Advances in Imaging of Subsurface Archaeology using GPR

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Abstract : Examples of GPR survey results at a variety of archaeological sites are presented. Several new analyses which include static corrections for the tilt of the GPR antenna are shown for imaging of burial mounds with significant topography. Example archaeological site plans developed from GPR remote sensing of Roman and Japanese sites are given. The first completely automated GPR survey, using only Global Positioning Satellite navigation to create 3D data volumes, is employed for a site in Louisiana to detect lost graves of the Choctaw Indian Tribe.

Introduction

Ground penetrating radar (GPR) has been widely used in a variety of applications. Beginning in the mid 1970s the first experiments with GPR were conducted for the purpose of discovering subsurface archaeology (Bevan, 1975). There were many early successes with the new technology and a great hope was permeating the archaeological community that a great savior for subsurface imaging had emerged. With this great new expectation for GPR, more and more archaeologists started applying the technology only to become quickly disenfranchised with the method. Early data outputs were confined to thermal graphic recorders. Data was rarely available in digital form until the late 1980s. Early output displays were also only limited to displaying vertical slices of the ground, which are just the radargrams. A great deal of emphasis was directed toward signal processing of datasets, however, these processes only mildly increased the utility of GPR datasets. Unless clear stratigraphic or strongly contrasted targets were available, subsurface information regarding potential subsurface archaeology could not be extracted from sites with weakly contrasted target reflections.

Not until the introduction of imaging processing, which was initiated only as early as the 1990s (Nishimura and Kamei 1990, Goodman et al. 1995), did the full potential of the monostatic-single fold GPR dataset begin to be realized. Time slice analysis is among the most useful image processing techniques. The method examines horizontal changes in recorded reflection across a survey site and displays recorded changes in reflection amplitudes at various levels within the ground. Time slices are particularly useful for creating estimates of archaeological site plans at various levels in ground, and all remotely – without destructively excavating a site. Isosurface rendering of volumes of GPR data have also given a useful visualization of radar reflections, and can help the archaeologist to see “GPR in 3D”.

In this study, several past examples of successful imaging of Roman and Japanese archaeological sites are presented. Among the site results briefly described are subsurface images made at the Villa of Emperor Trajanus of Rome and the Nutubaru Burial Mound in Japan. In addition, several new imaging techniques and data processing are shown for the first time. Among the newest image and data processing involve static corrections for surveys over sites with significant topography. A new static correction which accounts for the tilt of the GPR antenna across the topography was recently developed to study the Ikime 4th century burial mound in Japan. Finally, results from recent test surveys in which Global Positioning Satellite navigation is merged with GPR is presented. Several GPR-GPS experiments made in conjunction with the United States Forest Service and the Choctaw Native American Indians were done at a tribal cemetery with great success in rediscovering unmarked graves.

Villa of Trajanus

Next to the coliseum in Rome is the pillar of the Forum of Traianos (Trajanus in English). This pillar was erected to commemorate Rome's admiration and love for their emperor - Emperor Marcus Ulpius Trajanus (AD 52-117) - and to mark his victories in the Dacian Wars between AD 101-107. At the height of his reign, the Roman Empire controlled all of southern Europe, Britain, Asia Minor, Syria, Egypt and North Africa. The emperor enjoyed not only the lavish lifestyle that Rome offered, but he also enjoyed the ruggedness of the high alpines of the Affilani Mountains, located to the east of Rome. In this area where natural springs are fed by the Aneine River and travel through Miocene limestone rocks, a summer villa was erected for the Emperor on over 9 hectares of land. Documents indicate that Emperor Trajanus came to the villa often to engage in hunting expeditions (Fiore and Mari, 1999). The location for the villa was eventually rediscovered after early 18th and 19th century excavations were made. The villa is believed to be built over several terraces supported by thick walls with counterforts and niches. Walls from public buildings located at the entrance to the villa at the lowest terrace, have undergone recent excavations and restorations. The entire villa is too be partially resurrected over the next several decades.

Less than 5 % of the known buildings at the Villa have been discovered prior to GPR surveys, which initially begun in 1998 in conjunction with the Institute of Technologies Applied to Cultural Heritage (ITABC-CNR, Italy) and the Soprintendenza Archeologica per il Lazio (Italy). Extensive surveys, made from 1998 to 2002, of the villa grounds to date have covered approximately 5 hectares, with many hectares still to be investigated. Some of the initial results from the GPR survey indicate that beautiful geometric buildings once adorned the site. Shown in Fig. 1, 2 are two time slice maps of a total of 72 created at continuous depth/time windows for the Villa of Trajanus. A large oval structure is imaged very close to the ground surface. This oval structure seen on the 30 ns time slice map is not a swimming pool at the villa, but is believed to be an eel pond. Roman emperors ate eel fish sauce as a foodstuff for invigoration as these oily fishes are good for sustaining one in hot summer months. Eel eating is still practiced in the country areas in Italy, just as it is also a common practice in Japan during the summer as well for maintaining one's stamina in hot summer weather.

