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John J. Schultz,[1] Ph.D.; Mary E. Collins,[2] Ph.D.; and Anthony B. Falsetti,[3] Ph.D.

Sequential Monitoring of Burials Containing Large Pig Cadavers Using Ground-Penetrating Radar

ABSTRACT: Ground-penetrating radar (GPR) was used to monitor 12 pig burials in Florida, each of which contained a large pig cadaver. Six of the cadavers were buried in sand at a depth of 0.50–0.60 m, and the other six were buried at a depth of 1.00–1.10 m and were in contact with the upper surface of a clay horizon. Control excavations with no pig internment were also constructed as blank graves and monitored with GPR. The burials were monitored with GPR for durations of either 12–13 or 21–21.5 months when they were then excavated to correlate the decomposition state of the cadaver with the GPR imagery. Overall, cadavers in sand were easily detected for the duration of this study at 21.5 months, even when completely skeletonized. Conversely, in clay it became increasingly difficult to image the pig cadavers over the first year of burial, even when they still retained extensive soft tissue structures.

KEYWORDS: forensic science, ground-penetrating radar, forensic anthropology, forensic archaeology, pig cadavers

The continued emphasis toward using proper forensic archaeological techniques and methods for conducting body searches and recoveries has led to an ever-growing trend of incorporating multiple search methods (1–4). In particular, ground-penetrating radar (GPR) has proven to be a valuable search tool for forensic investigators. This equipment is now routinely used to search for buried bodies and forensic evidence, and to clear suspected areas where a body is thought to have been buried so investigations can be directed elsewhere. The increasing use of GPR with other methods for body searches is due to a number of reasons. GPR is a noninvasive search method that allows preservation of any potential crime scene and buried evidence during a search. Surveying with GPR before excavating can provide forensic investigators with an undisturbed view of subsurface features so target areas can be highlighted for further testing with other search methods. Conversely, this technology can be used as a follow-up method after using other noninvasive methods, such as visual or cadaver dog searches, to highlight the specific location of target areas for invasive testing. This technology has the best resolution of all the available geophysical methods used on land and depth of subsurface features can be estimated. The data is presented in real time and results are available immediately in the field. Furthermore, a major advantage of this technology is it can be used to search for bodies or evidence buried under cement or asphalt.

The application of using GPR for grave detection was first successfully demonstrated with historic and/or cemetery graves from various regions and time periods (5–8). GPR is routinely used to locate and confirm the location of hidden burials and human remains of homicide victims and mass graves (9–14). The success of using GPR for forensic contexts was first demonstrated with controlled research. These studies buried a large mammal, most often a pig cadaver that has been used as a proxy for a human body, and then detected and monitored the buried bodies with GPR for some length of time. This research has been vital in demonstrating the utility of using different geophysical instruments for locating buried bodies, and to provide experience to operators searching for buried bodies. The most important and initial research was conducted by personnel associated with NecroSearch, a Colorado-based forensic organization (1,2,15). Geoscientists and law enforcement personnel buried pig cadavers (an average of 70 kg or 154 lbs) to concentrate on multidisciplinary methods, including a variety of noninvasive technologies, used to detect buried remains. Overall, it was concluded that GPR was the most important geophysical tool used to delineate graves (1,2). However, although GPR was preferred for speed and accuracy over other geophysical methods, dogs, probes, intelligence, and landscape changes also contribute greatly to locating clandestine graves. Since the initial studies by NecroSearch, there have been a variety of other forensic GPR studies that have focused on regional approaches in other areas of North America such as British Columbia (16), Tennessee (17,18), and Florida (19,20).

Proxy forensic GPR studies have been very important for GPR operators because they provide them with experience in a known setting that is invaluable when they perform GPR searches in forensic contexts. The presence of soil features such as clay and high fluid electrical conductivity are the major limiting factors using GPR. Therefore, since local soil features will have a significant effect on GPR performance, it is important to have controlled forensic GPR studies in various areas of the county where studies test the efficacy of GPR for local conditions and environments. In addition, GPR research is important because operator experience can be a limiting factor using GPR for forensic contexts. Conducting a GPR survey for small and shallow subsurface objects or features that are routinely encountered in forensic and archaeological surveys requires training to learn how to use the equipment and to interpret the results. A GPR survey performed in a forensic context must be a controlled survey conducted in the same manner as an archaeological investigation where GPR transects

[1]Department of Anthropology, University of Central Florida, Orlando, FL 32816-1360.
[2]Soil and Water Science Department, University of Florida, Gainesville, FL 32611.
[3]C. A. Pound Human Identification Laboratory, Department of Anthropology, University of Florida, Gainesville, FL 32611.

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are collected over a grid that utilizes appropriate spacing between transects. Even an experienced GPR operator can miss a buried body when performing a GPR survey if their experience has primarily involved applications surveying large planar features such as stratigraphic horizons, water tables, and sink holes.

Until a number of preliminary observations were presented by Schultz et al. (19), there was no reported forensic GPR research conducted in Florida with commercially available equipment or in geographical areas with soils similar to Florida. There has been no published GPR research discussing the results of monitoring controlled or proxy graves with GPR for durations over 1 year, and no forensic GPR studies have made direct comparisons between different types of soil compositions. Furthermore, there is only one case study and no proxy forensic GPR studies that have made direct comparisons between unprocessed GPR imagery with processed imagery of buried human remains to remove noise in the data from ringing, also know as multiples. The only study that makes comparisons of unprocessed with processed imagery was from a small search area for a suspected inhumation of a murder victim located adjacent to a known cemetery grave (21). Overall, the processed data proved useful for interpretation of the site stratigraphy and geometry of the known cemetery grave to correctly establish that the suspected inhumation of the murder victim was not in located this area. The noise can be removed using most GPR software programs by applying a filter to the GPR data. This issue is directly related to forensic applications, because GPR assessments may be conducted in the field without processing the data to remove noise. Furthermore, in order to understand if the GPR anomalies are a function of the buried cadaver, as well as the "natural" soil features, blank control graves without cadavers must be constructed and monitored with GPR, and grave excavations must be performed to assess the decomposition state of the cadavers.

The purpose of this study was to test the applicability of using GPR in Florida to detect and monitor large pig cadavers in a controlled setting. The research objectives of this study were as follows:

- Document changes in GPR imagery characteristics of buried bodies resulting from decomposition and subsequent compaction of the backfill for periods of time longer than tested in previous studies (i.e., approximately 1 year);
- Determine if soil composition and time (length of burial) are factors in producing a distinctive anomalous response;
- Assess if processing of the GPR profiles to remove antenna noise (known as "ringing" or multiples in the geophysical literature) is necessary for grave detection;
- To correlate GPR imagery characteristics with the state of decomposing of buried bodies.

