort leveled in 1939 for recreational use. Note earthworks are not visible due to dense vegetation surrounding them. Present-day Butts Street (St.) is indicated north of the fort. (**b**) Surface map produced from RIGIS [17] LiDAR data processed in QGIS [18] (reference: EPGS:32619). Some present-day streets are labeled for reference. Red point inside dashed circle indicates Babits' 1978 datum [20] at 41.6148607885, −71.25041445 (circa 41°36′53.5″ N 71°15′01.5″ W). Note differences in topography inside the fort, including impact of 1939 leveling and higher elevation in northern end. Arrow indicates direction of possible sediment transport during 1939 leveling or, alternatively, revolutionary war ramp for optimizing the launch of artillery (see Figure 2b and discussion in main text).

1.3. Geology and Archaeology of Butts Hill

In addition to historical information on the site, Butts Hill has been studied using geological and archaeological approaches. The site sits on the Esmond-Dedham Subterrane

comprising primarily of Rhode Island Formation and Purgatory Conglomerate rock units from the Pennsylvanian Geological Age [24]. Data from the U.S. National Cooperative Soil Survey [25,26] documents the site within a landform of ridges and hills, with a substrate lithology that is characterized by very shallow soils, rapid runoff, and negligible water-holding capacity, presenting a well-drained upland ecological setting of approximately 50% igneous and metamorphic rock outcrop. In addition, about 30% of the area is a moraines landform comprising very stony Canton soils, formed from coarse-loamy glacial till derived from gneiss, granite, and schist. A typical profile is characterized by fine sandy loam in the upper layers ~5–53 cm below the surface and gravelly sandy loam at lower levels. Minor soil components include stony Sutton, Charlton, Leicester, and Lippitt, each between 3 and 7%.

Excavations undertaken by Babits in 1978 during the bicentennial of the Battle of Rhode Island opened several archaeological trenches in both the southern and northern ends of the earthworks to determine the preservation and condition of any subsurface remains [20]. One trench, Test Trench 2 (TT2) cut through the area of the barracks and described a "...dark brown loamy soil with some shale debris...with a good deal of gravel..." [20]. Two features in TT2 described large rocks mixed with dark brown soil and shale fragments, while two others comprised a layer of concentrated flat shale stones and cultural artifacts. The former was hypothesized by Babits to represent foundational piers or footing for the barracks while the latter was hypothesized to represent a walkway. In addition, Babits also described a feature comprising brick, flat shale, burned rocks, and cultural artifacts, which he hypothesized represented a central hearth in the barracks. Results of these excavations recommended more extensive work to ascertain these hypotheses. While no further excavations have taken place since then, a more recent archaeological assessment [6] classified areas surrounding Butts Hill by their sensitivity for archaeological preservation, indicating the areas along the perimeter of the earthwork to be most likely to include significant archaeological deposits (Figure S1).

1.4. Site Commemoration and Heritage Preservation

In 1974 the fort was added as a site within the Battle of Rhode Island Historic District, registered in the National Register of Historic Places (NRHP) and as a National Historic Landmark (NHL) [27]. Given the historical importance of the site, in 2021, through a collaboration between Portsmouth Historical Society and the newly formed BHF Restoration Committee of the Battle of Rhode Island Association (BoRIA), efforts to conserve the site were further formalized with the gradual clearing of heavy invasive plant overgrowth and the addition of temporary historical signage at key locations. In the same year, the U.S. National Parks Service made Butts Hill Fort a location on the National Historic Trail for the Washington-Rochambeau Revolutionary Route, commemorating the journey of the allied forces led by U.S. American General George Washington and French General Rochambeau (Jean-Baptiste Donatien de Vimeur, count of Rochambeau) from Rhode Island to Virginia during the American Revolutionary War [28]. Most recently in 2025, bills have been re-introduced in U.S. Congress to posthumously honor the members of the First Rhode Island Regiment with a Congressional Gold Medal in recognition of their service during the Revolutionary War [29,30]. These are some of many efforts documenting, preserving, and commemorating historical sites of the American Revolution in celebration of the nation's semiquincentennial [31,32].

As heritage management efforts continue at BHF, and given the high archaeological sensitivity of the site, the use of non-destructive techniques are important for providing additional information in determining its long-term management [33]. Remote sensing techniques, which acquire information without making direct contact with an object of

interest, have become increasingly important in archaeological research, in the preservation strategy of a site, and in public education efforts [33,34]. Because archaeological excavations are intrusive by their nature, non-destructive techniques are important alternatives and, indeed, complementary to the application of invasive field and laboratory methods. Within the framework of heritage science [35], remote sensing techniques offer scientific value to conservation practice and heritage management [36].

1.5. Remote Sensing at Butts Hill Fort

Because the historical record of BHF shows that the site once featured a barracks structure at the southern end of the fort, as well as a battery, guardhouse, and magazine in the northern end, remote sensing techniques can help to geolocate these features and identify areas of surface disturbance. For example, satellite imagery can be used to examine general landscape features, including vegetational growth around the site over time and across seasons. In addition, LiDAR can be used to digitally remove vegetational growth and render only the ground surface of the site. While satellite and LiDAR imaging techniques are ideal for aerial and surface-level mapping, Ground Penetrating Radar (GPR) can be used for subsurface mapping and to ascertain whether the architectural structures recorded in historical documents remain conserved underground today. Previous studies have demonstrated the potential of GPR in American Revolutionary-era contexts, including war forts [32,37].

The central aim of this study was therefore to survey the interior of BHF in order to identify historically documented architectural features hypothesized to still be present underground by earlier archaeological excavations. We focused on the southern area of the fort to determine the presence or absence of the barracks building erected by the British. Our null hypothesis was that we would be unable to detect systematic differences in the GPR signals corresponding to the area where the barracks would have been erected, suggesting that no structural elements are conserved underground. Our alternative hypothesis was that if structural elements were still present, we would find differentiated signals underneath the former barracks area, representing either a stone foundation, post holes, or other structural supports.

