Radiation in Art and Archeometry
D.C. Creagh and D.A. Bradley (editors)

# The use of ground-penetrating radar in archaeology

Lawrence B. Conyers

Department of Anthropology, University of Denver, 2130 S. Race Street, Denver, CO 80208

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.

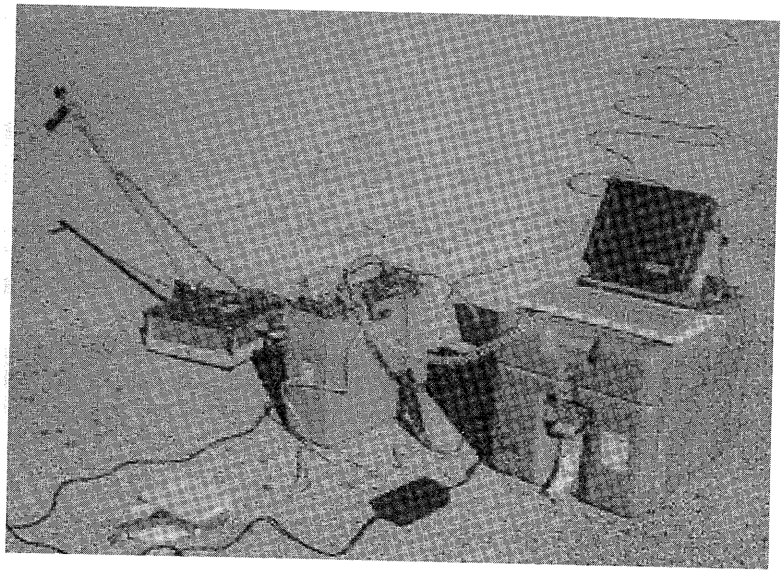
## 1. INTRODUCTION

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

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



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

uired by reflecting radar waves, created by pulses from a surface antenna, off
bjects, features or bedding contacts. Reflections that are generated from buried
ratigraphic changes are detected and recorded at a receiving antenna on the ground
yers and Goodman, 1997: 23 [1]). The elapsed time between when the pulse was sent
eries of reflections, from progressively deeper in the ground, are received back at the
n measured and recorded.
hange 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
lses are measured, and their velocity through the ground can be determined, distance
e ground) can be accurately measured (Conyers and Lucius, 1996 [2]).
tion 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.
f reflections 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.

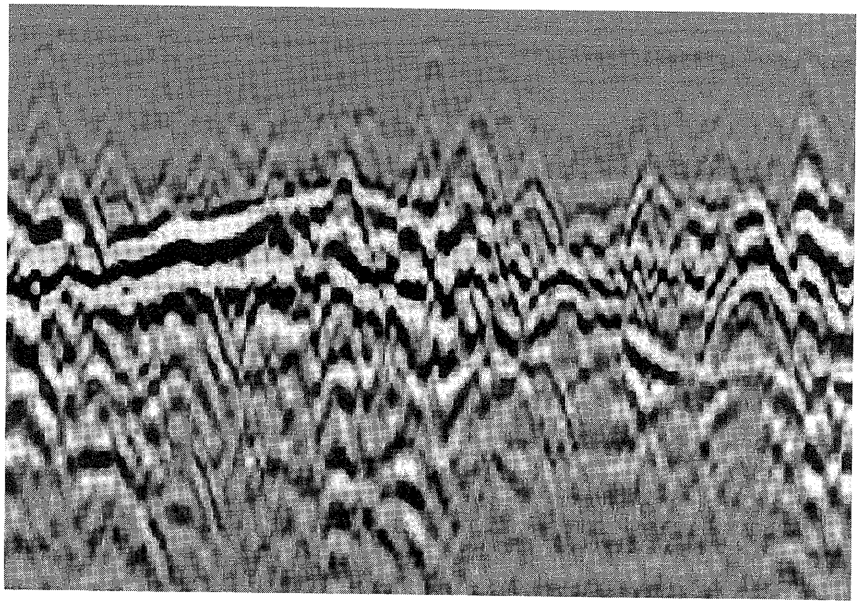


Figure 2. Ground-penetrating Radar Profile showing a buried living surface on the left side of the profile, which has been disturbed by anthropogenic disturbance on the right side of the profile. High amplitude reflections are dark black while areas of little reflection are gray.