Another interesting and subtle feature imaged shows part of what appears to be a part of a very faint oval which is co-located with stronger imaged oval. The faint oval may represent an early structure which may have been robbed of the stonework, thus accounting for the lower reflections in this area. These trenches where the stonework was probably removed are still detectable in the time slice maps. Several rectangular buildings juxtaposed next to the eel pond, and slightly lower in reflection strength, may also indicate that these areas may have had the wall material removed as well. On the time slice map a square like feature is also imaged. This reflection is thought to be a preserved mosaic floor. This inference is alluded to since at the deepest time slice map another structure that is square on its exterior and has a circular interior wall. This feature is more than likely a Roman cistern. A patio -mosaic floor would normally be adjacent to a cistern at a Roman villa. These remarkable time slice images, which detail the detection of Villa structures at a variety of depths, were developed from 500 MHz GPR profiles collected 50 cm intervals (Piro et al, 2003). Similar and also very successful results were obtained recently in the discovery of a 1st century A.D. Roman amphitheater using GPR (Goodman et al., 2004). Roman sites are relatively easy to map because of the strong contrasts between Roman walls and the surrounding soil materials.

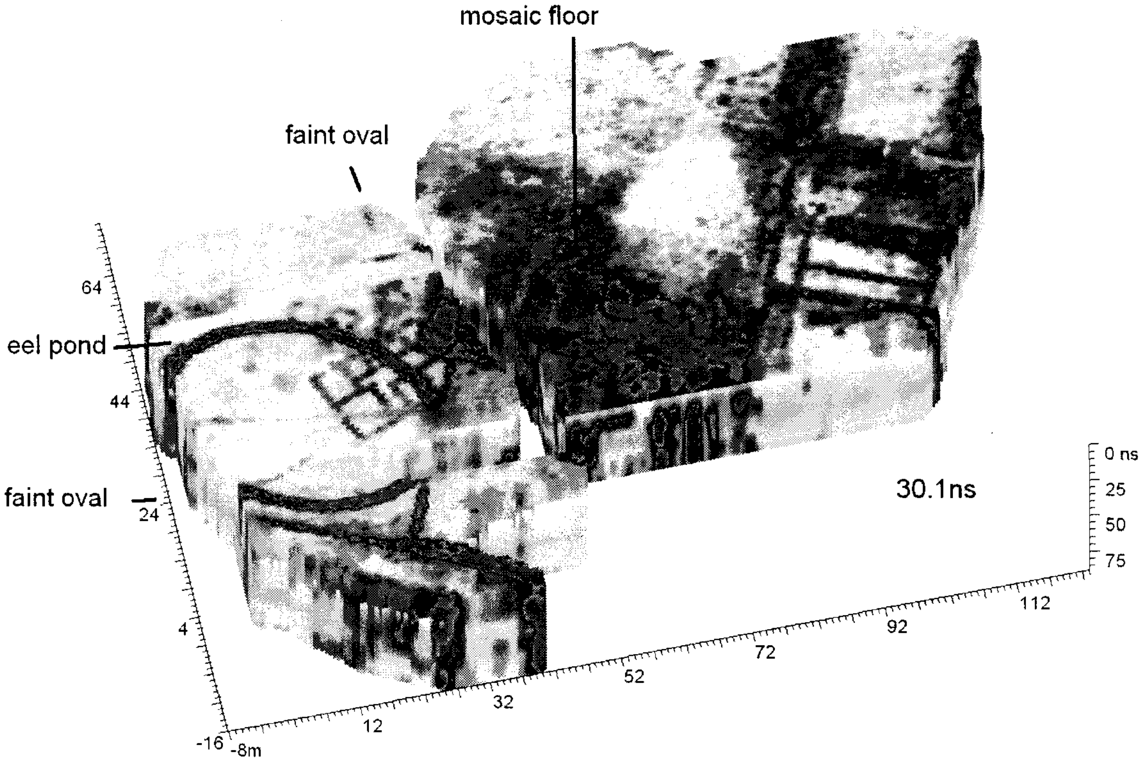

Fig. 1. Time slice image made at 30.1ns for the Villa of Emperor Trajanus. Location of an subsurface eel pond, rectangular buildings, and a suspected mosaic floor are shown.

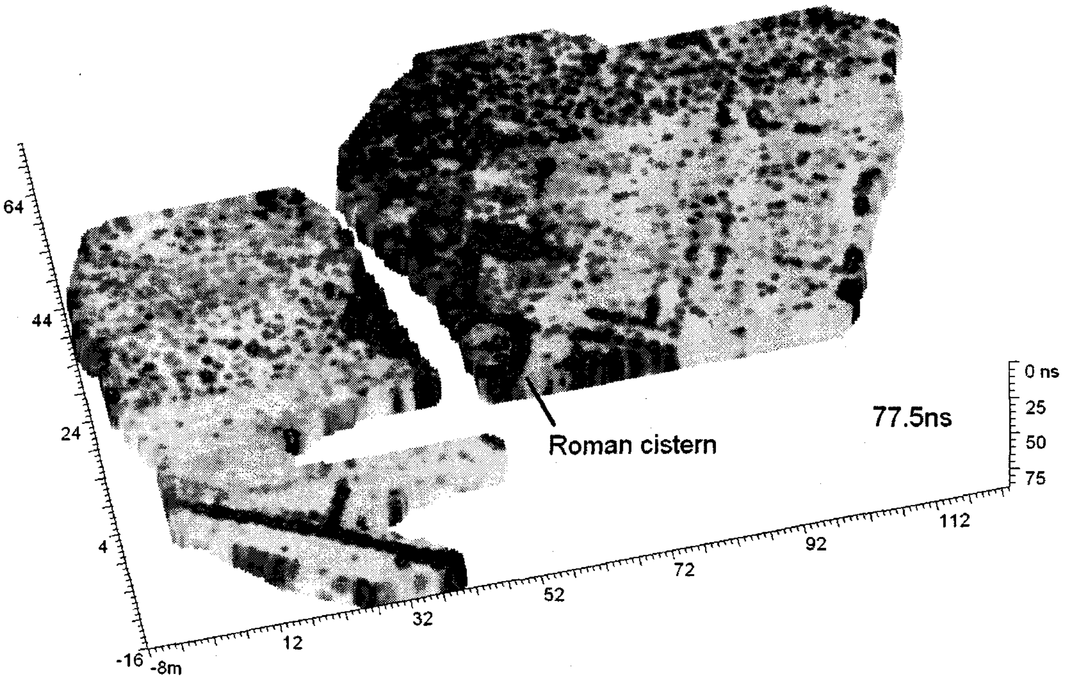

Fig. 2. Time slice image made at 77.5ns for the Villa of Emperor Trajanus. A reflection showing a square outside and a circular inside is indicative of a Roman cistern.

