SERDP Final Technical Report

DEVELOPING AN EFFICIENT AND COST EFFECTIVE GROUND-PENETRATING RADAR FIELD METHODOLOGY FOR SUBSURFACE EXPLORATION AND MAPPING OF CULTURAL RESOURCES ON PUBLIC LANDS

SI-1261

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Acronyms and Abbreviations

CATS	Constructed Archeological Test Site
CERL	Construction Engineering Research Laboratory, Champaign
GIS	Geographical Information System
GPR	Ground Penetrating Radar
GSSI	Geophysical Survey System Inc
MHz	mega-Hertz
ns	nano-seconds
RDP	Relative Dielectric Permittivity
S&S	Sensors and Software
SERDP	Strategic Environmental Research and Development Program
USACE	United States Army Corps of Engineers
USGS	U.S. Geological Survey

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1. EXECUTIVE SUMMARY

Background: In archeological surveys of artifacts hidden under the ground, there are a number of issues that must be faced in determining where to excavate and still only minimally disturb the artifacts. Some of these artifacts have spiritual significance while others are of general historical nature. In using noninvasive means to determine the presence of these artifacts, a number of options are available. A new, emerging technology is the use of ground penetrating radar (GPR). However, in using this device due to the number of variables that can impact energy penetration and resolution, researchers are often not guaranteed a successful survey. Simple factors such as soil mineralogy or moisture content can often generate sometimes confusing and difficult to interpret data.

The purpose of this project was to address such consistency problems with GPR surveys. To do this, the project sought to identify specific factors that will either benefit or complicate a GPR survey. Along with isolating the impacts of these factors, the project sought to develop a series of procedures to predict ahead of time what tools will be needed for a survey, and if that survey has a chance of success.

In general, the questions this study sought to answer included:

- Which variables are most affecting energy transmission and reflection?
- Which are most affecting data resolution?
- Depth of penetration?
- What parameters (geological, climatic, etc.) are most crucial to GPR surveys.

Technical Approach: This project conducted a systematic analysis of two sites. Both sites were constructed with buried features to simulate most archaeological sites (i.e. features were buried 1 meter or less in ground), and included various materials (metal, wood, etc.):

- The Construction Engineering Research Laboratory (CERL) test facility (Constructed Archeological Test Site - CATS) is located on the University of Illinois campus. The soil at this site is high in clay and moist or wet most of the year. Data were collected in normal wet conditions, during a dry period, and when the ground was frozen.
- The Hanford Test Site (Hammer) is located in central Washington. This site is in a dry area, and its soils are primarily sand and silt. Data were collected in normal dry conditions, and when the ground was flooded by a sprinkler to simulate heavy rain conditions.

Along with the different soils and "weather" conditions of each site, data were collected with different antenna frequencies (ranging from 300 MHz to 900 MHz), various transect separations, and various acquisition parameters. Using the data collected from these surveys, along with the known stratigraphy at each site the researchers also:

- Made a detailed stratigraphic analysis to compare the known stratigraphy of each site to each unit (geological or archaeological) reflected on GPR profiles.
- Produced computer-generated modeling of the two-dimensional profiles created from the known stratigraphy, to show what GPR profiles "should" look like. These were compared to the profiles collected in the field in order to determine what certain objects "should" look like.

CATS

GPR surveys were done over the artificially constructed site with known features to test how the physical properties of the buried materials change with regard to their radar reflectivity in differing conditions. Under dry conditions using the 400 MHz GPR, surveys generally had poor resolution. Desiccation cracks in the soil caused many point source hyperbolas, thus skewing the "appearance" of other reflections. Under wet (saturated) conditions, the radar only reflected the clay floor, while the other three floors were "invisible". This suggested that water, and how it is distributed and retained, is the primary factor in whether *anything* will generate radar reflection. In dry conditions, the compacted floors likely had enough water to distinguish them from the overlying material. In wet conditions, the compacted floors and overlying material retained the same amount of water. This lack of distinction in material type caused the floors to be "invisible" on radar. The clay floor, however, pooled water and showed up quite well. For frozen conditions, the results were similar to the dry conditions, but in general the feature resolution is poor.

Data collected in frozen conditions with the 900 MHz antenna, however, showed a much better resolution of the floor features. Along with these floor features, many unknown features were also reflected. It is predicted that radar is reflecting the changes in water content of the soils overlying the floors.

Another feature at CATS was studied, but not in the same fashion as the house floors discussed above. As part of the same feature burial process a simulated burial mound was constructed by placing two pig carcasses in “tombs” and then piling earth over them. Reflection data were collected over the pig tombs in the same way as the house floors, but for these data a topographic correction was applied to the data in the mound to develop a fast way to correct data for elevation. A surface map was created using a theodolite and stadia rod. Two computer models were attempted to create these maps. The *Surfer 8* model produced the better map which was gridded and smoothed so that it represented the mound as it existed in the field. Amplitude slice maps were then generated from the reflection data at every depth level, which proved to be an efficient slicing method. When this was done the “pig crypts” that were placed in the ground were easily visible which crosses the carcasses.

Hammer Site

The Hammer site included a variety of different objects buried at different levels, including metal objects, wooden objects, earthen "hearths," and brick. Objects were covered with homogenous sand.

Using the 400 MHz antenna under dry conditions, surveys proved to be moderately successful. The metal and larger objects showed up easily, but wood and less-compact earthern features were essentially invisible. Under dry conditions, surveys showed a large number of extraneous reflections, which are likely pockets of water. This may have been due to the artificial saturation of the site with a sprinkler, which may have not allowed enough time for water to percolate down. The wood objects showed up well when saturated.

The 900 MHz antenna was better at reflecting smaller objects in this homogenous soil. At times, however, reflection profiles appeared too "cluttered." This is because this

higher frequency antenna can resolve much smaller objects, and therefore resolves much more. This was especially true in wet conditions, when the antenna likely reflected every small pocket of water.

The Hammer test demonstrated the importance of water in resolving buried features. When the ground was dry, most buried objects were visible (except the wooden objects). The wood may not have contrasted enough with the surrounding sand to be visible in dry conditions. When the ground was saturated, many of the objects that contrasted with the sand when dry are often invisible. This is because the water in the system tends to "blend" and "homogenize" the matrix and the artifacts. In contrast, the wooden objects are quite visible in wet conditions, as they have acted as absorptive agents for the water (like large sponges), and therefore their very high water content produces distinct radar reflections along interfaces with the surrounding sand.

Laboratory Soil Analysis

An in-depth lab analysis of soil samples was necessary to gather additional information to explain statistical correlations and qualitative analyses. Soil samples were collected at each site using an auger at 20, 40, and 60 cm depths. The samples were tested by the U.S. Geological Survey in Denver, CO, for their physical and chemical properties. Tests determined the samples' relative dielectric permittivity (RDP) and how those values changed with differing water content. A range of electromagnetic frequencies were passed through the soil material under different moisture regimes and the response measured. An RDP value is a way to measure radar velocity in that soil. Therefore, an analysis of the changes in RDP values of different materials can be used to determine whether buried features will produce higher or lower amplitude reflections at their interfaces

For all samples at both the CATS and Hammer sites, the RDP value was between 3 and 5 when dry, regardless of whether it is composed of clay, silt, or sand. When wet, the RDP values changed significantly. It appeared that the addition of water (and the amount) was *the* determining factor in the RDP value. The amount of time the water had to filter was far less important than the amount of water put in the sample. Therefore, it is the way materials in the ground hold and distribute water that matters most in producing radar reflections.

Through soil conductivity and mineralogy analysis of the two sites, the soil clay content and type of clay which was determined to be important in how well the soil holds and distributes soil moisture. Also the high conductivity of clay limits the depth penetration of the radar energy, thereby limiting the depth of possible analysis.

Summary: The parameters that seemed to provide the best results based on what was known in the ground, regardless of the environmental conditions, were the use of a 900 MHz antenna with a 25 cm spacing, providing the best resolution at 10-15 cm in depth and the use of the 400 or 450 MHz antenna for general resolution work under most conditions to depth of 20 to 90 cm.

Future studies should concentrate on determining the effects of clay types on resolution, determining the effect of two versus one orientation transects, and better understanding the effects of soil moisture conditions on response

2. INTRODUCTION

2.1 Background

A large number of archaeological sites are often discovered to be buried below soil and sediments only after construction activities, such as road building, pipeline burial or other below-ground intrusion, have commenced. This leads to costly construction delays as compliance with regulations regarding cultural resources are met. Ground-penetrating radar (GPR) has recently proven to be very efficient at producing three-dimensional images of buried cultural features when information about the nature of radar reflections can be determined. The success of GPR surveys is to a great extent dependent on soil and sediment mineralogy, clay content, ground moisture, depth of burial, surface topography and vegetation. Although GPR is not a geophysical method that can be immediately applied to any geographic or archaeological setting, with thoughtful modifications in acquisition and data processing methodology, GPR can be adapted to many differing site conditions. However, the GPR signature for most archaeological features has not yet been estimated.

Ground-penetrating radar (GPR) is being increasingly employed by archaeologists and other scientists to explore for and to locate three-dimensional archaeological features, artifacts, and important cultural strata in the near-surface. The GPR method has been especially effective in certain sediments and soils within 1-5 meters of the ground surface, where the archaeological targets to be imaged have significant physical and chemical contrasts with the surrounding medium. Site conditions such as moisture, soil types, clay mineralogy, and matrix stratigraphy are factors affecting the success of a GPR survey. It is usually not known in advance if a GPR survey will be successful, and there have been many failures, few of which have entered the published record. As a result, there are common misconceptions about the utility of GPR in different environments, and often unsubstantiated “rules of thumb” are cited as reasons why GPR should or should not be used in any given area. Previous studies from many sites all over the world indicate that many of these preconceptions regarding GPR technology are incorrect, misleading, or uninformed.

Despite the tremendous potential of GPR technology, results of past GPR studies have been highly variable. Some earth materials are highly attenuating to GPR energy. In other materials the transmission, absorbency, and reflection of a clear GPR signal appears to be variable depending on moisture content and state (i.e., liquid vs. solid). Furthermore, common soil minerals (e.g., calcium carbonate, soluble salts, and clay minerals) influence the GPR signal in an un-quantified and unknown fashion. These and other complications lead to spurious or otherwise meaningless results in many instances.

2.2 Objective

The objective of this project was to quantify and calibrate GPR for known archaeological features that are commonly found in many areas of the U.S. under controlled conditions at two different artificially constructed archeological sites. A field and laboratory protocol that can be modified using specific site conditions and the extent of the target features (i.e., depth and aerial) was undertaken. This allowed for more accurate and efficient detection and mapping of buried cultural remains on Department of

Defense and Department of Energy lands, decreasing the reliance on traditional, arbitrary excavations that are both costly and destructive.

The project addressed these technical concerns of soil moisture and type and developed a series of procedures that can predict in advance what tools will be needed and whether a GPR or other types of geophysical surveys will have a reasonable chance of success. In addition it undertook development of modeling procedures that can predict what archaeological features will "look like" in radar images to help in the interpretation of data once it is processed. There is continual testing and discovery of how GPR operates in different geologic and environmental settings, and how these settings affect the success of locating and mapping archaeological features. The more researchers learn about GPR's applicability to certain sites, the better they can predict how successful a GPR survey will be.

3. TECHNICAL APPROACH

This project conducted a systematic analysis of two tests sites that have already been constructed for this type of geophysical archaeology analysis, the USACE Construction Engineering Research Laboratory's (CERL) Constructed Archeological Test Site (CATS) on the University of Illinois Champaign-Urbana Campus, and the Hanford Test Site, called "Hammer" in Hanford, Washington. Both of these facilities have constructed buried materials that simulate archaeological sites of many sizes and dimensions, with differing burial materials and matrix. The Hammer Site is in a dry area, with primarily sand and silt materials. Data were collected there in dry conditions, and the area was flooded with a sprinkler for 2 days to simulate very heavy rain. The CATS facility is in clay that is moist or wet much of the year, but fortunately during one period of collection, it was very dry. Data were also collected when the ground was frozen. These two areas provide two ends of the soil spectrum with respect to GPR efficacy. The stratigraphic framework, constructed from what is known about these test sites will permit us to calibrate the GPR signal in a variety of common archaeological earth materials. Along with the different soils and "weather" conditions of each site, data were collected with different antenna frequencies (ranging from 300 MHz to 900 MHz), various transect separations, and various acquisition parameters.

At the conclusion of the project's research, it has been possible to create a set of procedures that incorporate the results and interpretations of this systematic testing, as well as the results of other GPR surveys around the world. The research conducted at these sites was done under controlled and measurable settings. This means that interpretations can be made with a higher degree of confidence since it is possible to measure which variables are most affecting radar energy propagation, and to what degree. This research project was therefore invaluable to developing predictive procedures for conducting GPR surveys and collecting meaningful data.

3.1 Procedures for Data Collection

Field data collection commenced in August 2002 at the CATS site. In September 2002 and again during the winter of 2003 data were collected at both sites during frozen and wet conditions. Twenty-four GPR surveys have been conducted at these sites in both dry and wet conditions in typical summer and again in winter conditions. Three different GPR systems were used in this collection with 5 different types and frequencies of antennas. Geophysical Survey System Inc (GSSI) SIR-10 and SIR-2000 systems were used as was a Sensors and Software (S&S) PulseEKKO system. Three grids of electromagnetic conductivity data using the EM-38 system were also collected for all the grids as a guide to local variations in ground conductivity. A summary of all the data collected is shown in Table 1 below.

Table 1: GPR and EM-38 data collected at the CATS and Hammer test sites.

Location	System	Frequency	Time	Files	Spacing	Line Length	Profiling Direction	Marks	Conditions
CATS	GSSI	400MHz	30ns	100	50cm		Y	1m	Dry
CATS	GSSI	400MHz	30ns	83	50cm		Y	Survey Wheel	Dry
CATS	GSSI	300MHz	40ns	21	1m	20	Y	5m	Dry
CATS	GSSI	300MHz	40ns	11	1m	20	X	5m	Dry
CATS	GSSI	400MHz	30ns	42	25cm	20	X	1m	Wet
CATS	GSSI	400MHz	30ns	42	25cm	20	X	1m	Wet
CATS	S&S	450MHz	30ns	62	50cm	20	Y	1m	Dry
CATS	S&S	450MHz	30ns	24	50cm	20	Y	1m	Dry
CATS	S&S	450MHz	30ns	41	50cm	20	Y	1m	Dry
CATS	S&S	225MHz	30ns	21	1m	10	Y	1m	Dry
CATS	S&S	225MHz	30ns	11	1m	20	X	1m	Dry
CATS	S&S	225MHz	30ns	20	1m	20	Y	1m	Dry
HAMMER	GSSI	400MHz	30ns	71	50cm	10	Y	1m	Dry
HAMMER	GSSI	900MHz	20ns	176	20cm	10	Y	1m	Dry
CATS	GSSI	900MHz	20ns	102	20cm	10	Y	Survey Wheel	Frozen
CATS	GSSI	900MHz	20ns	52	20cm	20	X	Survey Wheel	Frozen
CATS	GSSI	400MHz	30ns	42	25cm	20	X	Survey Wheel	Frozen
CATS	GSSI	400MHz	30ns	82	25cm	10	Y	Survey Wheel	Frozen
CATS	GSSI	400MHz	30ns	42	25cm	10	Y	1m	Frozen
CATS	GSSI	400MHz	30ns	42	25cm	10	X	1m	Frozen
HAMMER	GSSI	900MHz	20ns	52	20cm	35	Y	1m	Wet
HAMMER	GSSI	900MHz	20ns	177	20cm	10	Y	1m	Wet
HAMMER	GSSI	400MHz	40ns	22	50cm	35	Y	1m	Wet
HAMMER	GSSI	400MHz	40ns	72	50cm	10	Y	1m	Wet

Visual analysis has been made between the modeled features and the amplitude maps, but this type of comparison is subjective and difficult to accomplish mathematically. In order to determine which of the methods and systems produces the best correlation to known features, a statistical correlation method has been developed in *Idrisi* that will mathematically compare the modeled features in the ground and the radar reflections produces in *GPR Process*[1]. Amplitude data from *GPR Process* were imported into *Surfer*[2] (an off-the-shelf gridding and mapping program) to produce maps of the features, and then these images were exported to *Idrisi*[3] for analysis. In *Idrisi*, linear regression was performed between the two images (within a given grid of values) for each depth slice in the ground. The model of the floors, which is what is known, is the dependent variable, and the reflection data from each survey is the independent variable.

[1] GPR Process: Developed as part of this project by Univ. of Denver. www.du.edu/~lconyers/SERDP/Gpr_Process.doc
[2] Surfer: © 1997-2006, Golden Software, Inc., Golden CO www.goldensoftware.com
[3] Idrisi: © 2006 Clark Labs, Clark University 950 Main Street, Worcester MA 01610-1477 USA idrisi@clarku.edu; www.clarklabs.org

Values of r are then produced between the two images to calculate the strength of correlation for each of the surveys. The results are displayed in a regression plot with the descriptive statistics listed for each acquisition and processing method. Results for these analyses are shown in the Appendix of this report. Another procedure in *Idrisi* produces a plot of the residuals from each regression analysis. This residual can map spatially where the GPR maps produced the best correlation with what is known, and where (and with what equipment and processing) the method was less successful.

Ultimately these types of analyses will be modified as laboratory analyses of the soils samples and additional processing of the field data produce more accurate information about both the known features and the GPR maps. At this point in the project the principal investigators are pleased to have developed the processing software and suitable mathematical and statistical methods for quantitatively determining the strength and weakness of each of the field methods and type of equipment.

3.2 Analysis of the GPR Data

Our analysis of the data produced some surprising results that have challenged the group's preconceptions of how the radar energy travels and reflects off features in the ground. It has always been assumed by most GPR practitioners that surveys performed in wet ground, especially clay rich ground, will be mostly unsuccessful. Our data collection at CATS began during a period of extended drought, so the clay soils were dry. The reflection data were therefore expected to be of good quality, as it was hoped the buried archaeological materials would have retained just enough moisture to produce a significant reflection at their interface with the surrounding matrix. The reflection profiles, however, were "noisy" and full of point source hyperbolas, presumably generated at vertical cracks in the soil, produced by the shrinking clays (Figure 1).

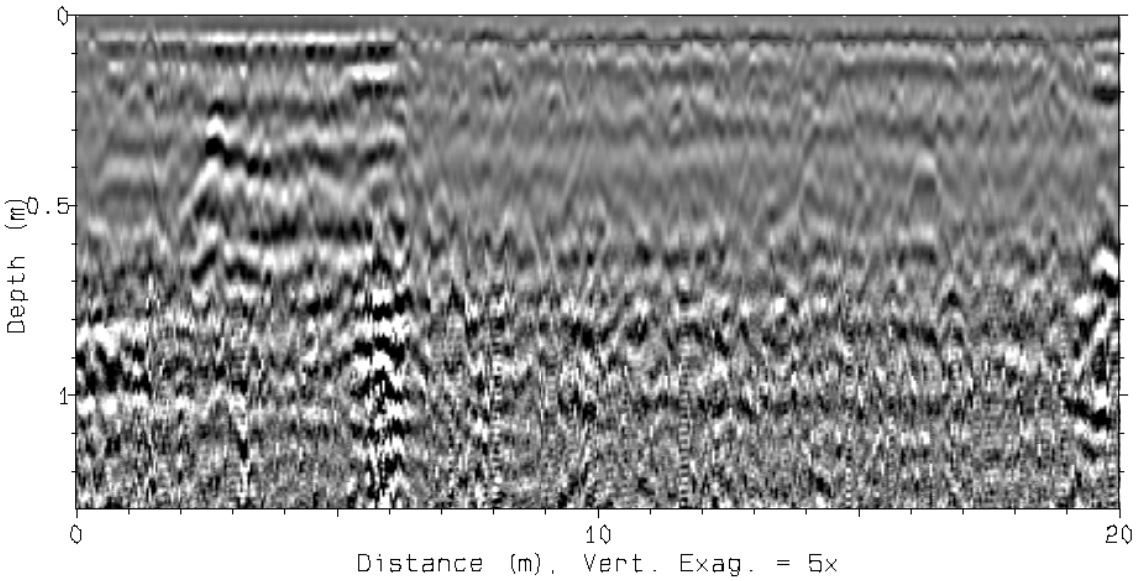

Figure 1: 400 MHz reflection profile from CATS when the ground was dry. There are an abundance of reflections, possibly produced from small cracks in the clay soils. A buried house floor is barely visible from 3-7 meters at about 30 cm depth.

The evening after those data were collected (Figure 1), more than 3 inches of rain fell, saturating the ground. Tensiometer measurements that next morning indicated almost complete soil saturation to a depth of 60 cm in the ground. Data were recollected over the buried features in a driving rainstorm that next day. To our amazement, the data were excellent, and many of the known features were visible and distinct (Figure 2).

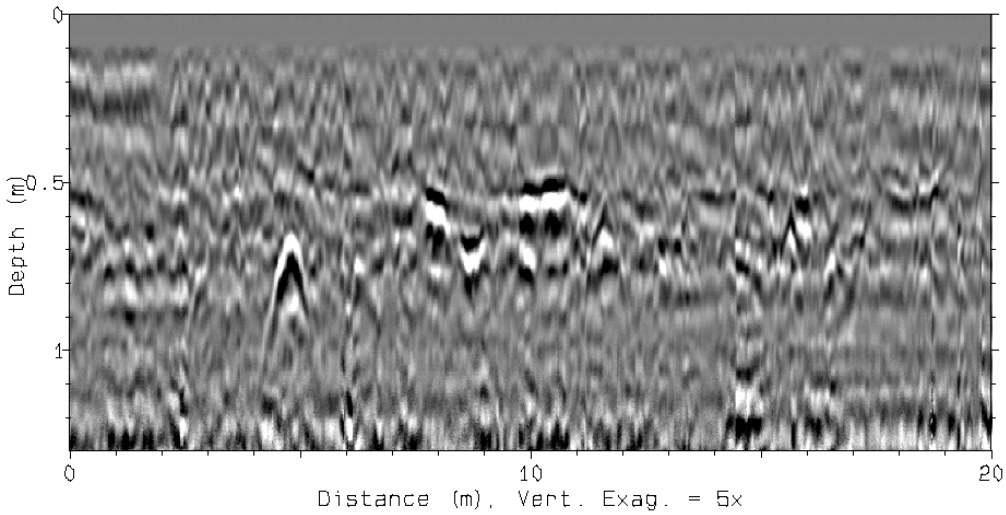

Figure 2: 400 MHz reflection data over a buried house floor at CATS when the ground was saturated. The reflections from the floor are very distinct, and sub-floor features are visible. This floor is located from 8-12 meters at a depth of .5 meters.

The addition of water to the system after the rain significantly slowed the radar travel velocities, but interestingly, did not attenuate the energy with depth. If anything, the reflections are even more distinct, and subtle sub-floor features are visible. Other smaller buried features, not visible at all in the data collected during dry conditions, were also visible in the reflection profiles. Our working hypothesis is that the addition of water to the system produced a greater physical and chemical contrast at the interface between the floor and the surrounding material, possibly because of differential moisture retention on the floor. The floor that was most visible on the wet day was the one that had been burned, which probably produced an impermeable surface upon which to pound water, producing a distinct reflection. The puzzle is why this clay soil did not attenuate the energy, as has been so widely reported elsewhere. Our suspicion is that the clay types in this area, when wet, have a low cation exchange capacity, and therefore are not as electrically conductive as most clays. To test these ideas, the soils collected in the field will be analyzed in the laboratory beginning in January, 2003 to determine their physical and chemical properties under different moisture conditions.

To test the correlation of the maps produced from data collected during both wet and dry conditions, our geographical information system (GIS) correlation method was applied to both data sets (Figures 3 and 4). Data for both days were processed in *GPR Process*, removing background noise and migrating reflections. Using the same processing and gridding parameters the data collected on the dry day show an abundance of reflections, some of which are showing the buried house floors and other features, but many of which appear to be un-related to the archaeology (Figure 3).

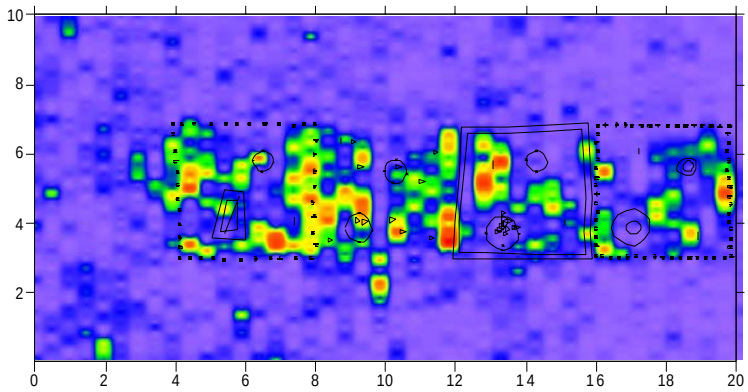

Figure 3: Amplitude slice-map of the CATS house floors from data collected on a dry day. The basic outlines of the floors are visible, but features are indistinct at best and many reflections were generated from non-archaeological materials.

A statistical correlation of this GPR map to the known features generated an r value of .2, which is a very poor correlation. When the same type of analysis was performed for the maps produced from data collected on the wet day, an r value showing a correlation of .54 was calculated. All correlation statistics and maps of these analyses are shown in the Appendix.

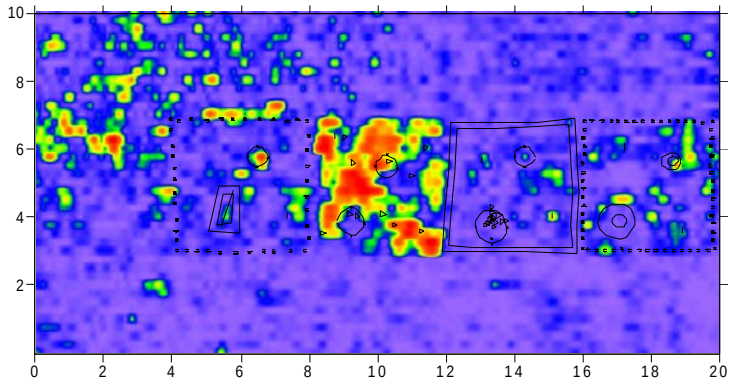

Figure 4: Amplitude slice-maps of the CATS house floors from data collected when the ground was saturated. The one house floor (with a baked clay surface) is very visible in this slice, while other features are not.

At the Hammer site in September, 2002, only dry soil conditions were encountered during data collection. It was hoped that wetter conditions would exist in winter 2002 for a second round of data collection, but if dry conditions persist, it was considered soaking the site with water from a nearby fire hydrant just prior to going to the field. The same types of field collection and data analysis procedures were followed as with the CATS data. Soil samples have been collected in the field and will be analyzed in the same fashion as those at CATS in order to produce more accurate models of the buried features.

The most interesting preliminary conclusions from those surveys are consistent with the ideas about GPR reflections in a sandy matrix. The researchers hypothesized that at this site the higher frequency antennas (900 MHz) would produce higher quality and more distinct reflections, and they did. Reflections within 1 meter of the ground surface with the 900 MHz antennas were very distinct, and produced images of the buried features that were expected (Figure 5). The 400 MHz data showed many of the same features, but less distinctly, which was also expected.

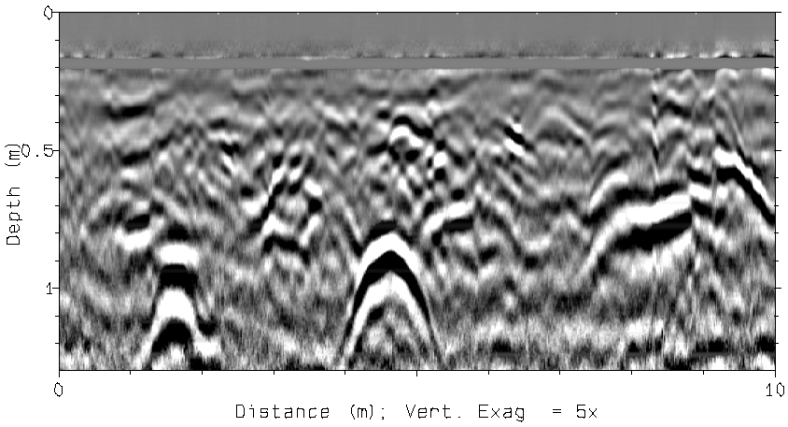

Figure 5: 900 MHz reflection profile over buried archaeological features at Hammer.

The Hammer test site is composed of mostly buried objects, with little stratigraphic complexity, and no aerially extensive features. Models were created in the same fashion as those at CATS, with the same types of statistical correlations (Figures 6 and 7).

Figure 6: Model for the shallow burial features at Hammer created in *Idrisi*.

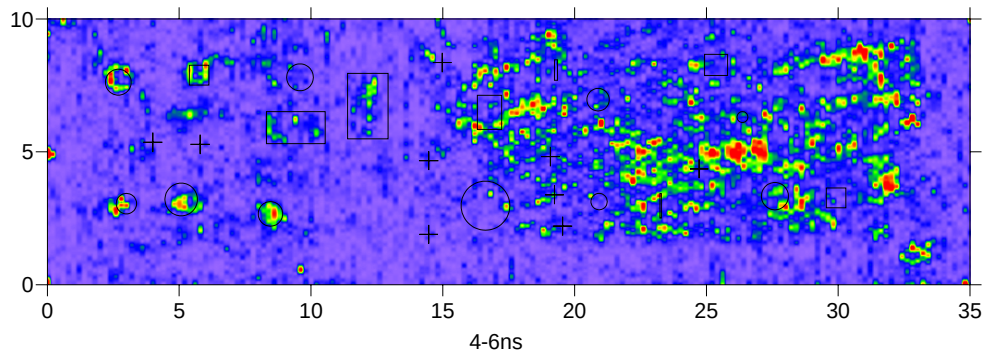

Figure 7: Amplitude slice-map from 4-6 ns at Hammer showing the results from the shallow buried objects

Correlations in *Idrisi* between the known features and the images produced in *GPR Process* have been made, but are still in the process of being evaluated. At this point in the project there are some good correlations for some of the objects, but others are not as visible

The databases collected during summer conditions have provided the project with an abundance of information with which to begin the analysis of GPR reflections at the two different sites. The reflection data from Hammer in the sandy soils have produced an excellent series of maps, and correlation with the known features appears to be fairly straight forward. The higher frequency antennas produced superior maps to the lower frequency ones, as expected.

The CATS data was in many ways very surprising, especially those databases collected when the ground was saturated. The reflections generated in wet conditions produced maps that defined some of the features very well, while others not at all. The reasons for this are still unknown, but could be related to higher coefficients of reflectivity at interfaces between burned clay and the surrounding matrix.