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.

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 he physical and chemical changes of the buried materials can also be mapped data measured in this three-dimensional volume of reflections includes the those reflected waves, which are indicative of the variations within the buried ers and Goodman, 1997: 149 [1]). The higher the amplitude of the reflected waves, electrical and magnetic contrast that exists at the contact between contrasting ground. For instance, a very high amplitude reflection would typically be generated y between dry sand and wet clay, because they have very different electrical and rties. 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 OGY

l-penetrating radar has been traditionally used as a method for identifying the ence 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 lysis of the surrounding stratigraphy. Only a limited amount of data processing was ecause of the difficulty in processing and interpreting large GPR data sets that might housands 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 entifying important reflections, and the massive amounts of data that are typically lly impeded any sophisticated data interpretation. In addition, the reflection profiles n-processed "raw" data that contained an abundance of "noise", which could be lections from surface objects and even from people moving about in the vicinity of omplicating two-dimensional images. Fortunately, even in these types complex and ts, significant reflection "anomalies" could usually be visually correlated with other tions in adjacent profiles. In this type of rudimentary data analysis most features were identified visually, based only on what buried archaeological features " to look like. If buried reflection surfaces were extensive enough, reflections could correlated from profile to profile within a grid, but often the abundance and detectable reflections precluded accurate correlation. In addition, without extensive nfirmation of the discovered features, little could actually be determined about the atial orientation of many reflections, and therefore most interpretation was usually e.

e breakthrough in GPR processing occurred in the late 1980s as digital recording ved 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 recorded 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 times 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 billionths 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.

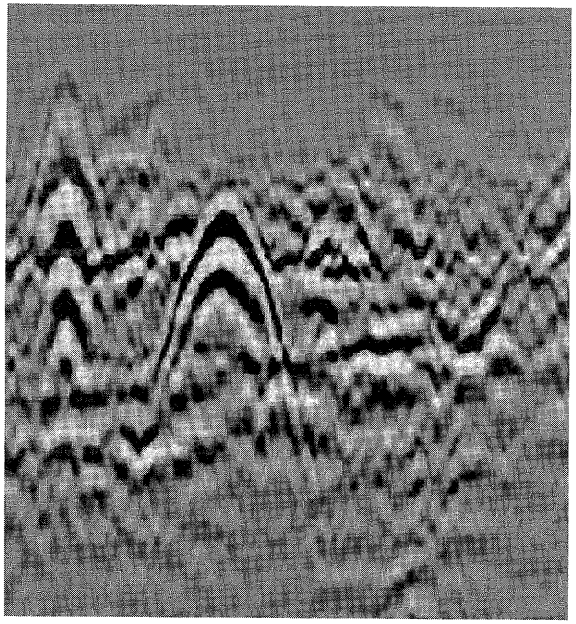


Figure 3. Hyperbolic reflection produced from a buried metal pipe.