Nutubaru Burial Mound, Kyushu, Japan

One of the earliest successes of GPR imaging in Japan was the detection of destroyed tumulus burial mounds beneath farmland. Shown in Fig. 3 is a time slice image of the Nutubaru site located on the southern island of Kyushu. The site was under alfalfa planting at the time of the survey. Using a 300 MHz radar antenna, transects were made at 1 meter intervals across the site. Time slice images at consecutive 6 ns intervals remarkable show a variety of structures at different levels. The most prominent feature detected is a round reflection at 30-36 ns, corresponding to approximately 0.9-1.08 m depth. The radius of the circular reflection is 22 meters and is the remnants of a moat surrounding a 6th century Kofun burial mound. The history of the site is identified in the cartoon in Fig. 3. First, a burial mound was created by the ancient builders by excavating a moat and building a round mound with the excavated material. Secondly, a deceased relative or wife or offspring is entombed beneath the round burial by excavating a hollow chamber. Access to the chamber is obtained by driving a shaft vertically down and then sideways into the mound. Thirdly, as time persists, the mound moat is filled in with altering soils. The mound is also cut down by either ancient or modern farmers. Lastly, additional soil layering has buried the chamber and moat.

The bottom time slice shows a strong round reflection within the circular moat reflection. This is a reflection from the chamber. Often, chambers of this type are still preserved beneath destroyed burials, particularly at sites where heavy farming equipment is still not being used on a regular basis. In Southern Kyushu, many coherently layered volcanic soils exist and are very resistant to alteration. This soil environment is very suitable for excavated burial chambers in volcanic soil to survive today, from their initial construction in the Kofun Period (Goodman, Nishimura, and Rogers, 1995).

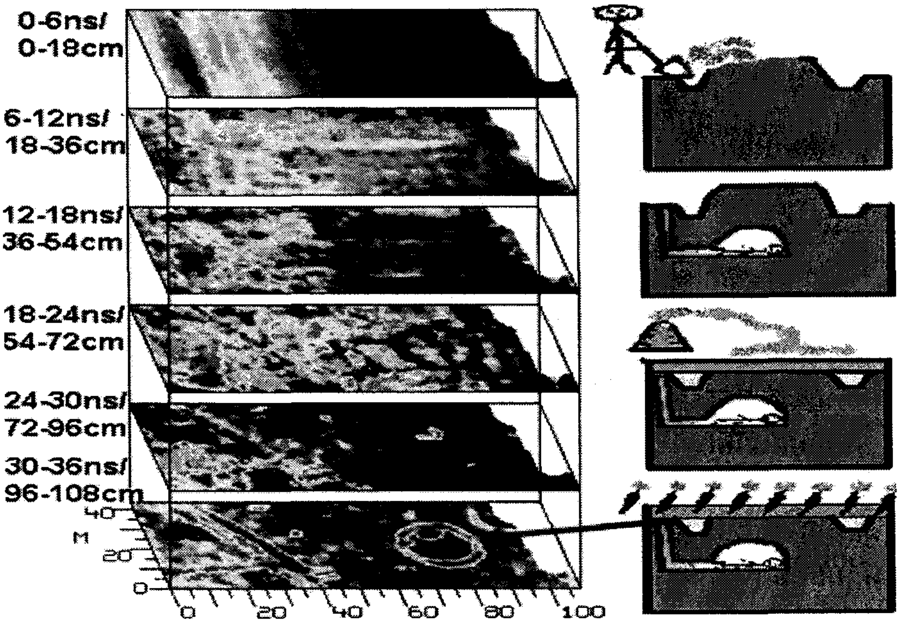

Fig. 3. Time slices of the Nutubaru Burial Mound, Kyushu, Japan. (300-700 AD).

Ikime Burial Mound #4, Miyazaki City, Japan

A 300 MHZ and 500 MHz GPR survey of Ikime Kofun #4 and surrounding areas was conducted in October 2003. This keyhole shaped burial mound was constructed in the late 4th century AD and is part of a cluster of several other important burial mounds located within Miyazaki City limits. The main purpose of the survey was to identify the type of burial that may be intact beneath the mound.

A variety of imaging analysis was applied in this study including, time slice analysis, static corrections, overlay analysis and isosurface rendering. Before the primary analysis could begin, new software needed to be developed to correct for the effects that steeply changing topography has on the tilt of the GPR antenna and the transmission of the vertical beam into the mound.