Materials and Methods

Research Site and Burial Construction

The research field site was located in unmanaged open pasture in Alachua County, Florida, because it provided a number of ideal characteristics for GPR surveying of small subsurface features: the field was open, the ground surface and topography was flat, there was excellent drainage, the soil represented one of the most common soil types in Florida, and the soil allowed testing of two soil compositions. The soil type, an Ultisol, consisted of horizons comprised primarily of sand to a depth generally around 1.00 m where a clay (argillaceous or argillic) horizon began. Domestic pig (*Sus scrofa*) cadavers were used as proxies for human bodies in this study. Pig cadavers are commonly used in taphonomy experiments to replicate humans because they are easy to obtain and entomology studies have shown that they are the most appropriate animal proxy for human decomposition (22,23). The pigs were euthanized in the morning by a veterinarian to ensure humane treatment, and the burial process was completed by the afternoon of the same day.

TABLE 1—*Detailed burial data for each pig cadaver.*

Cadaver #	Weight (lbs/kg)	Depth	Length of Burial (Months)
1	114/51.71	Deep	21
2	140/63.50	Deep	21
3	125/56.70	Deep	21
4	133/60.33	Shallow	12
5	143/64.86	Shallow	21.5
6	136/61.69	Shallow	21.5
7	148/67.13	Shallow	21.5
8	152/68.95	Deep	13
9	141/63.96	Deep	13
10	152/68.95	Deep	13
11	151/68.49	Shallow	13
12	154/69.85	Shallow	13

A total of 12 control graves, with each containing one large pig cadaver ranging in weight from 51.71–69.85 kg (114–154 lbs) with an average weight of 63.84 kg (140.75 lbs), were constructed for this study (Table 1). The size of the pig cadavers was chosen to represent an adult human size body. Also, the following variables were measured: the length of time a pig cadaver was buried, the depth a pig cadaver was buried, and the soil composition of the grave were the pig cadaver was located. Six cadavers were buried at a depth of 0.50–0.60 m, and the other six were buried at a depth of 1.00–1.10 m to represent deep and shallow burials that are generally encountered in forensic scenarios. The GPR response from the deep and shallow cadavers was expected to differ with regards to GPR performance because the shallow cadavers were only buried in sand and the deep cadavers were generally buried into the upper limit of the clay horizon (Fig. 1). The pig cadavers were not buried wholly within the clay horizon, as this layer would most likely represent the depth limit to which a potential murderer might dig a grave if they were burying a body. Finally, at the termination of 1 year (12–13 months), six pig burials (three deep and three shallow) were excavated to assess the decomposition state of the cadavers, and the remaining six were excavated after 21 months (21–21.5 months). See Table 1 for a summary of the detailed burial data for each cadaver. For purposes of this paper, the overall decomposition state of each cadaver is only noted in general terms. For more in-depth descriptions of the decomposition state of each cadaver see Schultz (20).

Two blank control graves (one deep and one shallow), containing only disturbed soil or backfill, were constructed the same time as the pig cadaver graves to qualitatively distinguish the response of the disturbed soil from that of the decomposing pig cadaver. The graves were of similar dimensions as the graves with the pig cadavers and were constructed by digging the grave and then returning only the backfill to the hole. Also, one additional deep control grave was constructed with a layer of gravel added to the floor of the grave, located at the top of the clay layer, to represent a gravel lens. This control grave was designed to simulate a false anomaly or a false positive that is encountered during a geophysical survey as a result of materials such as buried trash, tree roots, tree stumps, and gravel lenses or large cobbles. This control grave also provided a reference for the interpretation of the anomalies

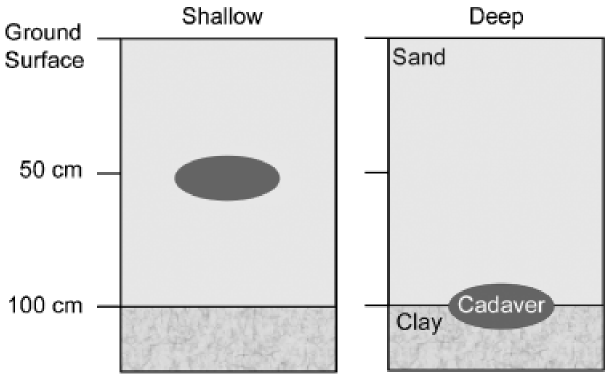

FIG. 1—*The cadavers buried at a shallow depth (50–60 cm) are in sandy horizons, and the cadavers at the deep depth (100–110 cm) are buried in the upper limit of the clay horizon.*

from the pig graves that were buried in the clay horizon because this anomaly provided a reference for size and depth.

The 12 pig cadaver graves and control graves were arranged in four rows that were oriented west to east. Row one included pig cadaver graves 1, 2, 3, followed by a blank control grave and lastly a control grave with a gravel lens. Row 2 included a blank control grave followed by pig cadaver graves 4, 5, 6, and 7. Row three included pig cadaver graves 8, 9, and 10, and row four included pig cadaver graves 11 and 12. Each GPR profile that is presented (Figs. 2–7) only includes graves that were in the same row. The graves were placed in an open field away from trees and fences. Permanent wooden markers were placed in the ground at the corner of each grave so transect lines could be replicated each time GPR data was collected. Furthermore, the transect that was collected over the middle of the graves is the only transect that is presented in this paper.

GPR Methods

The GPR system used in this study was the subsurface interface radar (SIR) 2000, manufactured by Geophysical Survey Systems Inc. (GSSI, North Salem, NH) with a 500 MHz center frequency antenna that was used in the standard position. Depth of investigation and vertical resolution are two important considerations when choosing the appropriate antenna. A decrease in antenna frequency (e.g., 250 MHz) will increase the depth of investigation, while decreasing the vertical resolution of the subsurface. Conversely, an increase in antenna frequency (e.g., 900 MHz) will decrease in the depth of investigation, while increasing the resolution of subsurface objects. A 500 MHz, or similar frequency, antenna is ideal when searching for buried bodies because it provides an excellent compromise between depth of penetration and resolution of subsurface features (12,19,20).

This equipment is used by pulling an antenna over the ground surface while it is emitting continuous electromagnetic pulses of short duration downward into the ground. The velocity of the electromagnetic (EM) wave is primarily controlled by the relative dielectric permittivity (ε_r), a geophysical property strongly dependent on water content. Therefore, as the EM wave penetrates the subsurface, it is reflected and refracted as it encounters interfaces where water content (hence ε_r) changes significantly. In addition, in forensic and archaeology contexts, the EM wave is reflected and refracted when it encounters areas of contrasting properties such as highly conductive objects (i.e., metal artifacts and weapons). The GPR antenna will receive the returning reflected waves and a cross-sectional picture of the subsurface is generated from the composite of the reflected waves. Please refer to the following references for detailed descriptions of GPR methodology for forensic and archaeological contexts (3,4,20,24).