Software has been developed to expedite the data analysis collected in the field, which has simplified and speeded up our data analysis. This software will be improved upon in the coming months as the project continues. Processed data have been successfully imported into GIS software programs to allow for statistical correlations between the models and the processed maps. This method allowed us to quantify the results from the field and laboratory in ways that will point to specific methods and equipment as the most effective under certain conditions.

In general the collection procedures that were used with all the reflection data are shown in Table 1. When processed and compared to the known features a “best visual fit” was then made to immediately determine whether maps were even close to the shape and size of the known features. The parameters that appeared to best match what was known in the ground are as follows:

- Collection with the smallest distance between transects in a grid. In general, with a 400 MHz antenna, a line spacing of 50 cm was good, but 25 cm was even better. With the 900 MHz antenna 25 cm spacing was optimal, and there was negligible difference between 25 cm and 20 cm.

- The high frequency antenna (900 MHz) was best at imaging from 10-50 cm depth in the clay rich area at CATS and at all depths at the sandy area at Hammer. The 400 and 450 MHz antennas also produced maps with good resolution at both sites, and had optimum depth resolution from about 20-90 cm depth. Low frequency antennas (300 MHz and lower) produced poor maps at both sites because of their poor resolution at the shallower depths.
- Reflection data were processed first to remove background noise and extraneous frequencies. Data were then migrated to remove hyperbola "tails" and collapse reflections to their point sources for "crisper" amplitude maps.
- Reflection profiles were sliced in 2 ns thick slices at a minimum for amplitude analysis. Thinner slicing cut across waveforms and tended to blur and distort the final maps. A 20 cm search radius or less was used for all amplitude slice creation, and there was no interpolation between profiles in grids, using the slicing procedure.
- Each amplitude time slice was then gridded in imaging programs, but this time with a 1 meter search radius or less, interpolating with a power of 4 (weighting the data closest to the center of the search radius) and smoothing the data at most at a factor of 1 or less.
- Image maps were then created for each slice using the Surfer 8 mapping program and colors were given to the amplitudes of each map in image creation.

Many different gridding and mapping procedures were attempted for all maps; many more than are indicated in the general procedures listed above. Some of these attempts created marginal images, where the known features were barely visible, and others somewhat better, but still not the best. The above collection, processing and gridding parameters proved to be the best methods for the two test sites irrespective of environmental conditions and equipment used. Keep in mind that both these sites had features buried only a meter or less in the ground, which almost always precludes the generation of good maps using the low frequency antennas. These shallow depths that were used as part of this study are common for most archaeological sites, but if these same features had been buried much more deeply in the ground, very different processing steps and equipment types may be necessary.

4. RESULTS AND DISCUSSION

4.1 CATS Site Analysis

A visual comparison is possible in all the grids of high frequency processed data at CATS and the known features in the ground. Known features are shown in Figure 8 below.

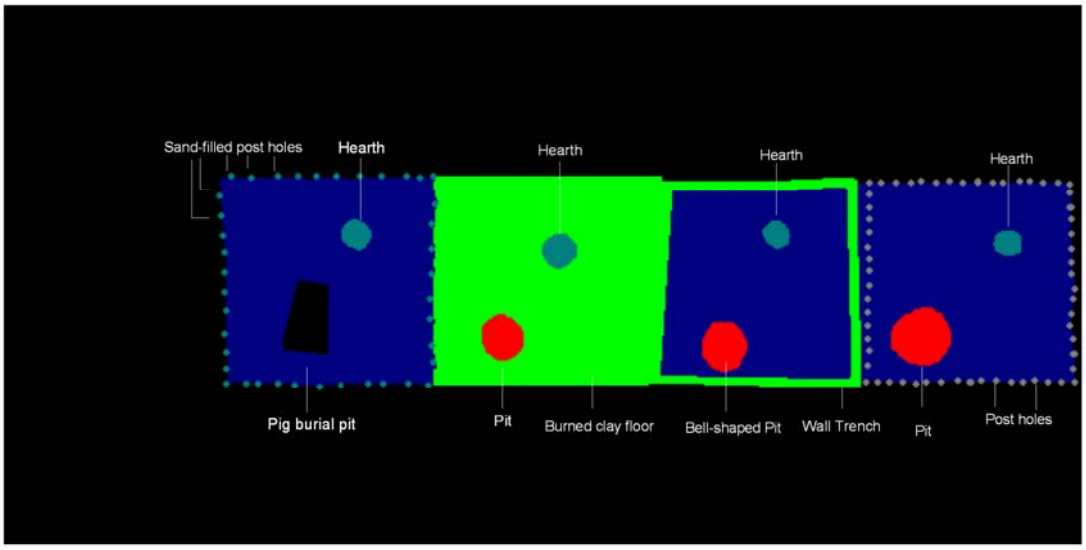

Figure 8: The CATS house floors model

In general all the amplitude maps of the floor features at CATS showed a general outline of some of the features and some of their internal features, but resolution was poor when the conditions were dry (Figure 9). This was partially a function of the high number of point source hyperbolas that were generated along shallow fractures in the soil, caused by desiccation cracks. Remember that the ground was extremely dry when these data were collected, which greatly affected the radar reflections in the ground.

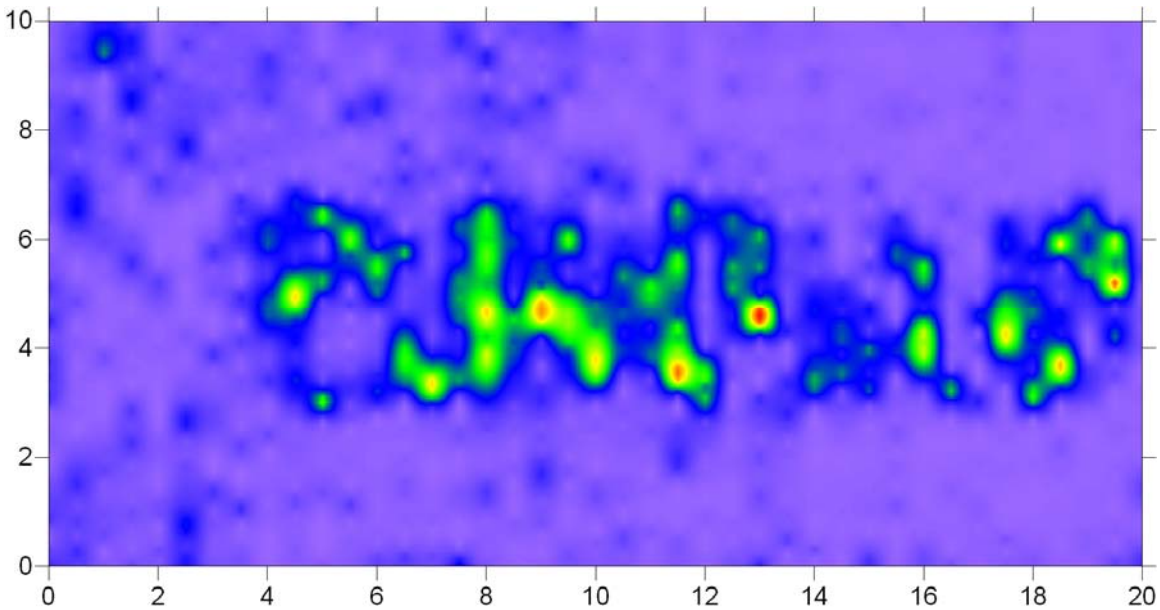

Figure 9: CATS Amplitude map using the 400 MHz antenna. Ground conditions were very dry.

When the ground was completely saturated a very different amplitude map is generated from the house floors (Figure 10). Three of the four floor features are almost invisible in the GPR maps, while floor number 2, which was the hardened clay surface that had been burned, was quite noticeable. The other three house floors were composed of compacted soil similar to that which was used to cover it. The question then remains as to why all four of the floors were visible in the dry data, but only one of them in wet conditions. As will be discussed further below, laboratory analyses of the CATS samples suggests that water, and how it is retained and distributed in the ground is the dominant factor in whether ***anything*** in the ground will generate a significant radar reflection. In the dry data, all 4 house floors were visible because there was enough contrast between the compacted dirt and that surrounding it, which was significantly less compacted, to generate a reflection. That is because the floors, even in dry conditions, differentially retained some water compared to the overlying material. But when those same floors were saturated with water, the compacted floors and the overlying material (composed of almost the same type of material) retained almost the same amount of water. Because it is the water that is producing the contrasts in velocity that generate the higher amplitude radar reflections, the difference in water saturation at the interface between the slightly compacted floors (3 of the 4) and the surrounding materials was negligible in wet conditions. There was therefore no reflection generated at the floor interface, or reflections that were so subtle as to be invisible. But in those wet conditions a significant amount of water was pooled on top of the impermeable baked clay floor, producing a significant reflection (Figure 2). These two slices (Figures 10 and 11) dramatically illustrate the importance of water in GPR reflection generation.

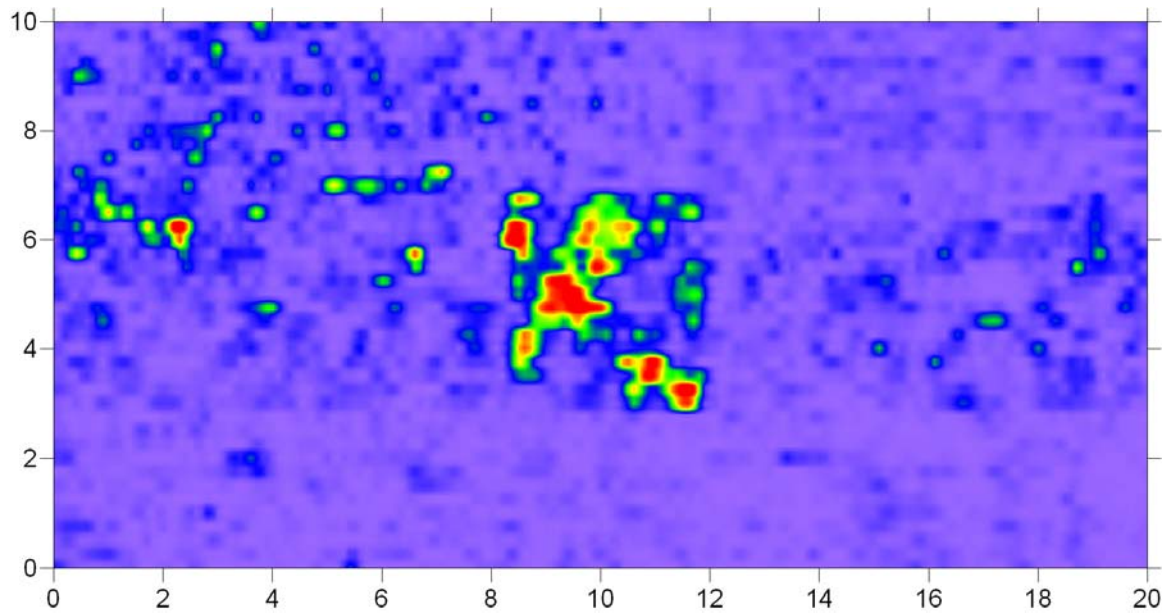

Figure 10: CATS Amplitude Map using the 400 MHz antenna. Ground conditions were totally saturated. The burned house floor is the only one visible in this map, as it pooled water on its surface.

The GPR slice over these same house floors produced from data collected when the ground was totally frozen produces an even different picture (Figure 11). With the 400 MHz data the image of the floors is similar to that when the ground was dry, with all four of the floors visible. Feature resolution within the floors, however, is still as poor as that seen in the data that were collected during dry conditions. It appears that even with frozen ground and presumably better energy coupling, the buried features are subtle enough to have generated few high amplitude reflections.

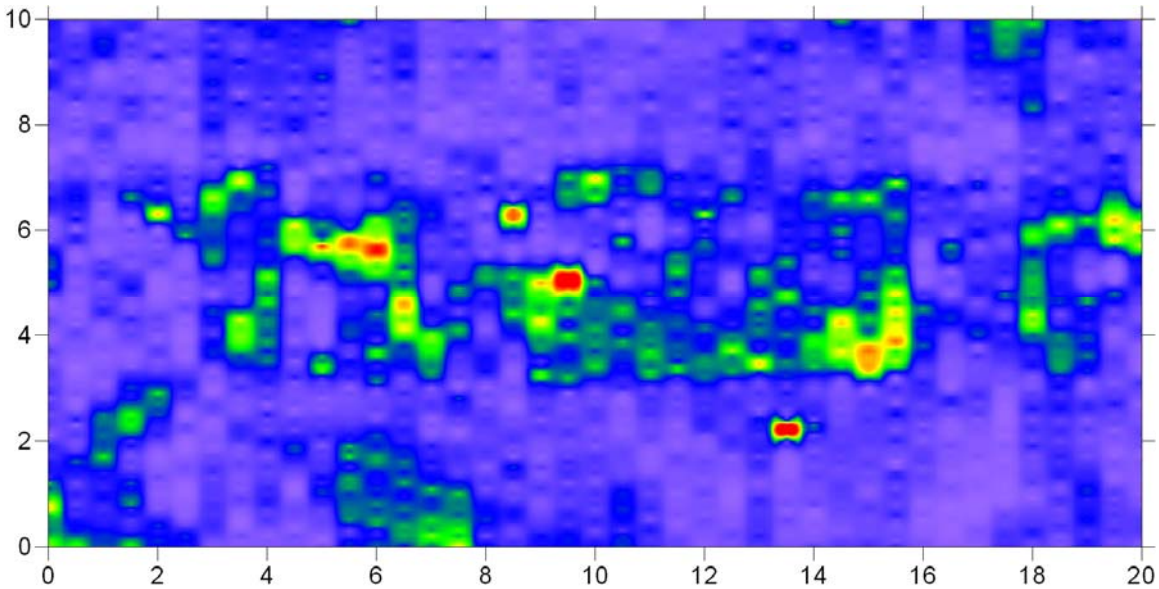

Figure 11: CATS Amplitude slice maps using the 400 MHz antenna. Ground conditions were frozen during data collection.

A very different picture of the CATS house floors is generated from the data collected in frozen conditions with the 900 MHz antenna (Figure 12). In general the floor features on the right are much more visible, as is the edge of floor number 1. Many other strange features, which are not related at all to the known feature floors, however, are visible in this slice. The origin of these amplitude anomalies is not known, but is suspected to be a product of changes in water content in the soils placed just on top of the floors, which was known to be a conglomeration of many different top soils scraped off the test area during test bed construction.

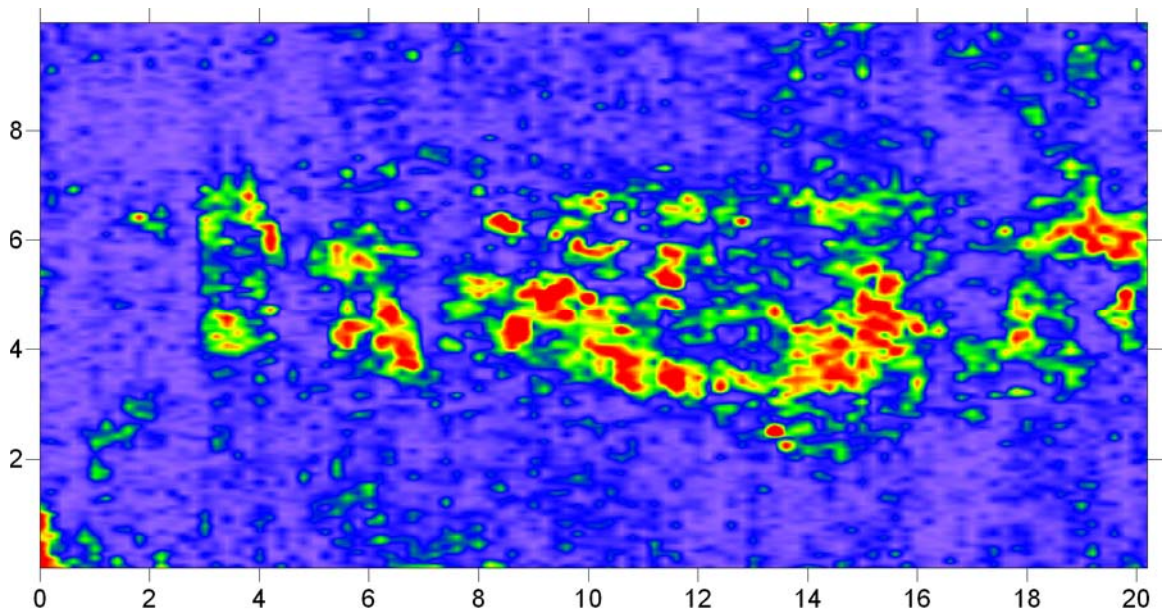

Figure 12: CATS amplitude maps using the 900 MHz antenna. Data were collected when the ground was totally frozen.

4.2 CATS Spatial Statistical Analysis

A spatial statistical analysis was then performed on all of the above maps to determine how good the correlation is between the models and the actual maps, in a spatial sense. These data are detailed below. In a qualitative way it appears that the dry and frozen ground data collection produced good, but not great, correlations of all the buried house floors. In the wet conditions, there was one superior images that correlated, but only of the floor that was burned. In the wet data the other three floors were essentially invisible. Although this phenomena, related to the way in which water is retained on buried surfaces, has been noted by some researchers, it has never been documented as dramatically as at the CATS site.

In the spatial statistical analysis models, each of the house floors and their associated internal features were generated using relative dielectric permittivity values derived from the laboratory analyses. These values were placed on the size and dimensions of the known features using feature and soil maps obtained in the original CATS report. The permittivity values for each feature were then transformed into values of coefficient of reflectivity, which are a relative measurement of the amplitude of

reflected radar waves generated from each of those features. The coefficients calculated ranged from close to 0, when there was essentially no contrast in buried materials, to as high as 16, when there was a very strong materials contrast in the ground. Those modeled features, with the assigned coefficients, were then gridded and mapped spatially for the horizon directly at the house floor surface. A grid file that represents the spatial placement of the coefficients on the floors was developed. This corresponds to the spatial placement of the actual features in the ground.

The actual radar reflections that correspond to the surface that was modeled were then gridded using exactly the same parameters as the modeled surface. In this way the x and y values in space were exactly the same in both grid maps, while the z values in the model were the coefficients of reflectivity and the z values in the radar slice maps were the actual amplitudes of the reflected waves. These two maps could then be directly compared to each other spatially and a residual of the two z values constructed (Figure 13). In these residual maps white is the mean value of the data amplitudes (essentially no reflection) which was in the same location as areas that were modeled as having no reflection, or very low coefficients of reflectivity. Red colors were assigned to areas where the high coefficients of reflectivity in the modeled features were ***not*** represented by high amplitude values in the data. This means the GPR data were not able to detect the known features. Blue is where GPR slice maps displayed high amplitude values that did not directly correspond spatially to the location where the model indicated there should be materials of high amplitude. This means the GPR data detected something in the ground that was ***not*** actually there. In each of the spatial models shown below the radar maps and model are shown, with the residual map below. A correlation coefficient was then calculated for the comparison of the model to the actual data. A perfect correlation produces a R^2 value of 1, while no correlation whatsoever is 0.

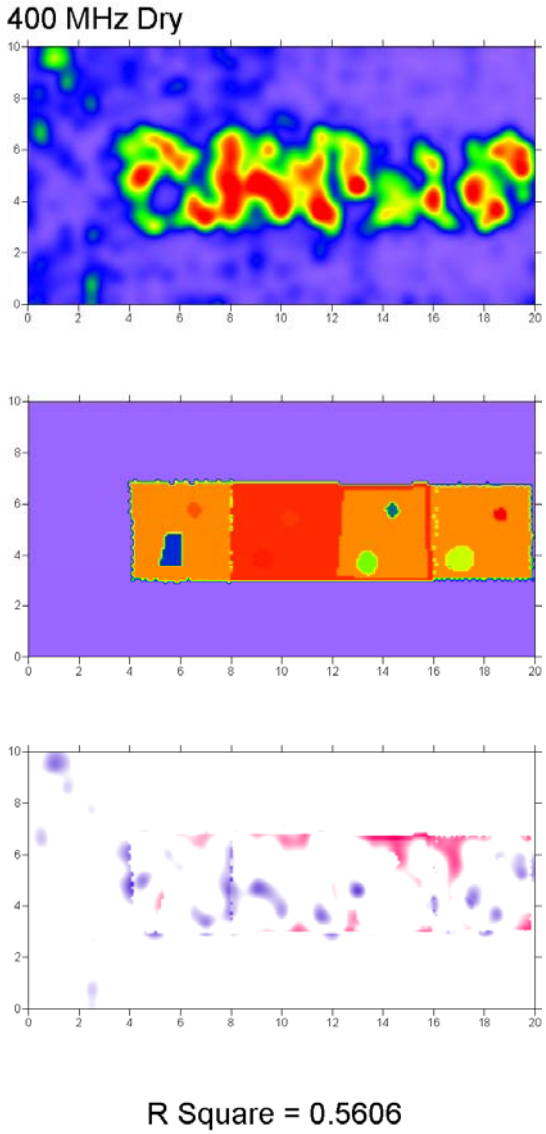

Figure 13: Spatial statistics for 400 MHz antenna in dry conditions at CATS

In the test with the 400 MHz antenna during dry conditions the R^2 value of .56 shows a good correlation, but not great (Figure 13). Some of the internal floor features were visible, while many were not. In addition, the edges of each of the floors tend to be somewhat blurred in the GPR map, probably as a result of the spherical spreading of radar energy with depth in the ground that produces hyperbolic reflections from the buried edges of the features. When these individual reflections are processed into slice maps, the edges of the buried features tend to become blurry. Although all the data were migrated in all the lines prior to processing, which should have removed many of these extraneous reflections, the process was still not perfect. In general, the outline of the floors is clearly visible and some of the more distinct floor features. Therefore, if a similar feature was present in an archaeological site with the same ground characteristics, it would be easily mapped with GPR when the ground was dry.

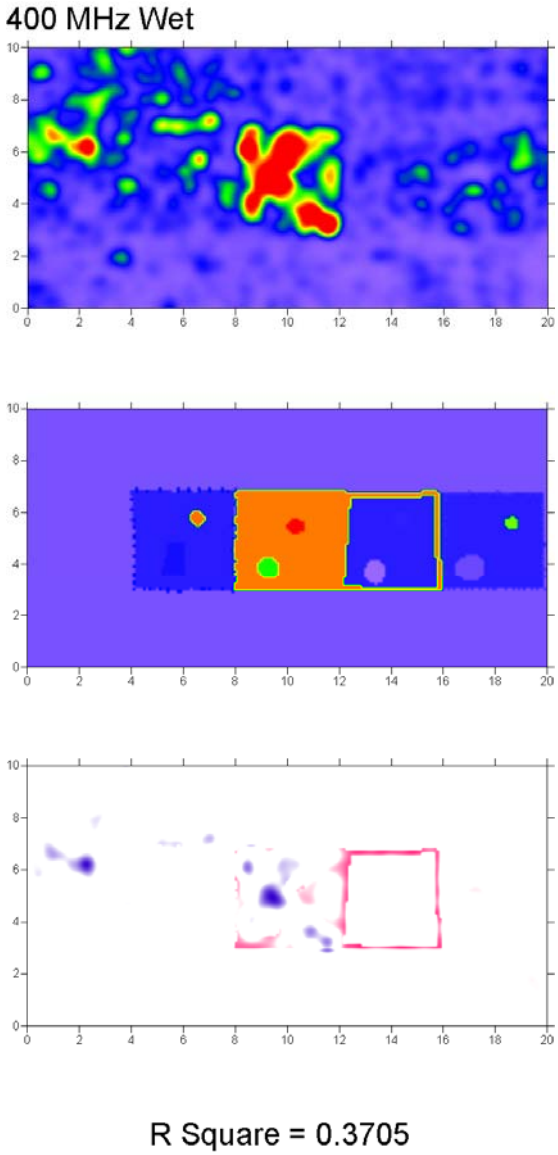

Figure 14: Spatial statistics for 400 MHz antenna in wet conditions at CATS

When the CATS floor features were imaged during wet ground conditions, very different results were obtained. The GPR slice map shows high amplitudes only of the second floor, which is the earthen floor that was burned prior to burial (Figures 14 and 15). Some of the floor features produced high amplitude reflections in the other three floors, but the floors themselves were not visible. Even when the model was adjusted with respect to coefficients of reflectivity that would be expected for the wet ground conditions, the three not-burned floors were not visible at all, and a low R^2 value was obtained for the floors overall (.37). It is likely that in similar conditions at an archaeological site only the burned floors would be visible in GPR maps.

This conclusion has very important implications for the use of GPR in archaeological mapping, and suggests that perhaps multiple surveys should be conducted in areas that are prone to alternating wet and dry conditions. If data are collected when the ground is very wet, the survey should be then performed again in dry conditions, as

very different features will potentially be visible. The importance of water, and its retention and placement in the ground, is dramatically illustrated in this example from CATS.

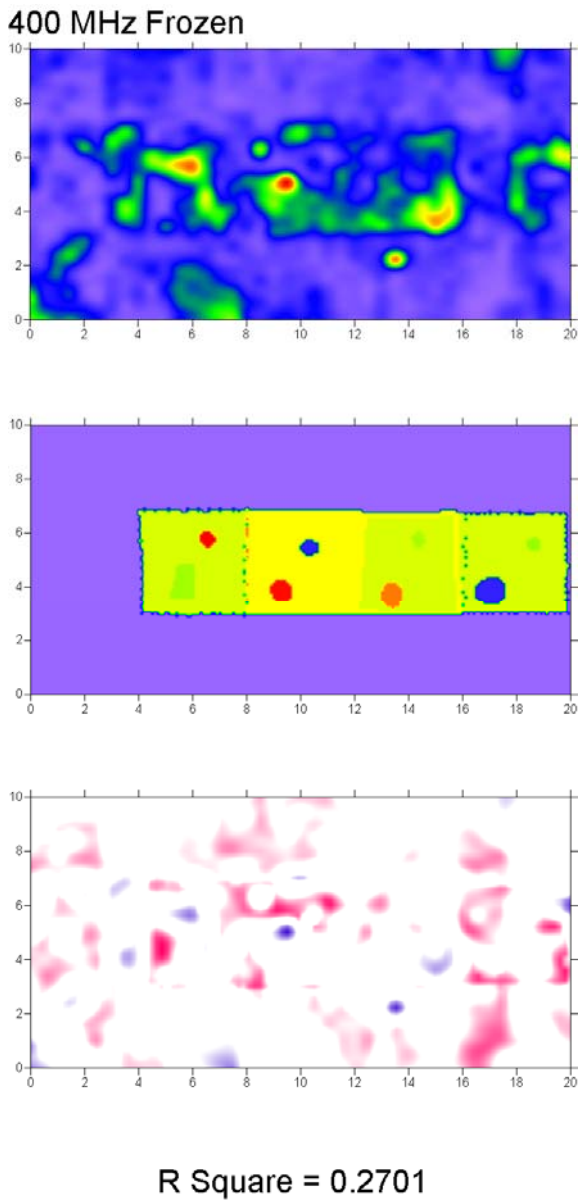

Figure 15: Spatial statistics for 400 MHz antenna in frozen conditions at CATS

The floor features at CATS were even less visible when the ground was frozen, which is very much different than was expected. Most GPR practitioners report that frozen ground usually allows radar energy to couple better with the ground, producing better definition of buried features. In the CATS area, however, that was not the case and at this point there is no satisfactory explanation. A maximum correlation of only .27 was obtained for the frozen ground at CATS, which was the poorest of all the GPR data. This suggests that in clay-rich areas frozen ground may disperse radar reflections, perhaps because of the fractures in the clay. If the underlying clay is relatively dry, even if the

ground surface is frozen, conditions in the ground are un-knowable, and difficult to model correctly.

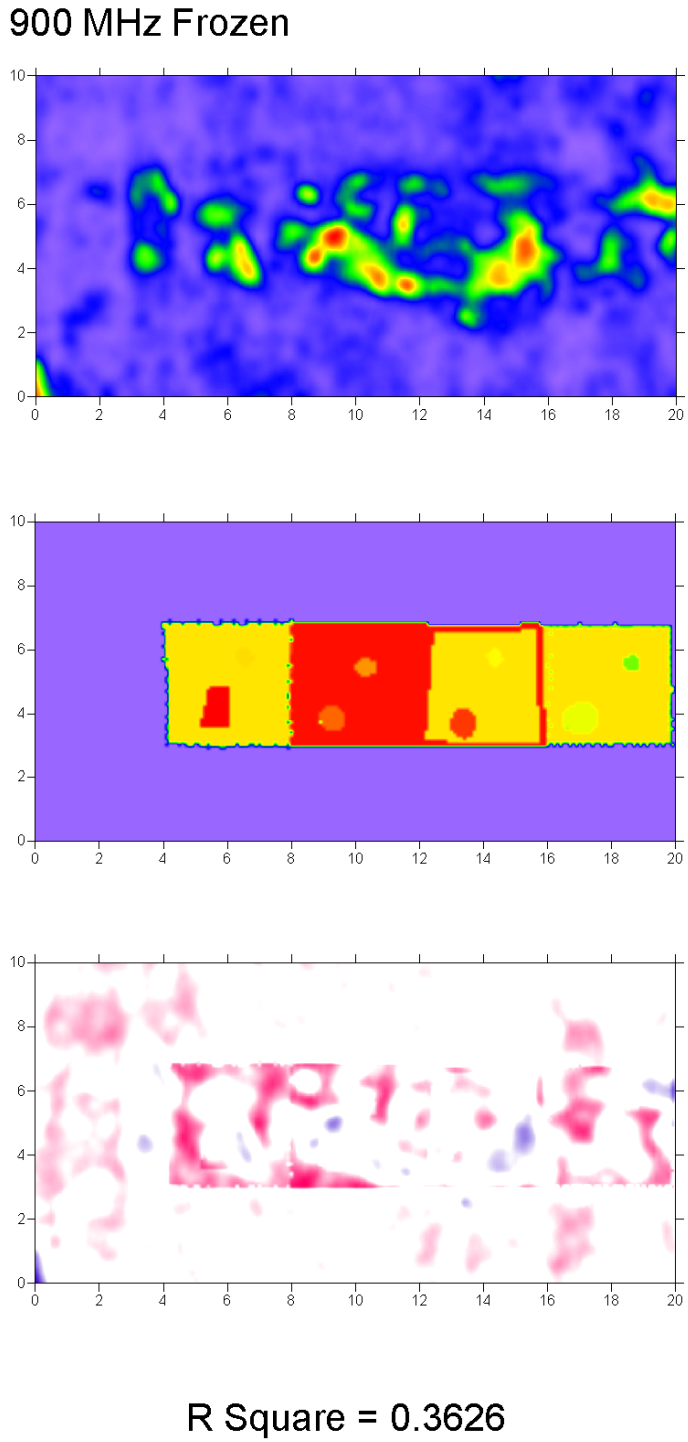

Figure 16: Spatial statistics for 900 MHz antenna in frozen conditions at CATS.