Shown in Fig. 4 is a diagram depicting the effects that topography has on sites with mild and abrupt topography. For the sites with abrupt changes in topography, radar scans can actually crossover the same locations at depth. The crossover becomes more pronounced depending on the velocity. A diagram showing the effects of crossover of the radar scan is shown in Fig. 5. The higher the velocity, the greater the possibility of crossovers regions of the radar scans. An example of a radargram taken across a site with significant topography is given in Fig. 6. A velocity of 1 cm/ns barely shows any horizontal changes. Making the correction for a microwave velocity of 0 cm/ns essentially gives the typical topographic correction that most softwares do – e.g. the radar scan is simply shifted up or down to account for the topographic change, without regard to the tilt of the scan. Some softwares will show warped radargram images which use a graphic option such as in Adobe Acrobat, however, the graphic adjustment is not capable of accurately correcting an inserting the effects of scan crossover. In addition, an original binary file, not a graphic file, is necessary for continued image processing of properly corrected – topographic datasets.

A new correction process which is unique to **GPR-SLICE©** Ground Penetrating Radar Imaging Software (www.GPR-SURVEY.com), accounts for the tilt of the antenna for making static and topographic corrections. Depending upon the density of the lines, the software will allow the user to sweep over a small angle to fill in any voids in the binary radargrams caused by abrupt changes in the scan direction. Currently in the software the crossover regions are filled in by the first scan to occupy the region. Future options in the software will include using averaged Hilbert transform data near the crossover regions, as well as weighting the crossover regions by the scan angle. For instance, more oblique scans crossing into a previously scanned area can be given a lower weight in creating the averaged scan. The Hilbert transform data would be necessary for the crossover regions since taking an average of many pulses with slightly different phases as a result of small inaccuracies in topography as well as knowing the true tilt of the antenna, would create low reflections. Converting to the envelope space of the Hilbert transform could better preserve the energy during the synthesis of the radargram at the crossover regions.

Using this new analysis to first correct the radargrams for topography as well as the effects of the tilt of the GPR antenna across the Ikime #4 burial mound, the traditional imaging analysis could begin. Time slices developed from specially corrected radargram datasets show a strong anomaly located on the flank of the round part of the keyhole shaped mound is most likely a hollow chamber burial (chikashiki, Fig. 7).

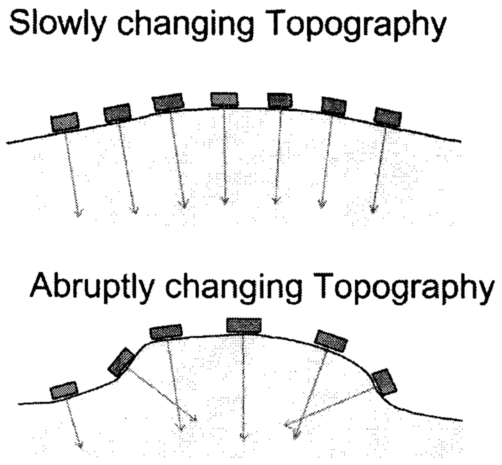

Fig. 4. Effects of mild vs abruptly changing topography on the creating regions where radar scans crossover.

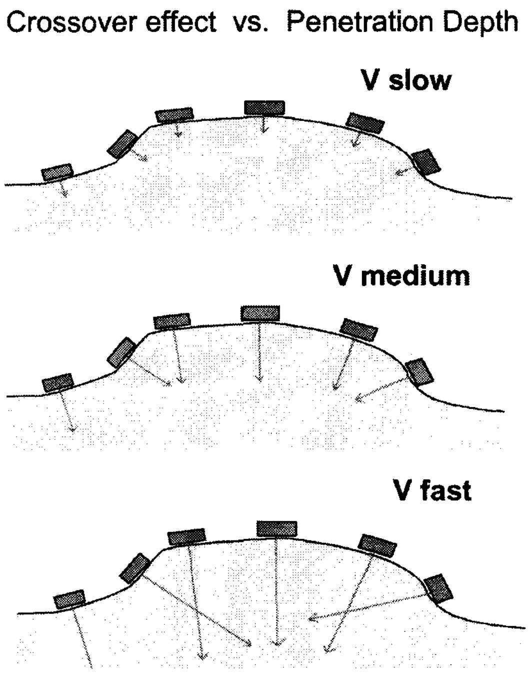

Fig. 5. Effects of microwave velocity on the degree of crossover of radar scans.

