The use of ground-penetrating radar in archaeology

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Ground-penetrating radar is a geophysical method that can accurately map buried archaeological features in three-dimensions. Data are collected when radar waves are transmitted from a surface antenna into the ground and reflected off buried archaeological features and stratigraphic horizons. The reflected waves are recorded back at the surface and the transmission time is measured, which can then be converted to depth in the ground. Digital data acquisition allows reflection profiles to be filtered and enhanced in order to produce high quality two-dimensional images. The spatial mapping of reflected wave amplitudes within a grid can be used to accurately map buried sites in three-dimensions.

1. INTRODUCTION

In today's climate of rescue archaeology, cultural resource management and the prevalent ethic of site conservation, non-invasive methods of subsurface exploration and mapping are becoming increasingly important. With many archaeological excavation budgets severely restricted, and strict political and conservation considerations that must be considered, it is often not feasible or is undesirable to excavate large areas or randomly dig test excavations in the hope of finding buried archaeological sites. New computer enhanced geophysical methods, including ground-penetrating radar, are being developed for site identification, mapping and analysis, which can non-invasively gather massive amounts of data from buried sites without having to dig. Archaeologists who are only familiar with the traditional methods of gathering data by the shovel and trowel method are being increasingly marginalized in this changing environment.

Increasingly sophisticated ground-penetrating radar (GPR) acquisition and processing methods can be employed to gather important subsurface information in un-excavated areas including the location, depth and orientation of important buried features and artifacts, precluding the time consuming and costly process of digging. Maps and images produced from the GPR data can not only identify buried features for possible future excavation but also interpolate between excavations into the unknown, projecting archaeological knowledge into areas that have not yet been, or may never be excavated.
GROUND-PENETRATING RADAR METHOD

Ground-penetrating radar equipment is very portable, consisting of paired surface antennas, a computer with monitor and keyboard (Figure 1). Power is supplied to the system, electrical generator or normal AC current.

Ground-penetrating radar equipment including a 500 MHz antenna (with handle), radar stem and hard drive, and computer monitor.

Ground-penetrating radar waves, created by pulses from a surface antenna, objects, features or bedrock contacts. Reflections that are generated from buried strigraphic changes are detected and recorded at a receiving antenna on the ground (Conyers and Goodman, 1997: 23 [1]). The elapsed time between when the pulse was sent and received, from progressively deeper in the ground, are received back at the antenna measured and recorded.

The change in the electrical or magnetic properties of features in the ground will cause a transmitted radar pulse to be reflected back to the surface. When the travel times of pulses are measured, and their velocity through the ground can be determined, distance to ground) can be accurately measured (Conyers and Lucius, 1996 [2]).

Data are collected as both surface receiving and transmitting antennas are moved und surface in tandem, while collecting a series of reflections in a linear transect. Each reflection recorded at one location on the ground is called a trace. When many traces along a transect are stacked vertically, they can be viewed as two-dimensional vertical reflection profiles of the subsurface stratigraphy and other buried features (Figure 2).

Different antenna frequencies, ranging from about 80 to 1200 MHz are typically used in archaeological mapping (Conyers and Goodman, 1997: 40 [1]). The lower the antenna frequency, the longer the wavelength of energy transmitted into the ground. These longer radar wavelengths can penetrate quite deeply in the ground, but are only capable of resolving fairly large buried features. For instance, 80 MHz antennas may be able to transmit and then receive energy back at the surface from a depth of 3 meters or more, but are incapable of resolving features smaller than a few meters in diameter. In contrast, a 1,000 MHz antenna can transmit radar energy to at most 50 centimeters depth, but the resulting reflections can resolve objects as small as a few centimeters in diameter.

Some ground conditions are favorable for radar energy transmission, such as dry sand, volcanic ash or dry soils. The media most conducive for radar transmission are electrically resistive materials with little magnetic permeability (Conyers and Goodman, 1997: 53 [1]). In contrast, wet clay and any other material that is highly electrically conductive will readily attenuate radar waves as they penetrate into the ground and most energy will be lost near the ground surface, irrespective of antenna frequency or power.