The 900 MHz antenna was also used to collect data at CATS during the frozen conditions and produced a better correlation than the 400 MHz in the same conditions (Figure 16). It appears that the 900 MHz antenna is recording reflections from not only

the floors of the houses, but also the material directly above them, which was used to back fill the holes. It is documented in the construction report at CATS that many different types of backfill material were used to fill in the holes after the features were built, and the 900 MHz data appear to be defining these differing materials. This is particularly noticeable in the amplitude time-slices located not only on the floors themselves, but in the levels above the floors. Using the 900 MHz antenna the floors are barely visible in frozen conditions, but the correlation is somewhat better than with the 400 MHz antenna, which is purely a function of better feature definition with high frequency antennas (Figures 14 and 15).

4.3 CATS Topographically Corrected Data

Another feature at CATS was studied, but not in the same fashion as the house floors discussed above. As part of the same feature burial process a simulated burial mound was constructed by placing two pig carcasses in "tombs" and then piling earth over them. Reflection data were collected over the pig tombs in the same way as the house floors, but for these data a topographic correction was applied to the data in the mound to develop a fast way to correct data for elevation. The usual way that GPR data are corrected for topography is to survey each transect about every meter. Each profile must then be "static corrected" manually, by inputting the data for each profile (Conyers and Goodman, 1997: 175). This method is very time consuming, both in data collection in the field, and in processing in the lab later on. In order to test a more efficient method the mound was surveyed quickly in arbitrary points using a theodolite and stadia rod. This could have been done even faster in a manner of minutes using a digital laser total station. Nonetheless, the data were collected over the mound quickly and a surface map of the mound surface was constructed from the elevations (Figure 17). This map was gridded and smoothed so that it represented the mound as it existed in the field. Slice maps were then constructed at 2 nanosecond levels, and the amplitudes were placed in a spreadsheet with x and y denoting location on the ground surface and z being the amplitude of the reflected waves. Each of those x and y locations was then assigned a depth in the ground that corresponded to their actual depth below the surface, which was possible because time-depth studies had been performed in advance. One large spreadsheet of every amplitude at every depth level in the ground was then made. When these data were sorted for only the depths from 0-10 cm below the crest of the mound, for instance, then a map could be made of just the amplitudes in a horizontal slice at the mound top. The same was then done for each of the horizontal slices through the mound, and image maps were then constructed (Figure 18).

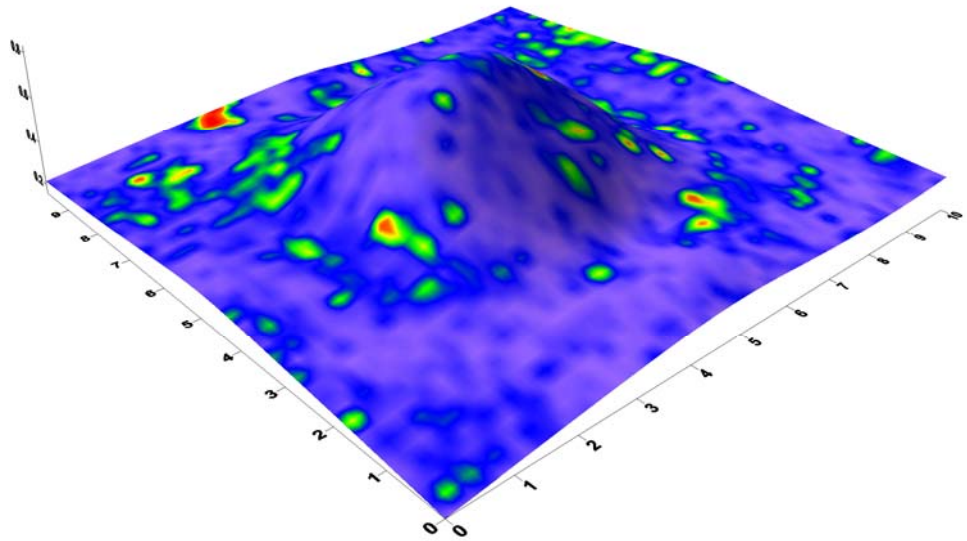

Figure 17: The surface amplitude slice "draped" over the pig burial at CATS. Each slice was topographically adjusted in this way to produce a corrected amplitude database.

When this was done the "pig crypts" that were placed in the ground were easily visible, as seen in the slice in Figure 18, which crosses the carcasses. This method of slicing the data was found to be very fast and accurate, as demonstrated at the pig burials at CATS, and should be used for all GPR reflections over topographically complex areas. It was done completely in *Surfer* by creating grid files of both topography and amplitudes that had the same x and y locations within the grid. The rest was easily accomplished by the sorting data function in *Excel*.

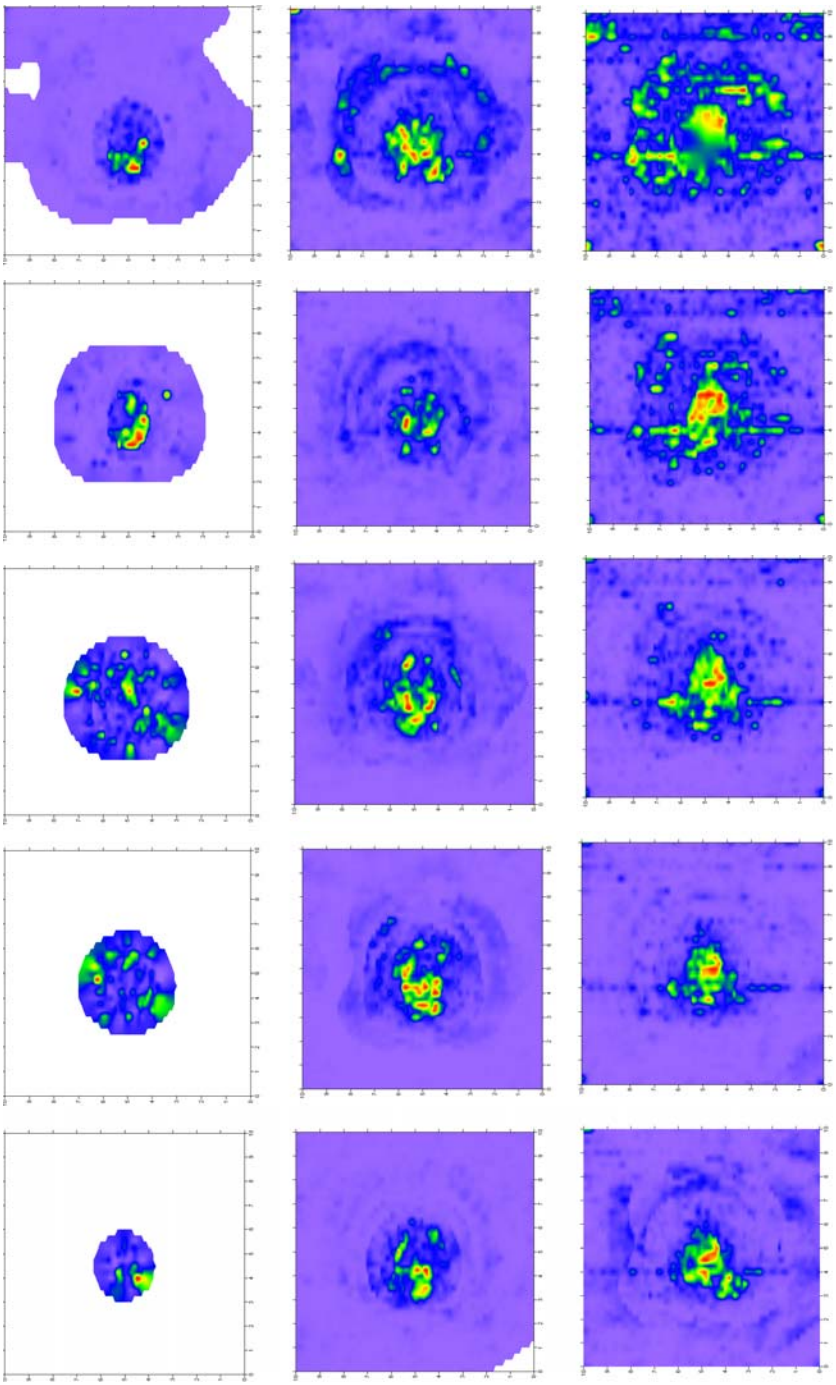

Figure 18: The pig burials at CATS sliced horizontally after having been first corrected for topography. The two distinct crypts are visible in the deeper slices.

4.4 Hammer Site Analysis

The Hammer site was constructed in a very different way than the test bed at CATS. It was set up to be a test bed consisting of mostly objects in the ground, as opposed to the broader and more realistic archaeological features that were buried at CATS (Figure 19). At the Hammer site many different objects and piles of objects were

placed at different levels in the ground and covered over with what was thought to be homogeneous sand (Figure 20). Those objects ranged from metal garbage to wooden artifacts to brick and stone features. Unfortunately the location of these objects in the ground was not mapped with the same accuracy as the CATS site, as became immediately apparent when comparing the models to the GPR data. Iimages of the objects were readily produceable, but when their location was compared to the maps constructed of the site by the developers, there were some noticeable discrepancies. Therefore, the location of the modeled features had to be modified to where we "knew" they existed (by looking at the GPR maps!) prior to analyzing the resolution of the amplitude maps produced. As a GPR expert and friend of mine always says: "The GPR doesn't lie" and at Hammer this was glaringly apparent as the researchers had to use the GPR maps to correct the placement of the features in the ground. But when this was accomplished, an excellent correlation between the location of the known objects and the GPR amplitude images was seen.

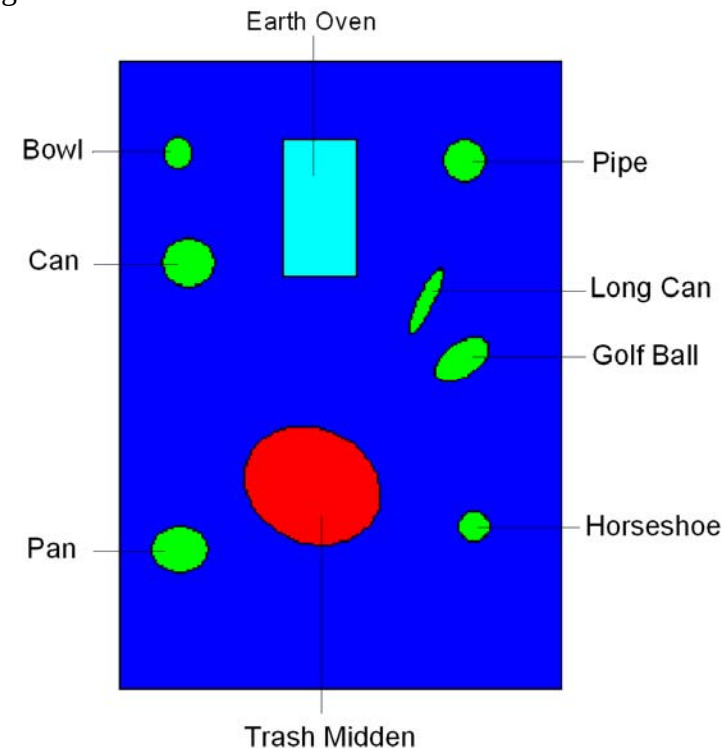

Figure 19: Some of the objects buried at the Hammer site. It appears that the people that constructed this site cleaned out their garages and trash cans to produce targets for the testing of GPR.

Figure 20: Construction of the Hammer test bed. In this sandy soil area mostly objects were laid in the ground and covered with homogeneous sandy silt.

The 400 MHz data at Hammer was moderately successful in imaging the features, but tended to blur them somewhat when processed, and the amplitude slice-maps constructed had much less feature definition (Figures 21 and 22). Metal objects, and some of the larger features composed of brick and packed earth are easily visible as anomalous high amplitude reflections, but the wooden objects and the less compacted earth features are essentially invisible in most of the GPR maps. There is also a noticeable amount of extraneous radar reflections generated in the data that was collected during wet conditions, especially in the 10-12 ns slice, but also in the shallower data (Figure 23). These reflections were likely produced by pockets of water that had been differentially retained on the contact of the underlying natural sand, which was partially cemented, and the overlying sandy back-fill above the features of interest. Remember that this site had been artificially "watered" by sprinkler for days just before the data were collected, and that water had therefore not had a chance to percolate downward through the underlying, undisturbed sediment. This differentially retained water therefore produced obscuring reflections in much of the wet condition data. This water retention phenomenon has been speculated on elsewhere (Conyers and Cameron 1998), but this test at Hammer was the first controlled experiment that demonstrates how significant the water retention problem is, especially in sandy soils.

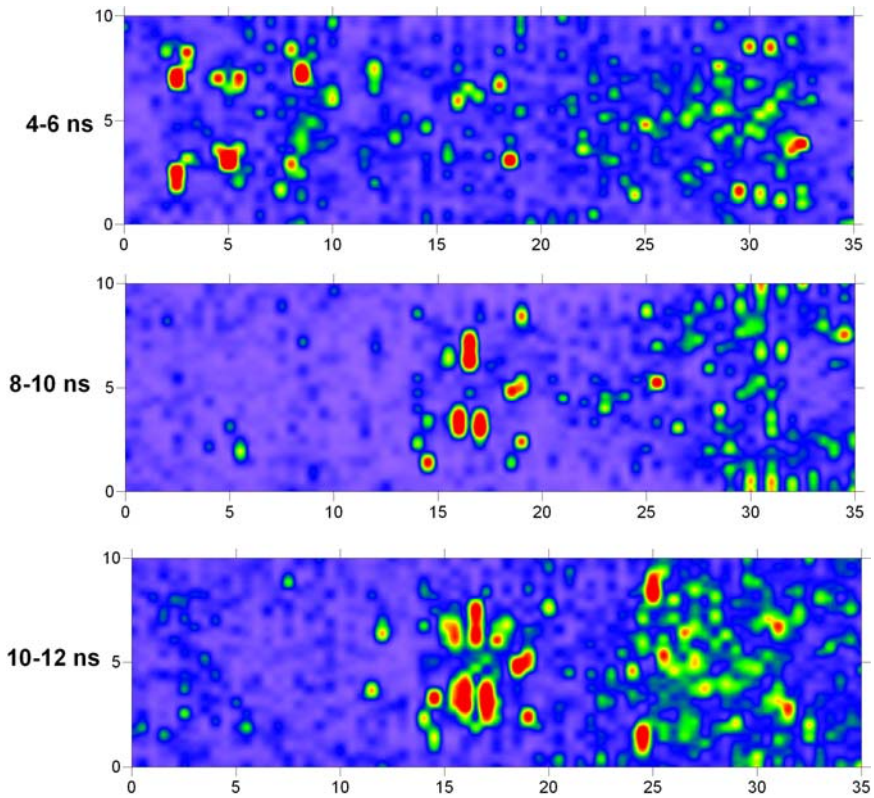

Figure 21: Hammer GPR amplitude maps using the 400 MHz antenna in dry conditions.

What was most significant at the Hammer test site experiments was the realization that water retention by buried wood would cause such a dramatic increase in visibility of those objects. Three large railroad ties were buried in the deepest portion of the test bed (Figure 20) and were invisible in the reflection data collected during dry conditions (Figure 21). In the wet data, however, the wooden artifacts were plainly visible, most likely because they had retained water much like a sponge (Figure 22). Because the soils were so sandy in this area, water quickly passed through the matrix and collected within the pores of the wood where it was retained. These objects therefore had a much greater velocity contrast at the interface of the wood with the surrounding sand, producing a high amplitude reflection. In dry conditions the interface between the wood and matrix produced a negligible velocity difference, and they were therefore not visible. Once again this study shows how the addition of water to the system produced very significant changes in the reflectivity of the radar energy (Conyers 2004).

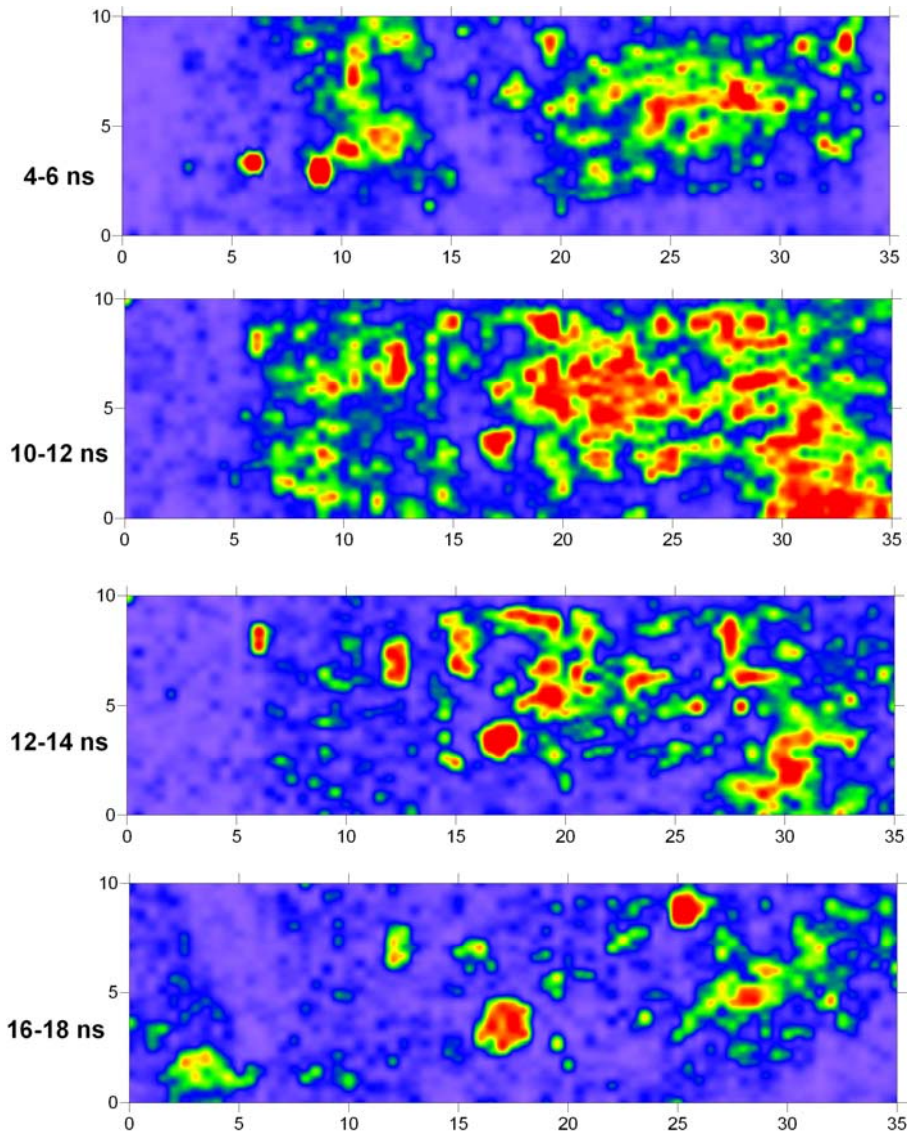

Figure 22: Hammer GPR amplitude maps using the 400 MHz antenna in wet conditions.

The difference between the resolution of the 400 and 900 MHz antennas was also significant, as even the smallest objects were visible in the 900 MHz data. Small objects such as a metal can, brick circles and foam bricks (why was this put in an archaeological test site I wonder?) were visible in the amplitude maps. Without a doubt, the higher resolution high frequency antennas were far superior in imaging small objects in this homogeneous sandy soil. This conclusion was never in question and has been documented elsewhere many times. The only aspect of the 900 MHz data that is partially detrimental was the fact that it sometimes produced reflection profiles that had "too high" a resolution. Therefore the 900 MHz data tended to be too cluttered, and reflections were recorded from even the smallest discontinuities in the sand matrix, which were not of archaeological origin. The conclusion here is that higher frequency antennas produce higher resolution data, but at the expense of being somewhat noisy because they record a higher degree of clutter. This was especially apparent in the 900 MHz wet data (Figure

23), which recorded every small pool of water that was retained at the contact with the underlying material.

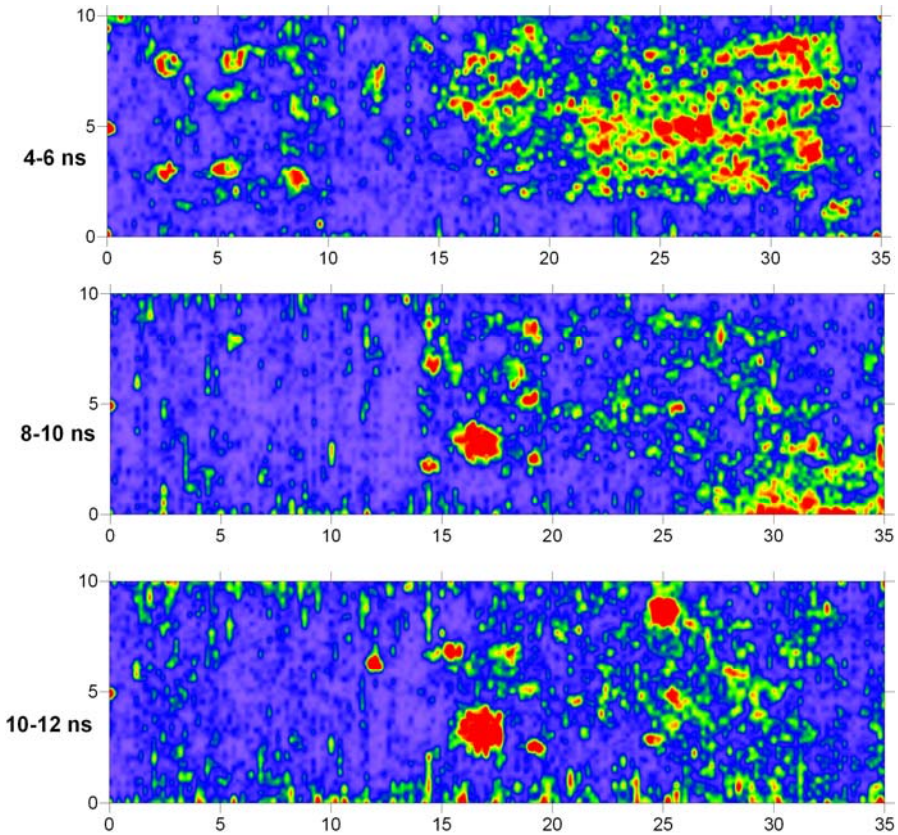

Figure 23: Hammer GPR amplitude maps using the 900 MHz antenna in wet conditions.

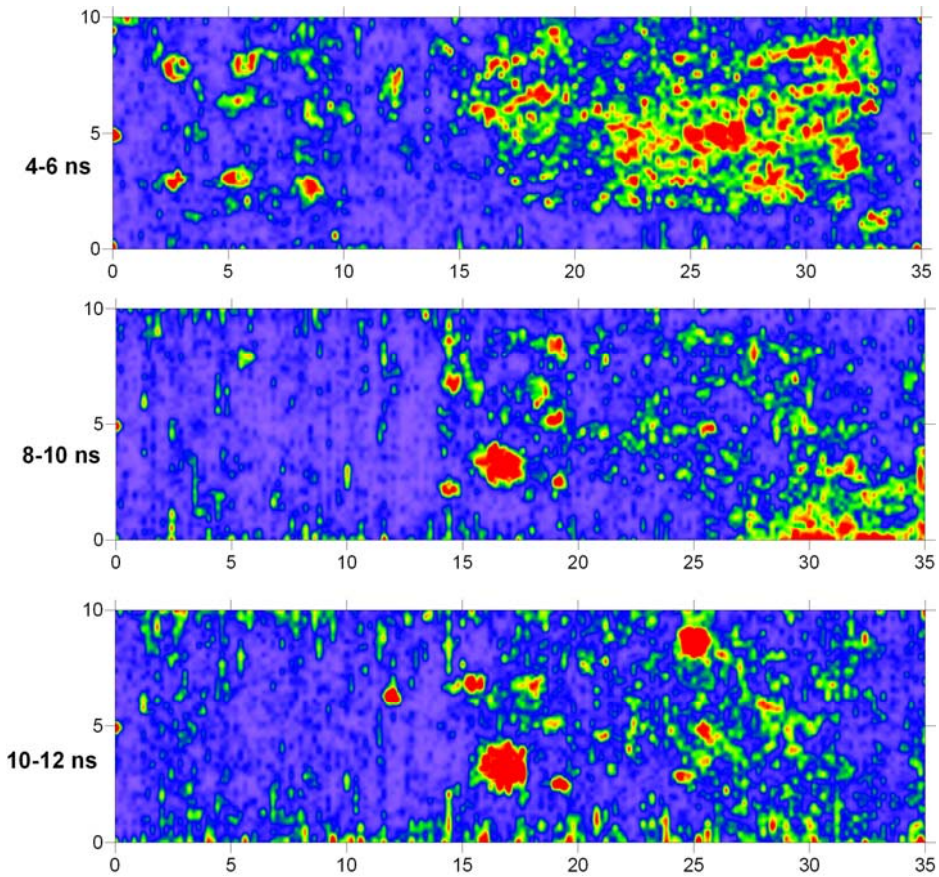

Figure 24: Hammer GPR amplitude maps using the 900 MHz antenna in dry conditions.

4.5 Hammer Spatial Statistical Correlations

The maps that appeared to produce the best image fit to the known features were then statistically visually compared to the known features in the ground. This statistical correlation was conducted for all antennas and all procedures, which produced what appeared to be even marginally good maps, for all environmental conditions. At Hammer the buried targets are almost all objects, many of which are metal or plastic. The few archaeological features that were constructed were made from the matrix material, and there was little discontinuity between the features and the burial material. For this reason there was little reflectance expected for those subtle features such as burial pits and earth ovens, and none was found in the radar reflections. The objects, however, were very visible. All appeared to have a very high coefficient of reflectivity, based on the high amplitudes of the reflections recorded from them. A detailed analysis of coefficients between objects and matrix, such as was performed for the CATS site was not conducted. It was instead decided to compare only the objects themselves and their shapes to the amplitude maps objects and shapes mapped. In this way a binary correlation could be obtained. Either the objects were there or not, in a very yes-no type of correlation. An analysis of each of these objects and their correlation is found in Table 2.

Two types of spatial correlation were then conducted at Hammer. One was a determination of where the reflections recorded by GPR were consistent with the model of the objects location and shape. A percentage of places in the grid where this correlation was found was then determined. The second correlation was where the model had a buried object in a known location and the GPR maps recorded one at that same location. The two are different in that the first correlation measures areas where if there are no buried materials, and none were found by GPR maps, then the correlation would be high. But, if there were many reflections recorded in places where there were no known objects, it would be low. This might yield a low correlation when there was a good deal of "clutter" recorded by GPR. The second correlation type performed here measures only the location where the model has a buried object, and there was a high amplitude reflection recorded. Clutter is therefore discounted in this correlation.

All 4 of the best amplitude maps from the two antennas in both wet and dry conditions were correlated in the above ways and each of the objects were tested against the model. This was done for all 3 depth levels in each of the grids, with GPR travel times converted to depth so that a direct comparison of object depth to reflection depth could be made.

The 400 MHz antenna produced good maps of the Hammer site, both when the ground was wet and dry (Figures 21 and 22). The shallowest depth slice, however, was only partially wetted by the sprinkler, and therefore there was an area, at the depth of the objects, which produced many high amplitude reflections (Figure 25). The water retained in the sandy soil therefore produced many anomalous reflections that did not correlate with known objects, lowering the overall statistical correlation. The same phenomena also occurred in the medium and deeper slices. Many of the shallow features, however, produced high amplitude reflections and were at least partially visible through the "water-clutter." One of the most exciting discoveries with this method was the good correlation in wet ground between the wooden features and the known locations of railroad ties in the deepest slice. This correlation occurred because the wood absorbed the water and therefore created a distinct velocity contrast at the interface with the surrounding sand. The wooden materials were not visible at all when the ground was dry (Figure 26), as discussed above.

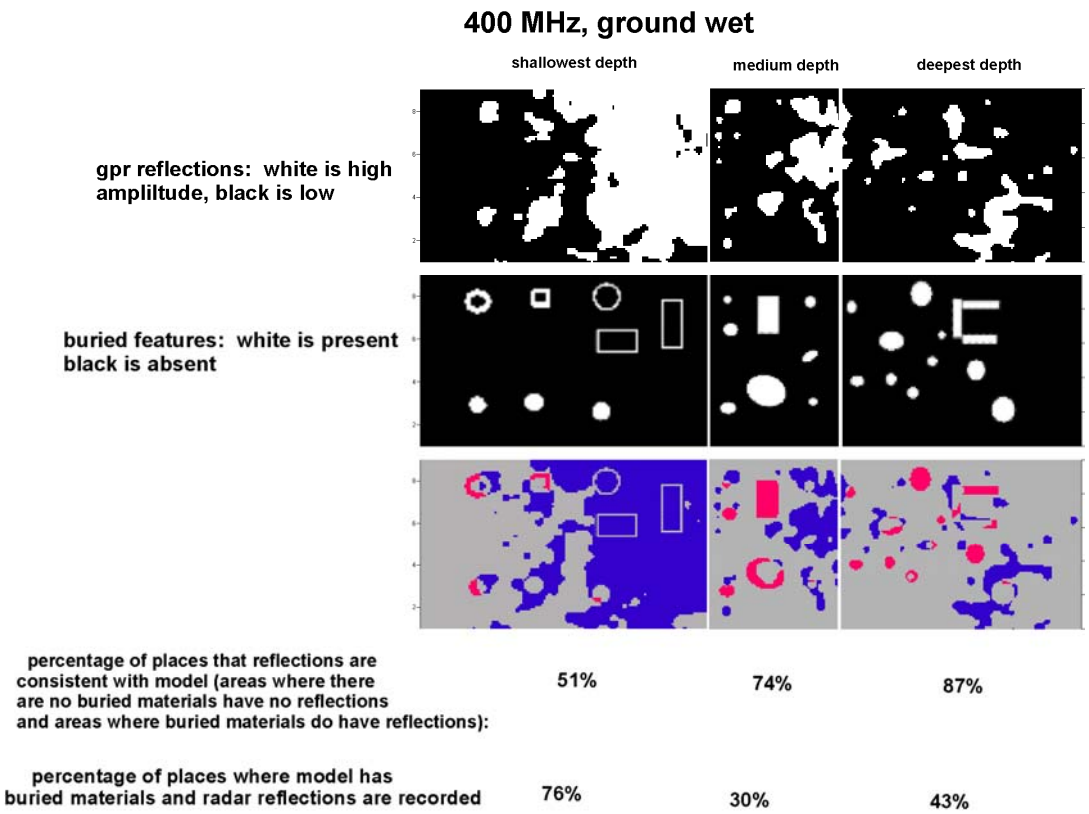

Figure 25: Correlations between radar reflections and modeled objects at three different depth levels. 400 MHz antenna data when the ground was wet.