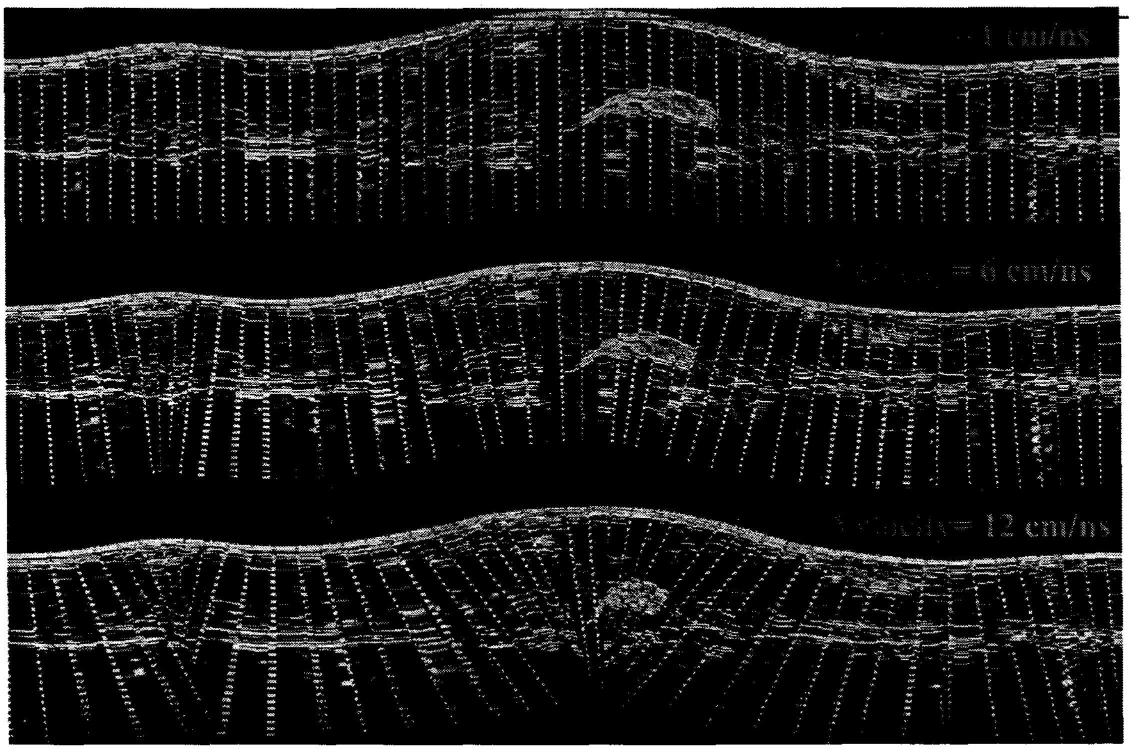

Fig. 6. Example of a radargram corrected for topography at 3 different microwave velocities. The crossover effect becomes very prounounced at v=12 cm/ns.

It useful to compare the changes of applying the topography plus correcting for the tilt of the GPR antenna. Given in Fig. 8 is an image showing the normal topographic corrected time slice which is calculated from radargrams where the scan lines are only shifted vertically to account for the topography. This time slice is compared with one generated using the topography plus the antenna tilt. The overall reflection patterns do not change significantly for this example. The most important difference between the images, however, is that the burial chamber is shifted almost 2 meters to the center of the burial when the tilt of the antenna is accounted for in the time slice analysis.

Isosurface rendering, in which a shaded relief is applied to an equal amplitude surface within the 3D volume, indicates the general shape of the burial chamber, and also shows a tunnel burial (yokoana, Fig. 9). The render also shows areas which may have higher concentrations of preserved stones (fukuishii) that are located near the top portions of the mound.

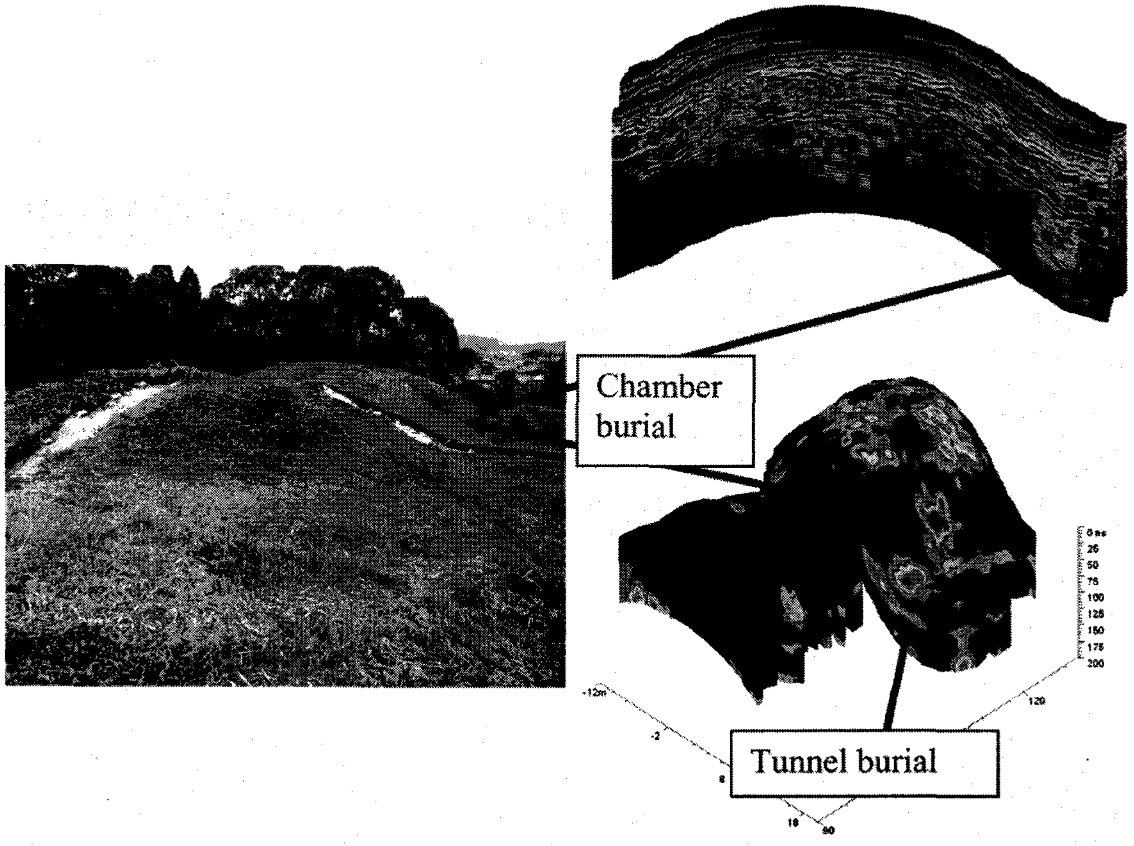

Fig. 7. 3D time slice Ikime Kofun #4, showing the location of chikashiki and yokoana reflections.