2. Materials and Methods

2.1. Geopositioning

To identify the structural features within the earthwork at the BHF site, we first overlaid historical maps with satellite imagery using Google Earth (v. 7.3.6.9750, ©2025 Google LLC) [23,38]. Due to dense vegetation overgrowth, much of the earthwork appears covered in dense foliage in satellite imagery, particularly during the summer months (Figure 3a). Thus, we then used publicly available data collected by the Rhode Island Geographic Information Systems (RIGIS) 2022 LiDAR surveys [17,39]. Data was downloaded and imported into the open-source software QGIS (version 3.22.7) [18,40] and referenced in the EPSG:32619 coordinate system, then converted into hillshade images (Figure 3b) using the LasTools plugin (v. 240522). Historical maps such as the Clinton Plan Nr. 19 [14] (Figure 2a) were overlaid with LiDAR imagery in planning the GPR survey (Figure 2b). This was in conjunction with expert historical knowledge (J.R. and P.R.M.) to target the location of the former barracks building. In addition, we collected GPS coordinates at the start and end of the area selected for further GPR analysis with a Spectra Geospatial SP80 base antenna Global Navigation Satellite System (GNSS) receiver (Trimble Inc. Westminster, CO, USA).

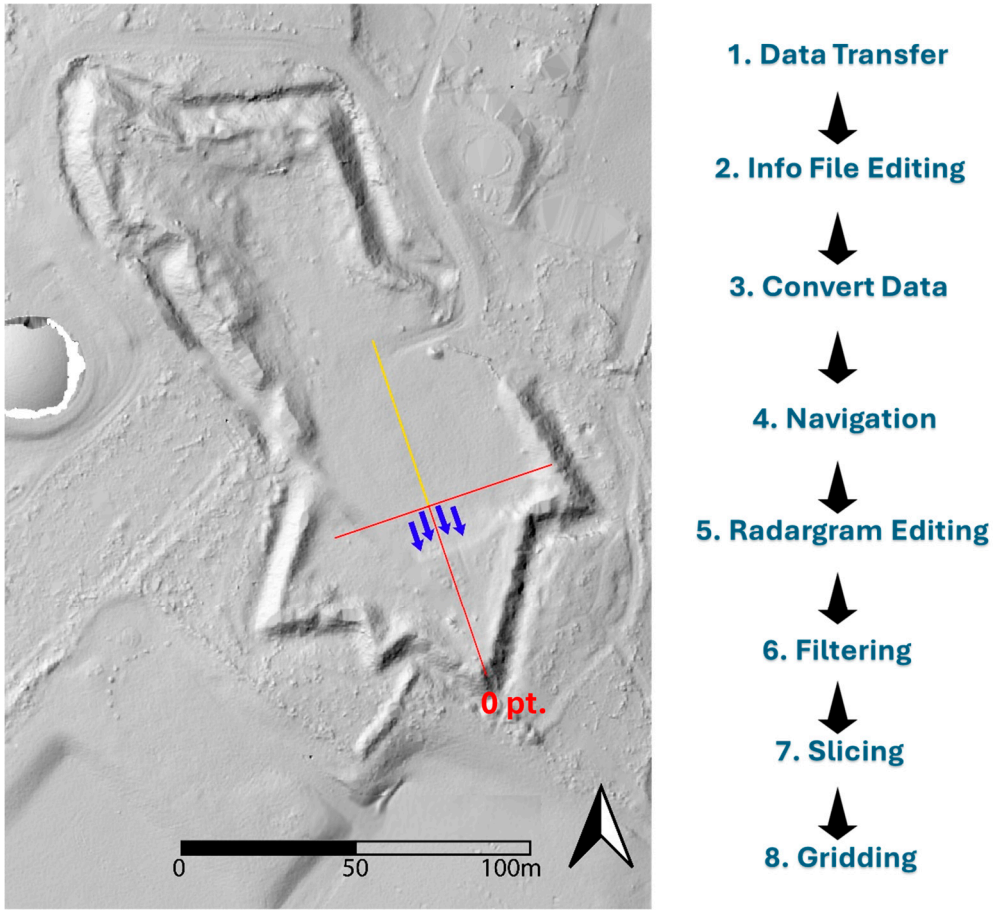
2.2. GPR Survey Design

GPR data collection was conducted with a MALÅ RAMAC GPR CU II module (firmware v. 3.2.41.5). The module was mounted on a 4-wheeled cart running a 500 MHz shielded antenna on a 71.9 ns time window at a 140 m/µS velocity and 0.060 m point interval (Table 1). The radiowave velocity settings are an approximate average of the minimum range for wet shale (m/µs = 113) and maximum range (m/µs = 170) for dry sand, following the dielectric constant for these different materials as outlined by Reynolds [41]. The setting thus considers two main factors: first, the known sand-loam soil composition documented by the U.S. National Cooperative Soil Survey at Butts Hill (Survey Area Data Version 24, 30 August 2024; Soil Survey Area Map Unit: Rp; National Map Unit: 2 wks3) and, second, the possible shale rock concentration that Babits hypothesized was a walkway associated with the barracks construction [20]. We reasoned that if a shale walkway was indeed still present, it would retain a higher water content than the upper sandy loam layers. We note that data was collected in July 2024 over a relatively dry surface, but in a season that was characterized by occasional rainfall.

Table 1. MALÅ RAMAC GPR CU II data collection parameters.

Parameter	Settings
Antenna	500 MHz (shielded)
Time Window	71.9 ns (5.12 m, 384 smp)
Velocity	140 m/µS
Acquisition Mode	Wheel
Wheel	Cart
Point Interval	0.060 m

The GPR unit was operated by two of us (J.G.K., M.R.) and by archaeological field school trained undergraduate students. In total, 2 grids were delineated for the GPR survey within the fort structure (Figure 4a). For the data collection plan of this area, we accounted for the complex topography and spatial orientation of the site. This included planning around the irregular shape of the fort boundaries including the angles of the earthwork, as well as the state of dense vegetation covering the grounds. Figure 4a illustrates the grid plan for the two GPR scan areas, with the placement of an approximate NW-SE reference line. The zero point of this reference line is at the southernmost point of the earthwork, running 100 m NW therefrom. The subdivision line marking the two scan units was delineated orthogonally at 50 m northwest of the 0-point along the NW-SE line. This subdivision line was laid out to sufficiently cover the area where we might find evidence for the barracks, as indicated by our historical map and LiDAR overlays, and under limitations of vegetation overgrowth. In total, it ran 30.5 m from the reference line southwestward, and 40 m northeastward at the intersection point. Data in these two delineated units were collected in transects spanning a southeastward direction. The GPR unit was operated as far to the edge of the fort as possible, stopping where vegetation overgrowth or the edge of the earthwork prevented further data collection. Each subsequent transect was collected in half-meter increments over the course of a week.