Figure 2. Ground-penetrating Radar Profile showing a buried living surface on the left side of the profile, which has been disturbed by anthropogenic disturbance on the right side of the profile. High amplitude reflections are dark black while areas of little reflection are gray.
data sets are acquired in a regular series of parallel and perpendicular transects and the reflections derived in many two-dimensional profiles are correlated and rate three-dimensional maps of buried features and associated stratigraphy can be the physical and chemical changes of the buried materials can also be mapped data measured in this three-dimensional volume of reflections includes the the reflected waves, which are indicative of the variations within the buried layers and Goodman, 1997: 149 [1]). The higher the amplitude of the reflected waves, electrical and magnetic contrast that exists at the contrast between contrasting ground. For instance, a very high amplitude reflection would typically be generated by between dry sand and wet clay, because they have very different electrical and magnetic. Often similar high amplitude reflections are generated at contacts between features, such as buried floors, and the surrounding materials.

STORY OF GPR DATA PROCESSING AND INTERPRETATION IN ARCHAEOLOGY

Penetrating radar has been traditionally used as a method for identifying the existence of buried archaeological features. Throughout the 1970s and 1980s its use was as an exploration tool, with limited given to detailed subsurface mapping of those sites of the surrounding stratigraphy. Only a limited amount of data processing was possible due to the difficulty in processing and interpreting large GPR data sets that might contain hundreds of individual reflections, most of which were printed out as paper records. In addition, the complexity of radar reflections that can occur in the ground, the interfering important reflections, and the massive amounts of data that are typically left uninterpreted or lost. In addition, the reflection profiles in-processed "raw" data that contained an abundance of "noise", which could be reflections from surface objects and even from people moving about in the vicinity of complicating two-dimensional images. Fortunately, even in these types complex and chaotic, significant reflection "anomalies" could usually be visually correlated with anomalies in adjacent profiles. In this type of rudimentary data analysis most features were identified visually, based only on what buried archaeological features "look like". If buried reflection surfaces were extensive enough, reflections could be correlated from profile to profile within a grid, but often the abundance and detectable reflections precluded accurate correlation. In addition, without extensive confirmation of the discovered features, little could actually be determined about the spatial orientation of many reflections, and therefore most interpretation was usually incomplete.

A breakthrough in GPR processing occurred in the late 1980s as digital recording and for post-acquisition data processing, filtering and manipulation of reflection an and Davis, 1992 [3]). These post-acquisition processing methods allowed noise, a common problem in all GPR records, to be routinely removed from the recorded data (Conyers and Goodman, 1997: 77 [1]). Background noise, which produces the horizontal banding common in typical un-processed GPR profiles, is caused by noise inherent in GPR systems, "ringing" within antennas and multiple reflected reflections that occur as radar energy is repeatedly bounced between the antennas and the ground surface (Conyers and Goodman, 1997: 78 [1]). Multiple reflections can also occur within the housing of radar antennas and sometimes between surface features and the antennas. Computers can easily remove these horizontal bands by arithmetically averaging all recorded waves that were recorded at the same time within all the traces collected in a transect. This "average" wave can then be subtracted from each trace, leaving only those reflections that are non-horizontal and presumably those that were generated from important geological or archaeological features in the ground.

A second form of post-acquisition data processing that also became common with the advent of digital data was the removal of portions of selected frequencies from the recorded signal. These data enhancement processes, sometimes called high and low-pass filters, remove extraneous noise that can be associated with FM radio, cellular phone, television and other electromagnetic transmissions. They can be applied either during data acquisition, or in post-acquisition processing of digital data (Conyers and Goodman, 1997: 74 [1]).