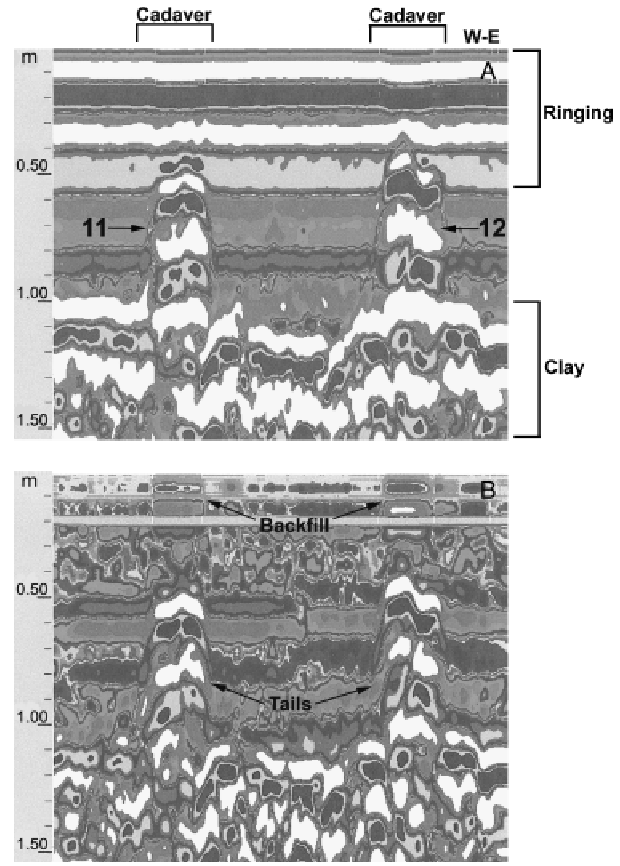

FIG. 2—*Ground-penetrating radar (GPR) profile of two shallow cadavers (11 and 12) collected at 2 weeks that compares the unprocessed imagery (A) with the processed background removal (B). Note the distinctive horizontal ringing at the top of the profile from antenna noise (A), the clay horizon (A, B), two hyperbolic-shaped cadaver anomalies (A, B), and the disturbed backfill above the cadaver anomalies (B). The profile is approximately 1.55 m deep and 13 m long.*

GPR surveys were conducted monthly from December 1999 to late June 2002 by pulling the antenna over the length of the graves in both directions (W–E and E–W). Depth was calibrated in the field each time data collection was performed by pulling the antenna over a buried piece of metal rebar that was at a known depth. If the depth scale needed to be adjusted slightly because of increased moisture retention in the soil from periodic rainfall, which rarely ever occurred, the depth scale was adjusted by changing the dielectric constant. The GPR files were downloaded to the computer for further analysis using RADAN for Windows NT, version 2.0.9.2, proprietary software of GSSI. The imagery of the grave anomalies was compared over time to qualitatively assess how the anomalies changed due to compaction of the backfill and decomposition of the pig cadaver. The imagery of the grave anomalies with the pig cadavers was also compared with the imagery of the blank control graves (containing only disturbed soil) to assess how the individual components of the grave (i.e., disturbed soil, decomposing body, and skeleton) contributed to the grave anomaly.

Also, a finite impulse response (FIR) filter was used for background removal using RADAN to qualitatively compare if the resolution of the grave anomalies increased. While there are various filters and procedures that can be used to process GPR data, this study only aimed to assess the issue of background removal.

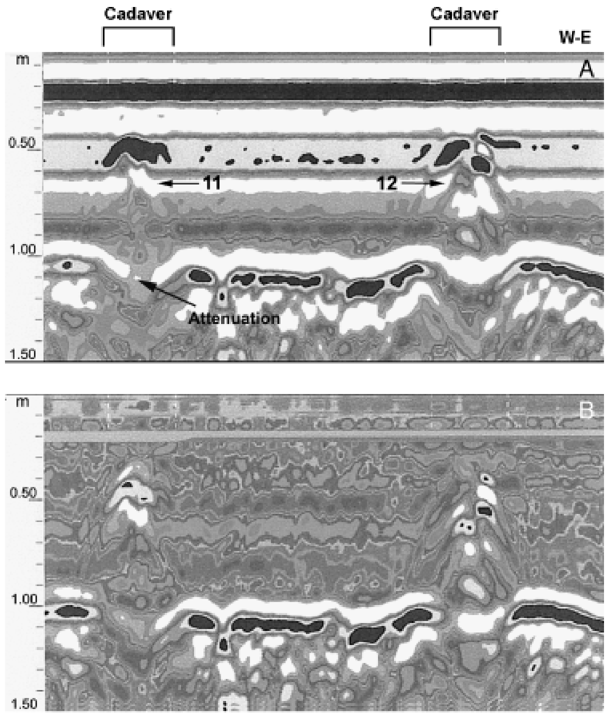

FIG. 3—*Ground-penetrating radar (GPR) profile of two shallow cadavers (11 and 12) collected at 13 months that compares the unprocessed imagery (A) with the processed background removal (B). Note the poorly demarcated hyperbolic anomalies on the unprocessed image (A) that are more discernable after background removal (B). Also, note the attenuation of the continuous clay horizon below both cadaver anomalies (A, B). The profile is approximately 1.50 m deep and 14 m long.*

The two most common types of noise in GPR data are from system ringing and scattering of the EM wave (24). Ringing, also called multiples, usually appears as horizontal or subhorizontal artificial reflections and can be the result of the EM wave bouncing off of surface objects (e.g., metal fences, headstones), bad antenna contact, different antenna elevation, or more typically by strong near surface reflectors caused by wet or clay-rich soils. In particular, antenna noise can appear as horizontal artificial reflections at the top of most GPR profiles due to ringing of some antennas and may obscure reflection data if it is not removed (25,26).

Results

A subset of the GPR profiles that were collected only over the center of each grave will be described in detail to show the specific cadaver and soil features that are imaged on the profile and to discuss how these characteristics changed over the duration of this study. Each of the GPR profiles that are presented includes both processed and unprocessed views. A description of the general decomposition state of each cadaver when they were excavated and a summary of the GPR results for each cadaver is provided in Table 2. Also, detailed climatic data (rainfall and temperature) that was obtained from the NOAA, National Climate Data Center (27) has been provided in Table 3 for each of the GPR profiles (Figs. 2–7). The climatic data has been provided for researchers who wish to compare their GPR data with this study.