(**a**) (**b**)

Figure 4. GPR Survey Grid Plan and Data Processing Workflow. (**a**) RIGIS [17] LiDAR surface map processed in QGIS [18] (reference EPGS:32619) overlaid with grid plan for GPR data collection. Grids in red indicate areas scanned for this study; line in yellow used as reference during planning. Blue arrows are representative of transect scan direction. Zero point is indicated in red type (0 pt). (**b**) Workflow in GPR-SLICE Software [42]. Parameters for each step are reported in Table S1.

2.3. GPR Data Processing and Visualization

Raw GPR data was exported and processed in the GPR-SLICE Software (version 7.MT) [42] by J.G.K., S.K., and A.W. Raw data processing was undertaken with the primary goal of visualizing data in a horizontal orientation. This approach, referred to as a C-scan, produces a three-dimensional data volume comprising multiple data slices [43]. Computationally, this is made possible by stacking multiple vertical radargrams (B-scans), which are based on single waveforms (A-scans) produced when moving GPR antennas along a traverse. Each C-scan shows a snapshot of data received with respect to the time of detection by the GPR's receiver, denoted in nanoseconds (ns). For this reason, C-scans are also referred to as time slices [44,45], horizontal slices [44,46], depth slices [44], or amplitude slice maps in Z-direction [47,48]. We deemed a C-scan more useful for our goal of identifying the barracks structure since the building's foundation is expected to occur at approximately similar depths. Nevertheless, we also inspected B-scans in order to assess our interpretations of a C-scan.

The data processing workflow is outlined in Figure 4b. First, GPR unit data of n = 113 transects was transferred into GPR-Slice. Second, the resulting information file was edited with a time window of 77.98 nanoseconds (ns) and a resampling of 25 scans per mark, which was determined by the GPR module's data collection configuration. Third, the data was converted from the GPR system manufacturer (Mala) format to GPR-SLICE

format. Fourth, the converted data was tagged to define the navigation range recorded, with n = 114 markers assigned across the radargrams at 0.5 m marks. Fifth, radargrams were edited to trigger time 0 detection using a threshold of 20% of the maximum signal, and a 3-point threshold detection to determine the starting point of each pulse, which is the recommended threshold by GPR-SLICE. Sixth, we applied data filtering including auto gain correction, bandpass filtering, kirchoff migration and Hilbert processing to respectively amplify deep signals, suppress background noise, sharpen resolution, and make features more defined. Seventh, we applied time slicing to our dataset at 4 bins per mark and 50% overlap to balance data interpolation with data resolution. Eighth, we created time slice pixel maps by gridding the data, interpolating the x-y-z data with 0.05 cell sizes and applying a low-pass 5 × 5 filter in order to remove gridding noises. Additional details and specific parameters are reported in the Supplementary Information (Table S1). Finally, we tested the effect of a low-pass 3 × 3 filter to the above workflow. Data from the two collected grids were appended during the first two stages of data transfer and information file editing.

2.4. Historical Maps & Remote Sensing Imagery Overlays

Figures overlaying GPR data, LiDAR data, and historical maps were made and compiled in QGIS [18,40] and Adobe® Photoshop® software (version 25.11.0) using the GPS coordinates captured in the field. To scale the historical maps with satellite and LiDAR maps, a handwritten scale in the Clinton Plan Nr. 18 barracks map [15] was used as reference. The barracks plan map was overlaid with the Clinton Plan Nr. 19 Map [14], such that the barracks buildings were sized in reference to each other. These map layers were then linked, and then both were sized so that the units in the handwritten scale corresponded to those in the digital scale in the LiDAR map. With the historical maps scaled, rotation and translation of the maps was undertaken to match the borders of the earthwork. Alphanumeric text outputs from GPR-SLICE were edited for clarity (i.e. to remove pixelation) in Adobe® Photoshop® (version 25.11.0).

3. Results

The processed GPR data penetrated ~346 cm below the surface, represented by 96 C-scans (i.e., horizontal slices or time slices). Figure 5 shows a selection of these results at increments of 7 time slices. As is shown in these images, most changes in feature density are present at or above 127 cm. C-scans between circa 10–25 cm in depth have a systematic pattern of anomalies that is consistent with the dimensions and directional placement of the former British barracks built in 1777, while some of the anomalies are visible between circa 5–50 cm. Figure 6 shows a compilation of LiDAR, GPR, and historical imagery overlaid to illustrate this: LiDAR imagery of the southern part of the earthwork with an outline of Babits' TT2 is shown first (Figure 6a), followed by an overlaid Clinton Plan Nr. 19 (Figure 6b) and then outlined schematically over LiDAR imagery (Figure 6c); next, a time slice at approximately 18.2 cm depth is shown overlaid with the LiDAR image (Figure 6d), then annotated with circles to note features of interest (Figure 6e), several of which correspond to the perimeter of the barracks and its dimensions, noted by a red dotted line (Figure 6f).