4. TIME-DEPTH CONVERSIONS

A significant aid in the reflection identification process is being able to convert the time at which reflected waves were recorded to their approximate depth in the ground. All GPR reflections are measured in two-way time, which is the elapsed time between when a radar pulse is sent from the surface antenna, travels into the ground, and then is reflected back to the surface and measured. Time is measured in nanoseconds, or billions of a second. To convert time to depth, the velocity of the radar energy travel in the ground must be determined.

Radar energy travels at almost the speed of light in air, but as it enters the ground, it begins to slow. Usually radar wave velocity decreases with depth as soils, sediment and rock become more compact and progressively more water saturated. However, velocity can also increase, if it enters a void space, or other medium of higher velocity.

The simplest way to convert measured travel time to depth is to directly measure the depth of reflections that are visible in reflection profiles. Many times objects, such as plastic or metal pipes, rocks or other "point source" objects will generate visible hyperbolic reflections in profiles (Figure 3). Hyperbolas are produced from point sources because radar energy travels into the ground from the surface antenna in a conical shape, with the apex of the cone at the surface antenna. Radar energy spherically spreads out from the antenna as it travels into the ground and therefore reflections will be recorded from an object before the antenna is directly on top of it, and will continue to be recorded as it passes away. The result is a hyperbolic shaped reflection, with the apex denoting the actual location of the reflection source.

When point source reflections are visible in profiles, their exact locations on the ground can be identified. If its exact depth below the ground is known or can be measured using a soil probe, post hole digger, or other tool, the average velocity of radar waves traveling through the ground can be calculated (Conyers and Lucius, 1996 [2]). An estimate of radar velocity can also be made by
analyzing the shape of the hyperbola arms. In general, the lower the velocity, the greater the spread in the arms of the reflection hyperbola.

5. REFLECTION MODELING

Two-dimensional reflection profiles do not typically "look like" what one thinks a feature "should look like" in cross-section because of the complex reflection, refraction and multiple reflections of radar waves in the subsurface. Synthetic radar profiles, produced on the computer, that can model how radar reflections are produced in the ground can be of great benefit in feature identification and analysis (Conyers and Goodman, 1997: 83 [1]). These two-dimensional models can be computer-generated if the approximate geometry of target features is input and the electrical and magnetic properties of the geological and archaeological layers are known (Goodman, 1994 [4]). Varying frequencies of radar data can then be passed through the modeled features and geological layers, producing a two-dimensional model of the generated reflections (Figure 4). These synthetic GPR profiles can then be compared to actual GPR profiles collected in the field as an aid in feature identification. They can also be prepared prior to data acquisition in order to study the potential resolution of suspected features, if geological and archaeological parameters are known in advance.

Figure 3. Hyperbolic reflection produced from a buried metal pipe.

Figure 4. Two-dimensional GPR simulation of a pit-structure with a fire hearth in the 500 MHz antenna. A storage cistern is modeled on the left side of the model. An i surface is buried by two stratigraphic units of differing composition. The results model shows that the cistern and the hearth in the floor of the pit-house would not b two-dimensional profile. The house floor would be the most visible feature in two profiles.

6. THREE-DIMENSIONAL AMPLITUDE ANALYSIS

The massive amount of GPR data collected, the complexity and abundance reflections recorded and the length of time it takes to identify visually and then manually reflections in order to produce valuable maps can still be a daunting task. An extra data processing tool that can quickly process large quantities of reflection data is the slice-map method (Conyers and Goodman, 1997: 149 [1]; Goodman et al., 1994
The American Southwest is an excellent environment for GPR mapping, but one where oral and written accounts of ancient cultures have mostly been lost to the exclusion of geophysical surveys. Only recently has GPR been successfully applied to a number of test sites and features. As a result, many new and previously undocumented archaeological sites have been discovered. This has led to new insights into the prehistoric cultures that inhabited the area.

Traditional archaeological exploration and mapping methods used for the discovery of sites include visual identification of artifacts in surface surveys, random test pit excavation, and analysis of subtle topographic features, all of which may indicate the presence of buried features. While these methods can be effective, they are often imprecise and random, often leading to misidentification or non-identification of features.