Shallow Cadavers in Sand

The image of a GPR profile is a 2D picture that displays depth (top to bottom) and length (left to right). Distinctive grave anom-

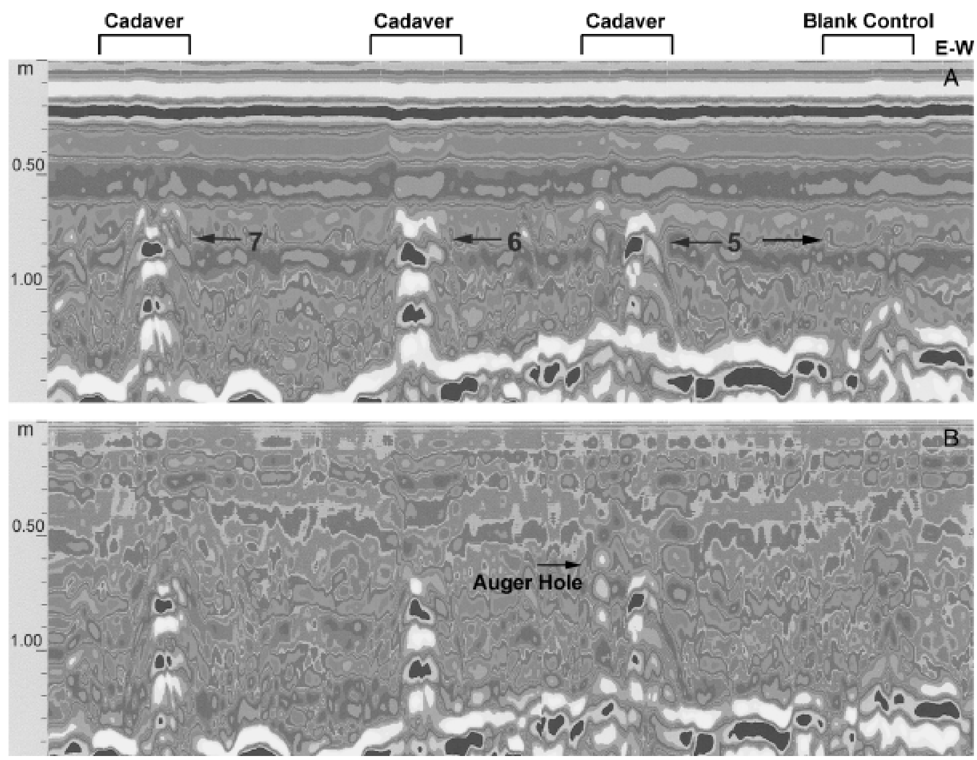

FIG. 4—*Ground-penetrating radar (GPR) profile of three shallow cadavers (5, 6, and 7) collected at 21.5 months that compare the unprocessed imagery (A) with the processed background removal (B). Note the anomaly from the soil auger hole (east of cadaver 5) and the lack of a response from the blank control grave (A, B) that contains only backfill. The profile is approximately 1.45 m deep and 27 m long.*

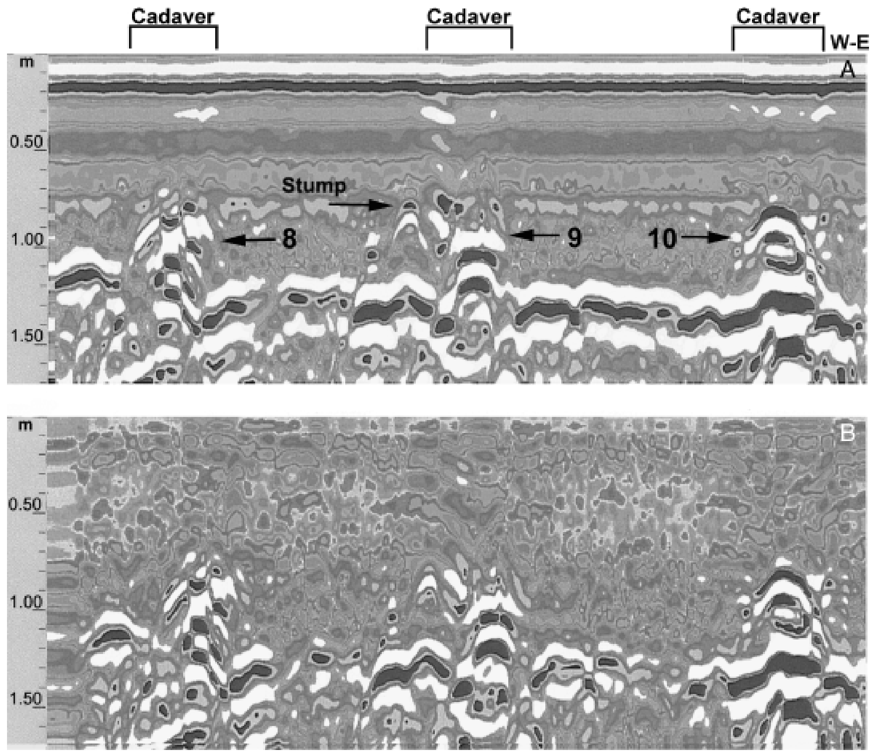

FIG. 5—*Ground-penetrating radar (GPR) profile of three deep cadavers (8, 9, and 10) collected at 4 months that compares the unprocessed imagery (A) with the processed background removal (B). The profile is approximately 1.70 m deep and 21 m long.*

alies were produced for all six of the cadavers (4, 8, 9, 10, 11, and 12) that were buried at shallow depths. For example, there are three distinctive features noted when viewing the unprocessed GPR profile (Fig. 2*A*) that was collected at 2 weeks and represents two cadavers (11 and 12) that were imaged after the short time period (12–13 months): the artificial reflections from ringing

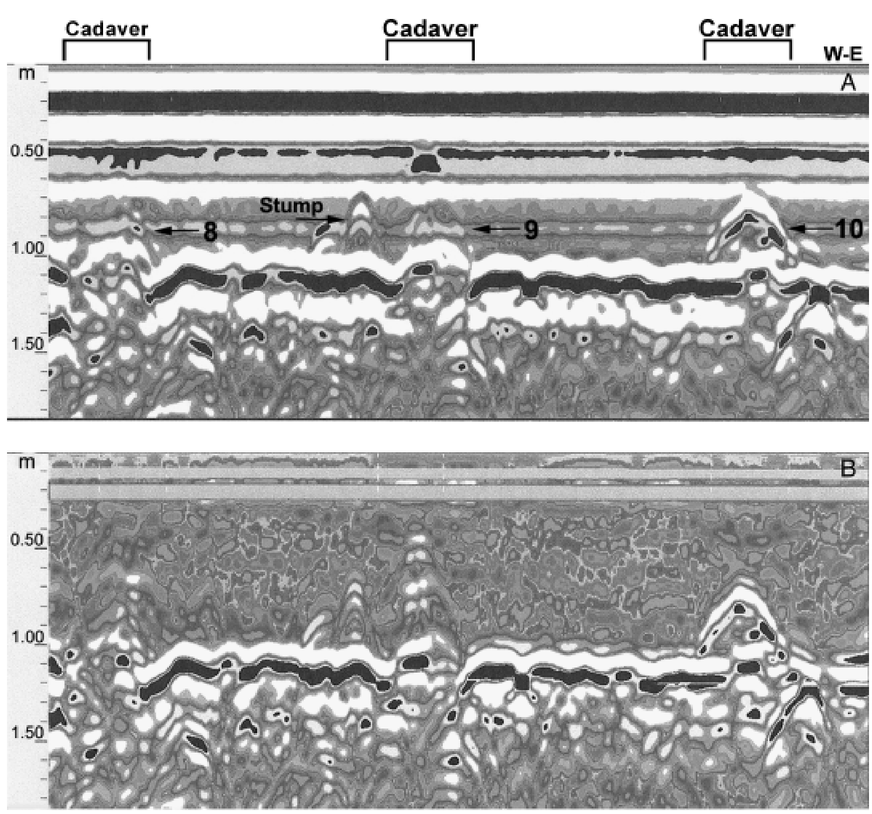

FIG. 6—*Ground-penetrating radar (GPR) profile of three deep cadavers (8, 9, and 10) collected at 13 months that compares the unprocessed imagery (A) with the processed background removal (B). Note the decreased response from cadavers 8 and 9 due to the prominent ringing (A). The resolution of the two cadaver anomalies (8 and 9) increased slightly after the background removal (B). The profile is approximately 1.85 m deep and 21 m long.*