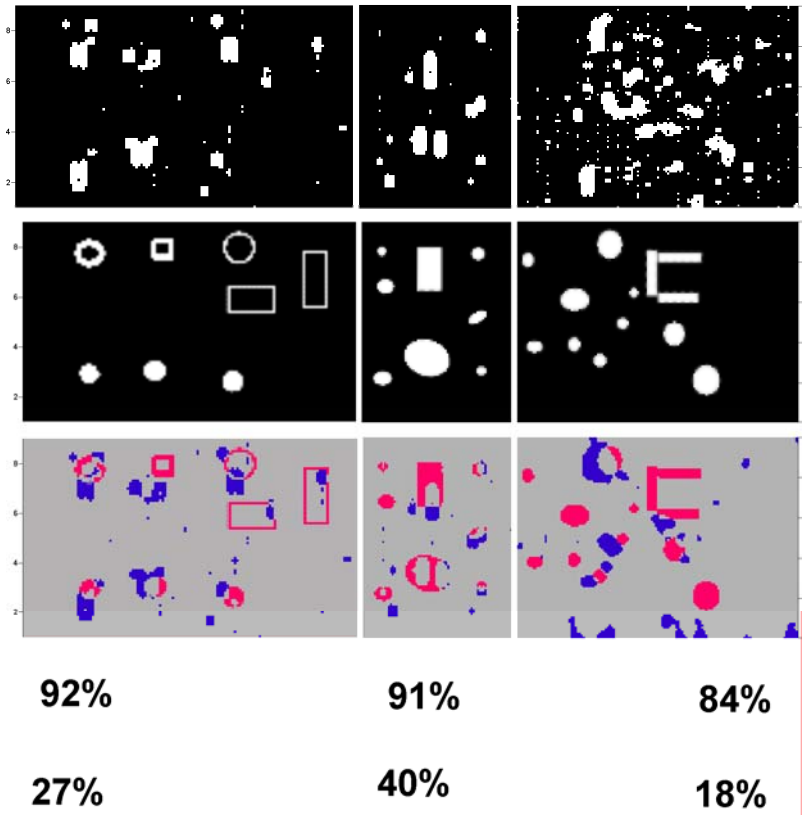

Figure 26: Correlations between radar reflections and modeled objects at three different depth levels. 400 MHz antenna data when the ground was dry.

The 400 MHz dry grids showed a generally good correlation between the buried features and the resulting GPR reflections. There was some misplacement of the reflections, however, because of the wide beam of the 400 MHz antenna. Reflections were therefore recorded before the antenna passed over the object, and again after it had moved away. The result was a "smearing" of the reflection to the south of their known locations, as the lines were collected in a north-south direction. It is not known why there was not a corresponding smear in the northern direction. This is a phenomenon has been noted at other sites, but not studied in detail, as there was no good subsurface confirmation. At Hammer the researchers now have the ability to study this, as they know the exact location and depth of these objects.

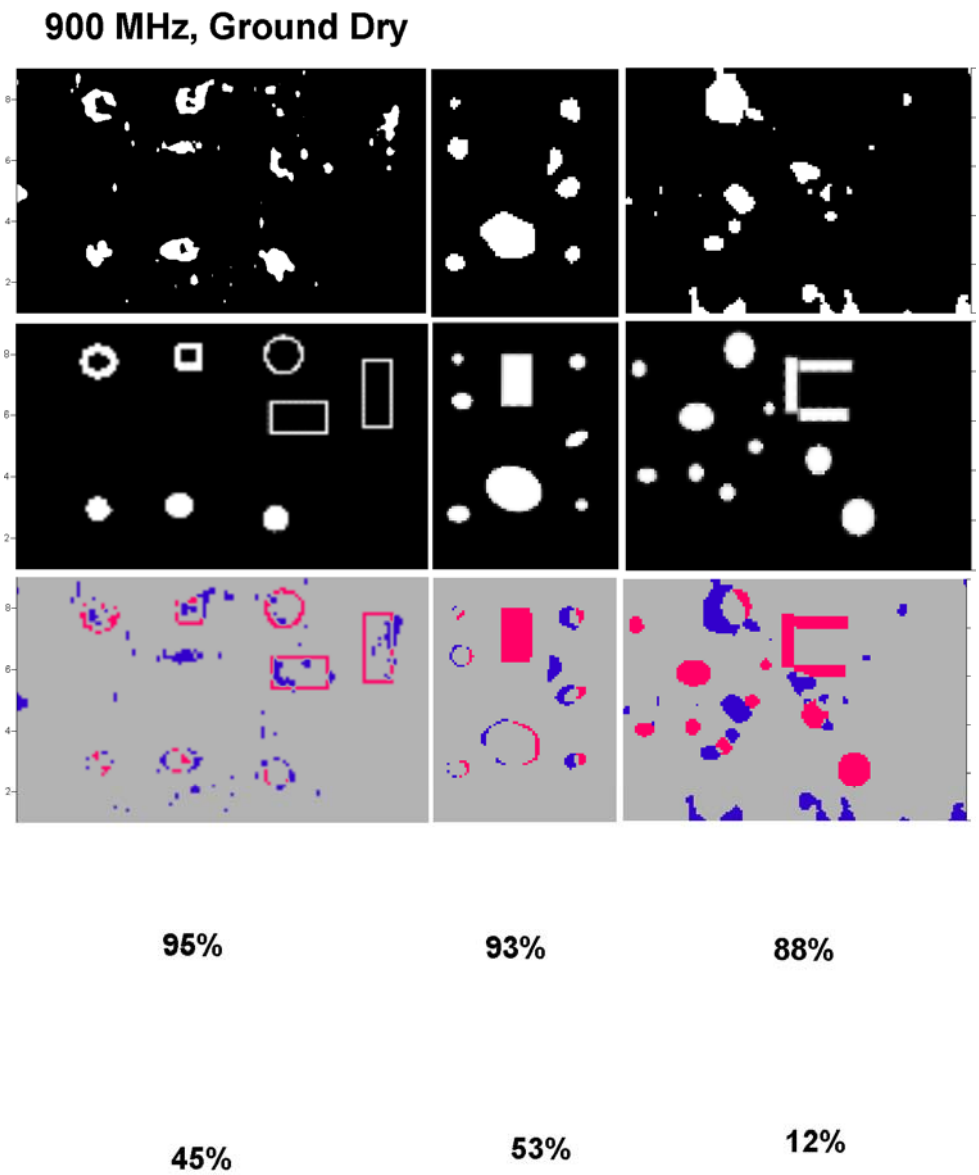

Figure 27: Correlations between radar reflections and modeled objects at three different depth levels. 900 MHz antenna data when the ground was dry.

The 900 MHz reflection data were far superior to the 400 MHz data in both wet and dry conditions. This frequency antenna produced a very clean signal that produced little energy spreading with depth. It also produced a much shorter wavelength, and the resulting resolution was also much higher. The small buried features such as rock rings, cairns and brick features were defined very well when the ground was dry (Figure 26 vs. 27). The same is generally true for the wet ground conditions for this same antenna (Figure 28), however the pooled water problem was still present, as discussed above for the 400 MHz antenna. The very subtle features that were constructed from sand and then covered by sand, such as the burials and earth ovens, were almost invisible in the 900 MHz data, whether in wet or dry conditions. This is probably because there was no velocity contrast between these constructed features and the burial material. In all cases they were all but invisible, as they were so subtle. The cans, trash midden deposits

containing a good amount of buried metal, and the plastic and metal objects were all well defined. As with the 400 MHz antenna in wet conditions (Figure 28), the 900 MHz data also imaged the buried wood when the ground was wet.

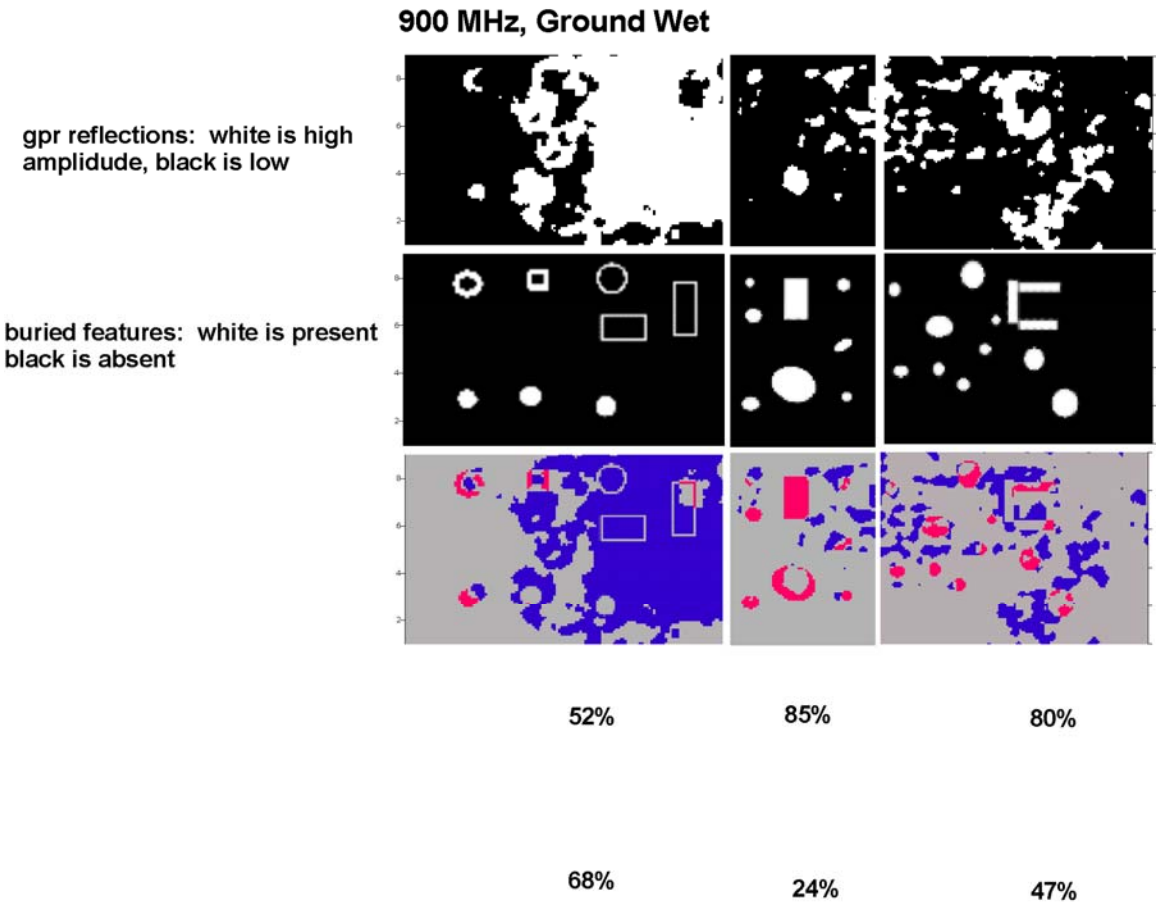

Figure 28: Correlations between radar reflections and modeled objects at three different depth levels. 900 MHz antenna data when the ground was wet.

In general the Hammer grids demonstrated a number of phenomena that were quite exciting. The dry soil data using both the 400 and 900 MHz antennas were good at imaging the metal and plastic objects, with the 900 maps producing superior images, as was expected. In all cases when sandy dry soils are mapped and velocities are high, as they were at Hammer, high contrast objects will reflect radar energy well and produce good amplitude maps of the buried materials. Even when the ground was wet, these maps were quite usable, although somewhat noisy because of the clutter produced by the pockets of water pooled at the buried interface that contained the objects. Most unusual was how well the buried wood showed up in the wet data, using both the 400 and 900 MHz antennas. These features were almost totally invisible in the dry soil data. This illustrates how wood can be almost invisible when the ground is dry (at least in sandy conditions), but very visible in wet conditions.

Table 2: Analysis of object identification with different antennas and conditions at the Hammer test site.

400 Wet	***400 Dry***	***900 Wet***	***900 Dry***	***Comments***
Good	Good	Good	Excellent	Visible in all grids, slightly shifted in 400 wet, 900 dry and 400 dry
Very Good	Good	Good	Excellent	Visible in all grids, spatially shifted in 400 Wet and Dry
Very Good	Good	Good	Excellent	Visible in all grids, shifted in 400MHz data
Excellent	Very Good	Excellent	Excellent	very apparent in all grids, spatially shifted in 400 Dry
Excellent	Very Good	Excellent	Excellent	Midden is very visible, shifted slightly in Dry
Very Good	Poor	Very Good	Poor	Dry Burials do not have the water retention to make them visible
Poor	Poor	Poor	Poor	Earth oven was not treated to cause greater reflectivity
Excellent	Very Good	Very Good	Very Good	slightly shifted in 900 Wet and Dry,
Good	Good	Good	Excellent	visible in Wet data but slightly shifted spatially
Good	Poor	Good	Excellent	visible in Wet data but slightly shifted spatially
Excellent	Very Good	Very Good	Very Good	Slightly shifted in Dry data, visible in all grids
Poor	Good	Good	Excellent	visible in all data, spatially shifted
Excellent	Very Good	Good	Very Good	900 Wet and Dry visible, shifted in 900 Dry and 400 Dry
Very Good	Very Good	Very Good	Excellent	In Wet data trash is more reflective in center and less so on periphery
Poor	Very Good	Very Good	Very Good	Generally very visible in each grid, appears shifted in 400 Wet
Good	Poor	Good	Poor	Visible in Wet but spatially shifted, not visible in dry
Good	Good	Very Good	Good	Rock ring appears shifted in 400 Wet and 900 Dry but is visible in all grids
Excellent	Poor	Excellent	Poor	Brick well is very apparent in wet data, not apparent in dry, bricks themselves may retain water
Very Good	Poor	Excellent	Poor	Railroad ties are very visible in Wet data, water is retained in the wood, not visible in Dry
Very Good	Poor	Good	Poor	is not apparent in Dry data, contents retain moisture
Poor	Poor	Poor	Poor	Pipe is not visible in wet data or dry data
Very Good	Good	Very good	Good	water is retained in foam in Wet, visible in Dry but shifted spatially
Poor	Poor	Poor	Poor	900 Wet stump is visible but off spatially, stump is not apparent in Dry
Poor	Poor	Good	Poor	Cache seems visible in 900 Wet, but spatially off, not visible in Dry, very small objects, may not be large enough to detect

4.6 Synthetic two-dimensional modeling

All profiles at CATS and Hammer were also compared to two-dimensional models produced on the computer. Models were constructed from data known about the conditions of burial, documented in the reports during site construction, and from our own laboratory measurements. Synthetic modeling using a computer was developed in an attempt to model buried objects, stratigraphy, and important reflection surfaces in two-dimensions (Goodman, 1994). Modeling can provide the interpreter with an idea of what real-world GPR reflection data "should look like" and will allow more accurate interpretation of GPR profiles once they are processed (Goodman 1994). It can also allow the interpreter to construct a model of the known stratigraphy and archaeological features prior to going to the field to determine if a GPR survey will be capable of delineating the features of interest. Once models are constructed, they can be quickly modified for different frequency antennas to determine the optimum equipment to take to the field. After GPR data have been acquired in the field and are processed, models can be readjusted to more accurately represent known field conditions. When used in this way they are a great benefit in interpretation, especially when features, whose origin are not immediately known, are visible in GPR profiles.

Computer-simulated radargrams are generated by tracing the theoretical paths of radar waves during transmission and reflection through various media with specific relative dielectric permittivities (RDPs), electrical conductivities and magnetic permeabilities (Goodman 1994). The two-dimensional geometry of the subsurface stratigraphy and archaeological features are programmed into the model to generate as close to a real-life case as possible. As is often the case, two-dimensional reflection profiles can look significantly different from how the buried structures would appear in cross section if viewed in the wall of a trench. Most importantly, they are not at all like images most of us are used to seeing such as those from x-rays or CT-scans in medical technology. One of the reasons for this is that GPR antennas transmit energy into the ground in a wide beam and therefore the antenna is not only looking straight down, but also in front, back, and to the sides. This modeling method allowed us to identify and spatially define the reflections produced in the ground from known features at both CATS and Hammer. In many cases this method was quite useful, as complex reflections were produced by objects and features whose geometry and orientation was different than expected.

As an illustration of this method, one of the midden features at Hammer was modeled using the synthetic method (Figure 29). These features were “built” on the computer in two-dimensions, using the known values for both the objects in the ground and the ground that covered them (Figure 30).

Figure 29: The large trash midden and a small burial pit at Hammer before burial. The midden pile contained wood, organic material and also metal objects. The burial pit was made to simulate an earth oven, but it was not actually burned. It was filled with material that was wood, metal and plastic, which was of a different composition than the back-fill materials.

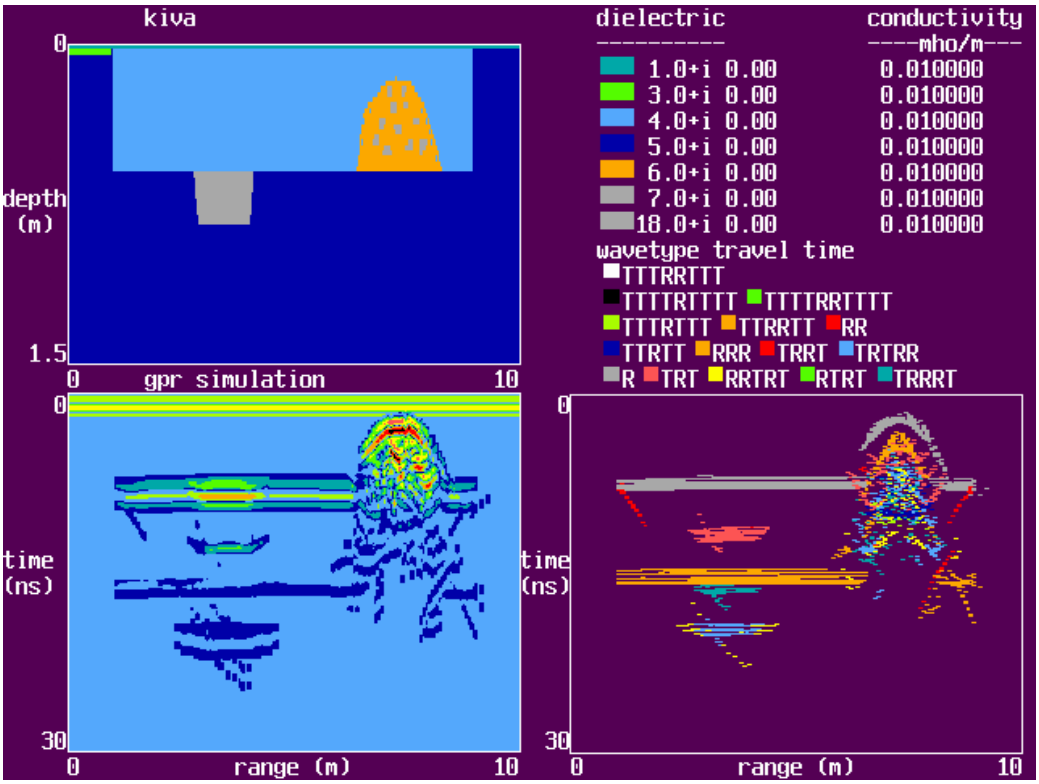

Figure 30: Synthetic model of the trash midden at Hammer.

The synthetic model suggests that the midden itself would be very visible as a series of high amplitude reflection hyperbolas, producing a “mound” like series of reflections. Only the highest RDP values, producing the highest coefficients of reflectivity, were creating the reflection anomaly visible in the actual profiles (Figure 31).

As modeled, the “floor” of the test bed, which was not at all different from the backfill material was essentially invisible (Figure 32). The “earth oven” of burial pit was also modeled to be very subtle, with only its base possibly visible, and that was also borne out in the actual profile crossing the feature (Figure 31). These types of analyses were done for most of the features at both CATS and Hammer, and helped a good deal in our final interpretations.

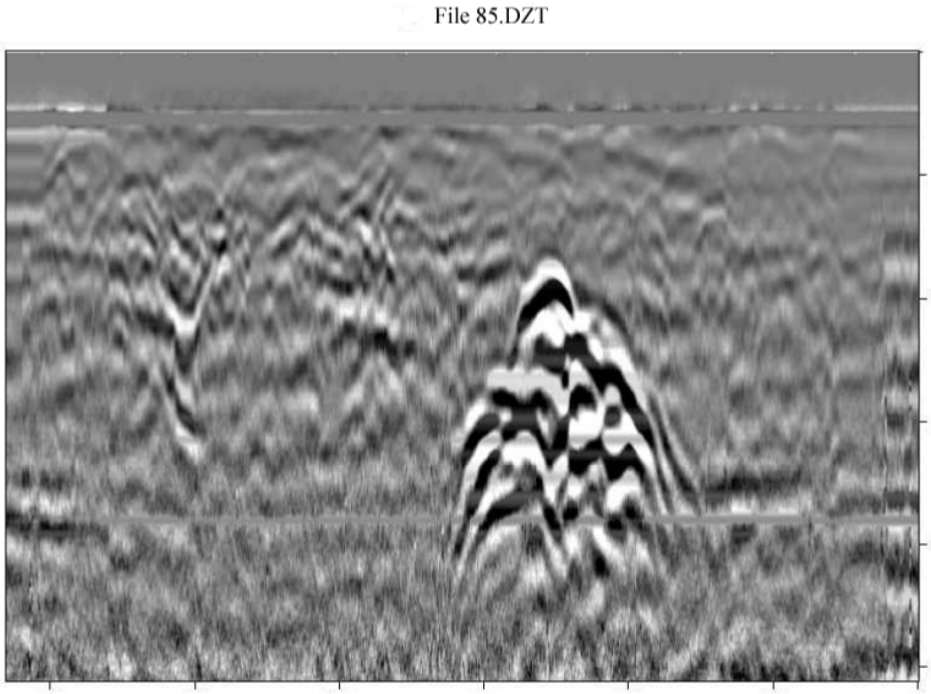

Figure 31: Actual GPR reflection across the trash midden, showing a good correlation with the synthetic model in Figure 29.

4.7 Laboratory Analysis of Samples

In order to have additional quantitative data with which to explain the results of the statistical correlations and the qualitative analyses of the produced images, laboratory analysis of the soil samples was conducted. In this process soil and sediment samples were collected using a hand auger at 20, 40 and 60 cm depths from both the CATS and Hammer sites. Samples were placed in plastic bags for storage, but not kept at exact ground conditions, as they had been partially disarticulated during collection and had already lost their in-place density and some of their retained moisture. Samples were therefore artificially desiccated and then distilled water was added back to each, while the physical properties that affect radar travel and reflection were measured.

The samples were analyzed at the U.S. Geological Survey (USGS) Physics Laboratory in Lakewood, Colorado using a H.P. Network Analyzer, which was developed to collect RDPs of many different sample types including agricultural crops and manufactured materials. Network analyzers are also used to study the frequency spectra of electronic components and communications devices, but can be modified to test the physical properties of materials. They have been used to test the water content of

grain and other agricultural products as well as the density and purity of certain industrial materials.

For this study the network analyzer was used to determine the RDP of soil and sediment samples by measuring this property at various frequencies. Any one RDP value of a soil is nothing more than a way to measure electromagnetic velocity in that sample (Conyers and Goodman, 1997). It has long been known that network analyzers are a good measure of the physical properties of materials, but especially how those properties are affected by water (Saarenketo 1998). The HP network analyzer system used in this study was modified by Robert Horton and Ray Johnson from the USGS to measure soil samples by constructing a stainless steel cylinder in which soil can be placed and then electrically measured over a frequency range from 10 to 1500 MHz. In the samples tested, a range of electromagnetic frequencies are passed through the material and its response to that energy is then measured. This was done when the samples were totally dry, and when different amounts of distilled water were added. In all tests of this sort most soils samples are highly electrically dispersive, especially at frequencies below about 200 to 400 MHz (Saarenketo 1998) because water molecules more easily rotate and vibrate with the changing induced field. The tests can be very instructive though because the measurements show how water affects RDP, and specifically how different water saturations will change these calculations. These can tell much about the field conditions that reflect radar energy.

This measurement of RDP is especially important for this study because the amplitudes of reflected GPR waves from within the ground are a product of changes in radar wave velocity at buried interfaces - the greater a change in velocity at an interface, the higher the coefficient of reflectivity, and the greater the amplitude of the reflected wave. Because any one RDP value is really a way to measure radar velocity in that specific soil or sediment unit, an analysis of changes in RDP of different materials in the ground can be used to determine whether buried materials will generate higher or lower amplitude reflections at their interfaces. In all the amplitude maps generated as part of this project, this is precisely what is being imaged: changes in amplitude as a result of differences in RDP in the ground.

The laboratory procedure used to analyze these samples was that detailed by Saarenketo (1998). The RDP of each sample was measured for each sample after they had been totally desiccated in a high temperature oven over night, and when certain amounts of distilled water were added. The total sample size placed in the test cylinder was 13 cubic centimeters. To each sample 0.5 cc of water was added and allowed to filter into the sample for a certain amount of time, varying from between 0.5 hours and 12 hours. They were then measured in the network analyzer and the RDP was measured at a large range of frequencies. Additional water was again added, and allowed to filter in for some additional time, and then measured again. All data were then plotted on a graph for visual interpretation (Figure 32).

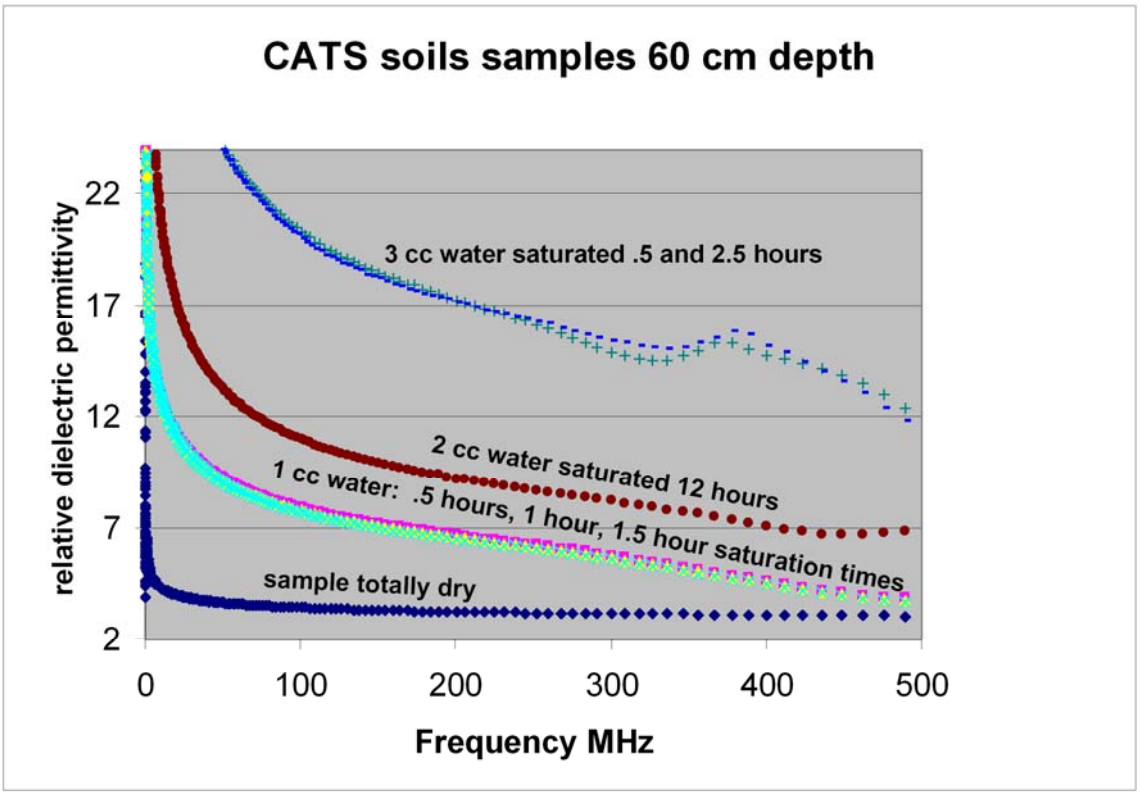

Figure 32: Analysis of the sample from 60 cm depth at CATS derived from the HP Network Analyzer.

What was most amazing about all the samples analyzed in this fashion was that all had an RDP of between 3 and 5 when dry, irrespective of whether they were clay, sand or silt. Even more exciting was the realization that it was only the amount of water placed in the sample that was important, not the amount of time it was allowed to filter into the material. This was the case for *all* samples studied at both CATS and Hammer. Water, and specifically the amount of water in a sample, therefore appears to be the determining factor in RDP measurements. These results mimic those reported by Saarenketo (1997) in his analysis of different clays from Texas, but in his study it was the variations in RDP with the soil layers in the ground that were noted, not their total water saturation. He also studied the degree of compaction in soils and noticed how soil structure affected water saturation, which then affected RDP measurements.

The implications of our soil data are very significant, in that almost all dry soil, or sediment, and probably even bedrock, were found to have an RDP of about 4. It is only when those materials become water saturated that they change their radar reflective properties significantly. Most importantly, it is only the ability of those soils to hold water and the distribution of that water in a gross sense that appears to matter. For instance, very dry soils will have little contrast in RDP along bedding planes or other interfaces, as they hold little water, and therefore offer no contrast with which to reflect radar energy. In other words their coefficient of reflectivity is very low. If one of those buried materials has the ability to hold water, meaning it is less permeable perhaps or has the ability to pool water on a horizontal surface, and the other material can “shed” the water faster, then the unit with the water will create a high amplitude reflection.

These laboratory analyses have allowed us to look at radar reflections in a very different way, especially in the interpretation of those amplitudes in three-dimensions. The "old" idea that higher amplitudes are caused by reflection off of different materials is correct only in so far as it is the way that those materials hold or distribute water that matters. In the future more attention must be paid to what water "does" in the ground: how it is retained by some materials, incorporated into the molecular structure of others and drained, or equally distributed in some. The importance of water distribution is especially important when analyzing the difference between reflection amplitudes in data sets collected in wet, dry, and even frozen conditions.

This realization concerning the dominance of water in the generation of radar reflection amplitudes helped us a great deal in our interpretation of the amplitude slice maps at the Hammer site (Conyers 2004). At this site the buried wooden artifacts were not visible at all in the profiles or amplitude slices when the ground was dry. As soon as the ground was wetted, however, those features became immediately visible because the buried wood had absorbed water in its pore spaces, and it was the water that was being imaged, not the wood *per se*. Apparently when the ground was dry, there was very little velocity contrast between the wood and the surrounding sandy soil and therefore no reflection amplitudes of any significance were generated. There are many other possible conclusions that can be drawn from these important laboratory and field discoveries, which the reseachers will be working on in the coming months.