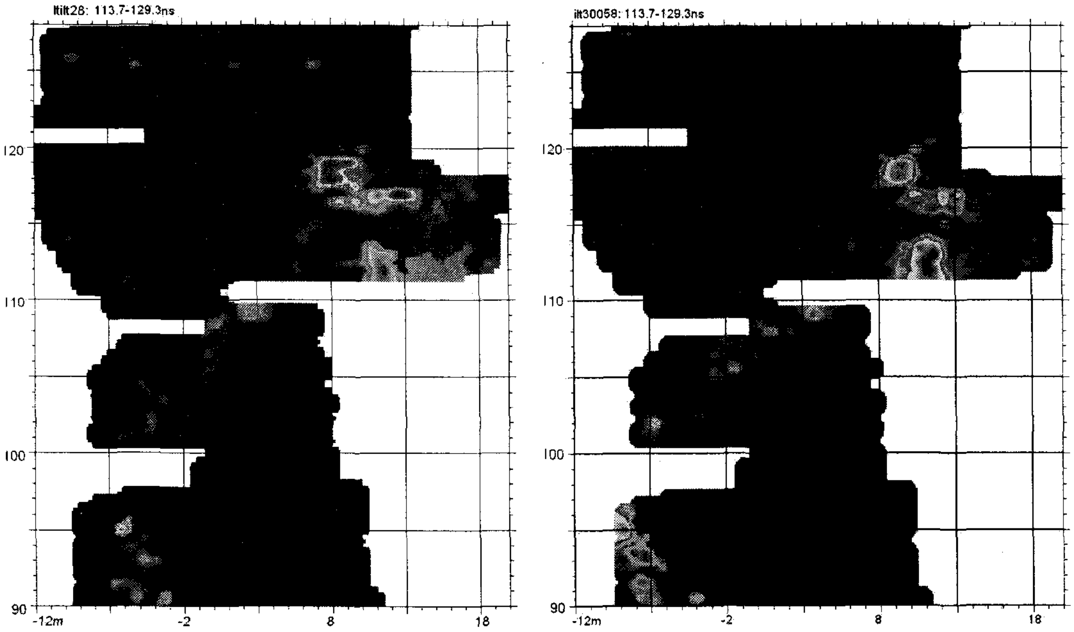
Topography +Antenna Tilt Corrected **Topography corrected**

Fig. 8. Comparison of a time slice corrected for topography plus antenna tilt, with a typical topographic corrected image where only the radargram scans are shifted vertically. Note: a re-location of the burial chamber of almost 2 meters results from properly accounting for the tilt of the GPR antenna across the site.

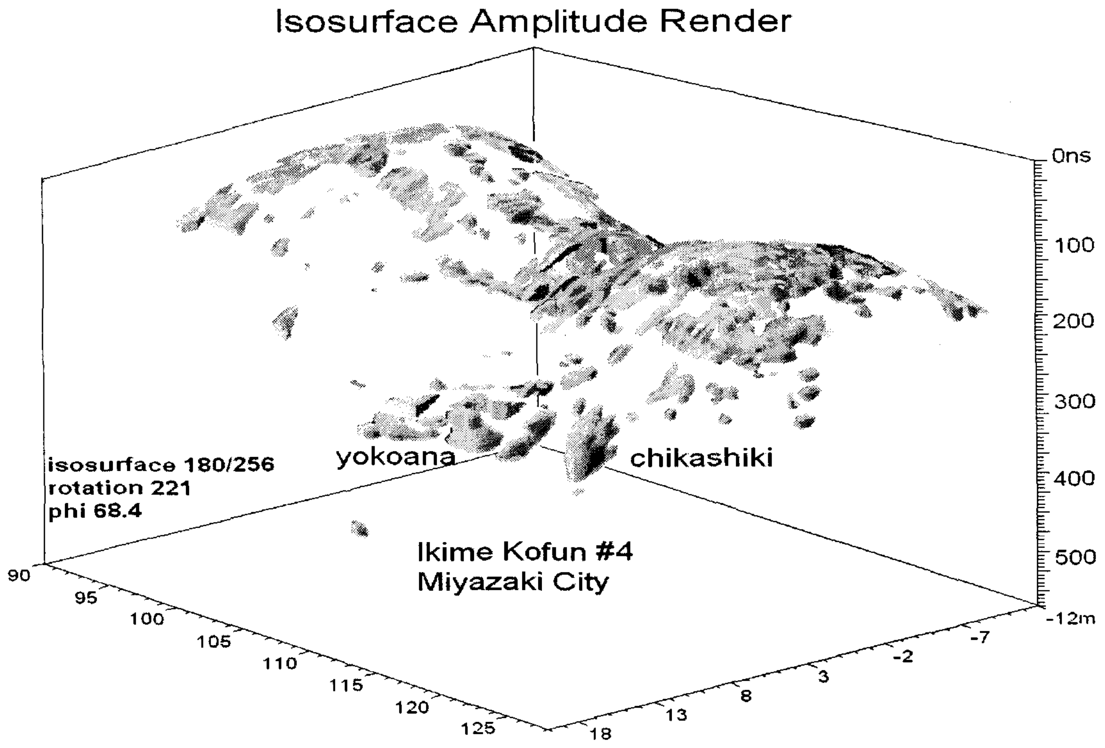

Fig. 9. Isosurface render of the strongest 70% reflecting surfaces for Kofun #4.