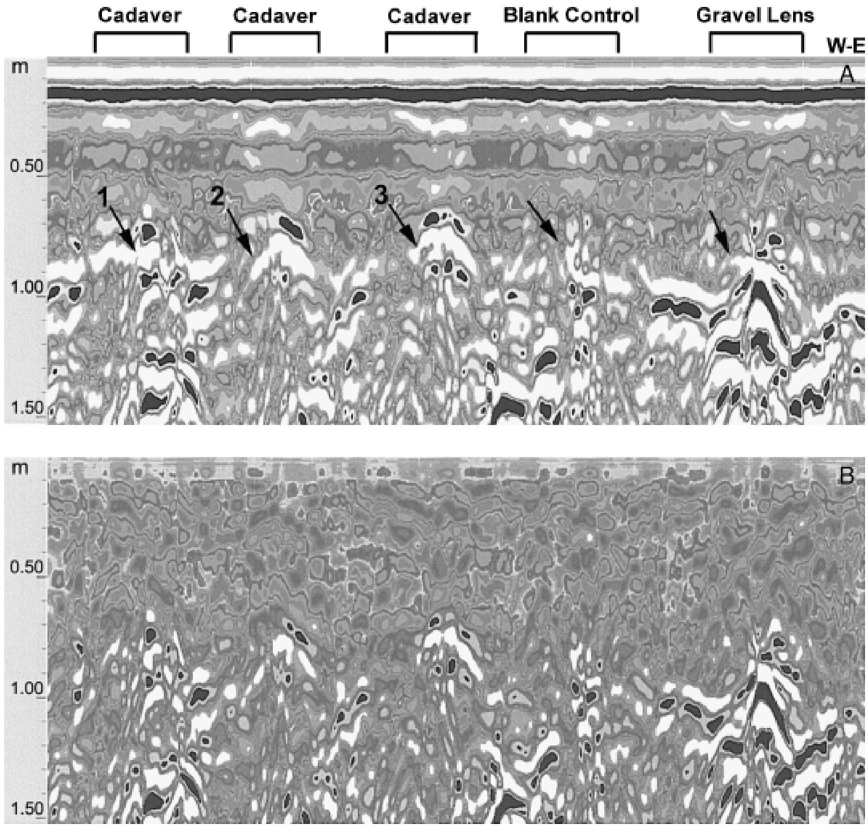

FIG. 7—*Ground-penetrating radar (GPR) profile of three deep cadavers (1, 2, and 3) collected at 21.33 months that compares the unprocessed imagery (A) with the processed background removal (B). Note the poor response from all the three cadavers (A, B), the prominent hyperbolic response from the gravel lens (A, B), and the lack of a response from the blank control grave (A, B) that only contains backfill. The profile is approximately 1.50 m deep and 25 m long.*

(noise), the reflection from the clay horizon, and the anomaly from the buried cadaver. Along the top of the entire profile are artificial reflections, or ringing from noise, that are oriented horizontally. The ringing is most prominent between 0.0 and 0.6 m and the ringing does represent stratigraphic horizons. The thickness and depth of the ringing changed minimally during the study. Along the bottom of the profile is a distinctive reflection from the continuous clay horizon between 1.0 and 1.2 m that appears as a series of horizontal and undulating layers. Two hyperbolic-shaped anomalies begin at a depth of approximately 0.40 m and continue to the clay horizon. Each anomaly appears as a vertical series of hyperbolic or bell-shaped curves. The cadaver is located at the apex of each anomaly and the anomaly continues inferiorly to a depth deeper than the buried cadaver. Although there is extensive

TABLE 2—*Summary information describing the general decomposition state of each cadaver at the time of excavation and an overview of the ground-penetrating radar (GPR) imagery results for each cadaver.*

Cadaver #	General Decomposition State	Overview of GPR Imagery Results
1	Extensive soft tissue preservation of body	Significantly reduced return due to clay that exhibited a weak hyperbolic anomaly that was difficult to detect; slightly increased resolution of grave anomaly after postprocessing, but still difficult to detect
2	Extensive soft tissue preservation body	Significantly reduced return due to clay that exhibited a weak hyperbolic anomaly that was difficult to detect; slightly increased resolution of grave anomaly after postprocessing, but still difficult to detect
3	Extensive soft tissue preservation of body	Significantly reduced return due to clay that exhibited a weak hyperbolic anomaly that was difficult to detect; slightly increased resolution of grave anomaly after postprocessing, but still difficult to detect
4	Near complete skeletonization	Excellent detection for duration; postprocessing not needed
5	Completely skeletonized	Excellent detection for duration; postprocessing not needed
6	Completely skeletonized	Excellent detection for duration; postprocessing not needed
7	Completely skeletonized	Excellent detection for duration; postprocessing not needed
8	Extensive soft tissue preservation of body	Significantly reduced return from grave due to clay but still detectable: slightly increased resolution of grave anomaly after postprocessing
9	Extensive soft tissue preservation of body	Significantly reduced return from grave due to clay but still detectable: slightly increased resolution of grave anomaly after postprocessing
10	Extensive soft tissue preservation of body	Excellent detection for duration; postprocessing not needed
11	Retention of dessicated skin and soft tissue of torso	Significantly decreased return exhibiting a weak hyperbolic anomaly that can be detected; anomaly obscured by antenna noise and is clearly discernable after postprocessing
12	Retention of dessicated skin and soft tissue of torso	Decreased return but still detectable; postprocessing not needed

TABLE 3—*Climatic data for each of the ground-penetrating radar (GPR) profiles (Figs. 2–7) obtained from the NOAA, National Climate Data Center (27).*

Fig. #	Daily Maximum Temperature (°F)	Daily Mean Temperature (°F)	Average Monthly Temperature (°F)	Average Monthly Maximum Temperature (°F)	Daily Rainfall (Inches)	Total Monthly Rainfall (Inches)
2	86	71	76.5	90.6	0.00	0.51
3	93	80	75.0	88.3	0.00	2.67
4	88	75	79.6	88.7	0.00	6.87
5	83	70	81.0	90.7	0.37	2.81
6	93	80	75.0	88.3	0.00	2.67
7	94	84	81.0	90.7	Trace	2.81

antenna noise noted from 0.0 to 0.6 m on the GPR profile, the noise does not mask or obstruct the cadaver anomalies.