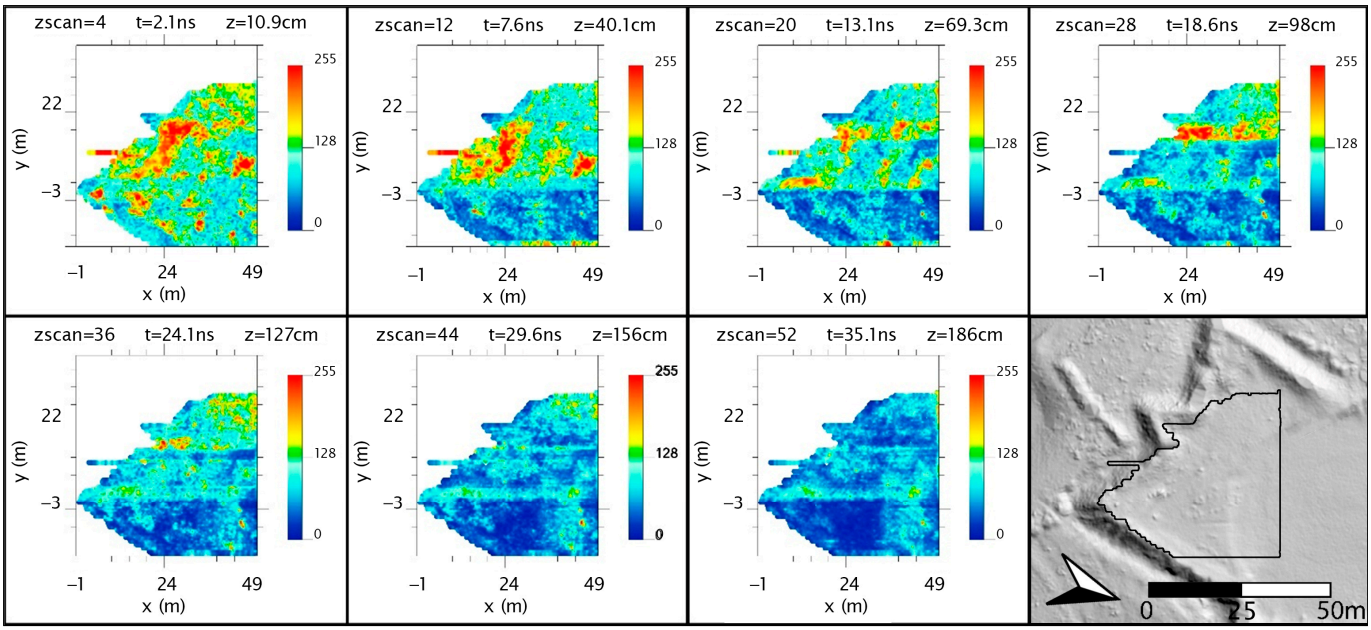


Figure 5. GPR Imaging. A selection of C-scan graphs (i.e., horizontal z-plane scans or time slices) at increments of 7 slices from ~11 cm (upper left) to 186 cm below the surface alongside an inset of the scan outline overlaid on LiDAR surface map (lower right) processed in QGIS [18] (reference EPGS:32619) with RIGIS [17] data. C-scans processed in GPR-SLICE [42]. Heat bars are relative subsurface density values, with red (n = 255) designating high density and blue indicating low density (n = 0). Graph axes are distances in meters (m); see also scale at bottom right inset. Abbreviations: zscan = z-plane scan (i.e., C-scan or time slice), t = time, ns = nanoseconds, z = depth from surface in centimeters (cm).

Figure 7 shows additional detail, with a to-scale overlay of the Clinton Plan Nr. 18 [15] map of the barracks (Figure 7a) overlaid atop the annotated GPR data (Figure 7b). The oval circles highlight spreads of denser material that also align well with the overlaid map. We note that there are additional spots of density in areas outside the hypothesized barrack's location. In addition, we note that our alignment is consistent with Babit's hypothesis that the central chimney of the barracks would align with the central redan of the earthwork, consistent with architectural style of the time [20]. Figures 8b and 9a–d show B-scan cross sections (i.e., vertical slices) of the data at the location of the signals that align with the barracks plan, with arrows indicating the location of each feature. Along the northern end of the barracks, we detected few anomalies at depths below circa 20 cm (Figure 8). However, along the western end of the barracks, we detected several anomalies at depths below 20 cm. We tested the effect of our filtering procedure but found this signal consistently (Figure 9a–d). We also removed the Hilbert filter in Step 6 and used a 3 × 3 low-pass filter in Step 7, finding similar results for the identification of the barracks perimeter in a C-scan (Figure S2).