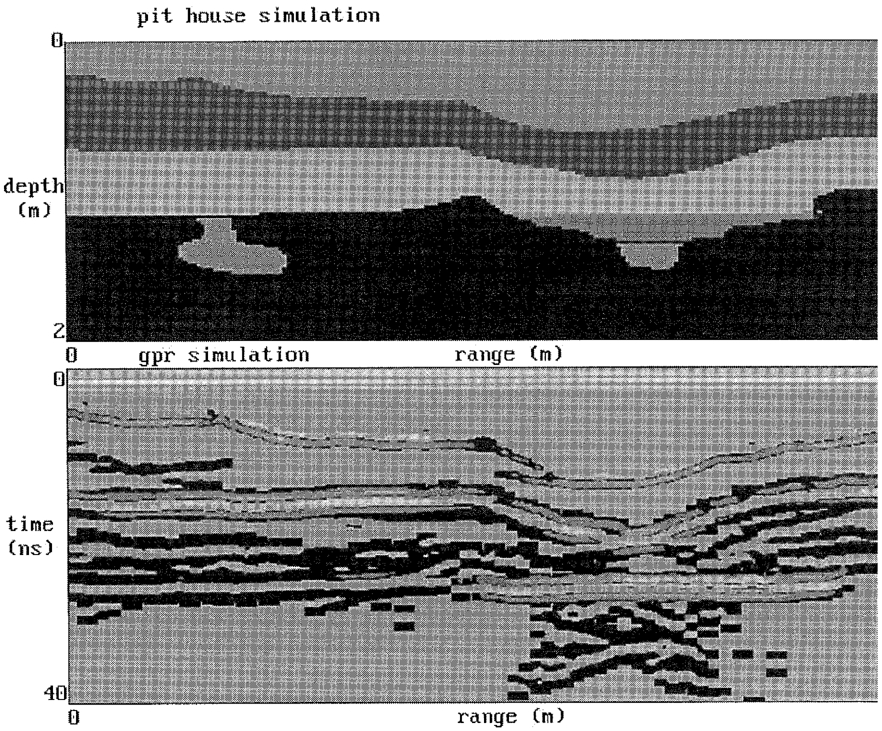


Figure 4. Two-dimensional GPR simulation of a pit-structure with a fire hearth in the
500 MHz antenna. A storage cistern is modeled on the left side of the model. An
surface is buried by two stratigraphic units of differing composition. The resulti
model shows that the cistern and the hearth in the floor 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 abun
reflections recorded and the length of time it takes to identify visually and then manu
reflections in order to produce valuable maps can still be a daunting task. An extre
data processing tool that can quickly process large quantities of reflection data is
slice-map method (Conyers and Goodman, 1997: 149 [1]; Goodman et al., 1994

ue analyzes the relative amplitudes of reflections recorded at specific depths within a grid of Amplitudes of reflected waves are primarily a function of the contrast in electrical and tic properties between buried materials. The greater the contrast, the larger the amplitude of ed waves is produced as radar energy crosses that boundary.

The slice-map method analyzes reflection amplitudes at defined depths and then correlates hroughout a grid. The computer can then produce maps of the spatial extent of resulting udes at specific depths in the ground. In this way GPR reflection amplitudes can be analyzed e-dimensions, by viewing progressively deeper slices in the ground. The spatial distribution plitudes can then be color coded and adjusted according to the relative strength of the ions. If the buried archaeological materials produce significantly different amplitudes red to the surrounding materials, their exact depth and dimensions can be mapped.

At some archaeological sites, where buried features have very distinct physical properties e surrounding matrix is relatively uniform, the production of amplitude slice maps may be n to accurately map the site. For instance, in an area where pit-house floors or burial ers are surrounded by fine-grain sand and silt, a high amplitude reflection will be generated floor, but few if any other reflections will be produced. Amplitude slices-maps in these cases used to quickly map all significant archaeological features. However, if the stratigraphy of edia surrounding archaeological features is highly variable, high amplitudes can be produced many non-archaeological elements, producing a potentially very complex and possibly ding set of maps. This phenomenon can be accentuated if stratigraphic layers are lying at an to the slice orientation. If this were the case, when a time-slice crossed a stratigraphic n, a high amplitude anomaly would be produced, also leading to possible misinterpretations.

## XAMPLES OF GPR SUCCESSES FROM THE AMERICAN UTHWEST

The American Southwest is an excellent environment for GPR mapping, but one where onal archaeological techniques have mostly been used to the exclusion of geophysical ds. Only recently has GPR been successfully applied to a number of site identification and l feature mapping problems that typically confront archaeologists in this area. This high u and desert area of Colorado, Utah, New Mexico and Arizona is an area of abundant buried ns, including pit houses, kivas (semi-subterranean circular pit features used for ceremonial ies) and storage pits. The climate and geological processes active in this area produces an ance of dry sandy sediments and soil, an excellent medium for radar energy penetration.

Traditional archaeological exploration and mapping methods used for the discovery of l sites include visual identification of artifacts in surface surveys, random test pit excavation nalysis of subtle topographic features, all of which may indicate the presence of buried es. While these methods can sometimes be indicative of buried sites, they are extremely zard 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 nsidered 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 50x30 meters in diameter, surface su had located 4 or 5 topographic depressions that appeared to be subtle expressions of pit hous what was presumably a small buried village. Lithic debris from stone tool manufacture as w abundant ceramic sherds were found in and around these depressions, further enhancing preliminary interpretation.