With the background removal (Fig. 2*B*), there is only a slight increase in the resolution of the anomalies. The hyperbolic shape of the anomalies increased because the tails are now more discernable, extensions of the hyperbola that produce the hyperbolic shape, with the background removal. In addition, a significant change in the profile is the detection of the backfill above both cadavers from 0.0 to 0.25 m. The backfill is only detected when the antenna noise is removed. The resolution of the clay horizon has not changed, and there is no need to process the profile to detect these cadavers at 2 weeks.

The last unprocessed profile of cadavers 11 and 12 (Fig. 3*A*) was collected at 12 months and 23 days, just before their excavation at 13 months. Although the imagery is not shown for cadaver 4, this cadaver exhibited similar imagery characteristics as cadaver 12. Overall, all three cadavers exhibited variable degrees of skeletonization with some retention of desiccated soft tissues (Table 2). In this profile (Fig. 3*A*), the ringing at the top of the image extends from 0.0 to 0.90 m and reduces the contrast of both cadaver anomalies that begin at approximately 0.45 m and continue to the clay horizon. In addition, below each cadaver anomaly, particularly 11, there is a gap in the continuous clay horizon even though it is not disturbed. The gap helps to highlight the location of the cadavers and is the result of attenuation (reduction of signal strength) of the EM wave by the cadaver that blocks it from reaching the clay horizon. Furthermore, the anomalies of both cadavers (11 and 12) are easily discernable as hyperbolic shapes with prominent tails with the background removal (Fig. 3*B*), and attenuation of the clay horizon is still discernable below both cadavers.

Discernable grave anomalies were produced for the cadavers (5, 6, and 7) buried at the shallow depth that were monitored for the long time period at 21.5 months. Figure 4*A* is an unprocessed image of the last GPR profile from this group of cadavers that was collected before they were excavated at 21.5 months. It is important to note that all three cadavers were completely skeletonized when they were excavated (Table 2). The only major change to the anomalies over time was a decreased return that is represented by a smaller, yet distinctive, grave anomaly. The three large cadavers are still represented by hyperbolic anomalies with discernable tails descending to the clay horizon. There is also a small hyperbolic anomaly immediately east of cadaver 5 that is the result of an old soil auger hole (Fig. 4*A*). In addition, the control grave with only backfill barely exhibited a discernable response. It is clear from the comparison of the blank control hole with that of the pig graves, that the grave anomaly is the result of the pig skeleton and not the disturbed soil. Overall, there was no problem detecting these pig cadavers using the unprocessed imagery when they were completely skeletonized.

Background removal of the profile did not increase the resolution of the three cadaver anomalies (Fig. 4*B*), but resolution of the backfill above each cadaver increased slightly. In addition, the resolution of the soil auger hole, immediately east of cadaver 5, increased and is now visible as a narrow series of vertical hyperbolas, or a spike, that terminates at the clay horizon.

Deep Cadavers in Clay

Out of the six cadavers buried at a deep depth (1.00–1.10 m), five intruded into the upper segment of the clay horizon (1, 2, 3, 8, and 9), while cadaver 10 was buried directly on top of the horizon because the clay was slightly deeper at this location. Since the response for the deep graves in clay was similar for the two cadavers buried for 13 months (8 and 9) as those buried for 21.5 months (1, 2, and 3), only the results of cadavers 8 and 9 will be discussed in detail. Figure 5*A* represents an unprocessed GPR profile of the three cadavers (8, 9, and 10) that was collected at 4 months for the short time period at 13 months. All three cadavers exhibit clear hyperbolic anomalies, and minimal soil disturbances are retained above each cadaver. The anomalies from cadavers 8 and 9 begin at approximately 0.85–0.90 m, and they extend into the clay horizon resulting in disruptions of the horizon that are easily detected. In addition, the small anomaly immediately west of cadaver 9 at 0.70 m is caused by a possible buried root or small stump from brush that was in this area at one time. Cadaver 10 also exhibits a distinctive anomaly, but does not exhibit a disruption of the clay horizon because this cadaver is buried directly above the clay. Slight soil disturbances of the backfill are detected above each cadaver. Background removal did not increase the resolution of the cadaver anomalies because they are buried below the strong antenna noise at the top of the profile (Fig. 5*B*).

Over the first year the response from the five cadavers (1, 2, 3, 8, and 9) that were buried into the clay decreased considerably even though the cadavers all exhibited extensive soft tissue preservation (Table 2). For example, Fig. 6*A* is the last unprocessed profile of cadavers 8, 9, and 10 that was collected before excavating the short time period cadavers at cadavers at 13 months. The ringing is more prominent in this profile (Fig. 6*A*) than it was in Fig. 5*A*, where it extends from 0.0 to 0.90 m and is the thickest from 0.0 to 0.70 m. The return from cadaver 10 is the most distinctive of the three cadavers. It is represented by a number of prominent hyperbolas around 0.75 m that terminate at the superior surface of the clay horizon at a depth of 1.05 m. There is also a small break or disruption through the continuous clay horizon due to attenuation of the EM wave directly below the buried cadaver.

Conversely, cadavers 8 and 9 are represented by small hyperbolic anomalies at 0.90 m that terminate into the clay layer. The resolution of these two cadaver anomalies (8 and 9) decreased significantly in this profile (Fig. 6*A*) compared with Fig. 5*A*. The anomalies are somewhat masked by the clay layer even though the pig cadavers had undergone very little decomposition and still retained extensive soft tissue structures that were noted when the graves were excavated (Table 2). Also, immediately below both reflections are breaks in the clay horizon due to attenuation. Seasonal changes in local moisture content can be ruled out as a factor causing the decreased response of the anomalies from cadavers 8 and 9 in Fig. 6*A*, because the monthly rainfall was very similar when the data profiles were collected for Figs. 5 and 6 (Table 3). Overall, the resolution of the backfill increased slightly with background removal (Fig. 6*B*).

Figure 7*A* is the last unprocessed profile for the long time period cadavers (1, 2, and 3) that was collected at 20.33 months before they were excavated at 21 months. It is important to note that all three cadavers exhibited extensive soft tissue preservation when they were excavated (Table 2). The return from the gravel lens is a distinctive hyperbolic anomaly that starts at 1.0 m and extends sporadically through the clay. This control grave provides a reference for size and depth of the grave anomalies in the clay horizon. Overall, the weak returns from the three cadavers (1, 2, and 3) are very similar in appearance and appear as poorly demarcated hyperbolic shapes starting at approximately 0.80 m. These anomalies could easily be missed if the location of the graves was not known. However, the lack of a recognizable return from the blank control grave (control 1) is still a clear indication that the anomalies are produced by the buried pig cadavers, not just the disturbed soil. Removing the ringing did not increase the resolution of the anomalies from cadavers 1, 2, and 3 (Fig. 7*B*), because the noise is concentrated on the upper part of the profile above the buried cadavers.