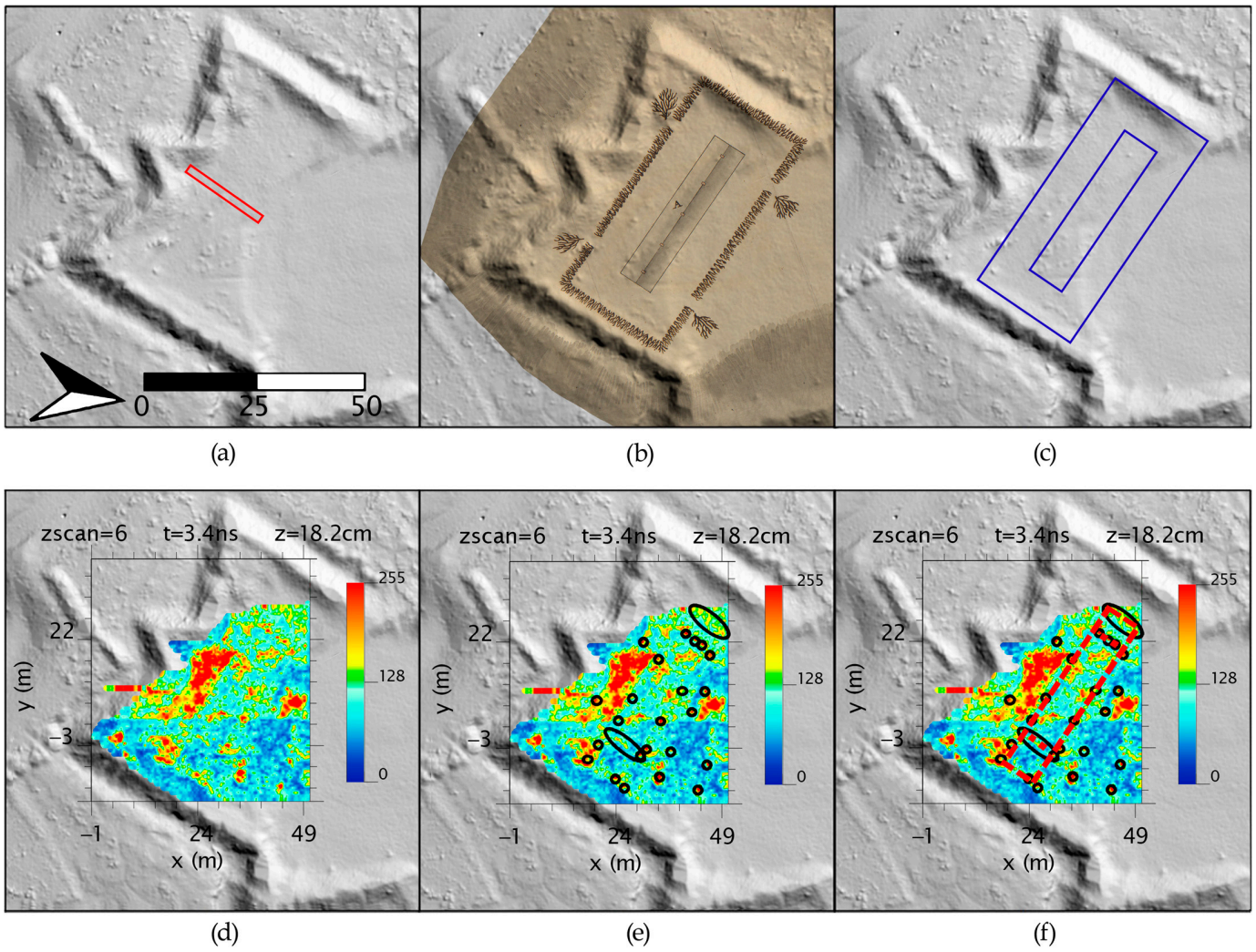
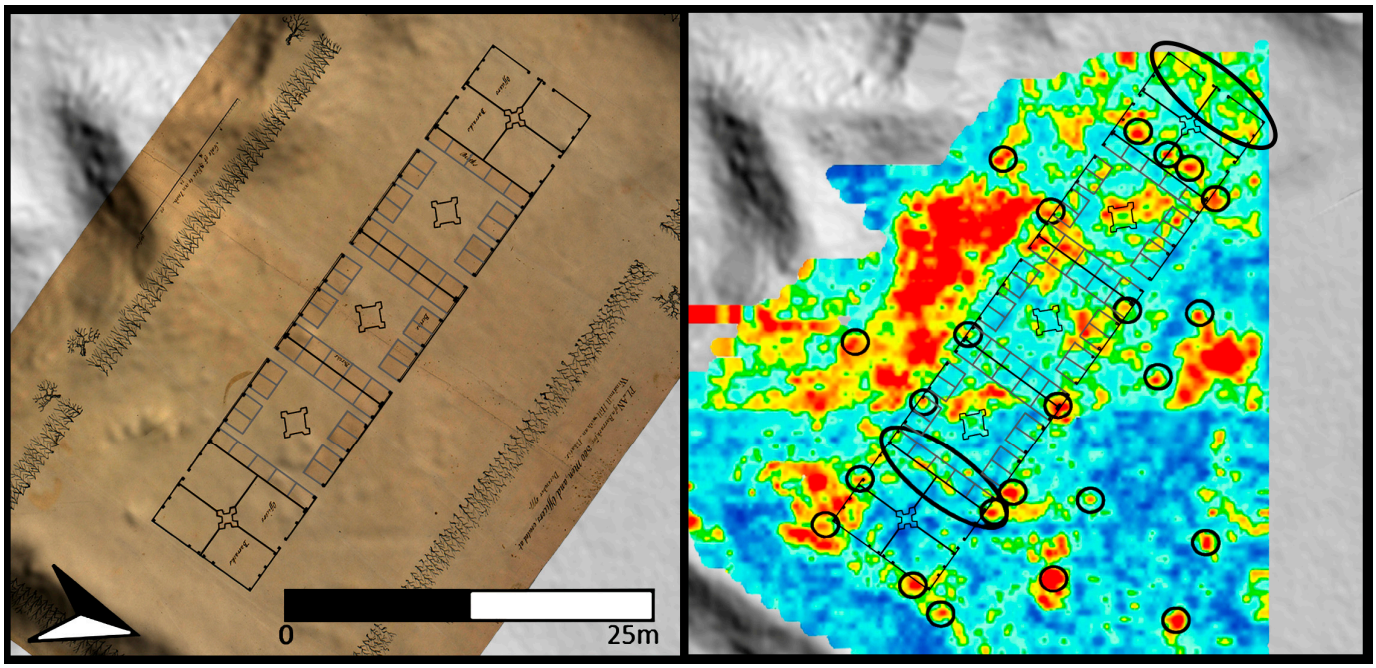
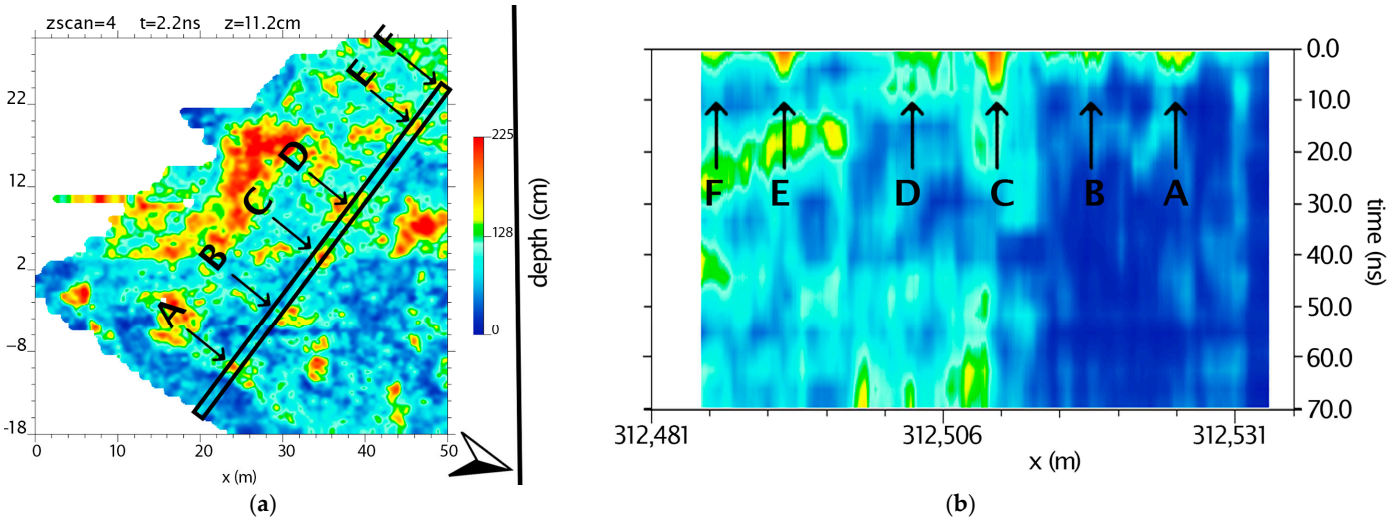