Another aspect of the laboratory work on the soil and sediment samples was the x-ray diffraction analyses. These were undertaken in order to determine the nature of the clays that were present at both sites. Some types of clays are very electrically conductive, especially when wet, while others are much less so. The conductivity of different types of buried clays can be measured by their cation exchange capacity, which is a function of the number of ions adsorbed to the surface of each clay mineral that can be mobilized when an electrical current is placed upon them. When clay minerals with a certain structure are immersed in water the adsorbed ions will partially dissociate themselves from the clay mineral surfaces and become available for this ionic conductivity, which is how an electrical current flows. The ion capacity of a clay is proportional to the surface area of their minerals on an atomic level, and therefore more complex clays with greater numbers of layers such as montmorillionite and smectite are more conductive while simpler clays with fewer layers such as kaolointe and illite are less conductive. This is very important when attempting to understand radar transmission and attenuation in the ground because the higher the conductivity, the faster the electrical component of an electromagnetic wave will be lost with transmission. The shallower the radar energy attenuates in the ground, the shallower the depth of potential investigation will occur, no matter what the frequency of the antenna.

It has always been assumed that wet clays are extremely poor mediums for radar energy penetration, and that dry sand is the best. Therefore, the researchers were greatly surprised during their data collection at CATS, immediately after the torrential rainstorm, when they got very good energy penetration to far below the depth of the buried features. The CATS site is well known as a very clay-rich area, but our x-ray diffraction analyses of the soil samples showed little if any clay in the samples, with only hints of illite and kaolinite (Figure 33)! The researchers were expecting very high amounts of montmorillionite and smectite, which are common pedogenic clay minerals in the

American Midwest. The only significant constituent discovered in the tests at CATS was quartz. It was only after the results of these analyses that considered the possibility that the soils at CATS were not composed of mineralogic clays, which are those that are the produce of weathering in place of a parent material. After consulting the regional surface geology map of the Champaign-Urbana Illinois area where CATS is located, it was seen that surface soils are formed directly on the Drummer silty clay loam (Isaacson et al 1999). This unit is described by the Illinois State Soil Classification Association as a ***very deep, poorly drained soil that formed in 40 to 60 inches loess or silty material and in the underlying loamy stratified outwash. Drummer soils are found on nearly level or depressional parts of outwash plains, stream terraces and till plains*** (http://www.illinoissoils.org/statesoil.htm).

This soil is formed on what was a wind-blown layer deposited during the late Pleistocene. The soils at CATS are therefore clay-rich, but these clays are primarily clastic clays, meaning they are composed of quartz and perhaps other very small rock fragments that are of clay size, but are not actually composed of clay minerals.

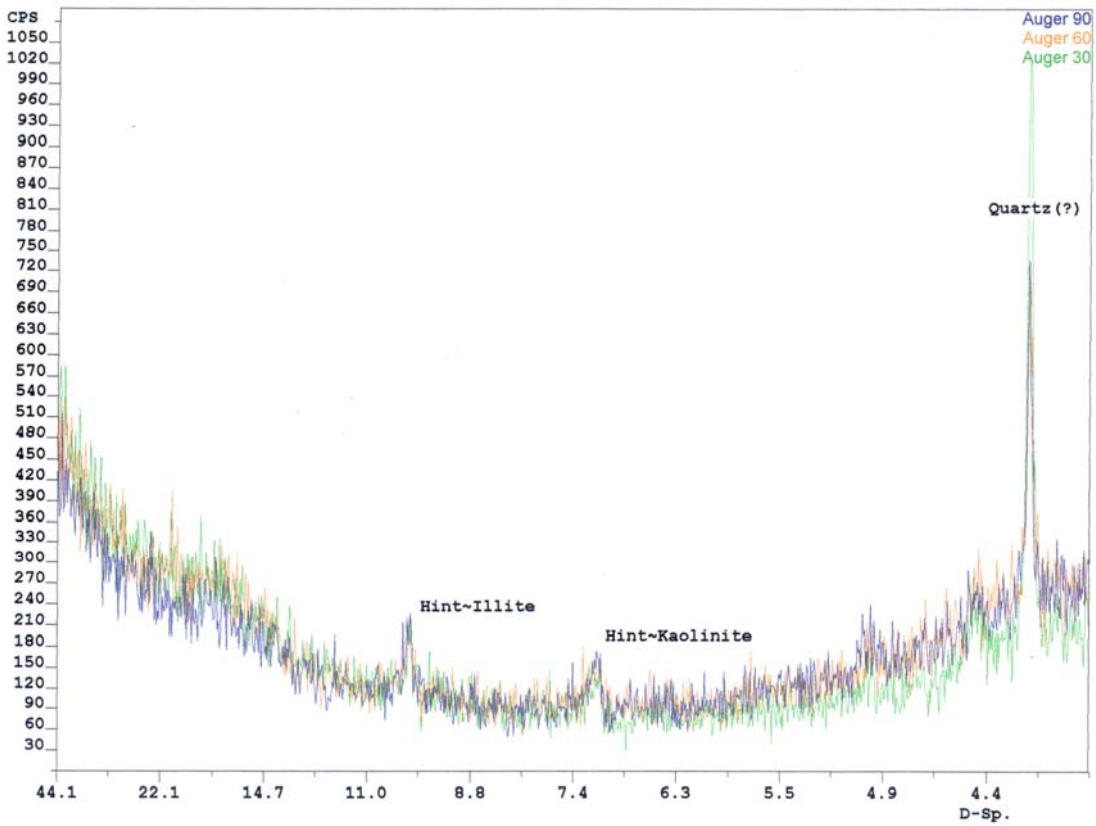

Figure 33: X-ray diffraction test of three soils samples from the CATS site. There is little mineralogic clay, but a high percentage of quartz in the soil.

This discovery then poses the obvious question of how one would determine if clays at a site where GPR data are to be collected are pedogenic or clastic. Apparently the archaeologists that built the CATS facility considered “clays” to be “clays” no matter whether they are mineralogic clays or just units composed of clay-sized particles. This

project's principal investigator suspects this is a common mistake in all fields, not just archaeology, as there is no ready way to determine clay types without laboratory analyses. The importance of understanding what types of clay are present is highlighted by our work at CATS. If an area has a high degree of mineralogic clay, especially montmorillionite or bentonite, much if not all of the radar energy transmitted into the ground will be lost by attenuation at a very shallow depth, especially if the clay is wet or even moist. But if the clay is a clastic unit, composed of just clay size quartz and rock fragments, it will appear to be clay, but still have excellent radar transmission properties.

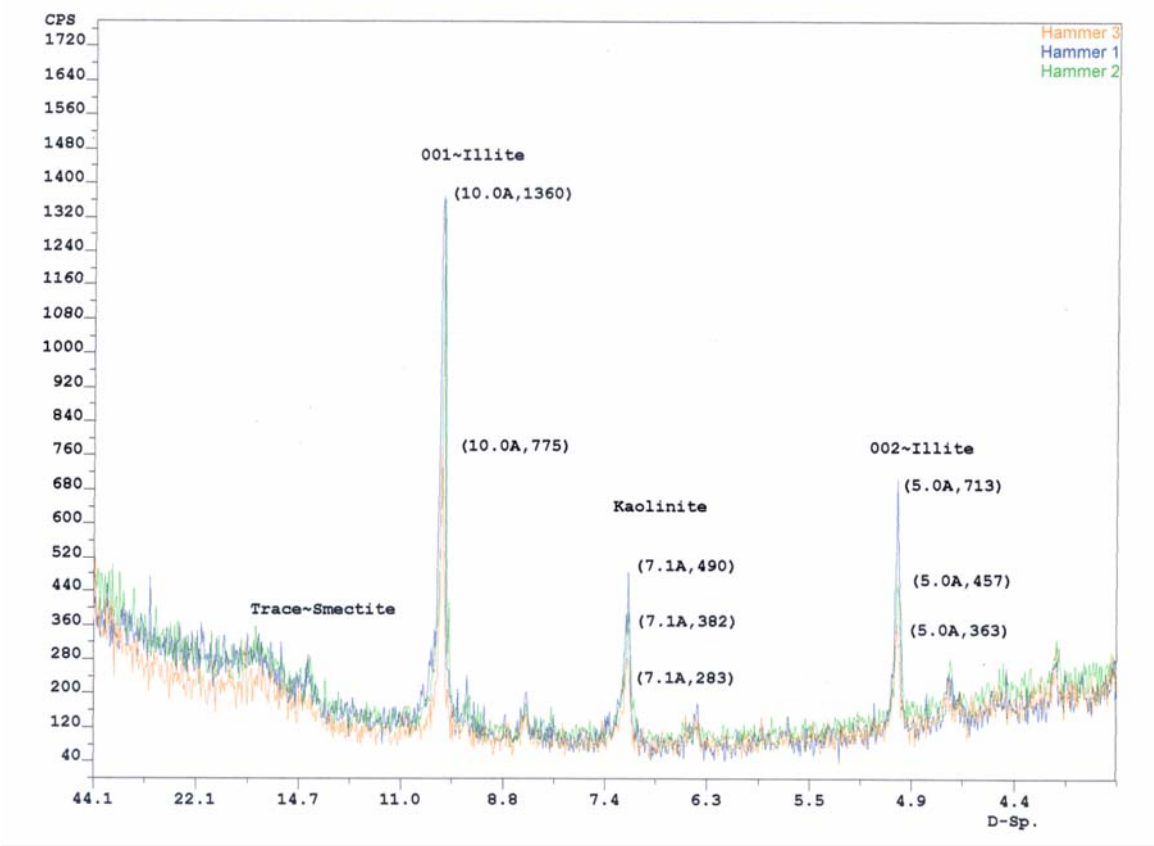

Figure 34: X-ray diffraction analysis of the samples from Hammer site. Even though soils in this area are described as sandy, they have some illite and kaolonite clays.

Similar x-ray diffraction tests were conducted at Hammer, and small amounts of illite and kaolonite clays were found, but apparently not enough to have interfered with the radar energy transmission or reflections in the ground (Figure 34). These clay minerals are probably distributed throughout the sandy soil in such a way that an electrical current has very little pathway with which to travel, and therefore there was little conductivity of the electrical component of the radar signal. Also illite and kaolonite are the less conductive of the clays, even when wet. It therefore appears that in this sandy area the amount of dry sand far outweighs the dispersed and less conductive clay in the ground, and overall the material still allows excellent radar transmission to the necessary depth.

In a general sense our research to date has developed procedures for data collection and processing that should be used for most archaeological sites in most shallow conditions, whether dry, wet, sandy, or clay-rich. These procedures are that a maximum number of profiles should be collected with as close a spacing as possible. Our tests have shown that for a 400 MHz antenna, a line spacing of 50 cm is good, and 25 cm is even better. Often the lowest spacing is not possible because of time or financial constraints, but the resulting maps from those fine-grained surveys will be far superior to the ones performed with a greater spacing. Efforts should therefore be made to collect a maximum amount of data possible, at least over known or suspected buried features. If little or nothing is known about ground conditions in advance, a greater transect spacing may be necessary to collect as large a grid as possible as a "first pass" with subsequent in-filling at a later date for greater resolution.

The investigators found that the Geophysical Survey System Inc. (GSSI) antennas and system produced maps that were far superior to those produced by the Sensors and Software (S&S) systems. Upon reflection, however, the S&S data were collected in a different way than the GSSI, with a greater stacking of traces and a resulting "smoothing" of the data along transects. In both the CATS and Hammer areas, this smoothing lowered the ultimate resolution of the amplitude maps, and produced much less well defined reflections. It may not therefore have been a "fair test" between the two systems, as both collection and system differences were being tested. Instead it may have just turned out that the collection procedures with the GSSI, where traces were not stacked, proved superior.

The amplitude slice-maps produced by the software developed as part of this project, however, produced far superior images than those prepared by the S&S software designed for their reflection data. Again, this may have been a function of the inherently poor S&S data caused by our chosen collection parameters. The result was that only the GSSI data were used in the final spatial statistical models, as the maps from those reflection datasets were far superior.

Some reflection data were collected at CATS using the 300 MHz antennas, which was almost totally unusable. This is because the buried features were much too shallow for those antennas, and much of the energy had not yet coupled with the ground when it encountered the reflection surfaces of interest. Only a minor amount of it was therefore reflected back to the surface and recorded. Amplitude maps created from the 300 MHz antennas showed that the edges of the burned floor at CATS was possibly visible, but little else. These antennas were therefore not used at Hammer, as depth was comparable to the CATS site.

The best quality maps were produced by removing the background noise as well as collapsing the reflection hyperbola tails to their sources. In all cases, this should be done prior to amplitude slicing procedures at most sites. The two-dimensional synthetic models illustrated to us how dramatic the energy spreading was for some of the buried materials, especially those at the Hammer site. This hyperbola removal was therefore preferable for all data.

In the slicing procedure a very small search radius along the transect line (but not between lines) was also preferable, as a small interpolation radius created maximum definition of buried features. A 10 cm or less interpolation of reflection traces sometimes created a very "busy" series of reflection amplitudes in the raw sliced data, but these

could be smoothed and interpolated in later mapping steps for better feature resolution. Amplitude data were created during processing by interpolating only "along the transects" in a very tight spacing, with a comparison of trace amplitudes within 10 cm or less of each other in the same profile. In this way there were no "false points" created between lines, which would have tended to smooth and possibly remove important high or low reflections throughout the grids.

Amplitude data from the slicing software were then imported to *Surfer 8* for interpolation and image map creation. Our initial attempts to use GIS software such as *Idrisi* for this procedure were found to produce very inferior maps when compared to Surfer, and were quickly abandoned. *Idrisi* was chosen because it was hoped its statistical analysis software would allow us to immediately test our amplitude maps with the modeled features. Those attempts were also quickly abandoned, as easier ways were found to produce the statistical correlations using *Surfer* and *Excel* spreadsheets. It was found that models could be created in *Idrisi* and these bitmaps could be easily imported into Surfer and gridded. Those grid maps could then be directly compared to the grid maps used to create the GPR image maps, and a direct correlation could be made between z values, when the x and y values of the two maps were identical. In this way a direct correlation coefficient (R^2 value) could be calculated in an *Excel* spreadsheet, which proved to be a very efficient and accurate way to test the correlations.

The laboratory data processing spatial statistical analyses preformed at the two test sites has led to some very interesting conclusions not documented before in the GPR literature. All these conclusions allowed us to produce very accurate models in *Idrisi* for comparison to the GPR image maps. What was most exciting about the laboratory analyses was that all samples from both sites, one being clay and the other sand, had exactly the same relative dielectric permittivity (RDP) when totally dry. Similar measurements have since been done on other ground materials from other sites in the U.S. and found exactly the same thing. When the samples were wetted, however, they reacted in very different ways, depending on how the water was bound to the material. The clay samples at CATS showed a very dramatic increase in RDP with added water. The time at which the water was let to soak into the samples did not apparently matter, as these dry samples quickly absorbed the moisture into their structure. Similar measurements were made with the sandier materials at Hammer, but in this case the water was more likely retained in the sand-sand grain interstitials or within the clay that was part of the material matrix. But even with this very different soil material at Hammer it was noticed the same dramatic increase in RDP with amount of water added.

These measurements suggest that water and how it is held and distributed is the dominant factor in RDP in the ground, and therefore controls the amplitude of reflected radar waves. Differences in RDP at contacts between units in the ground that are different in some way is what creates reflections, with the greater the difference, the greater the resulting radar wave amplitude. The difference between dry and wet conditions at both CATS and Hammer were therefore better understood knowing their water saturations and especially determining how that water was retained in the ground. At CATS the burned clay floor was extremely visible in wet conditions, but almost invisible when the ground was dry. The more subtle clay features of the other floors (and to some extent the burned floor) were much more visible in dry conditions. This is likely because the non-burned floors were moderately compacted and therefore somewhat

different than the materials placed on top of them, and could potentially be resolved with reflected radar waves if the recorded reflections were "gained up" enough during collection. In the wet conditions, the added water apparently made these subtle differences in ground conditions even less distinct, and the non-burned floors were completely invisible, as there was little velocity contrast in the ground.

Similar distinct differences were found at Hammer when the dry and wet amplitude maps were compared. The wet conditions at Hammer created large pools of water at the contact between the back-fill sand and the underlying, more compacted sand. This produced a very "noisy" and therefore cluttered data set at the horizon where the artifacts were placed. These buried objects were still somewhat visible in the wet data, but more obscured by the water reflections. The differences in water absorption, and how it created differences in radar reflection amplitude and distribution between the two sites still remains somewhat obscure. For instance, it is still not understood why the water was apparently more uniformly absorbed in the CATS clay when very wet, thus creating few extraneous signals. At CATS the data is "noisier" in dry conditions than in wet, which is counterintuitive. At Hammer the exact opposite occurred and the wet data produced a great deal more random reflections, apparently from the pooled water. It would have expected the sand to have drained better than the clay, but this was apparently not the case. Intuitively it would seem that the sandy soils would have greater permeability, and therefore allow the water to percolate downward more evenly, creating less water clutter in the overlying burial material. It would also intuitively seem that the opposite would occur in the clay soils, as found at CATS. But the exact opposite was found to be happening, with the wet CATS data producing less cluttered reflections. This problem needs to be studied further, but the conclusions of these experiments are fascinating, important, and not described before in the GPR literature.

Another exciting conclusion related to water and its importance for GPR was discovered with the buried wood objects at Hammer. They were totally invisible in reflections collected during the dry conditions, but very visible after water was introduced, probably because the wood had absorbed water, creating a velocity contrast at its contact with the overlying sand. Again, the importance of water was shown dramatically in these tests (Conyers 2004).

At Hammer the buried metal and plastic objects were visible in both wet and dry conditions, but were somewhat more visible when the ground was dry, which was expected. Unfortunately the Hammer site had a number of other buried features built to simulate archaeological materials, but they do not contrast enough with the surrounding material to be visible. This in itself demonstrates that there may always be buried materials in the ground that are essentially invisible to GPR if they do not have enough velocity contrast with the surrounding material.

As with most research projects of this sort, they tend to foster many new areas of inquiry that were not even contemplated at the outset. The importance of water in the ground, and its ability to enhance or diminish radar reflections has always been understood but perhaps not fully appreciated. This study, however, has shown in very dramatic ways how water may be **the** dominant factor in radar reflection (Conyers 2004). Most importantly how that water is retained and distributed is what really matters in GPR studies. With the data we already have it will be possible to compare how that water is distributed in the more subtle features at Hammer, such as the burials and "earth oven."

It is possible that those very subtle features may be more or less visible in these differing conditions. This comparison has not yet been done because the nearby metal, brick, and stone objects have "overwhelmed" the data set. We plan to take the same reflections and factor out the highest amplitude ones first, leaving only the most subtle reflection amplitudes that were likely recorded from these features. This dataset will then be compared and contrasted to see if these features show up during data processing. In addition it will be important to see how the water is retained and distributed by the more distinct features, which is now possible by having the two datasets. These comparisons can also be done using two different frequency antennas, and we have the data set available to make these comparisons.

As an adjunct to the important discoveries made with respect to the water at both sites, it will also be important to study in greater depth the clay type and conductivities at each site. It was found that the clay at CATS was not mineralogic clay but only rock "flour" that happened to be of clay size. More mineralogic clay was found at the Hammer site than at CATS, but here it does not apparently play a role in radar reflection or attenuation. I suspect, however, that different clay types, their mineralogy, and most important conductivity, plays a very important role, especially with regard to how radar energy travels and is reflected. For instance, bentonite clay when dry probably produces very different reflection properties than if they were wet, as they are known "swelling" clays. An interesting question, which is very important for all GPR data collected in clay areas, is therefore what types of clay produce what types of GPR data, and how those change with moisture content. This study can only pose a number of interesting hypotheses regarding this important phenomenon, and further controlled field and laboratory tests will be necessary to begin to test these hypotheses.

The topographically corrected data at the CATS pig burial site will be compared to the non-corrected reflections to see if our processing method produces better images. If it does, then quick processing steps will be developed so that all reflection data collected on topographically complex surfaces can be immediately corrected and processed. In a similar study we have collected reflection transects within grids that are perpendicular to each other, and so far have only processed the data in profiles that are parallel. Now that we have easy ways to compare these to the known features, and to each other, we can study how profile orientation might relate to feature definition. This can be done in the future by other studies at both the CATS and Hammer sites.

Finally, some of the data at Hammer still needs to be reprocessed to remove more of the reflection hyperbola tails by migrating them back to their sources. This will be done using a number of different methods in the hope of removing some of the "smearing" that was apparent, especially in the 400 MHz data. These processed maps will then be re-compared to the known buried features to determine how effective this step is in producing "crisp" images of the ground.

5. CONCLUSIONS

In a general sense our research to date has developed procedures for data collection and processing that should be used for most archaeological sites in most shallow conditions, whether dry, wet, sandy, or clay-rich. Archaeological sites occur in a variety of environmental settings, with various soils and sediments. Most sites, however, occur at a fairly shallow depth, probably within 2 meters of the subsurface. These procedures are that a maximum number of profiles should be collected with as close a spacing as possible. Our tests have shown that for a 400 MHz antenna, a line spacing of 50 cm is good, and 25 cm is even better. Often the lowest spacing is not possible because of time or financial constraints, but the resulting maps from those fine-grained surveys will be far superior to the ones performed with a greater spacing. Efforts should therefore be made to collect a maximum amount of data possible, at least over known or suspected buried features. If little or nothing is known about ground conditions in advance, a greater transect spacing may be necessary to collect as large a grid as possible as a "first pass" with subsequent in-filling at a later date for greater resolution.

The Geophysical Survey System Inc. (GSSI) antennas and system-produced maps were far superior to those produced by the Sensors and Software (S&S) systems. Upon reflection, however, the S&S data were collected in a different way than the GSSI, with a greater stacking of traces and a resulting "smoothing" of the data along transects. In both the CATS and Hammer areas, this smoothing lowered the ultimate resolution of the amplitude maps, and produced much less well-defined reflections. It may not therefore have been a "fair test" between the two systems, as we were trying to test both collection and system differences. Instead it may have just turned out that the collection procedures with the GSSI, where traces were not stacked, proved superior.

The amplitude slice-maps produced by the software developed as part of this project, however, produced far superior images than those prepared by the S&S software designed for their reflection data. Again, this may have been a function of the inherently poor S&S data caused by our chosen collection parameters. The result was that only the GSSI data were used in the final spatial statistical models, as the maps from those reflection datasets were far superior.

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The laboratory data processing spatial statistical analyses performed at the two test sites has led to some very interesting conclusions not documented before in the GPR literature. All these conclusions allowed us to produce very accurate models in *Idrisi* for comparison to the GPR image maps. What was most exciting about the laboratory analyses was that all samples from both sites, one being clay and the other sand, had exactly the same RDP when totally dry. We have since done similar measurements on other ground materials from other sites in the U.S. and found exactly the same thing. When the samples were wetted, however, they reacted in very different ways, depending on how the water was bound to the material. The clay samples at CATS showed a very dramatic increase in RDP with added water. The time at which the water was let to soak into the samples did not apparently matter, as these dry samples quickly absorbed the moisture into their structure. Similar measurements were made with the sandier materials at Hammer, but in this case the water was more likely retained in the sand-sand grain interstitials or within the clay that was part of the material matrix. But even with this very different soil material at Hammer we noticed the same dramatic increase in RDP with amount of water added.

These measurements suggest that water and how it is held and distributed is the dominant factor in RDP in the ground, and therefore controls the amplitude of reflected radar waves (Conyers 2004b). Differences in RDP at contacts between units in the ground that are different in some way are what create reflections, with the greater the difference, the greater the resulting radar wave amplitude. The difference between dry and wet conditions at both CATS and Hammer were therefore better understood knowing their water saturations and especially determining how that water was retained in the

ground. At CATS the burned clay floor was extremely visible in wet conditions, but almost invisible when the ground was dry. The more subtle clay features of the other floors (and to some extent the burned floor) were much more visible in dry conditions. This is likely because the non-burned floors were moderately compacted and therefore somewhat different than the materials placed on top of them, and could potentially be resolved with reflected radar waves if the recorded reflections were "gained up" enough during collection. In the wet conditions, the added water apparently made these subtle differences in ground conditions even less distinct, and the non-burned floors were completely invisible, as there was little velocity contrast in the ground.

Similar distinct differences were found at Hammer when the dry and wet amplitude maps were compared. The wet conditions at Hammer created large pools of water at the contact between the back-fill sand and the underlying, more compacted sand. This produced a very "noisy" and therefore cluttered data set at the horizon where the artifacts were placed. These buried objects were still somewhat visible in the wet data, but more obscured by the water reflections. The differences in water absorption, and how it created differences in radar reflection amplitude and distribution between the two sites, still remain somewhat obscure. For instance, we still don't understand why the water was apparently more uniformly absorbed in the CATS clay when very wet, thus creating few extraneous signals. At CATS the data is "noisier" in dry conditions than in wet, which is counterintuitive. At Hammer the exact opposite occurred and the wet data produced a great deal more random reflections, apparently from the pooled water. We would have expected the sand to have drained better than the clay, but this was apparently not the case. At this time we do not have a good explanation for this phenomenon observed in the GPR data. Intuitively it would seem that the sandy soils would have greater permeability, and therefore allow the water to percolate downward more evenly, creating less water clutter in the overlying burial material. It would also intuitively seem that the opposite would occur in the clay soils, as found at CATS. But the exact opposite was found to be happening, with the wet CATS data producing less cluttered reflections. This problem needs to be studied further, but the conclusions of these experiments are fascinating, important, and not described before in the GPR literature.

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6. PROCEDURES FOR SPECIFIC CONDITIONS

There are a number of variables to take into consideration before doing a GPR survey. The above descriptions can be considered good general guidelines for collecting and processing GPR data, regardless of specific environmental conditions or type of archaeological site. There are, however, a number of environmental factors that can greatly impact the success of a GPR survey. The number of combinations these geologic, climatic, and archaeological factors can occur in is nearly infinite. While the environmental aspects of a site are extremely important, the antenna frequency can also be a key component to a good survey. There are four primary geologic and environmental factors to take into consideration before doing a GPR survey. These include: moisture, soil type, clay mineralogy, and matrix stratigraphy. The primary consideration for antenna frequency involves these geologic conditions, as well as the desired depth for energy penetration and desired resolution of the buried features. We can begin to understand how to treat surveys in the most common environmental settings by developing more specific sets of procedures. To do this, it is necessary to understand how radar energy is transmitted and reflected in different particular combinations of field settings.

It is important to remember that the cultural remains of most archaeological sites occur at a fairly shallow depth, usually within 2 meters of the ground surface. The collection parameters that have been developed as preferential for mapping buried cultural remains are therefore described with this in mind. For example, lower frequency antennas, such as those below 400 MHz, are not considered here because of their poor resolution of features at shallow depths. There are, of course, some archaeological sites with features and artifacts found much deeper than 2 meters, and these require a different set of procedures and parameters. The development of such procedures for these less-frequent sites is beyond the scope of this project, but should be kept in mind for future research endeavors.

The research of this SERDP project has yielded information to develop a set of procedures under which to conduct similar archaeological investigations using ground-penetrating radar. The benefit of this SERDP project was that the two test sites, CATS and Hammer, encompassed a wide variety of common environmental settings that GPR surveys are conducted in. As described above, GPR data were collected at the CATS test site when the ground was dry, wet, and frozen. At Hammer, data were collected when the ground was dry and wet. The soil conditions of each site are also different, as Hammer has soils that are primarily sand and silt, and CATS has soils that are clay-sized particles. The antenna frequencies utilized during data collection with the GSSI SIR-2000 system were 900 MHz and 400 MHz central frequency antennas. Collecting GPR data under the various combinations of factors was a beneficial and insightful means of developing procedures for performing GPR surveys at other archaeological sites. For clarity, the specific developed procedures using these combinations of parameters are described under the headings of these two antenna frequencies.

6.1 400 MHz Antenna

There is a long-standing belief that dry, sandy soils are optimal conditions for radar energy propagation. This is only true, however, depending on the antenna frequency being used, depth of buried materials, and physical properties of the buried materials. That is, when using a 400 MHz antenna, the optimal depth for buried features in this type of soil will be 1-2 meters below the surface. Anything shallower may not be resolvable using this frequency, unless the objects are very large. The type of feature being prospected for is also an important consideration. As shown at Hammer, dry wooden objects are not easily "seen" in the GPR data when the surrounding matrix is also dry. This is due to very little variance between the chemical and physical properties (and thus RDP) of the object and its surrounding soil. Objects with a significant difference in these properties, such as a metal object, will show up quite well.

While areas that are dry may work well for energy propagation, areas that are *too* dry may be detrimental to data. As seen at the CATS test site, which is an area that is very naturally dry, desiccation cracks in the soil produced numerous point-source hyperbolas, which tended to skew objects in reflection profiles and made interpretation more difficult. Desiccation cracks are typical in soils that contain a lot of clay, which was the case at CATS.

Using a 400 MHz antenna in wet sandy conditions can have a considerable difference on the data. Soil that is entirely sand may have enough porosity to drain water quickly, and thus the water would primarily affect the objects in the ground by pooling on them or permeating them. The presence of other soil types such as silt or clay (which is almost always the case in nature) has a different impact on how water is retained. Water may not percolate down as quickly, or become absorbed in pockets of soil, especially in bentonitic or kaolinitic clays. Water may also pool in areas of slightly cemented sandy soil, which typically occurs beneath the disturbed loose soil on the surface. This has potential to produce a number of extraneous radar reflections, as seen at the Hammer test site under these conditions (Conyers 2004a). The way water interacts with the buried objects, however, may be quite beneficial for producing reflections. For example, wood tends to absorb and hold water, and this in turn makes it physically different enough from the surrounding dry soil to generate strong reflections on radar profiles. Other objects may also collect and pool water, and these will also produce strong reflections in the data. In this case, such objects are easily picked out on amplitude slice maps, and thus may be easily interpreted.

As with dry soils, areas that are *too* wet can be harmful for a successful survey. As seen at the CATS test site, when the area was artificially flooded the constructed floor layers retained the same amount of water. There was therefore little difference in the physical properties of the floors and their surrounding material (Conyers 2004a). The lack of reflections produced at these interfaces meant that all but the top floor layer was essentially invisible in the data. The uniform distribution of water in this soil type is an interesting phenomenon. It has long been held that clay-rich soils will attenuate radar energy very quickly, and this is amplified when that clay soil is wet. The data from this project, however, show that this is only partially true. Clay will attenuate radar energy quickly, but only when it is a *mineralogic* clay. That is, bentonite or kaolinite are examples of mineralogic clays that are electrically conductive, and will absorb the

electrical component of a radar wave swiftly. Clays that are only *clastic* will not have the same effect. These are sediments that are clay-particle sized, but can come from any parent source, from quartz to granite. The soils at CATS fit this latter description, which explained the relatively good energy propagation in its soils far below the depth of the buried features. Since this type of soil appears to hold and distribute moisture uniformly, the type of cultural materials being prospected for (wood, stone, metal, etc.) should have a weighted influence on the decision to perform a GPR survey, as different materials will show up much differently in wet versus dry conditions.