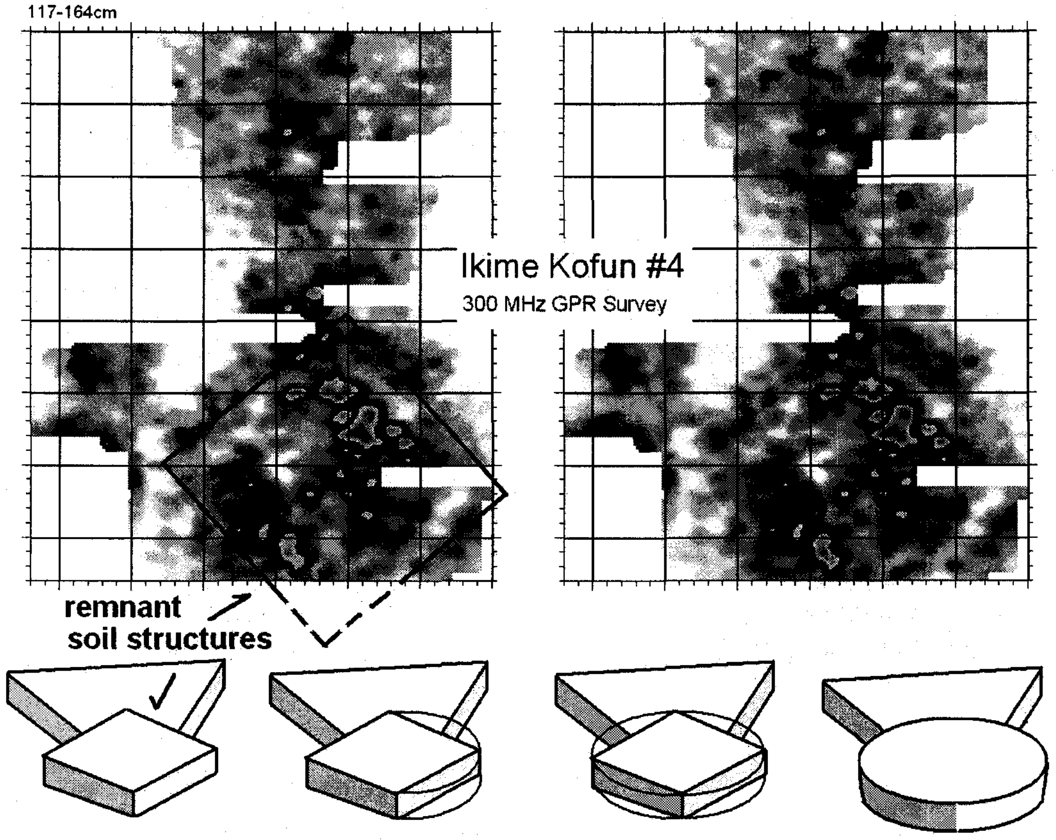

Fig. 10. Time slice showing a square reflection that may represent an ancient construction episode for Kofun #4.

One 2D time slice generated below 117 cm shows a faint square-like reflection that is rotated 45 degrees from the axis of the Kofun and is located on the round part of the mound (Fig. 10). This square feature is believed to be reflections that indicate an original building episode. In this scenario, the rounded keyhole portion of the mound was first formed as a rotated square structure shape by the ancient builders. After this first building episode was completed, the mound had soil layers added on to the flat edges of the square top portion, eventually creating a rounded mound. GPR is able to recover these ancient building episodes which are stored in the remnant soil structures.

GPR-GPS Survey at a Native Indian Cemetery, Louisiana

In November of 2003, GPR data sets were recorded simultaneously with continuous real-time differential GPS navigation at several archaeological sites. The purpose of GPS integration is to automate the collection of GPR data sets, particularly at sites where establishing grids or using survey wheels is problematic. Proper navigation of ground-penetrating radar equipment is a tedious chore in the field. However, it is the most essential factor in dictating the accuracy of the data and allowing the re-occupation of anomalous areas. With advances in global positioning satellite technology, the potential for using this instrumentation for navigation of GPR survey remains to be evaluated in a variety of field conditions.

Using differential GPS navigation, 3D volumes of GPR data (following Goodman et al, 2004) were used to map subsurface archaeological structures at a Native American Indian cemetery. The chosen study site was part of a United States Forest Service workshop to introduce GPR technology to Federally Recognized Indian Tribes. The site was the Jena Choctaw Tribal Cemetery, located in the Kisatchie National Forest, Pineville, Louisiana (Fig. 11). One objective of the GPR-GPS survey was to locate unmarked burials. Many headstones had been lost during many years of neglect at the cemetery. In order to accurately safeguard potential graves which had lost their markings, GPR was employed to assist in the relocation of these graves.

To expedite the study, navigation of the GPR antenna's track across the Jena Choctaw Tribal Cemetery was recorded using a Trimble Pro XRS GPS system with real-time differential correction capabilities. Real-time differential GPS data were available from a CORS station in the field and recorded at 1 second intervals. The track of the GPR-GPS system is shown in Fig. 11. A total of 10 minutes of continuous data were recorded in survey. An isosurface render of the top 70 % strongest reflector, in a 3D volume of data collected at the Jena Choctaw cemetery, indicates the location of known graves and several reflections from unmarked graves are also discovered at the site (Fig. 12).