Discussion

In this study, the type of soil that the body was buried in had the greatest effect on whether a distinctive anomalous response was discernable over the duration of the monitoring period. Cadavers that were buried in sandy soils were easily detected for the duration of this study at 21.5 months while exhibiting variable states of decomposition that included complete skeletonization. Furthermore, the blank control graves, comprising only disturbed backfill, were very important in demonstrating that the hyperbolic anomaly was primarily the result of the decomposing body or skeleton and not the disturbed soil. Pertinent anomalies in sand were produced for the duration of this study because there was a strong enough contrast between the skeleton and the surrounding soil to be detected by GPR due to differences in dielectric permittivity. When a skeleton was detected in this study, the GPR was detecting a contrasting area in the soil that included bone, soft tissue, decomposition products, and leached minerals from the skeleton.

Conversely, in clay it became increasingly difficult to image the pig cadavers that were buried at the deeper depths. Over the first 6 months, graves in clay were generally detected. However, as the disturbed ground compacted over the first year, the response from these graves become more difficult to discern even though the cadavers had undergone very little decomposition. The poor hyperbolic response from the cadavers buried in clay became difficult to discern because they appeared as natural undulations of the clay horizon. Mineral soils with high clay content can attenuate the EM wave propagation, thereby reducing the depth of penetration in the ground, and therefore prevent detection of burial sites or other features contained within the soil. In other words, the clay horizon masked the cadaver by limiting the dielectric permittivity of the pig cadavers with that of the horizon. It was not a surprise that the cadavers buried in the clay became difficult to detect because clay is a limiting factor that significantly reduces the ability to detect forensic and cemetery graves using GPR.

Although it became difficult to image the cadavers buried into the clay horizon in this study, it was possible to image disruptions or breaks in the clay horizon that were the result of the soil disturbance from the grave and attenuation of the radar wave by the cadaver. However, detecting a clandestine body based solely on soil features may not be possible because over time the response from the disturbed soil of the grave will be significantly reduced. Initially, the backfill may be detected by GPR because the dielectric permittivity of the disturbed soil has increased compared with the surrounding undisturbed soil as a result of larger pore spaces between the sand grains that retain higher levels of moisture. However, over time backfill consisting of sandy soil will become compacted and somewhat homogenous with that of the surrounding undisturbed soil where it may no longer be detected using GPR. Conversely, detecting a clandestine body in soils with stratigraphic horizons comprised of clay can be the result of imaging the body, soil disturbances, or both. When soils containing clay horizons are disturbed by digging, it is less likely that the soil can homogenize with that of surrounding undisturbed soil because of the different soil compositions. As a result, the disturbed area will remain less dense than the undisturbed soil surrounding the burial, and the disturbed soil can retain a mottled appearance from the mixing of stratigraphic horizons of different soil compositions. This is the reason why T-bar, soil coring, and penetrometer (provides a quantitative measurement of soil compaction) probes can be useful to locate clandestine burials from forensic contexts and much older burials from cemetery contexts (3,4,28).

This research has also shown that in sandy soils in Florida, processing the GPR data to remove the horizontal ringing is generally not needed to make assessments in the field. While the densest horizontal ringing in this study was generally between 0.0 and 0.60 m, the response from both the deep and shallow burials was normally not obscured by the ringing. Conversely, the cadaver anomaly may be obscured by ringing if a shallow burial exhibits a weak return. In this instance, processing the profile to remove the ringing may be required for detection of the cadaver. Furthermore, removing the horizontal ringing did periodically increase the response from the grave such as the backfill above the cadaver. Detecting the disturbed soil can be helpful in locating a clandestine grave when there is a weak response from the body. Unless extensive ringing is noted and anomalies have very little contrast, background removal may not be needed for grave detection. An assessment concerning the need for processing can initially be determined in the field by noting the resolution of shallow subsurface features and the extent of the ringing during calibration of the equipment. Also, depending on the GPR manufacturer, there are newer GPR models that offer an option to process the data for background removal during data collection in the field.

While GPR provides a high-resolution image of subsurface features, it does not provide an actual picture of the buried features or objects. Detecting a clandestine burial with GPR can be the result of detecting contrasting properties of the grave with that of the surrounding soil due to soil features and the body. The most obvious response from the body is an anomaly with a hyperbolic shape, with or without distinctive tails. Directly below the body there can be a loss of the signal due to attenuation that is sometimes present on the GPR profile without a hyperbolic anomaly. The hyperbolic shape is the result of the wide angle of the transmitted radar wave that is radiated into the ground in the shape of an elliptical cone. The long axis of the ellipse is parallel to the direction that the antenna travels, and as a result, it will detect subsurface objects before arriving directly over them, when it is directly over them, and it will continue to detect the objects after passing the objects (3,24,29). The hyperbolic characteristic, including the tails, of the anomaly is due to the increased travel time of the radar signal when the subsurface object or feature is detected by the antenna before and after passing over the buried object.

Depending on the length of time that the body was buried and the soil type, grave features such as the backfill above the cadaver, detection of grave walls, and gaps or disruptions of continuous stratigraphic horizons that produce localized soil changes can also produce responses that are detected with GPR. Finally, detection of the body may also be the result of nonbiological items included in the grave with the body because these items may increase the dielectric contrast with the area surrounding the body. These include items added on top of the victim (i.e., metal and debris) to help with concealment before the adding the backfill to the grave and items used to wrap the victim (i.e., tarpaulins and rugs).

GPR has become a very important search tool for death investigators in various geographical regions and soil types. In particular, this technology can be an effective search tool in Florida and other geographical areas where bodies are buried in soils comprised primarily of sand. For example, out of the 48 contiguous states, a considerable area of Florida, including central Florida, received the highest possible rating for GPR soil suitability by the USDA-Natural Resources Conservation Service (30). Florida is an ideal geographical area for GPR research and numerous types of applications because most of the soils provide advantageous conditions such as a predominance of sand horizons, sand horizons with deep clay horizons, and the soils do not contain large boulders or gravel lenses that can produce false anomalies.

Continued forensic GPR research is essential to clarify its usefulness in different micro-environments, soils, and burial scenarios. In particular, further research is needed to determine the utility of GPR for locating buried remains that have been interred for extended time frames of many years, including mass graves that contain victims of war crimes. If a unit is available, obtaining experience searching for clandestine graves with GPR can be obtained by constructing controlled graves and monitoring them regularly as was done in this study, and to form a cooperative relationship with local law enforcement to regularly assist with searches for clandestine forensic graves. If the only option available when using GPR for body searches is to bring in an outside consultant, then inquiries should be made as to their experience and how they will perform the survey before securing their services.