Surveys using a 400 MHz antenna on frozen sandy ground conditions have even less predictable results than wet or dry conditions. Many GPR practitioners report that frozen conditions provide excellent energy coupling. In many ways it would seem that frozen conditions reflect energy in much the same way as dry conditions. In frozen conditions, however, ice fractures in the soil may result in a number of point-source hyperbolas, which can make processed data look cluttered. If these ice fractures are restricted to the topsoil (which is common in most temperate zones), a 400 MHz antenna may provide enough depth penetration to "see past" these fractures and minimize the impact the extraneous reflections have on the remaining data. Therefore using a 400 MHz antenna on frozen ground is desirable because such a survey can yield very good data with excellent energy coupling.

Using the 400 MHz antennas on frozen clay soil yields a different scenario. As seen from CATS, data collected under these conditions showed many similarities to the data collected when the ground was dry. Specifically, all four floor layers were visible in the processed amplitude slice maps, but the feature resolution was poor. Since it is known from other projects that frozen conditions provide good energy coupling, a logical hypothesis might be that the clay soils at CATS "crack" when the ground is frozen. This would produce desiccation cracks similar to the ones found in very dry conditions, thus creating a number of point-source hyperbolas in the reflection profiles. Again, a 400 MHz antenna may allow a deep enough penetration where these point-source hyperbolas are minimized to the shallower amplitude slice maps and easily taken into consideration.

6.2 900 MHz Antenna

While 400 MHz frequency antennas are usually excellent for penetrating depths of about 1-2 meters, there is a trade-off with feature resolution. That is, only larger objects can be resolved with lower frequency antennas. A 900 MHz antenna will resolve much smaller objects, often the size of a brick or smaller, but only within about a meter of the ground surface. A very important consideration before performing a GPR survey is therefore the size of the objects to be resolved, and the depth at which they are buried.

In dry, sandy soils, a 900 MHz frequency antenna may be optimal for prospecting for cultural materials within the first 2 meters of the subsurface. This is because the dry matrix allows for excellent energy propagation, thus allowing radar energy to penetrate deeper than it might in soils that are wet or clay-rich, while maintaining the resolution of smaller objects a higher frequency allows. At Hammer, the 900 MHz antennas provided excellent resolution of objects, better than the 400 MHz antennas at all depths.

Soils that are high in clay affect radar energy differently. At the CATS site, the 900 MHz antenna was better at imaging objects in the shallower depths, between 10 and

50 cm below the surface. Below this depth, radar energy is quickly attenuated in clay-rich soils. Soils that contain mineralogic clay may absorb this energy even shallower than 50 cm. One immediate drawback to using a higher frequency antenna in very dry, clay-rich soils is the amount of desiccation cracks that are imaged, similar to what is described above using a 400 MHz antenna. The 900 MHz antenna, however, resolves even more of these cracks in the shallow depths than the 400 MHz antenna. This results in numerous point-source hyperbolas, which obscure and complicate the data, making interpretation difficult.

Soil moisture is perhaps the strongest determining factor in energy propagation (Conyers 2004a). An area that has been completely saturated with water may procure meaningless data if the flooded objects do not differ enough physically from their surrounding matrix. In sandy areas, water may percolate quickly through the matrix, especially in the upper subsurface. For a 900 MHz antenna then, which concentrates within the first meter below the surface, the "flooding effect" may not be an issue. Depending on the amount of water and the presence of other soils such as silt or clay, a 900 MHz antenna may not be appropriate because it will resolve every small pocket of water in the upper subsurface (Conyers 2004a). This will tend to look like clutter on amplitude slice maps.

As described above, soils that contain a high amount of mineralogic clay such as bentonite will attenuate radar energy quickly. This effect is magnified when such clay is wet, as water tends to carry a certain amount of soluble salts when it interacts with the ground. Wet, mineralogic clay-rich soil is therefore undesirable for GPR surveys. Any antenna frequency will be ineffective in these conditions, but most especially a higher frequency such as a 900 MHz, which has shallow ground penetration anyway. When the soil does not have mineralogic clay, but only clay-sized soil particles, the energy will not be attenuated as quickly (Conyers 2004b, Saarenketo 1998). As seen at CATS, radar successfully reflected the burned clay floor under these conditions. Not all four floors are seen on the amplitude slice maps, however, as the flooding of the site saturated the floor layers enough to provide negligible physical difference between them and the matrix surrounding them.

Frozen ground conditions can be quite effective for radar energy propagation. Often frozen conditions allow excellent antenna coupling. The data gathered from these surveys, however, can vary considerably. It seems that data collected in frozen conditions tends to resemble data collected in dry conditions, with good resolution of ground features. When processed, there can be a number of extraneous reflections from frozen conditions. These include point-source hyperbolas, which can result from ice fractures in the soil. Such ice fractures are resolved to a greater extent using a higher frequency antenna. There can also be anomalous reflections on amplitude slice maps, which usually result from changes in water content in the soil (Conyers and Cameron 1998). Sandy soils may help to minimize these extraneous reflections, as these soil types do not swell and crack as clay-rich soils do from freezing and thawing.

For clay-rich soils, frozen conditions are similar to dry conditions in terms of reflecting buried features. As seen at CATS, the 900 MHz antenna was successful at reflecting all four layers in frozen conditions. The data, however, contained a good amount of the extraneous reflections just described. This is likely common in clay-rich soils. Even clastic clays may not have enough porosity to drain water before it freezes,

creating fractures in the subsurface that are then reflected by the radar. A higher frequency antenna means that smaller objects in the shallower subsurface will be reflected, and so these fractures are more likely to appear in the data. The greater number of these point-source hyperbolas in the data means they may be harder to process out, and thus make data interpretation more difficult. This must be taken into account when processing data collected under these conditions.

From this research, specific and general parameters involving both data collection and data processing were developed. To summarize, the general parameters that appeared to best match what was known in the ground, irrespective of environmental conditions and equipment used, are as follows:

- Collection with the smallest distance between transects in a grid. In general, with a 400 MHz antenna, a line spacing of 50 cm was good, but 25 cm was even better. With the 900 MHz antenna 25 cm spacing was optimal, and there was negligible difference between 25 cm and 20 cm.
- The high frequency antenna (900 MHz) was best at imaging from 10-50 cm depth in the clay rich area at CATS and at all depths at the sandy area at Hammer. The 400 and 450 MHz antennas also produced maps with good resolution at both sites, and had optimum depth resolution from about 20-90 cm depth. Low frequency antennas (300 MHz and lower) produced poor maps at both sites because of their poor resolution at the shallower depths.
- Reflection data were processed first to remove background noise and extraneous frequencies. Data were then migrated to remove hyperbola "tails" and collapse reflections to their point sources for "crisper" amplitude maps.
- Reflection profiles were sliced in 2 ns thick slices at a minimum for amplitude analysis. Thinner slicing cut across waveforms and tended to blur and distort the final maps. A 20 cm search radius or less was used for all amplitude slice creation, and there was no interpolation between profiles in grids, using the slicing procedure.
- Each amplitude time slice was then gridded in imaging programs, but this time with a 1 meter search radius or less, interpolating with a power of 4 (weighting the data closest to the center of the search radius) and smoothing the data at most at a factor of 1 or less.
- Image maps were then created for each slice using the *Surfer 8* mapping program and colors were given to the amplitudes of each map in image creation.

Using these general parameters as guidelines, it is possible to adjust accordingly to the specific field conditions of a site. The above collection, processing, and gridding parameters proved to be the best methods for the two test sites regardless of precise environmental and geologic conditions. Keep in mind that both these sites had features buried only a meter or less in the ground, which almost always precludes the generation of good maps using the low frequency antennas. These shallow depths that were used as part of this study are common for most archaeological sites, but if these same features had been buried much more deeply in the ground, very different processing steps and equipment types may be necessary.

A number of variables must be considered before performing a GPR survey. While this report has attempted to describe some of the most common soil and environmental conditions using two common antenna frequencies, it is by no means exhaustive of the conditions that may be encountered in the field. It is important to remember that while many variables *affect* a survey, some certainly impact one more than others. For instance, soil moisture has been shown to be the dominant factor in reflecting energy, more so than the type of soil being worked in. Therefore when considering a GPR survey, these more influential factors should be given more thought than other variables that may only have a minor impact on the data. This research has shown that many commonly held beliefs concerning field conditions and successful GPR surveys are incorrect. For example, one should not discount the possibility of a successful GPR survey just because the soil type of the site is clay. It has been shown many times that good and meaningful data can be gathered in this type of soil. One should, however, weigh the consequences of surveying in a mineralogical clay-rich area that has recently experienced heavy rainfall. The more researchers understand how different variables impact radar energy, the way it is reflected, and to what degree, the better decisions concerning GPR surveys can be made.

6.3 Web Page: The Protocol

At this point in the project, a website has been created to make information on this SERDP project, and on GPR in general, accessible to a wider public, including Federal employees and agencies (Figure 35). An outline of the website structure is provided in Figure 36. The website currently has two main sections; one is dedicated to the GPR method in a broad sense, most specifically acquisition and processing procedures (Figure 37). The other section is devoted to this SERDP research project and the data and interpretations that led to our conclusions in section one (Figures 38 and 39). In the GPR section are pages about GPR method and theory, variables that affect surveys, data collection and processing, examples of successful surveys, and examples of unsuccessful surveys. In essence this is the GPR protocol, as outlined in our “tasks to be completed.” The SERDP project section includes pages on the research goals, the technical approach, analyses of CATS and Hammer test facilities, lab analyses, and areas for future study. This website also contains software downloads available for processing and viewing GPR data, which were completed as part of this project. Below is a copy of the home page with its URL address (Figure 35).

Figure 35: The Home Page of the website, which can be accessed at: ***http://www.du.edu/~lconyers/SERDP/GPR2.htm***

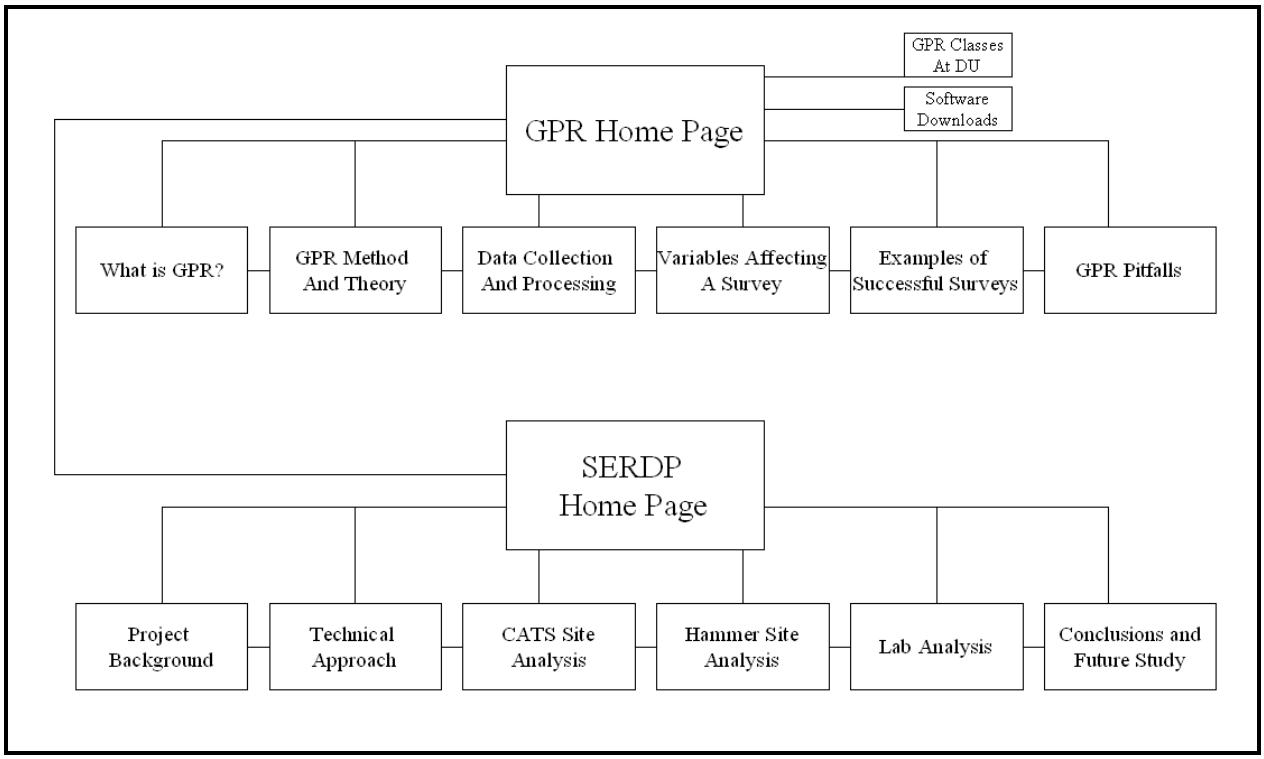

Figure 36: Flowchart showing primary pages on website.

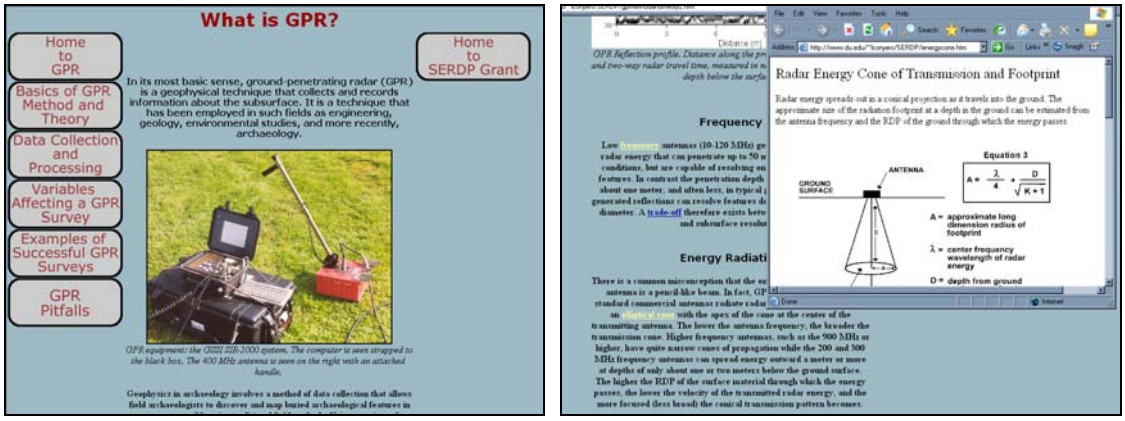

Figure 37: Examples of two of the pages under section one of the web page.

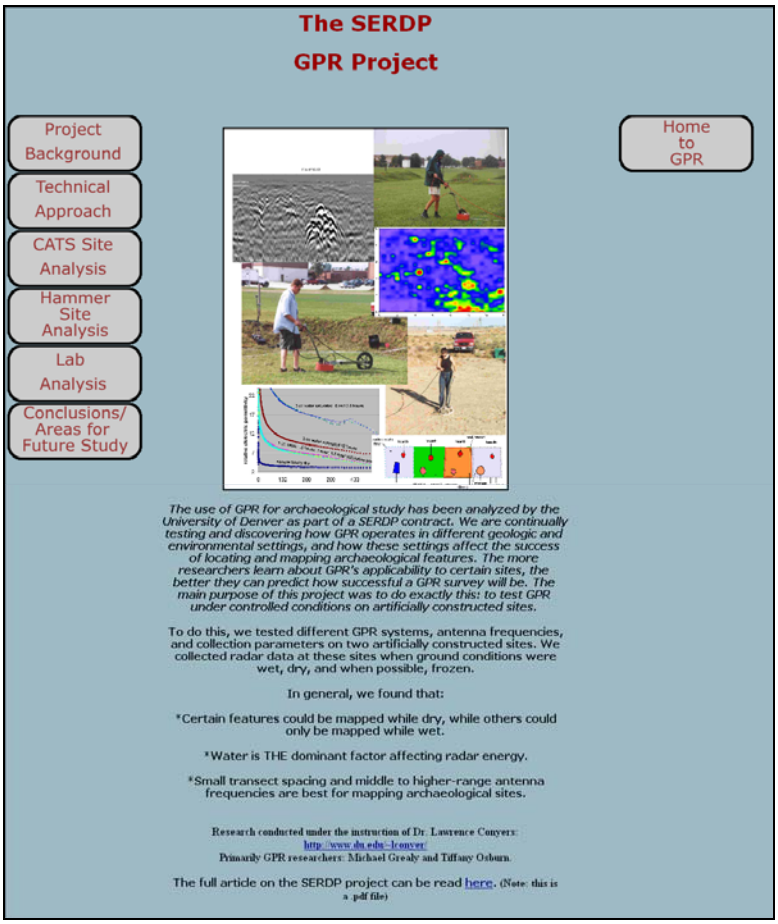

Figure 38: The main page for section two, the SERDP GPR Project.

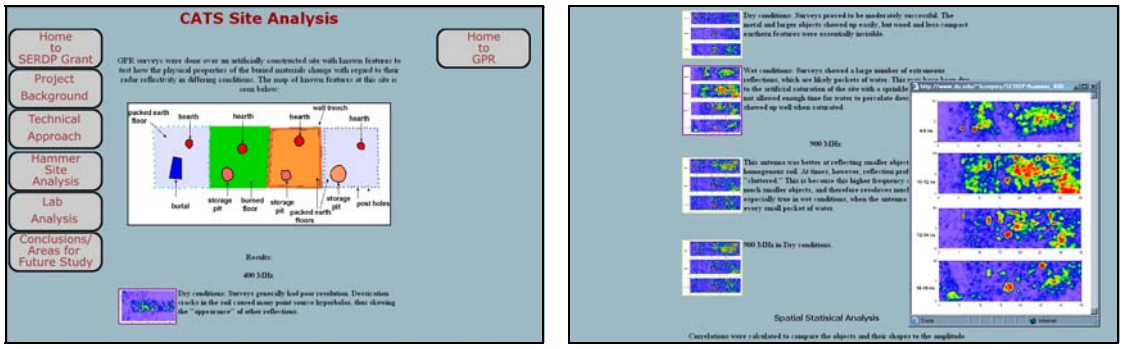

Figure 39: Examples of two of the pages under section two of the web page.

One of the most important themes developed throughout both sections of the web page is a protocol for carrying out GPR surveys. This protocol incorporates the most current research and results of GPR studies and the factors that most impact them. As new research and information about GPR investigations are acquired, this web page will be updated to reflect these latest advances. This will help keep the knowledge on GPR surveys current, building upon the research started under this SERDP contract. For

people just beginning to use the GPR method, this information will prove invaluable for performing surveys that stand a reasonable chance of success. It is hoped that not only newcomers will find such a protocol useful, but also veterans of using the GPR method.

7. REFERENCES

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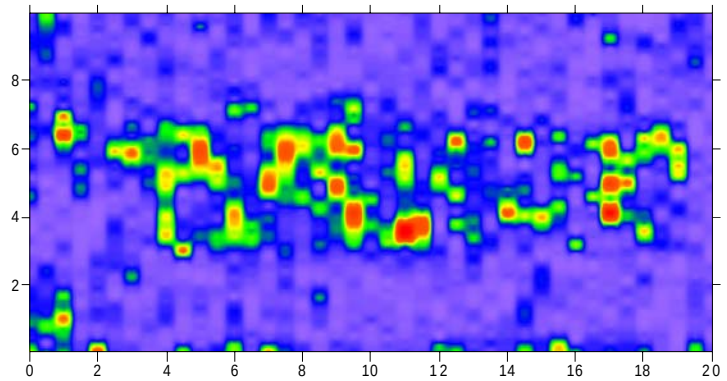
Isaacson, John, Hollinger, R. Eric, Gundrukm, Darrell and Joyce Baird. 1999. A Controlled Archaeological Test Site Facility in Illinois: Training and Research in Archaeophysics. Journal of Field Archaeology, v. 26, pp. 227-236.

Saarenketo, Timo. 1998. Electrical properties of water in clay and silty soils. Journal of Applied Geophysics, v. 40, pp. 73-88.

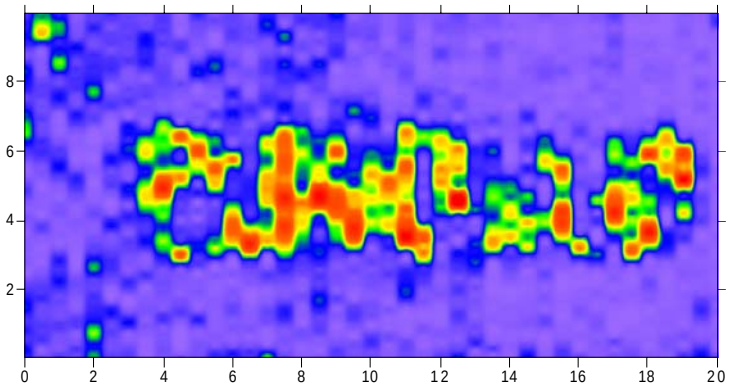
Appendix:

Statistical Analysis of Maps from CATS and Hammer

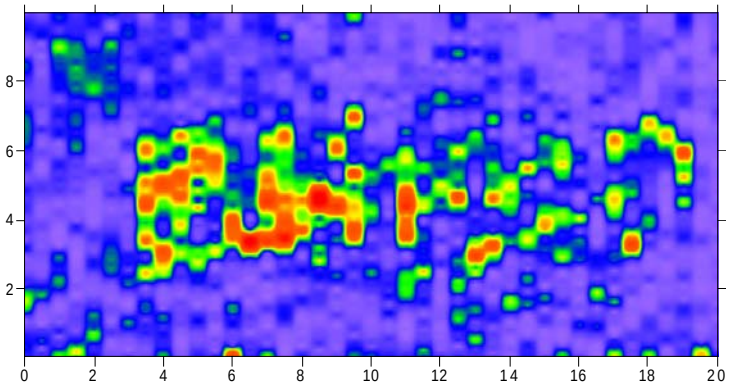
GSSI 400MHz
CATS House Floors .50m spacing
8_21_02 Foreground Removal at 11



4ns – 6ns



6ns – 8ns



8ns – 10ns

Processing/Slicing Parameters

	X	Y	Z
First	-.25	0	0
Last	20.25	10	28
# Cells	41	400	14
Box Size	.1	.1	2

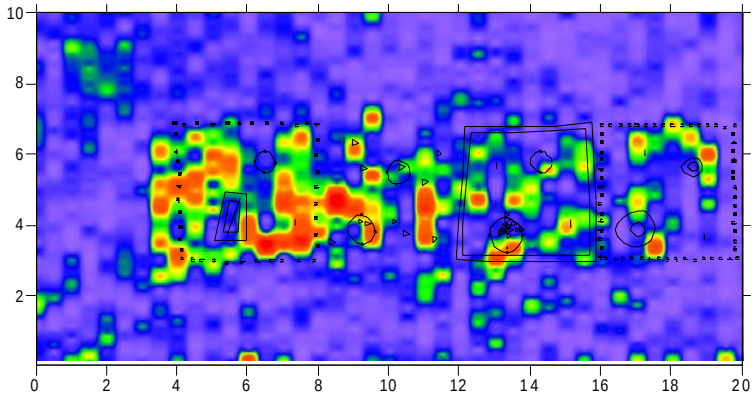
Gridding Parameters

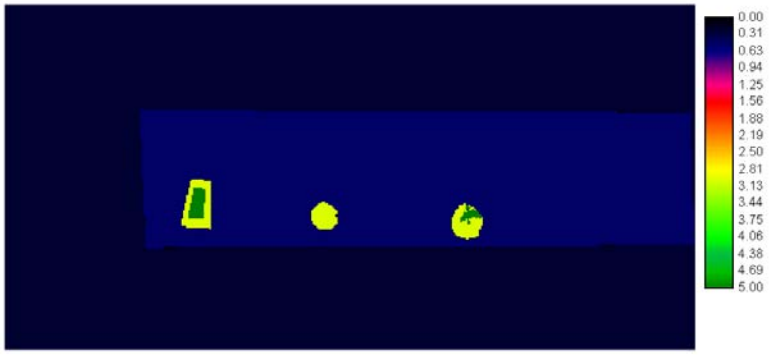
	Min.	Max.	Spacing	# Lines
X	0.025	20	.1	201
Y	0.0125	9.875	.1	101

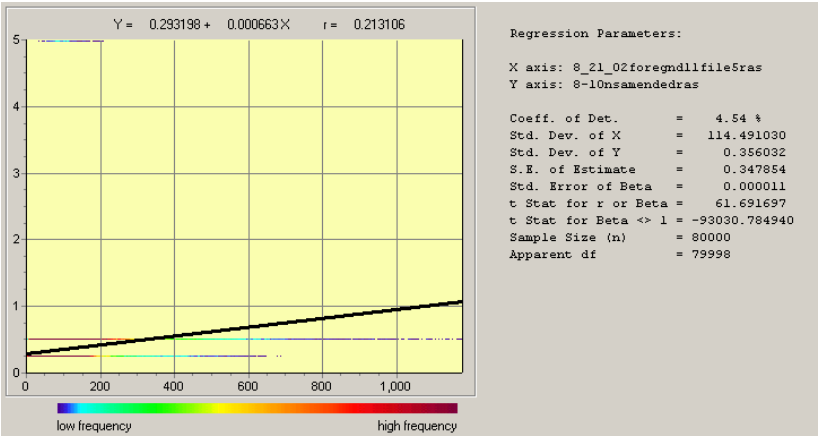
GSSI 400MHz

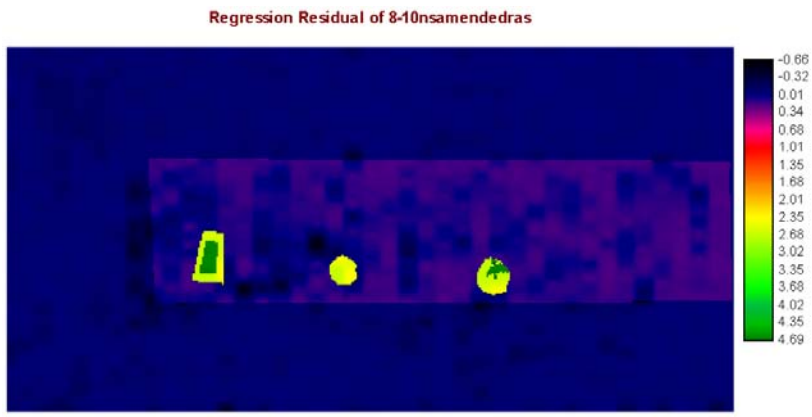
<u>CATS House Floors 8ns – 10ns</u>

8_21_02 Foreground removed at 11





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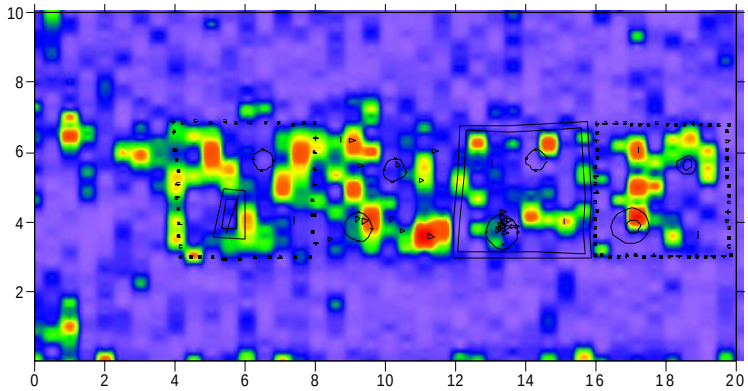
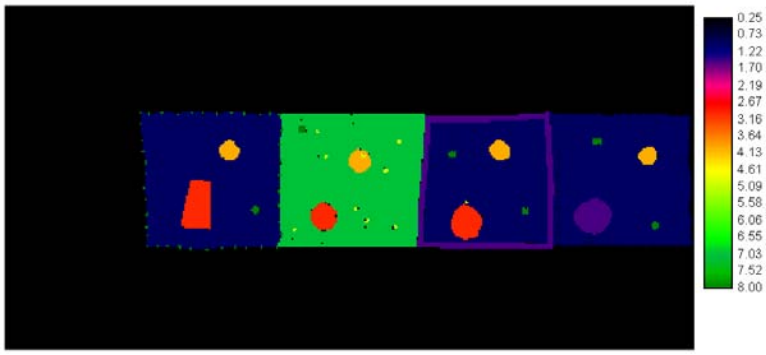
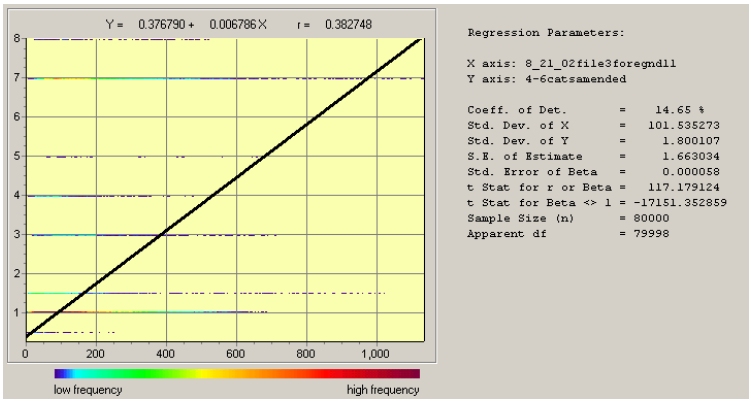
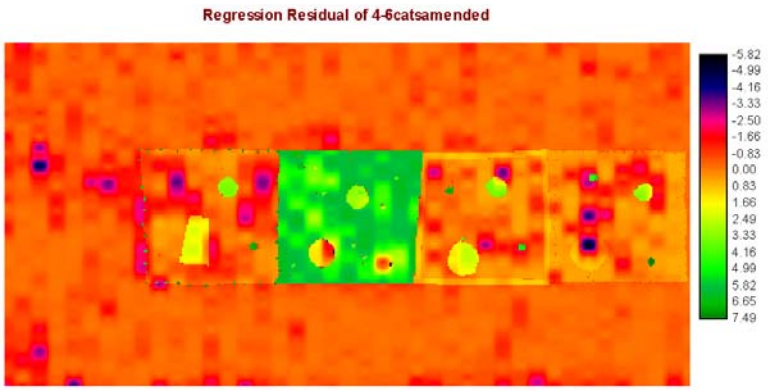
0.01
0.34
0.68
1.01
1.35
1.68
2.01
2.35
2.68
3.02
3.35
3.68
4.02
4.35
4.69