Figure 6. Overlay of Historical Map, LiDAR, and GPR Imagery. (**a**) LiDAR surface map projection of the southern fort processed from RIGIS [17] data in QGIS [18] (reference EPGS:32619). Outline shows approximate location of 1978 archaeological test trench 2 (TT2) from Babits [20]. (**b**) Overlay of selection from Clinton Plan Nr. 19 map [14] showing the barracks. (**c**) Outline of barracks and abbatis on LiDAR surface map: compare to (**b**). (**d**) Overlay of GPR C-scan (i.e., time slice) graph at circa 18 cm depth. (**e**) Overlay (**d**) with circled clusters of high-density features, primarily around perimeter of barracks and abbatis; (**f**) Overlaid (**e**) with dashed red outline of barracks without abbatis: compare to (**b**,**c**). C-scans processed in GPR-SLICE [42]. Heat bars in graphs are relative subsurface density values, with red (n = 255) designating high density and blue indicating low density (n = 0). Graph axes are distances in meters (m). Abbreviations: zscan = z-plane scan (i.e., C-scan or time slice), t = time, ns = nanoseconds, z = depth from surface in centimeters (cm).



(**a**) (**b**)

Figure 7. Overlay of Barracks Plan Historical Map, LiDAR, and original GPR data. (**a**) partial plan Clinton Nr. 18 [15] overlaid to-scale atop RIGIS LiDAR [17] surface map processed in QGIS [18] (reference EPGS:32619). Plan notes placement of windows, doors, and berths along building walls, as well as central, diamond-shaped hearths in each room. Trees around the building indicate abbatis. (**b**) Extracted borders of barracks (abbatis removed) from (**a**) overlaid atop annotated GPR C-scan at 18.2 cm depth. C-scans processed in GPR-SLICE [42]. Circles indicate clusters of high-density features, primarily around perimeter of barracks. Ovals denote density anomalies at greater depths.



(**a**) (**b**)

Figure 8. GPR Imagery of Barracks Area Along Northern Wall. (**a**) C-scan of GPR data at circa 11 cm depth showing cross-section location (black rectangle) and hypothesized barracks post holes (arrows). Compare to Figure 8b at circa 18 cm depth. (**b**) B-scan of cross section shown in (**a**) and location of hypothesized post holes (arrows). Capitalized letters in (**a**,**b**) indicate spatial correspondence. Scans processed in GPR-SLICE [42]. Heat bar in (**b**) indicates relative subsurface density values, with red designating high density (n = 255) and blue indicating low density (n = 0). Graph x-axes are distances in meters (m). Y-axes in (**b**) indicate depth and time. Abbreviations: zscan = z-plane scan (i.e., C-scan or time slice), t = time, ns = nanoseconds, z = depth from surface in centimeters (cm).