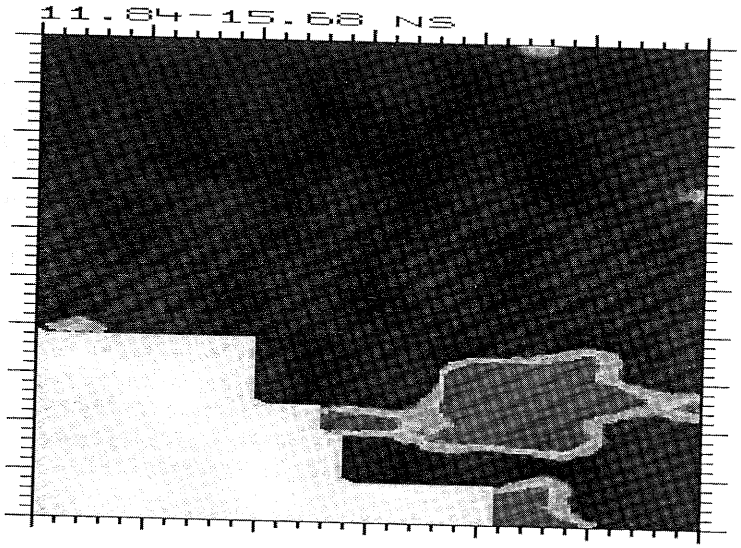
A GPR survey was conducted over this prospective area, using paired 500 MHz ante which transmitted data to a maximum depth of about 2 meters (Conyers and Cameron, 1998 While data were being acquired, reflection profiles were viewed on a computer monitor, as recorded digitally. A preliminary interpretation of the raw data in the field showed no evider pit house floors in the areas containing the depressions. Surprisingly, a large distinct floo located in one corner of the grid, an area not originally considered prospective. Ve 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 r 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 antechamber a entrance at opposing sides of the pit structure (Figure 5). In order to confirm this interpre derived only from the GPR maps, nine core holes were dug on and around the feature. All dug within the mapped feature encountered a hard-packed floor covered with fire-cracked ceramic sherds and even a small bone pendant, at exactly the depth predicted from the GPR r Those cores drilled outside the pit house, and in the area of the shallow depressions orig thought to be the location of the houses, encountered only hard, partially-cemented fluvial sec with no archaeological remains.

This GPR survey demonstrates the advantages of performing GPR surveys in conju with typical surface topography and artifact distribution mapping. The standard methods exploration indicated the presence of nearby pit houses, but both the artifact distributions a subtle depressions pointed to the wrong area. If only these indicators were used as a gu subsurface testing, it is doubtful any archaeological features would have been discovered when used in conjunction with the GPR data was the pit house discovered. It is not known time what may have created the subtle depressions that were originally interpreted as pit l The artifact and lithic scatters noticed on the surface were likely produced by rodent burr which brought these materials from depth and then concentrated them randomly across the si

A cautionary lesson about how changing conditions can affect GPR mapping was lea this site when a second GPR survey over the known pit house was conducted a few mont after a large rain storm. This survey produced no significant horizontal reflections in the are confirmed pit house, but many random non-horizontal reflections throughout the grid, r which looked like house floors. These anomalous reflections were probably produced by of rain water that had been differentially retained in the sediments.

At a well known archaeological site, also near Bluff, Utah, a second GPR surv performed in an area where a distinct surface depression indicated the presence of a Great large semi-subterranean structure typical of Pueblo II sites in the American Southwest (Con neron, 1998 [6]). A 30x40 m$^2$ GPR survey using both 300 and 500 MHz antennas was ducted over this feature, to be used as a guide to future excavation. Individual GPR profiles of i frequencies showed only a bowl shaped feature, which appeared to be filled with nogeneous 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.



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

Amplitude time-slice maps were then produced for the grid in the hope that subtle changes plitude, not visible to the human eye in normal reflection profiles, might be present in the 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 ll of a deeper feature within the depression (Conyers and Cameron, 1998 [6]). igin and function of this feature is not yet known. What can be concluded from this exercise R data processing is that the computer is capable of producing images of subtle features that be readily processed by the human brain. Without this type of GPR processing, this deep would most likely not have been discovered or excavated.

Near Tucson, Arizona, a well documented Hohokam Period village has been partially ited 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 nial ball courts. The archaeological site is covered by sheet wash and wind blown sediment, g most 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 backho method can be quite effective in locating features, as long as they are in the path of the tre often, significant structures are destroyed during discovery. In addition, little can be di about the exact orientation of the buried features encountered, and nothing at all can be det about the areas between the trenches.