GSSI 400MHz
CATS House Floors 4ns –6ns
8_21_02 Foreground Removed at 11





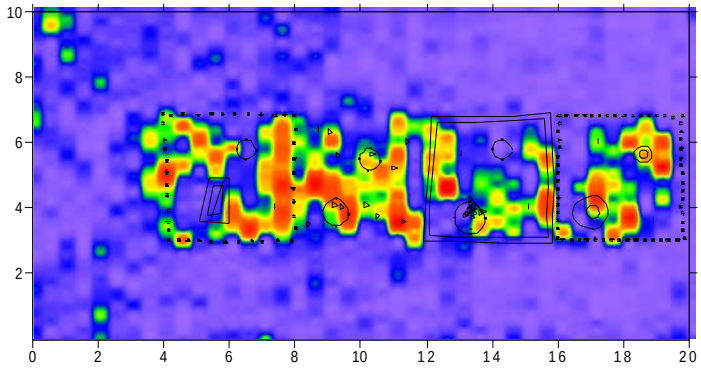


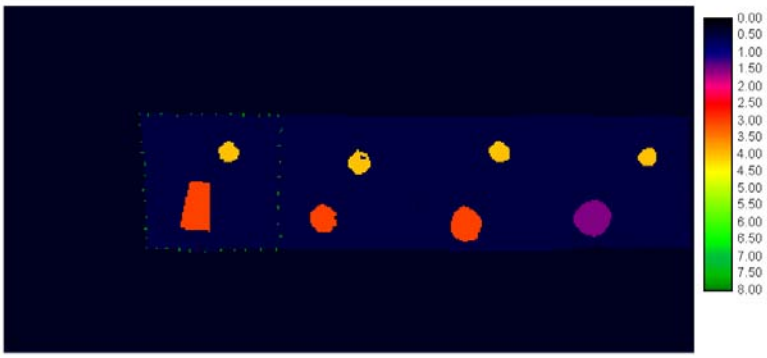

Regression Residual of 4-6catsamended
-5.82
-4.99
-4.16
-3.33
-2.50
-1.66
-0.83
0.00
0.83
1.66
2.49
3.33
4.16
4.99
5.82
6.65
7.49

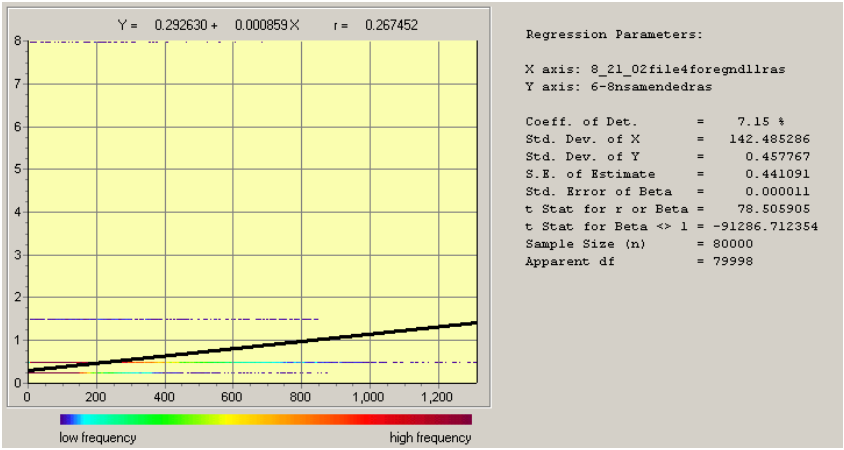
GSSI 400MHz

CATS House Floors 6ns – 8ns

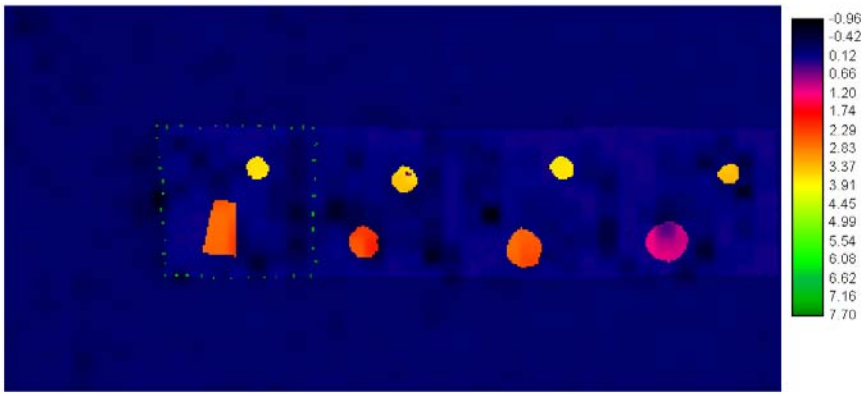
8_21_02 Foreground Removed at 11







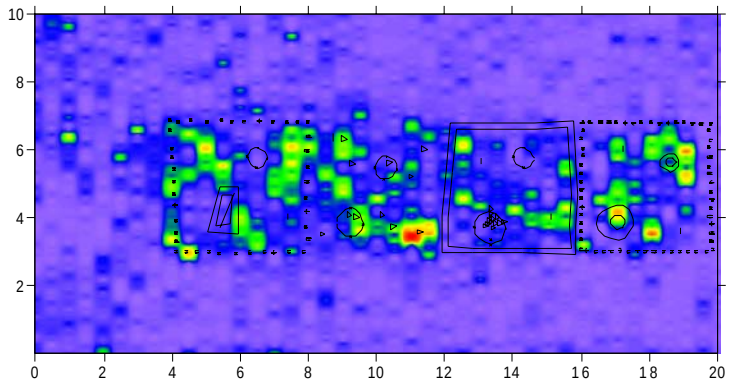
Regression Residual of 6-8nsamendedras

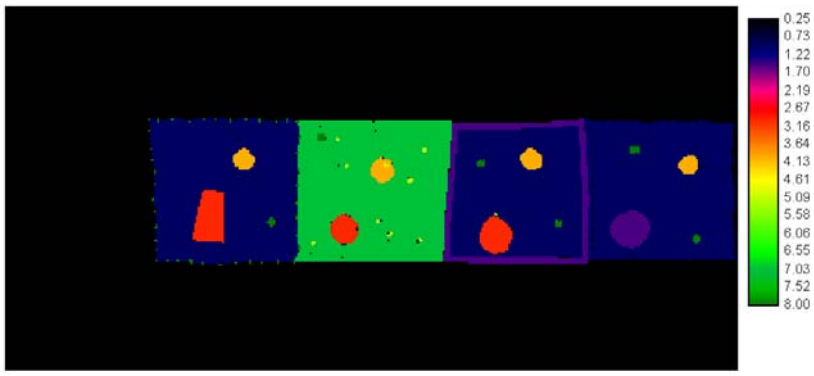


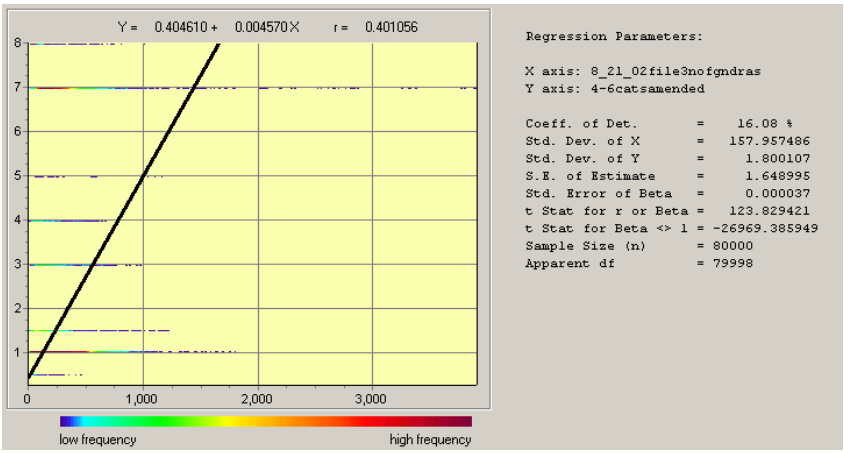
GSSI 400MHz

<u>CATS House Floors 4ns – 6ns</u>

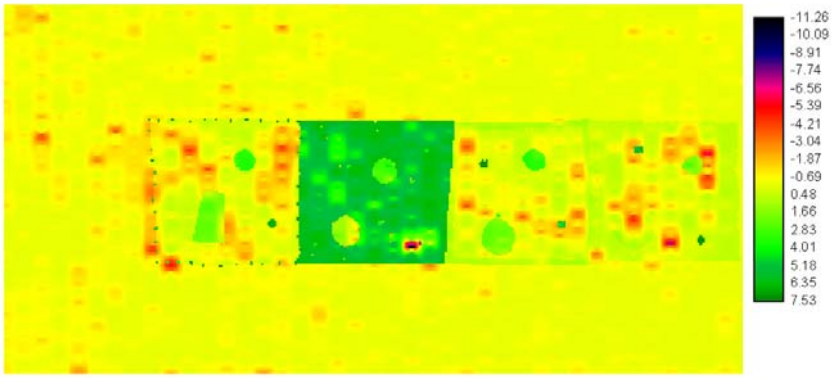
8_21_02 No Foreground Removal



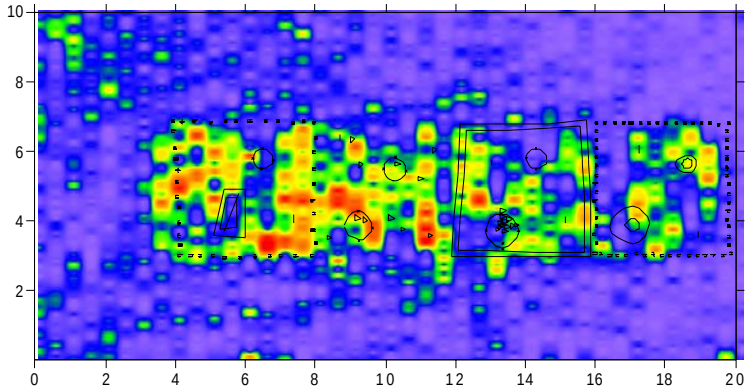


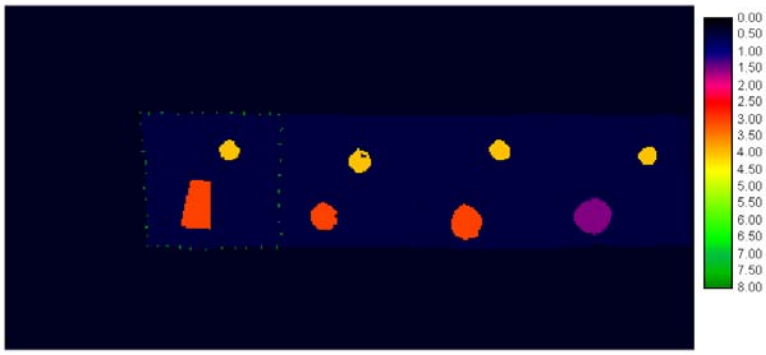


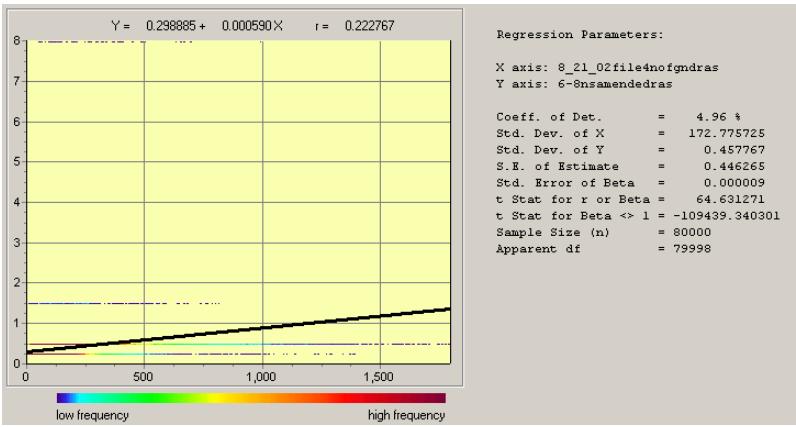
Regression Residual of 4-6catsamended

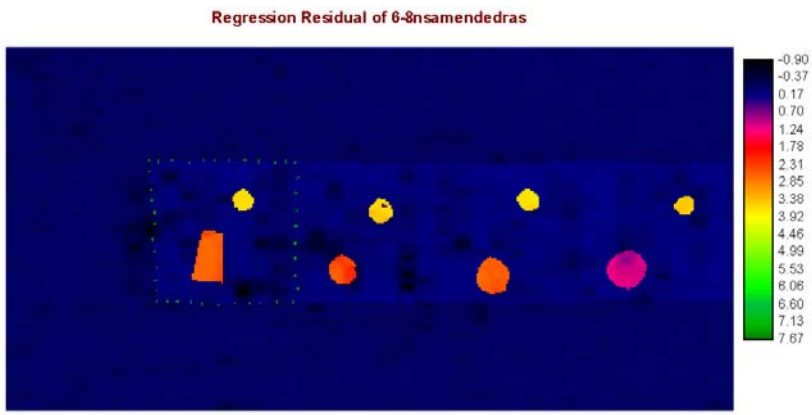


GSSI 400MHz
CATS House Floors 6ns – 8ns
8_21_02 No Foreground Removal





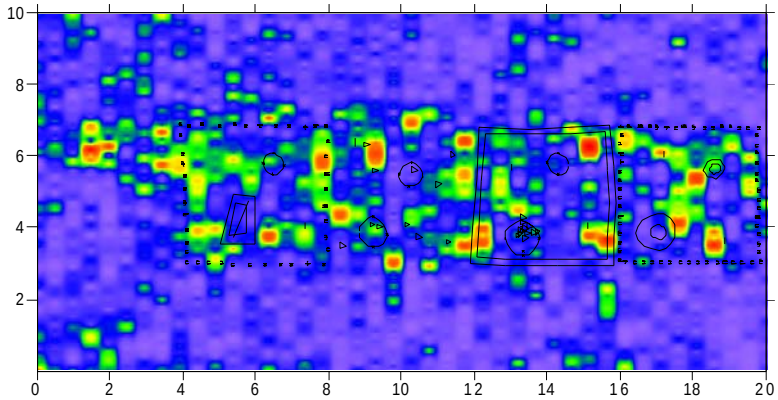


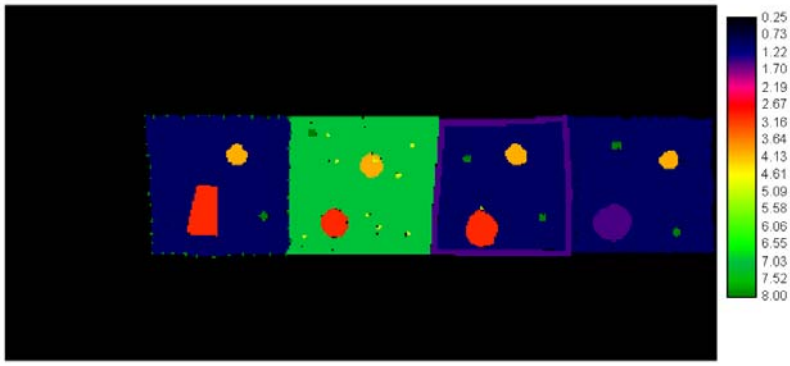

Regression Residual of 6-8nsamendedras
-0.90
-0.37
0.17
0.70
1.24
1.78
2.31
2.85
3.38
3.92
4.46
4.99
5.53
6.06
6.60
7.13
7.67

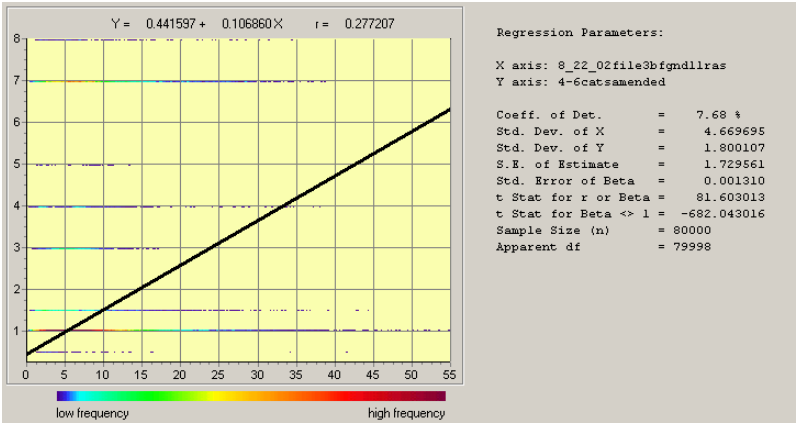
GSSI 400MHz Survey Wheel

<u>CATS House Floor 4ns – 6ns</u>

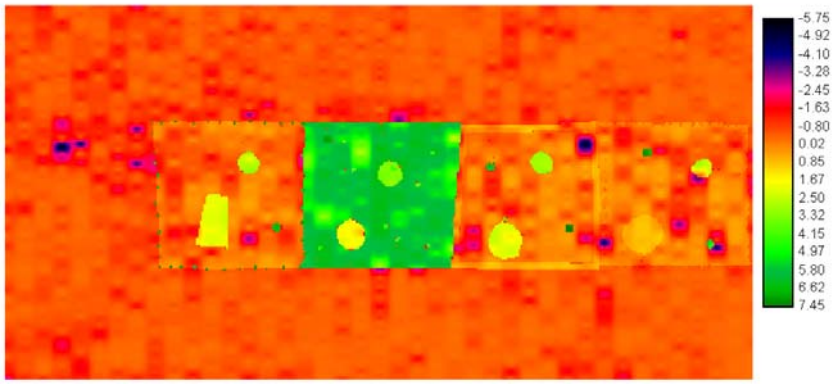
8_22_02 Foreground Removal at 11



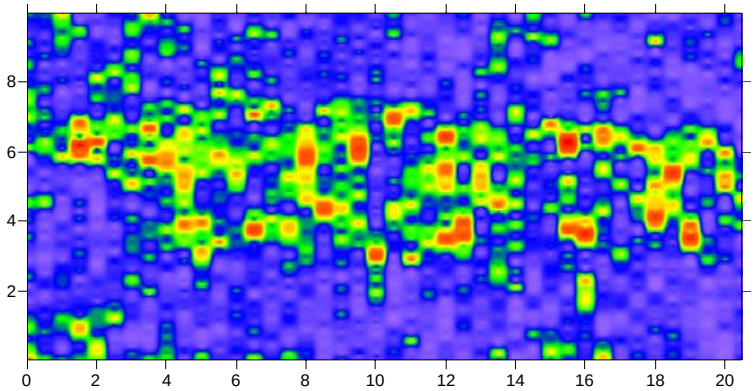




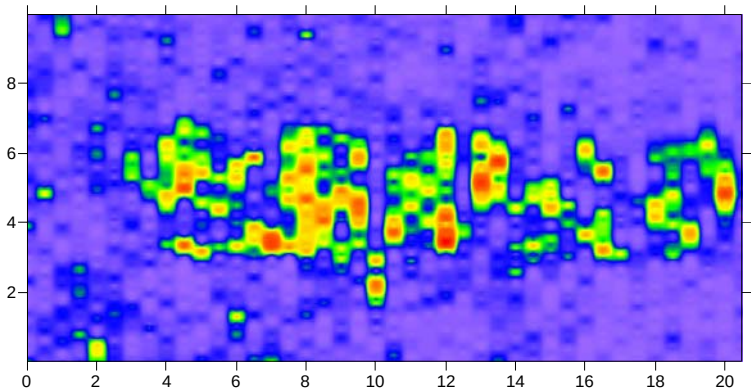
Regression Residual of 4-6catsamended



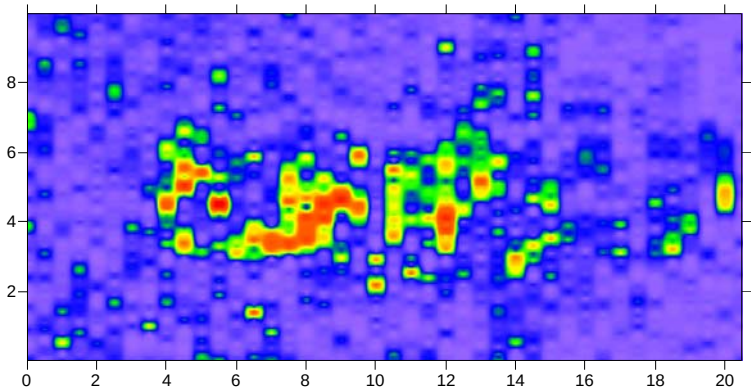
GSSI 400MHz Survey Wheel
CATS House Floors .50m spacing
8_22_02 Foreground Removed at 11



4ns – 6ns



6ns – 8ns



8ns – 10ns

Processing/Slicing Parameters

	X	Y	Z
First	-.25	0	0
Last	20.75	10	28
# Cells	41	400	14
Box Size	.1	.1	2

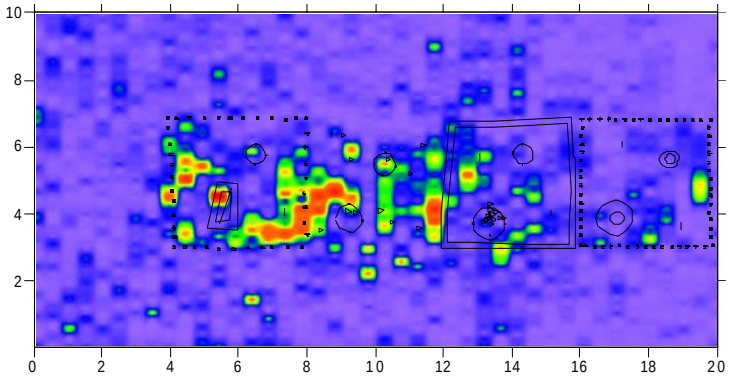
Gridding Parameters

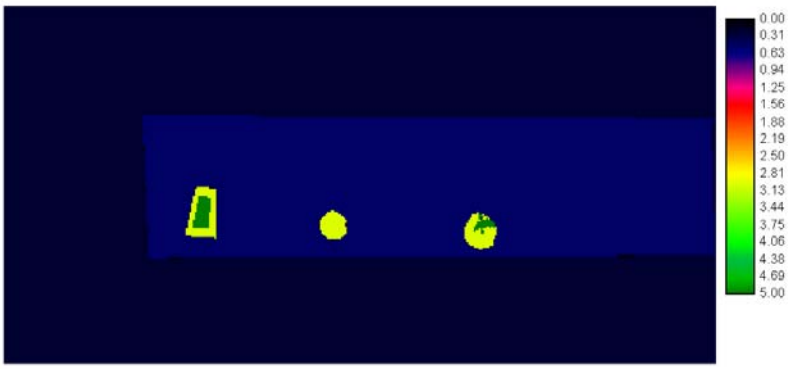
	Min.	Max.	Spacing	# Lines
X	0	20.5	.1	206
Y	0.0125	9.875	.1	101

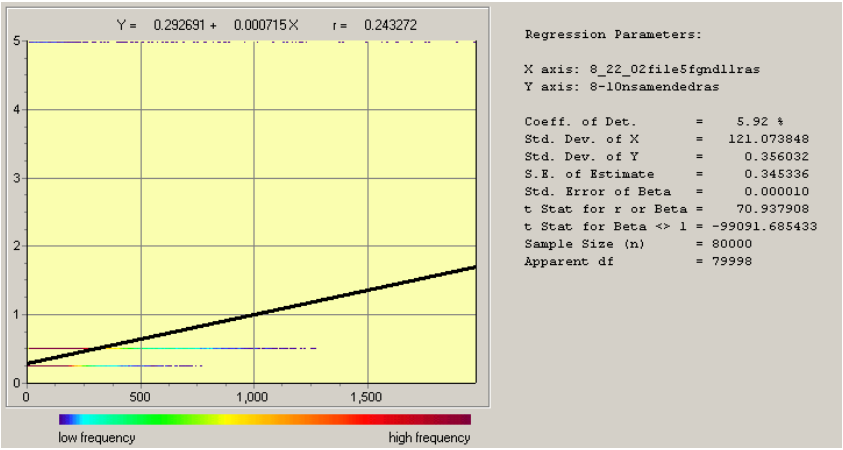
GSSI 400MHz Survey Wheel

CATS House Floors 8ns – 10ns

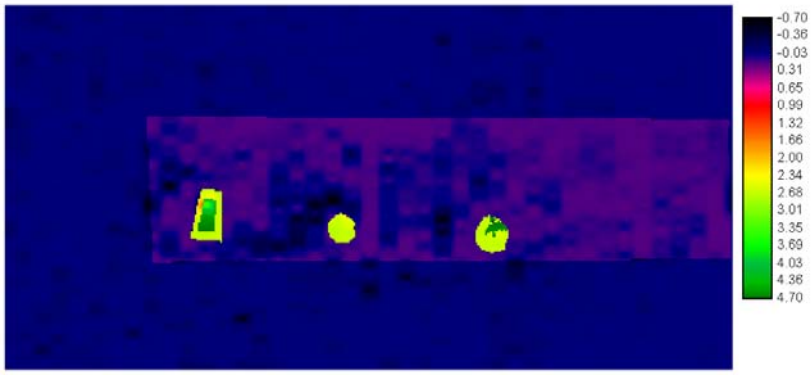
8_22_02 Foreground Removal at 11



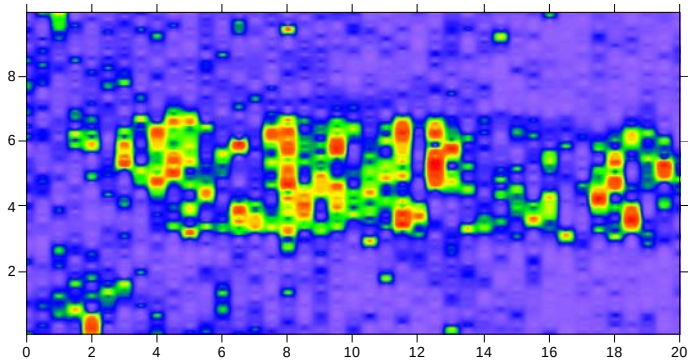




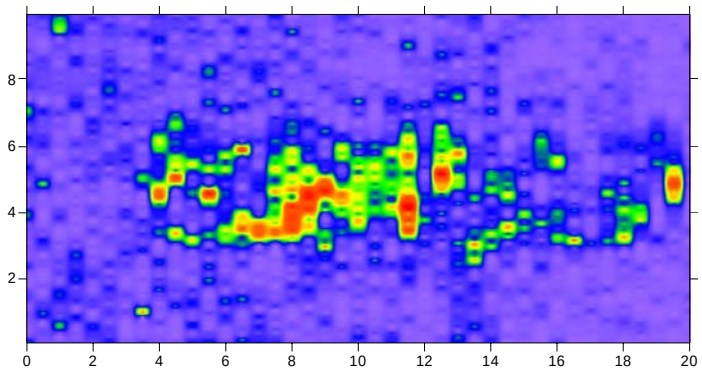
Regression Residual of 8-10nsamendedras



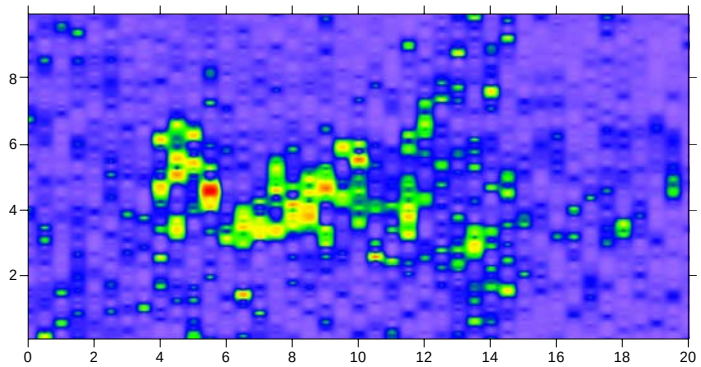
GSSI 400MHz Survey Wheel
CATS House Floors .50m spacing
8_22_02 No Foreground Removal



4ns – 6ns



6ns – 8ns



8ns – 10ns

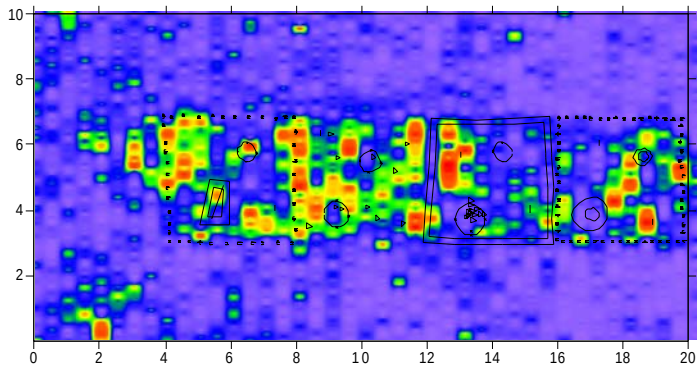
Processing/Slicing Parameters

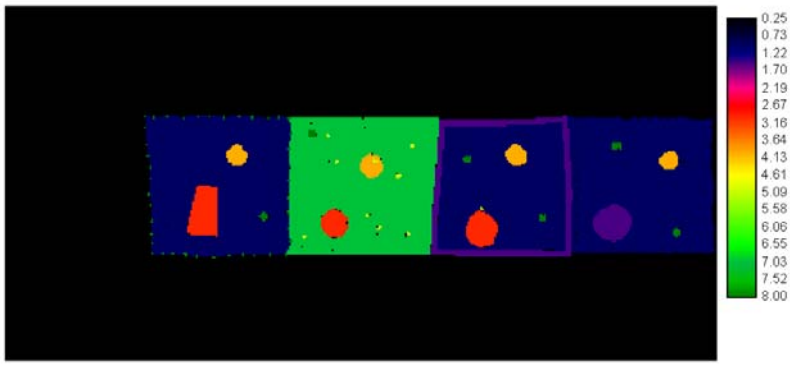
	X	Y	Z
First	-.25	0	0
Last	20.75	10	28
# Cells	41	400	14
Box Size	.1	.1	2