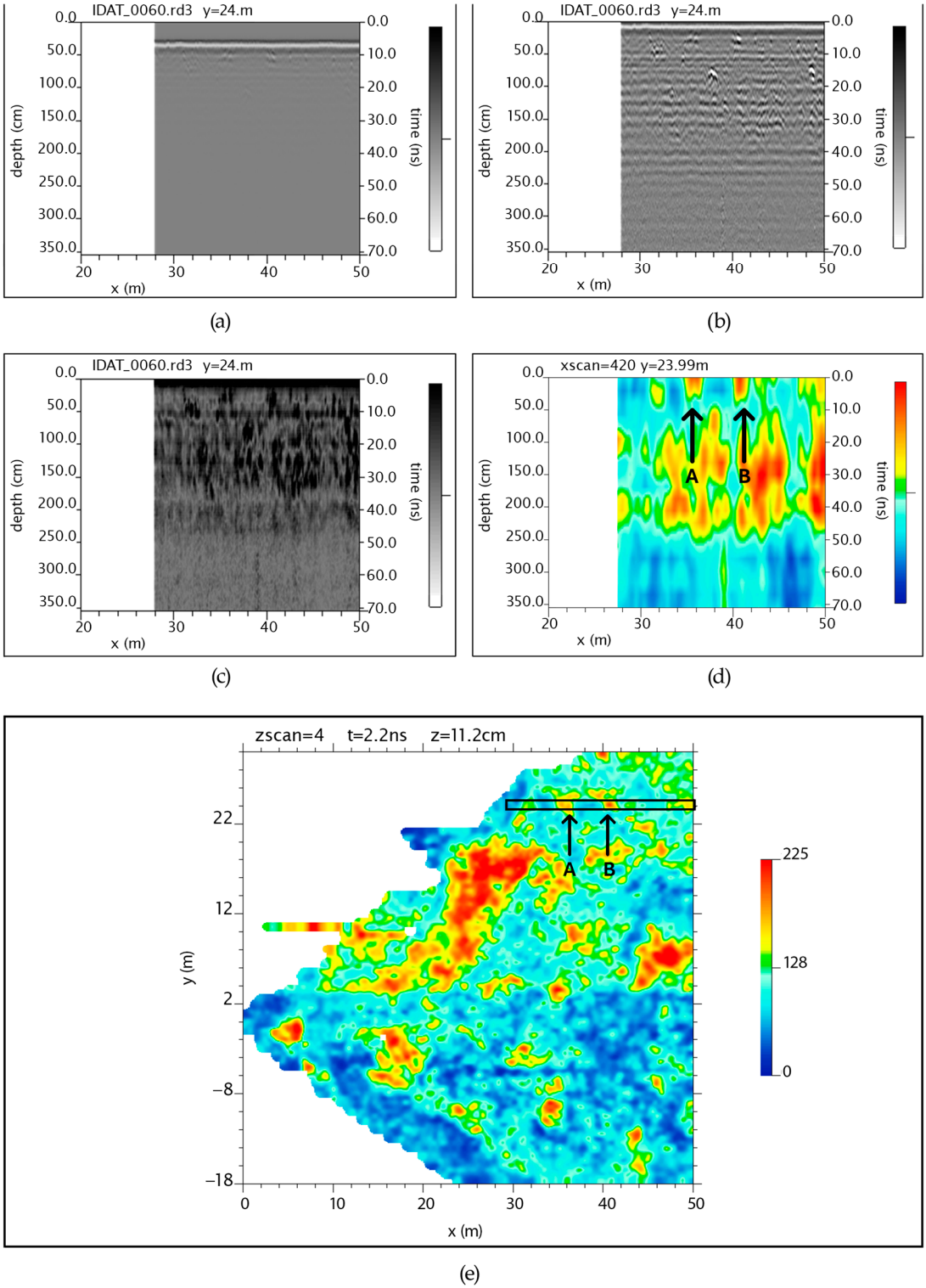


Figure 9. Scan Transects at Progressive Stages of Data Processing Along Western Wall of Barracks. (**a**) Raw radargram B-scan (after step 5 in data processing workflow, see Figure 5 and Table S1) along southwestern part of barracks area: see transect outline in (**e**) and compare to Figure 8b. (**b**) Radargram B-scan with bandpass filter, (**c**) Hilbert transformation added, and (**d**) 3D interpolation B-scan cross section with 5 × 5 low pass filter (step 6 in Figure 5 and Table S1). (**e**) C-scan showing cross section location (black rectangle) and hypothesized barracks post holes (arrows). Scans processed in GPR-SLICE [42]. Graph axes are distances in centimeters (cm) or meters (m). Abbreviations: (**a**–**d**): .rd3 = radargram file, y = *y*-plane scan (i.e., B-scan); (**d**,**e**): xscan = *x*-plane scan (i.e., B-scan), y = position in meters (m), zscan = z-plane scan (i.e., C-scan or time slice), t = time, ns = nanoseconds, z = depth from surface in centimeters (cm).

4. Discussion

Our results utilizing remote sensing techniques with historical records are consistent with the presence of barracks built by the British in 1777 at BHF and thus support our hypothesis that GPR signals could identify foundational structures that remain preserved underground. While the highlighted sections in Figures 7 and 8 align convincingly with the borders of the barracks in the two Clinton maps, the precise material composition of these features remains to be answered. Typically, the remains of buildings with stone foundations uniformly laid across the ground appear in GPR data as stark contrast to the soil matrix below and surrounding the building's perimeter; however, we do not see this in our results and therefore rule out a horizontally uniform foundation underlying the barracks. Instead, we interpret the GPR features as consistent with structural support clusters acting as piers or footing for the barracks, supporting Babits' hypothesis. In particular, our findings align with Babits' TT2 features of clusters of shale and field stone rocks, which transected the area we surveyed (see Figure 6a) and likely would have supported wooden posts. Historical records which we have reviewed do not clearly detail the construction materials of the barracks at the site. Nevertheless, Bartlett [3] documents the auction of timber at Butts Hill and, to our knowledge, the closest description is from an 1846 United States Bounty Records firsthand account, which mentions the British construction of the barracks contemporaneous to the cutting of local trees [49].

If our interpretations are correct, we hypothesize that the shale and stone support clusters identified by Babits and in our GPR results served to sustain timber posts. The BHF barracks could possibly be comparable to the 17th century buildings at the historic James Fort site in Jamestown, Virginia, known for being the first long-term British settlement in North America [50]. Structures at James Fort, and particularly the building designated as the barracks, employed a post-in-ground method of construction that is compatible with the GPR signals we find [51]. Information from the diary records of British Lieutenant Frederick Mackenzie suggests that the number of housed men (200–300) would likely have fit in a one-story seasonal wooden barracks [16]. He also noted that the barracks construction took longer than expected, so it is possible that this delay necessitated hastier building techniques, resulting in the construction of a wooden structure without a longer-term stone foundation structure. The auctioning of removable materials that took place in 1783 suggests that most of the above-surface barracks material would have been removed from the site.

Within the barracks, other anomalies in the GPR data appear in the central region. These could be indicative of brick remnants of central hearths that would have been built in each of the soldiers' and officers' quarters of the barracks, as indicated in the Clinton Plan Nr. 18 (Figure 7). This interpretation is in line with finds by Babits' TT2 feature that included burned rocks alongside brick, flat shale, and cultural artifacts. Outside of the barracks, we find several GPR signals that could be associated with other structures built using the same method. For example, some clusters similar to those found along the perimeter of the barracks building are found roughly around the perimeter of the planned abbatis, which would have served as an additional barrier to the barracks [15,20]. Some of the trees harvested to create the abbatis could have been stabilized with the use of shale rock clusters, for example. Another possibility is that they are remnants of the time period when the barracks were fortified independent of the northern structures [5], prior to the reconfiguration by the French. Alternatively, they could have also been built during a different time period pre- or post-dating the revolutionary war.