At a site near Bluff, Utah, a local archaeologist used some of these techniques to map what was considered to be a large pit house village. The area is located in the floodplain of the San Juan River, an area that was subjected to repeated floods during prehistoric time, often burying low structures in fluvial sediment. In a grid that was roughly 50x50 meters in diameter, surface test pits had located 4 or 5 topographic depressions that appeared to be subtle expressions of pit houses. However, what was presumably a small buried village. Lithic debris from stone tool manufacture as well as abundant ceramic sherds were found in and around these depressions, further enhancing preliminary interpretation.

A GPR survey was conducted over this prospective area, using paired 500 MHz antennas which transmitted data to a maximum depth of about 2 meters (Conyers and Cameron, 1998). While data were being acquired, reflection profiles were viewed on a computer monitor, as recorded digitally. A preliminary interpretation of the raw data in the field showed no evidence of pit house floors in the areas containing the depressions. Surprisingly, a large distinct floor was located in one corner of the grid, an area not originally considered prospective. No information, obtained in a nearby pit being dug for a house foundation, was used to convert travel time to depth.

An amplitude time-slice map was then constructed in a slice from about 1.2-1.5 meters in depth, a slice that would encompass the pit house floor and all sub-floor features. A map high amplitudes in this slice shows an irregular shaped floor with a possible anechoic entrance at opposing sides of the pit structure (Figure 5). In order to confirm this interpretation, a series of profiles were taken from the GPR antenna. Those cores drilled outside the pit house, and in the area of the shallow depressions, were thought to be the location of the houses, encountered only hard, partially-cemented fluvial sediments with no archaeological remains.

This GPR survey demonstrates the advantages of performing GPR surveys in conjunction with typical surface topography and artifact distribution mapping. The standard methods of exploration indicated the presence of nearby pit houses, but both the artifact distributions and subtle depressions pointed to the wrong area. If only these indicators were used as a guide for subsurface testing, it is doubtful any archaeological features would have been discovered. When used in conjunction with the GPR data, the pit house was discovered. It is not known what may have created the subtle depressions that were originally interpreted as pit house entrances.

The artifact and lithic scatters noticed on the surface were likely produced by rodent burrows which brought these materials from depth and then concentrated them randomly across the site. A cautionary lesson about how changing conditions can affect GPR mapping was learned at this site when a second GPR survey over the known pit house was conducted a few months after a large rain storm. This survey produced no significant horizontal reflections in the area confirmed pit house, but many random non-horizontal reflections throughout the grid, which looked like house floors. These anomalous reflections were probably produced by rain water that had been differentially retained in the sediments.

At a well known archaeological site, also near Bluff, Utah, a second GPR survey performed in an area where a distinct surface depression indicated the presence of a Great House, a large semi-subterranean structure typical of Pueblo II sites in the American Southwest (Conyers and Cameron, 1998).
A 30x40 m² GPR survey using both 300 and 500 MHz antennas was conducted over this feature, to be used as a guide to future excavation. Individual GPR profiles of frequencies showed only a bowl shaped feature, which appeared to be filled with homogeneous material with no significant reflection (Figure 6). There were no discernable features in the depression that would correspond to floor features or possible roof support structures.

![Amplitude slice map showing a square pit-structure with an entrance and possible antenna](image)

5. Amplitude slice map showing a square pit-structure with an entrance and possible antenna.

Amplitude time-slice maps were then produced for the grid in the hope that subtle changes at plitude, not visible to the human eye in normal reflection profiles, might be present in the data. When this was completed, the slice from 1.33 to 1.54 meters in depth (Figure 7) showed a feature deep within the depression, which was later found in two excavation trenches to be all of a deeper feature within the depression (Conyers and Cameron, 1998 [6]).

5. Amplitude slice map showing a square pit-structure with an entrance and possible antenna.

The function and origin of this feature is not yet known. What can be concluded from this exercise is that the computer is capable of producing images of subtle features that can be readily processed by the human brain. Without this type of GPR processing, this deep feature would most likely not have been discovered or excavated.