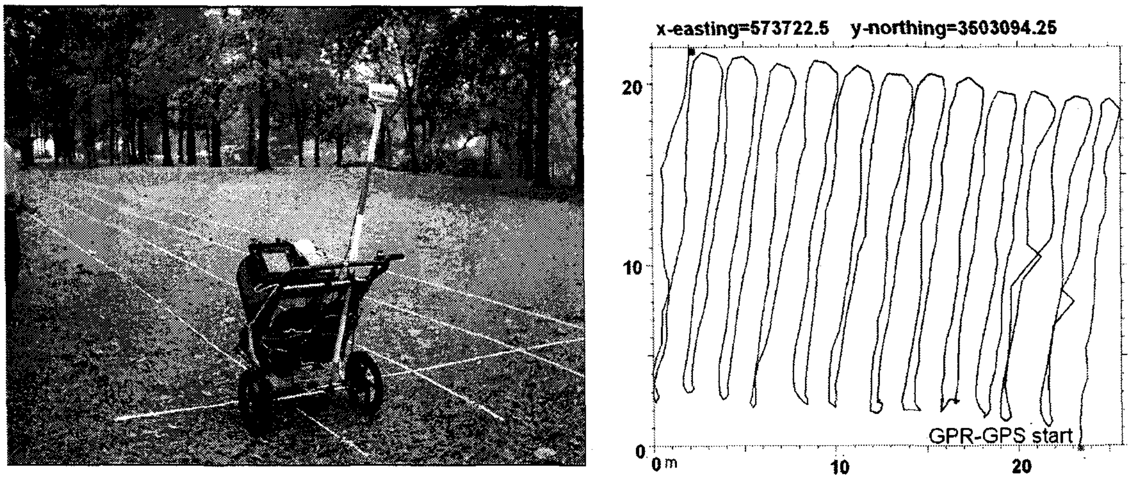

Fig. 11. Photograph of the GPR-GPS system used, along with the antenna track recorded over the Jena Choctaw Tribal Cemetery site, Louisiana.

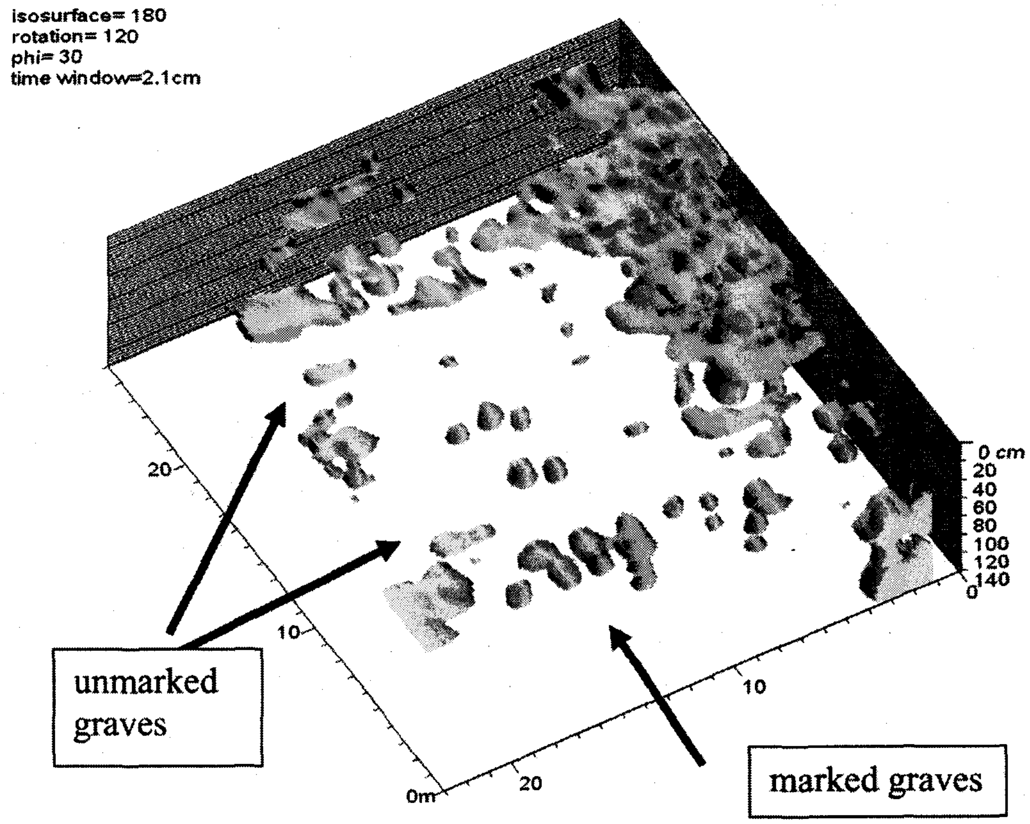

Fig. 12. An isosurface render of marked and unmarked graves at the Jena Choctaw Native American Indian Cemetery, Louisiana.

Conclusions

The utility of the GPR datasets for detection of subsurface archaeology has been advanced by the application of imaging analysis as a fundamental data process. Time slice analysis and isosurface render are shown to be valuable imaging tools for displaying GPR data.

Analysis from sites in which significant topography exists, such as at burial mounds or other kinds of earthenworks, suggests that adjusting the radargrams for the tilt of the antenna is an essential correction that is needed to accurately map subsurface structures.

Finally, the marriage of GPR and GPS will greatly enhance the flexibility of using radar in field, particularly as more inexpensive units can provide smaller positioning errors. For many, but not all, applications in archaeology, survey grade GPS units that have positioning better than 1 meter can be used in the reconnaissance search of grave sites.

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