The anomalies documented by the GPR data in the southern end of the fort along the inner perimeter of the central redan (Figure 7) could be associated with what Babits interpretated as a walkway made from flat shale. Interestingly, the attenuation signal of

these clusters is similarly observed at greater depths (Figures 8 and 9). We speculate that these deeper signals may be natural clusters of igneous and metamorphic rock characteristic of the landscape outcrop. Along the southwestern corner of the barracks in particular, the attenuation of clusters between circa 18–20 cm, which we interpret as pier or footing for the barracks, is repeated at lower depths between circa 50–250 cm (Figure 8).

North of the barracks, our LiDAR analysis clearly shows the surface topography resulting from the 1939 leveling operations, with a circular depression that has been documented with exposed bedrock outcrop [6]. An opening into this circular depression is also observed on the eastern part of the earthwork, connecting the modern-day Fort Street and Butts Street (Figure 3b). It is possible that this opening served to pile sediments removed in 1939 from the central part of the fort into the northern end (see arrow in Figure 3b). However, inspection of the site and comparison of LiDAR imagery with historical maps (Figures 2 and 3) suggest that the sloping of sediment in the northwestern end was likely an intentional ramp that enabled artillery to be wheeled into the battery (Figure 2b). This interpretation is consistent with the fact that the northwestern end of the fort is the highest point of Butts Hill and offers the best view of the surrounding region, thus likely serving as a focal point for optimizing the launch of artillery. Nevertheless, additional GPR survey in the northern part of the fort is necessary to evaluate these competing hypotheses.

We note that our work was limited by several factors, such as differential site and soil conditions across the data collection period. For example, the GPR C-scans clearly show a marked boundary of density values between the two grids sampled (Figures 6–9), suggesting differences in soil condition likely due to differential water content from one day to another. In addition, vegetation in several areas, including the growth of large trees and seasonal plants, made some areas inaccessible for data collection, such that we could not capture the western area of the barracks which could potentially preserve evidence of the abbatis (see Figure 6). While we consider it likely that our GPR results indicate the presence of foundational structural features of the historical barracks, future work is necessary to further ascertain our findings. For example, archaeological test pits could confirm the physical boundaries of the barracks and verify the presence of rock support clusters or remnants of wooden poles used for their construction. Archaeological excavation and analysis can also provide further information on the site formation processes.

From a technical point of view, other non-invasive methods, including magnetometry, could serve to further validate our results, as well as better elucidate the previous magnetometry data collected by Babits [20]. For example, magnetometry image overlays with the remote sensing data presented here would serve to further validate our interpretations of the barracks. While we have focused on two-dimensional image overlays in our analyses, future work could apply multi-modal imaging approaches in three-dimensions. For example, surface LiDAR maps could be superimposed with magnetometry data and fused with three-dimensional renderings of GPR data, although such multi-sensor and multi-platform approaches would need to be carefully processed to ensure compatibility [52]. Adding an additional line of evidence like magnetic surveying would also allow us to employ a wider range of analytical approaches (e.g., Ref. [53]). Additional GPR data collection under different parameters could also improve the resolution of our 2024 field results. For example, GPR data at different velocities could be collected within restricted time periods to mitigate any effects of variation in soil composition, particularly in water content. In addition, while we collected our data at 0.5 m transects for this study, future work should prioritize smaller transect increments to increase subsurface data resolution. Additional GPR surveys also present an opportunity to identify other possible structural features

documented in historical records, such as the guardhouse, battery, and the magazine in the northern end of BHF (Figure 2).

From a historical point of view, additional written records and maps could further elucidate the site formation processes of the last circa 250 years. In particular, we have not reviewed historical war records produced by the German and French allies, which could further inform the mode and timing of architectural methods and changes across the time of battle. For example, while it is clear that the French allies were responsible for the major reconfiguration of the earthwork fortification at Butts Hill, it is unclear whether they also reconfigured the inner structures. Similarly, it is unclear whether the Hessian forces were involved in independent construction of architectural features or reconfiguration of structures built by the British. Moreover, we have not researched information from the 1800s during the period of the site's abandonment. Thus, further historical research from the 19th century could further inform factors that could have affected the site into the present day.

From a heritage management standpoint, historical research is recommended as a first next step. Such work would inform the aims and scope of additional non-destructive remote sensing approaches. This joint humanities and field heritage science approach could then be utilized to carefully plan for targeted archaeological excavation. In addition, artifacts retrieved by Babits in the 1978 excavations commemorating the bicentennial of the Battle of Rhode Island could also be analyzed with a range of modern heritage science laboratory approaches [36]. For example, chemical analyses and microscopy of existing artifacts could further inform our interpretations of the use of wood and the presence of hearth features in the barracks. As BHF approaches its semi-quincentennial, the time is ripe to further reconstruct the circumstances of its important role in U.S. American Independence and to ensure the preservation of the site for future generations.

5. Conclusions

In this study, we used remote sensing techniques, including satellite, LiDAR, and GPR imagery, overlaid on historical maps to target the area within the Butts Hill fortification where a military barracks building was erected by the British in 1777 during the American Revolution. Our results support our hypothesis that GPR imagery reveals foundational structural features of the barracks, which we identified between 5 and 50 cm below the current ground level. Future field work at BHF should focus on additional methods, including magnetometry, and additional GPR surveys. If the location of the barracks structures is confirmed with these complementary imaging approaches, our results would further confirm the utility of applying non-destructive remote sensing heritage science approaches for elucidating information on historical sites and, more broadly, for enabling heritage preservation and management strategies.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/heritage8100430/s1, Supplementary Information file: Table S1: Data processing parameters in GPR-SLICE; Figure S1: Archaeological Sensitivity Map; Figure S2: Alternative GPR Imaging.

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Abbreviations

The following abbreviations are used in this manuscript:

BHF	Butts Hill Fort
BoRIA	Battle of Rhode Island Association
EPSG	European Petroleum Survey Group
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPR	Ground Penetrating Radar
GPS	Global Positioning System
LiDAR	Light Detection and Ranging
NHL	National Historic Landmark
NRHP	National Register of Historic Places
RI	Rhode Island
TT2	Test Trench 2

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