Near Tucson, Arizona, a well documented Hohokam Period village has been partially exposed on a gravel terrace above the Santa Cruz River (Conyers and Cameron, 1998 [6]). Archaeological features at the site include pit structures, large storage cisterns and miah ball courts. The archaeological site is covered by sheet wash and wind blown sediment, so many features under more than a meter of sediment. The usual method for identification of subsurface remains in this area is by excavating long trenches using a mechanized backhoe. This method can be quite effective in locating features, as long as they are in the path of the trench. Often, significant structures are destroyed during discovery. In addition, little can be done about the exact orientation of the buried features encountered, and nothing at all can be done about the areas between the trenches.

![Reflection profile across a Great Kiva](image)

Figure 6. Reflection profile across a Great Kiva. The walls of the kiva are the high area reflections, while the interior of the kiva is filled with wind blown sand, which reflects little energy.

To map the known features, found in previous trenching operations, more accurate to prospect for possible other remains between trenches, a 30x40 meter grid of 500 MHz GPR was acquired. The initial results were very disappointing. The radar profiles visible on the computer screen during acquisition were so "noisy" as to be indistinguishable (Figure 8). It appeared from first glance that the survey would be a total failure. The noise that was observed was the result of reflections from within the ground appearing to have been created by radio and television transmissions common in the city.

In an attempt to filter out the extraneous frequencies and remove background noise, a pass filter that removed all frequencies above 800 MHz was applied to all reflection data returning from the field. This filtering process effectively removed the interference from the transmission in the band width that include UHF Television and FM radio, leaving only reflections of importance (Figure 9).
When this was accomplished, reflection profiles within the grid were capable of mapping the buried archaeological features that were known from the trenching operation (Cony Cameron, 1998 [6]). Ten other features were discovered between the trenches, which probably not have been detected in any other way. The GPR amplitude slice-maps were capable of producing maps of the exact dimensions of all features and using velocity data their exact depths in the ground were also determined (Figure 9).

Figure 9: Processed reflection profile from the same data shown in Figure 8. Background noise removed, frequencies were filtered to enhance reflections from within the ground and the reflections were amplitude enhanced.

8. CONCLUSIONS

Ground-penetrating radar surveys can be of tremendous value for the rapid, noninvasive determination of the number, character and orientation of subsurface features at archaeological sites. The GPR mapping method can be used to produce maps that are far more complete of a site than is possible using excavation alone. Furthermore, where buried features are known to exist, GPR surveys conducted prior to excavation can delineate the location and approximate depth of features of interest. Excavation strategies can then be formulated to efficiently test only those features, preserving others.
REFERENCES


Electrochemical impedance in the field of protective coatings
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Electrochemical Impedance Spectroscopy (EIS) in the field of protective coatings has undergone a significant growth in recent years. Until recently this technique had limited application to cultural heritage protection aspects. The development of the technique of interest, and the classical method of measurement.

This paper presents a short review of EIS research in the field of cultural heritage protection. The paper focuses on measurement methodology and its application in the field. The development work is still in progress, and the results are promising.

1. INTRODUCTION

Metals and alloys have a tendency to form a thin, protective, and stable layer on their surface, which is known as a protective film. In other situations, the product forms a continuous film of metal. Studies in corrosion science show that the corrosion behavior of a metal depends on several factors, such as structure, environment, and surface treatment. In the case of atmospheric corrosion, the presence of pollutants such as humidity, exposure to hot/cold, and cloudy weather play a significant role. In its commercial applications, they can develop more or less resistant initial environmental exposure. In marine environment and as a salinity, it allows for its easy migration in turn it may prevent the formation of the protective film.

Several studies addressing the problem of corrosion in the field have been made to enlighten their corrosion behavior. The study of the corrosion behavior of metals and alloys in the marine environment has been a significant area of research. The understanding of the electrochemical behavior of metals and alloys in the marine environment is essential for the design and development of materials with improved corrosion resistance.