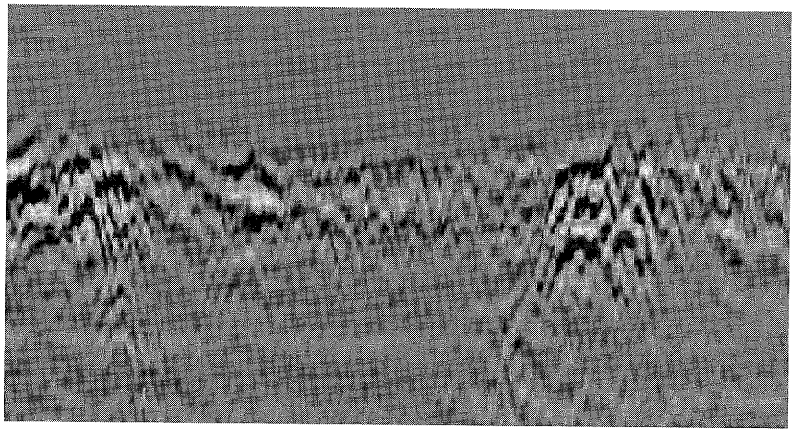
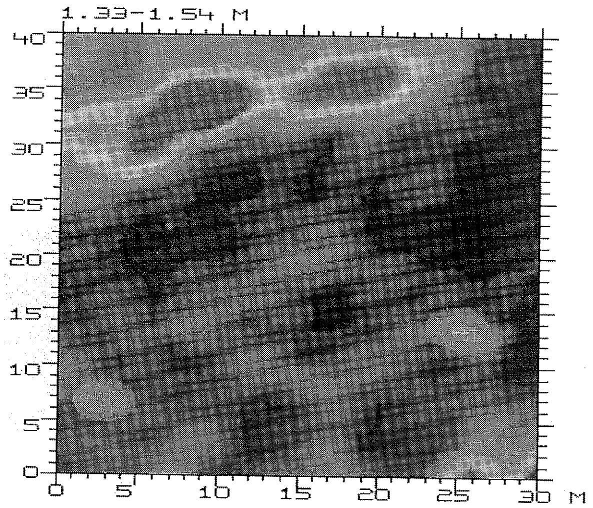


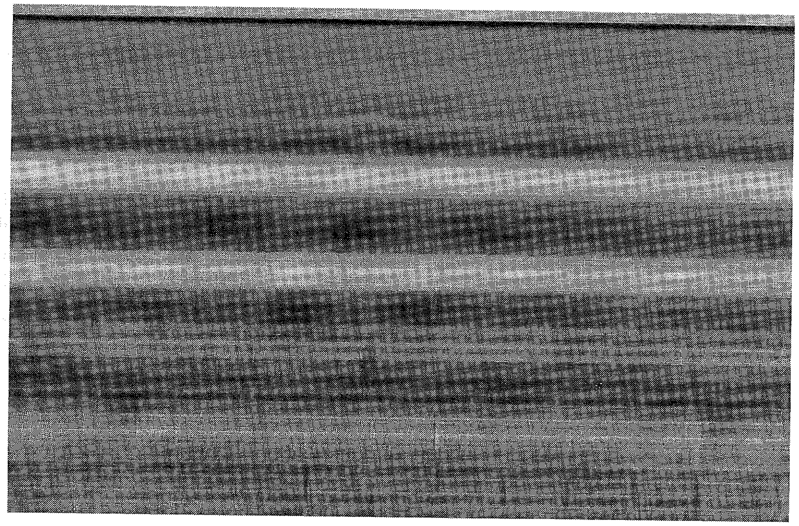
Figure 6. Reflection profile across a Great Kiva. The walls of the kiva are the high am reflections, while the interior of the kiva is filled with wind blown sand, which reflects littl energy.

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 GI was acquired. The initial results were very disappointing. The radar profiles visible computer screen during acquisition were so "noisy" as to be indecipherable (Figure 8). In appeared from first glance that the survey would be a total failure. The noise that was ob any reflections from within the ground appeared to have been created by radio and tel transmissions common in the city.