Conclusions

Overall, GPR is a valuable search tool for investigators when searching for buried bodies from forensic contexts. This study has shown that cadavers in sand can be easily detected with GPR in advanced stages of decomposition and when they are completely skeletonized. Furthermore, the blank control graves, comprising only disturbed backfill, were very important in demonstrating that the hyperbolic anomaly was primarily the result of the decomposing body or skeleton and not the disturbed soil. Conversely, cadavers that were buried in proximity to the clay horizon became increasingly difficult to image, and after the first year of burial they were difficult to detect while retaining soft tissue structures. However, although detection of the cadaver became difficult, it was still possible to discern the location of the grave because of soil disturbances of the clay horizon and breaks in the horizon due to attenuation of the EM wave by the cadaver. Finally, processing background removal of the GPR data is generally not needed for assessments that are made in the field when profiling soils comprised primarily of sand. However, removing the horizontal ringing can be helpful for grave detection because there may be an increased response from the backfill that can indicate the location of the grave when there is a weak response from the body.

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References

1. France DL, Griffin TJ, Swanburg JG, Lindemann JW, Davenport GC, Trammell V, et al. A multidisciplinary approach to the detection of clandestine graves. J Forensic Sci 1992;37:1445–58.
2. France DL, Griffin TJ, Swanburg JG, Lindemann JW, Davenport GC, Trammell V, et al. NecroSearch revisited: further multidisciplinary approaches to the detection of clandestine graves. In: Haglund WD, Sorg MH, editors. Forensic taphonomy: the postmortem fate of human remains. Boca Raton, FL: CRC Press; 1997:497–509.
3. Dupras TL, Schultz JJ, Wheeler SM, Willimas LJ. Forensic recovery of human remains: archaeological approaches. Boca Raton, FL: CRC Press; 2005.
4. Killam EW. The detection of human remains. Springfield, IL: Charles C. Thomas; 1999.
5. Bevan BW. The search for graves. Geophysics 1991;56:1310–9.
6. Davis JL, Heginbottom JA, Annan AP, Daniels RS, Berdal BP, Bergan T, et al. Ground penetrating radar surveys to locate 1918 Spanish flu victims in permafrost. J Forensic Sci 2000;45:68–76.
7. King JA, Bevan BW, Hurry RJ. The reliability of geophysical surveys at historic-period cemeteries: an example from the Plains Cemetery, Mechanicsville, Maryland. Hist Archaeol 1993;27:4–16.
8. Vaughn CJ. Ground-penetrating radar surveys used in archaeological investigations. Geophysics 1986;51:595–604.
9. Davenport CG. Remote sensing applications in forensic investigations. Hist Archaeol 2001;35:87–100.
10. Davenport CG. Where is it? Searching for buried bodies and hidden evidence. Church Hill, MD: SportWork; 2001.
11. Mellett JS. Location of human remains with ground-penetrating radar. In: Hanninen P, Autio S, editors. Fourth international conference on ground penetrating radar June 8–1. Rovaniemi, Finland: Geological Survey of Finland, Special Paper 1b; 1992:359–65.
12. Nobes DC. The search for "Yvonne": a case example of the delineation of a grave using near-surface geophysical methods. J Forensic Sci 2000; 45:715–21.
13. Reynolds JM. An introduction to applied and environmental geophysics. New York: John Willey and Sons Inc.; 1997.
14. Schultz JJ. Forming research partnerships with law enforcement: using GPR to locate graves of homicide victims. In: Salfati CG, editor. Homicide research: past, present, and future. Proceedings of the 2005 meeting of the homicide research working group: 2005 June 3–6. Orlando, FL: HRWG Publications; 2006, In press.
15. Davenport CG, Griffin TJ, Lindemann JW, Heimmer D. Geoscientists and law officers work together in Colorado. Geotimes 1990;35:13–5.
16. Strongman KB. Forensic applications of ground penetrating radar. In: Pilon J, editor. Ground penetrating radar, Geological Survey of Canada, paper 90–4, 1992:203–11.

17. Freeland RS, Miller ML, Yoder RE, Koppenjan SK. Forensic applications of FM-CW and pulse radar. J Environ Eng Geophys 2003;8:97–103.
18. Miller ML, Freeland RS, Koppenjan SK. Searching for concealed human remains using GPR imaging of decomposition. In: Koppenjan SK, Hua L, editors. Ninth international conference on ground penetrating radar, 2002 April 29–May 2, 2002: Santa Barbara, CA. Bellingham (WA): SPIE, 2002; 4758:539–44.
19. Schultz JJ, Falsetti AB, Collins ME, Koppenjan SK, Warren MW. The detection of forensic burials in Florida using GPR. In: Koppenjan SK, Hua L, editors. Ninth international conference on ground penetrating radar, 2002 April 29–May 2, 2002: Santa Barbara, CA. Bellingham (WA): SPIE, 4758:2002; 443–8.
20. Schultz JJ. Detecting buried remains in Florida using ground-penetrating radar [dissertation]. Gainesville, FL: University of Florida; 2003.
21. Ruffell A. Searching for the IRA "disappeared": ground-penetrating radar investigation of a churchyard burial site, Northern Ireland. J Forensic Sci 2005;50:1430–35.
22. Goff ML. Estimation of postmortem interval using arthropod development and successional patterns. Forensic Sci Rev 1993;5:81–94.
23. Catts EP, Goff ML. Forensic entomology in criminal investigations. Ann Rev Entomol 1992;37:254–72.
24. Conyers LB. Ground-penetrating radar for archaeology. Walnut Creek, CA: AltaMira Press; 2004.
25. Sternberg BK, McGill JW. Archaeology studies in southern Arizona using ground penetrating radar. J Appl Geophys 1995;33:209–25.
26. Shih DG, Doolittle JA. Using radar to investigate organic soil thickness in the Florida everglades. Soil Sci Soc Am J 1984;48:651–6.
27. NOAA, National Climate Data Center. http://www.ncdc.noaa.gov/oa/ncdc.html.
28. Owsley DW. Techniques for locating burials, with emphasis on the probe. J Forensic Sci 1995;40:735–40.
29. Miller PS. Disturbances in the soil: finding buried bodies and other evidence using ground penetrating radar. J Forensic Sci 1996;41:648–52.
30. Doolittle JA, Minzenmayer FE, Waltman SW, Benham EC. Ground penetrating radar soil suitability map of the conterminous United States. In: Koppenjan SK, Hua L, editors. Ninth international conference on ground penetrating radar, 2002 April 29–May 2, 2002: Santa Barbara, CA. Bellingham (WA): SPIE, 4758:2002; 7–12.

Additional information and reprint requests:
John J. Schultz, Ph.D.
Department Anthropology
University of Central Florida
4000 Central Florida Blvd.
Orlando, FL 32816-1360
E-mail: jschultz@mail.ucf.edu