In an attempt to filter out the extraneous frequencies and remove background noise, pass filter that removed all frequencies above 800 MHz was applied to all reflection dat returning from the field. This filtering process effectively removed the interference from th transmission in the band width that include UHF Television and FM radio, leaving only reflections of importance (Figure 9).



re 7. Amplitude slice from 1.33-1.54 meters depth showing a subtle square feature within the
t Kiva.



e 8. Unprocessed reflection data over a pit-structure in southern Arizona. This image is totally
red by background noise.

When this was accomplished, reflection profiles within the grid were capable of mapping e
the buried archaeological features that were known from the trenching operation (Cony
Cameron, 1998 [6]). Ten other features were discovered between the trenches, whic
probably not have been detected in any other way. The GPR amplitude slice-maps w
capable of producing maps of the exact dimensions of all features and using velocity conv
their exact depths in the ground were also determined (Figure 9).

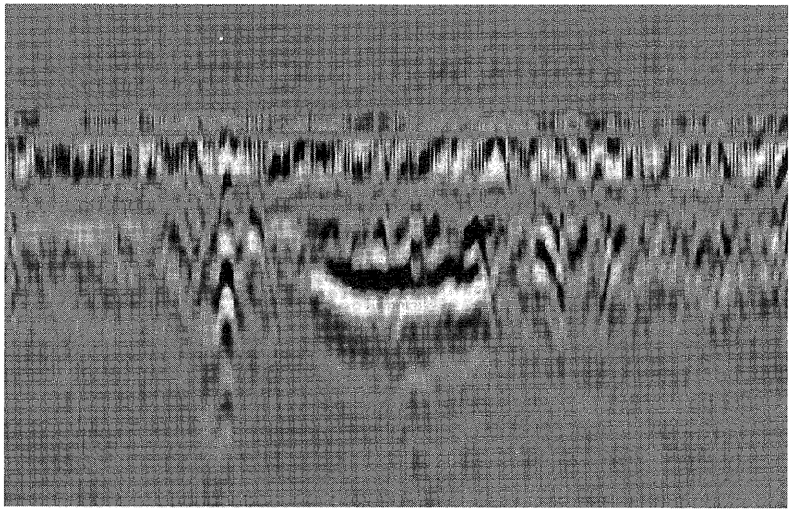


Figure 9: Processed reflection profile from the same data shown in Figure 8. Background n
removed, frequencies were filtered to enhance reflections from within the ground and the re
reflections were amplitude enhanced

## 8. CONCLUSIONS

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

## REFERENCES

[1] L.B. Conyers and D. Goodman, Ground-penetrating Radar: An Introduction for Archaeologists. Walnut Creek, CA: Altamira Press.(1975)

[2] L.B. Conyers and J. E. Lucius, Archaeological Prospection 3 (1) (1996) 25-38.

[3] A.P. Annan. and J.L. Davis,"Design and Development of a Digital Ground- penetrating Radar System," in J.A. Pilon, ed., Ground penetrating radar. Geological Survey of Canada, (1992)Paper 90-4, 49-55.

[4] D. Goodman., Geophysics 59 (1992) 224-232.

[5] D. Goodman, Y. Nishimura, and J.D. Rogers, Archaeological Prospection 2 (1995) 85-89.

[6] L.B. Conyers and C. M. Cameron, Journal of Field Archaeology, 25, 4 (1998) 417-430.

---

Radiation in Art and Archeometry
D.C. Creagh and D.A. Bradley (editors)

# Electrochemical impedance

P.Letardi

CNR - Istituto per la Corrosione

Electrochemical Impedance Sp
science, in the field of protective
Until recently this technique h
application to cultural heritage p
aspects. The development of the
interest, and the classical method
measurement.
This paper presents a short ov
cultural heritage field which a
measurement methodology is d
development work is still in prog

## 1. INTRODUCTION

Metals and alloys have a tend
other compounds, which are mor
adherent and stable layer on the
In other situations the product fo
continuous loss of metal. Studie
science. The corrosion behaviou
several factors related to both
structure, etc.) and to environme
the case of atmospheric corro
(humidity/dry, hot/cold, cloudy/s
pollutants play a key role. In its i
They can develop a more or les
initial environmental exposure c
marine environment and as a sal
allows for its easy migration in t
in turn may prevent the formatio
Several studies addressing th
made to enlighten their corrosio
The important role of sulphuric c
force for the degradation of outd