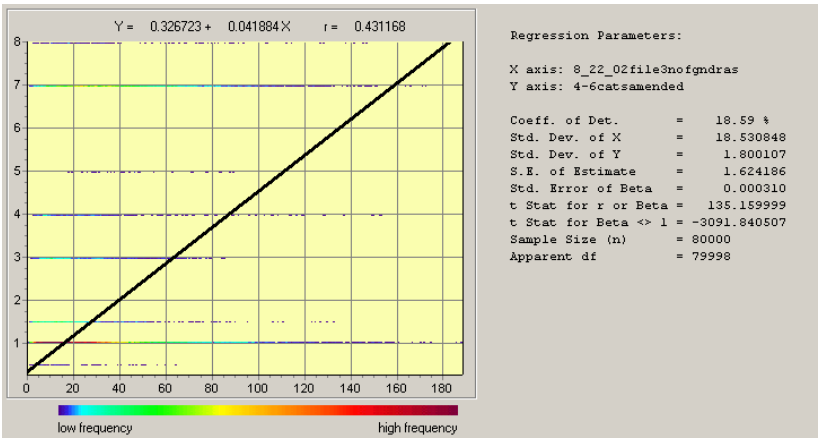
Gridding Parameters

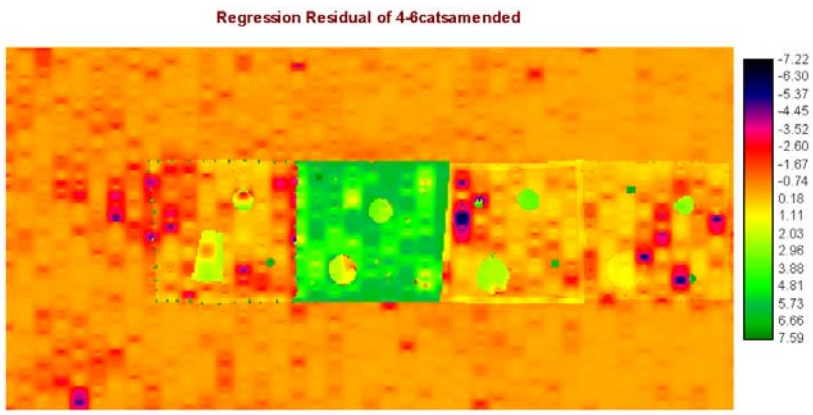
	Min.	Max.	Spacing	# Lines
X	0	20.5	.1	206
Y	0.0125	9.875	.1	101

GSSI 400MHz Survey Wheel
CATS House Floors 4ns – 6ns
8_22_02 No Foreground Removal

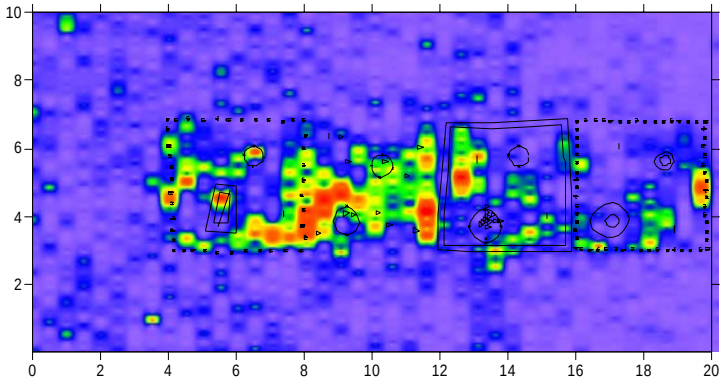


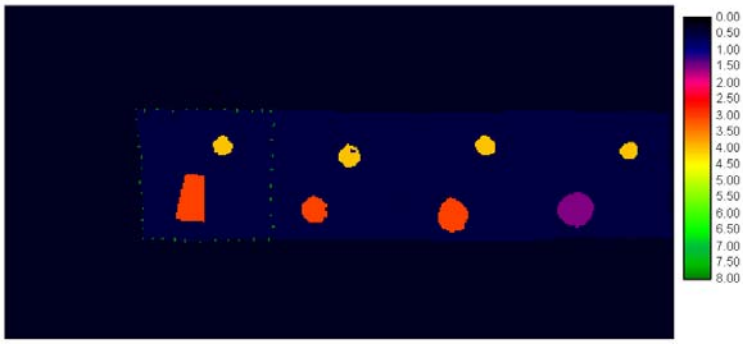


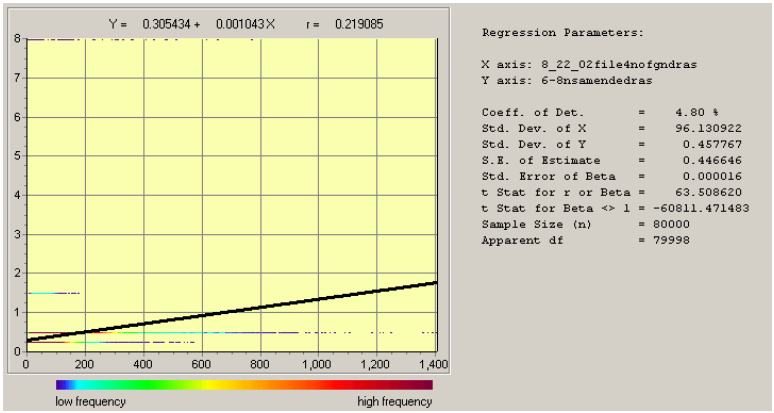


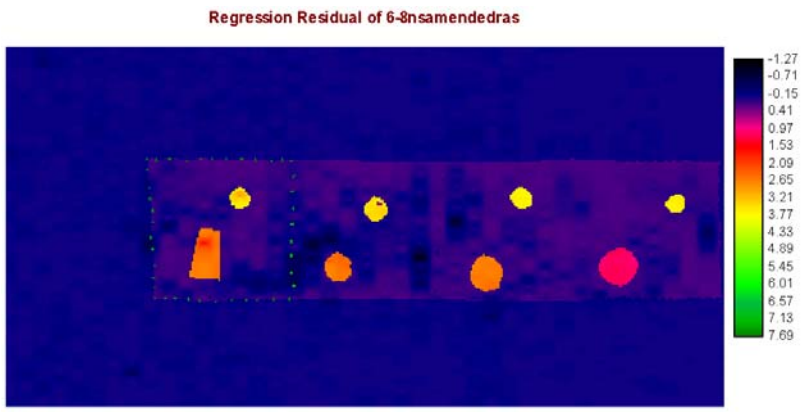

Regression Residual of 4-6catsamended
-7.22
-6.30
-5.37
-4.45
-3.52
-2.60
-1.67
-0.74
0.18
1.11
2.03
2.96
3.88
4.81
5.73
6.66
7.59

GSSI 400MHz Survey Wheel
CATS House Floors 6ns – 8ns
8_22_02 No Foreground Removal





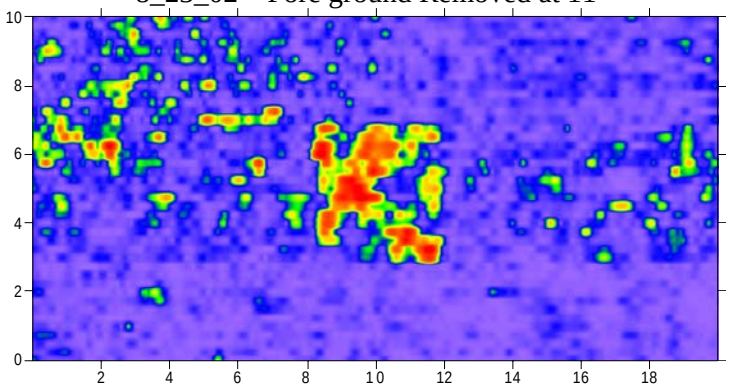



Regression Residual of 6-8nsamendedras
-1.27
-0.71
-0.15
0.41
0.97
1.53
2.09
2.65
3.21
3.77
4.33
4.89
5.45
6.01
6.57
7.13
7.69

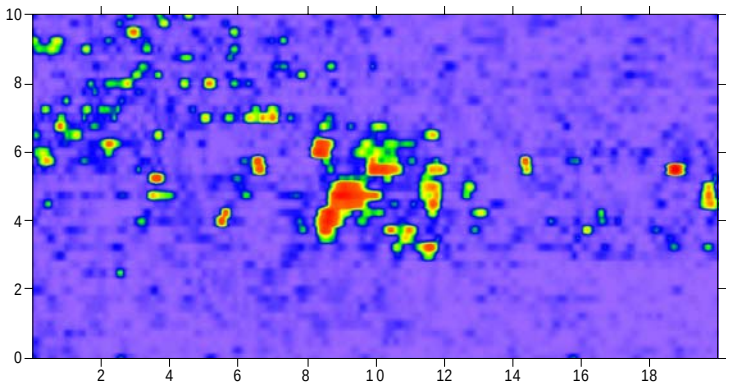
GSSI 400 MHz Rainy Day

CATS House Floors .25m spacing

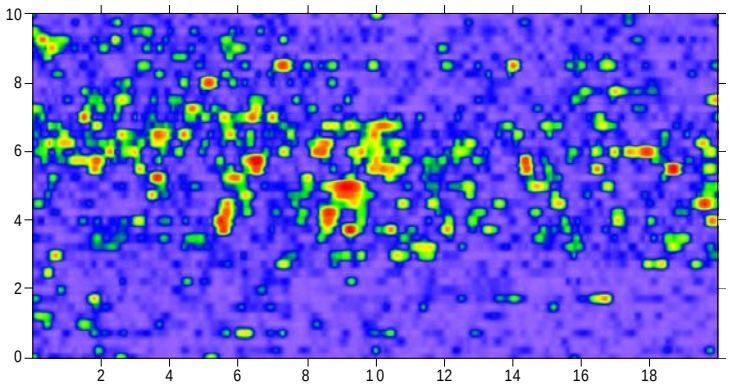
8_23_02 Fore ground Removed at 11



10ns – 12ns



12ns – 14ns



14ns – 16ns

Processing/Slicing Parameters

	X	Y	Z
First	0	-.125	0
Last	20	10.125	28
# Cells	400	41	14
Box Size	.1	.1	2

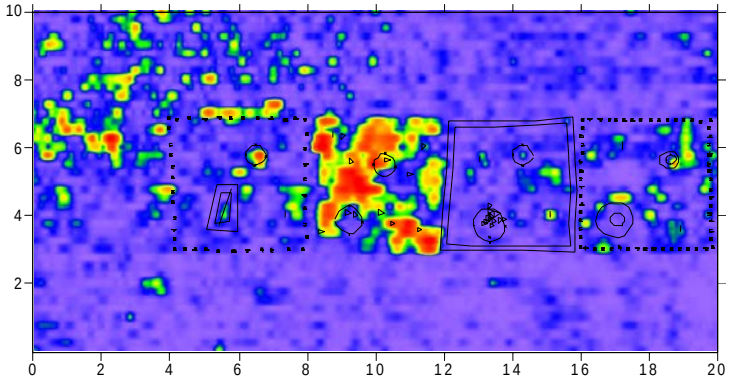
Gridding Parameters

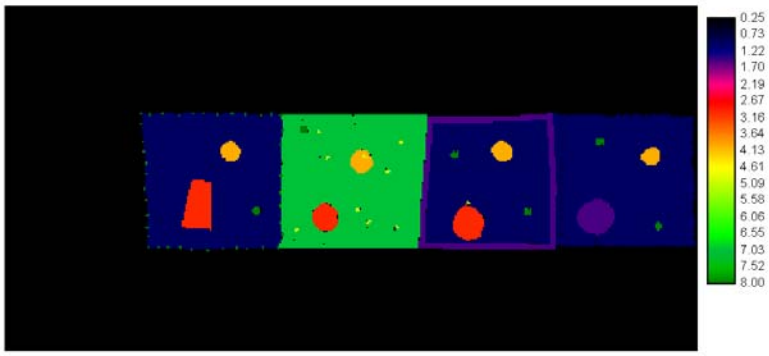
	Min.	Max.	Spacing	# Lines
X	0.025	19.975	.1	201
Y	0	10	.1	101

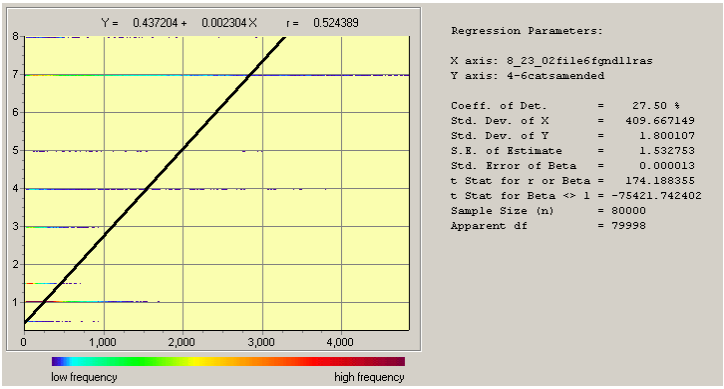
GSSI 400MHz Wet

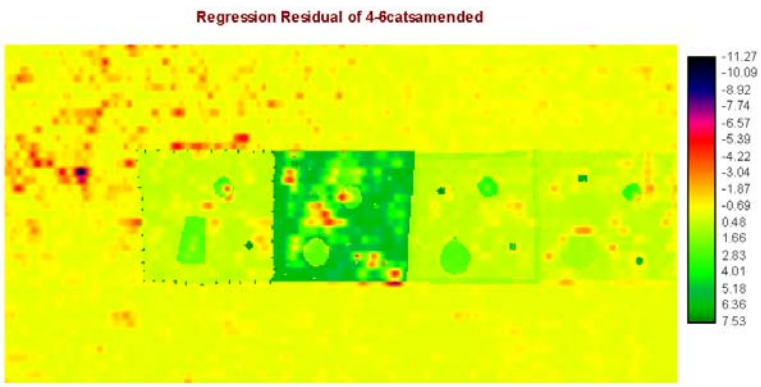
CATS House Floors 10ns – 12ns

8_23_02 Foreground Removal at 11

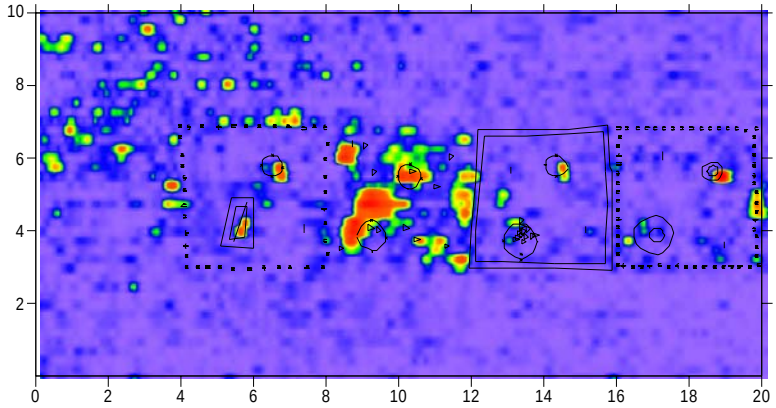


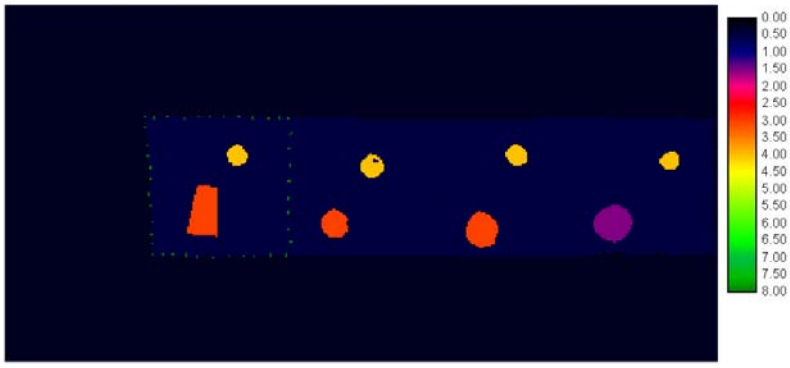


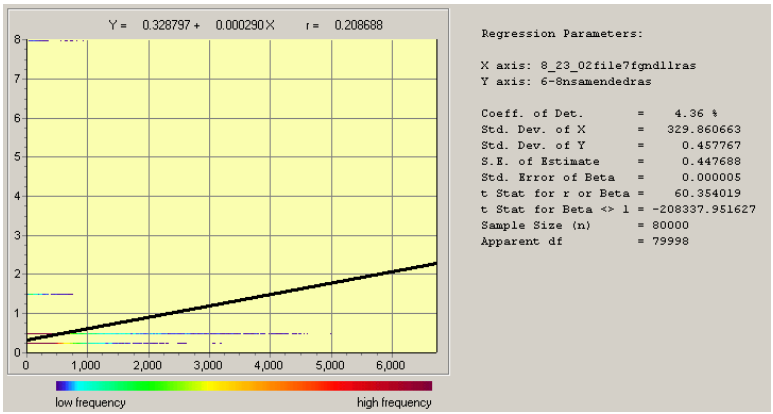



Regression Residual of 4-6catsamended
-11.27
-10.09
-8.92
-7.74
-6.57
-5.39
-4.22
-3.04
-1.87
-0.69
0.48
1.66
2.83
4.01
5.18
6.36
7.53

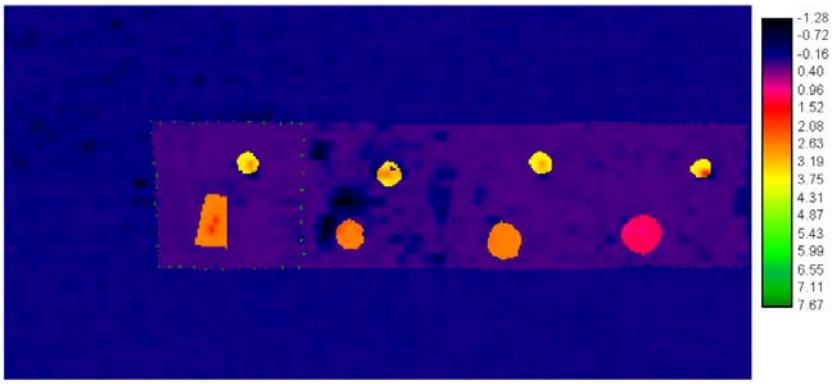
GSSI 400MHz Wet
CATS House Floors 12ns – 14ns
8_23_02 Foreground Removal at 11



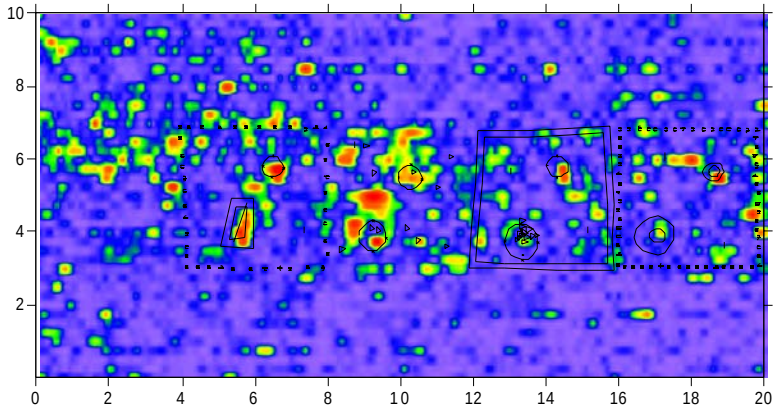


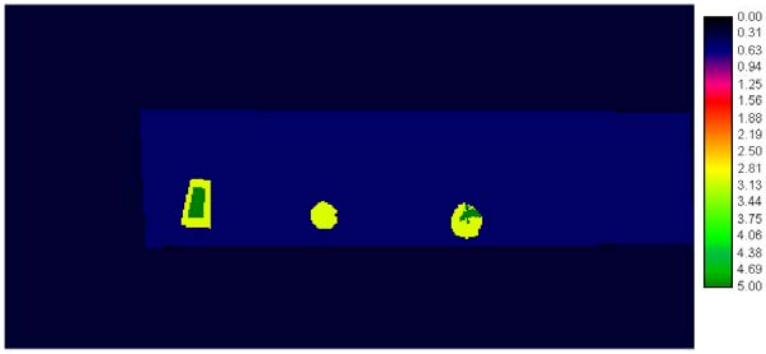


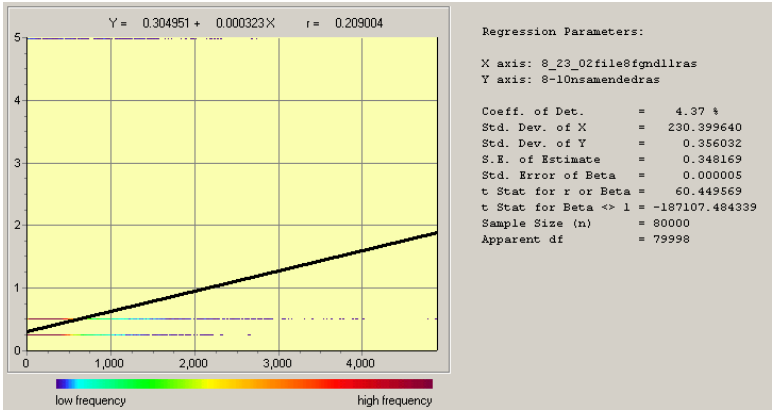
Regression Residual of 6-8nsamendedras



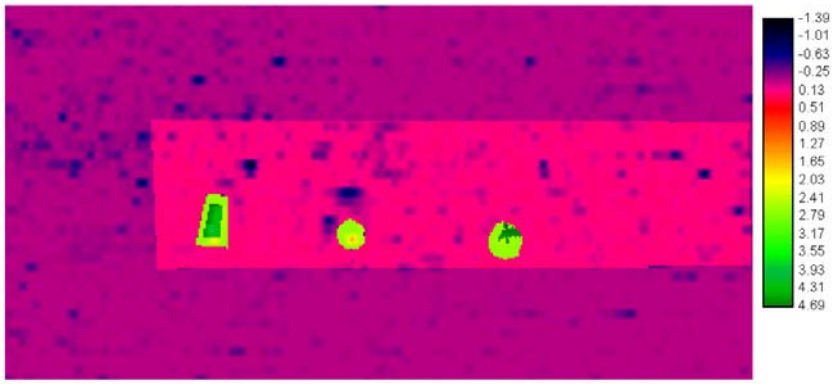
GSSI 400MHz Wet
CATS Housefloors 14ns – 16ns
8_23_02 Foreground Removal at 11



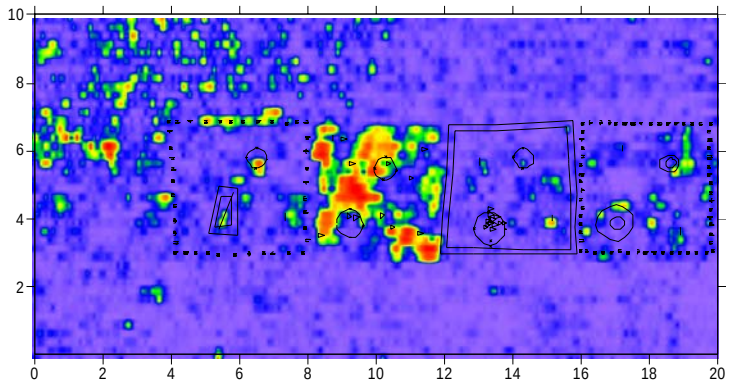


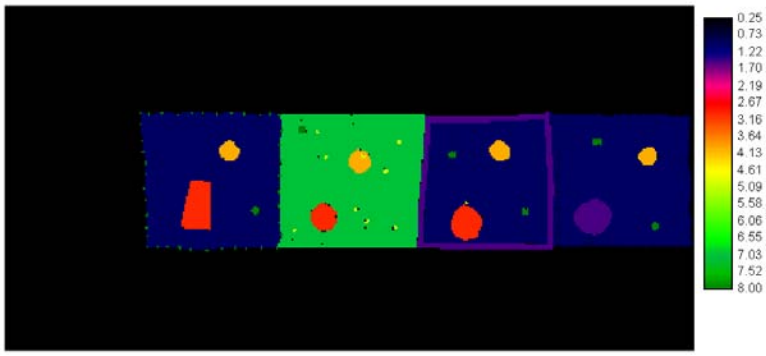


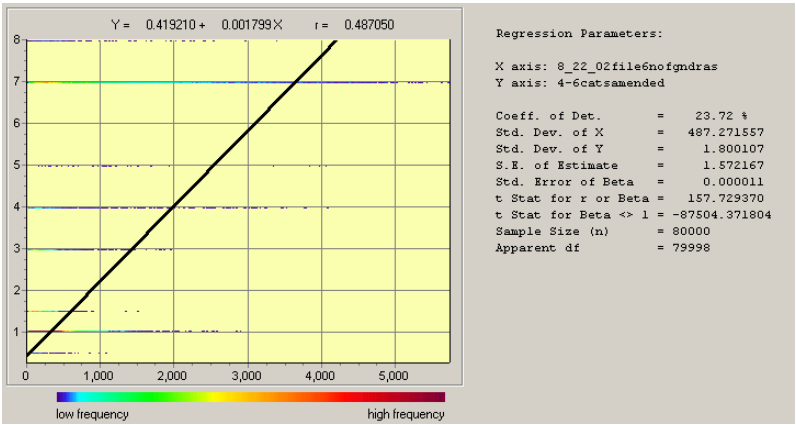
Regression Residual of 8-10nsamendedras

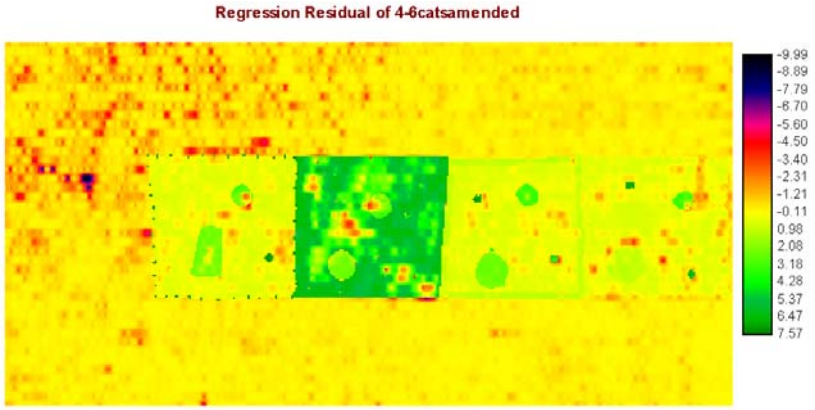


GSSI 400MHz Wet
CATS House Floors 10ns – 12ns
8_23_02 No Foreground Removal

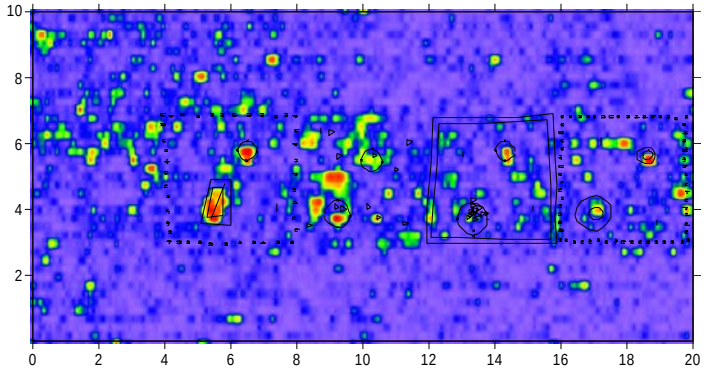


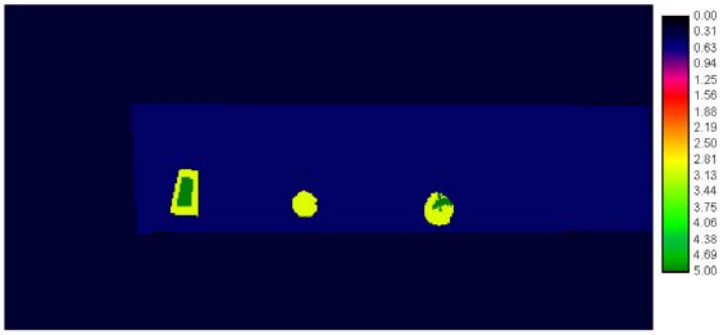


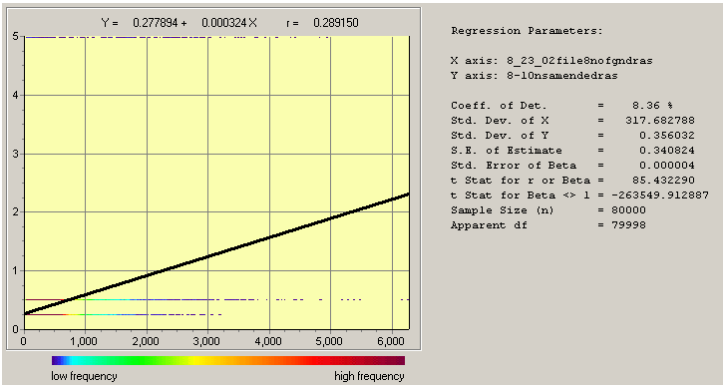


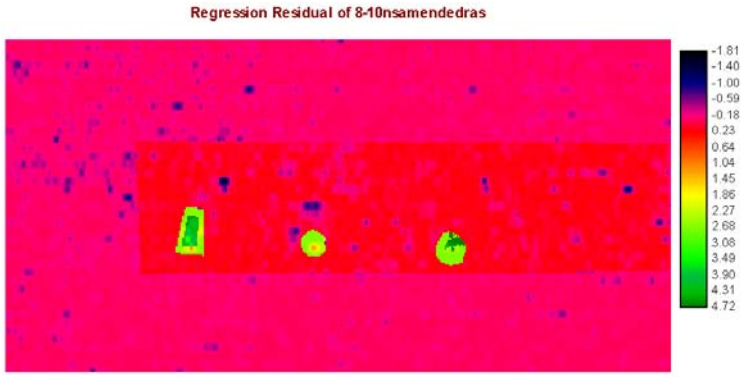

Regression Residual of 4-6catsamended
-9.99
-8.89
-7.79
-6.70
-5.60
-4.50
-3.40
-2.31
-1.21
-0.11
0.98
2.08
3.18
4.28
5.37
6.47
7.57

GSSI 400MHz Wet
CATS House Floors 14ns – 16ns
8_23_02 No Foreground Removal

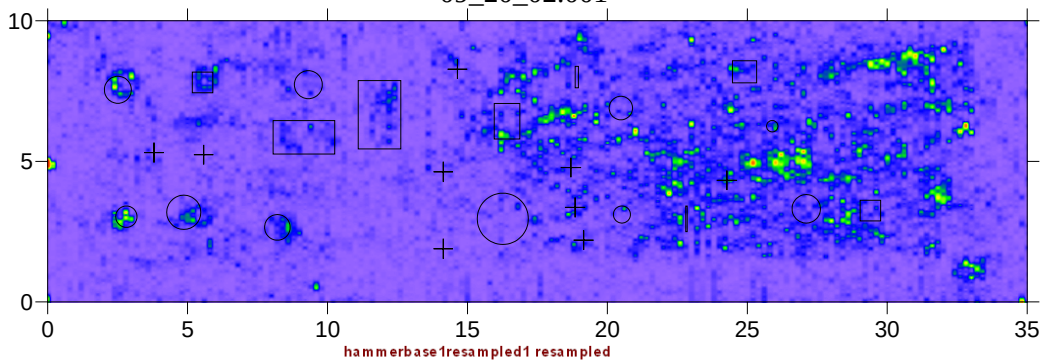


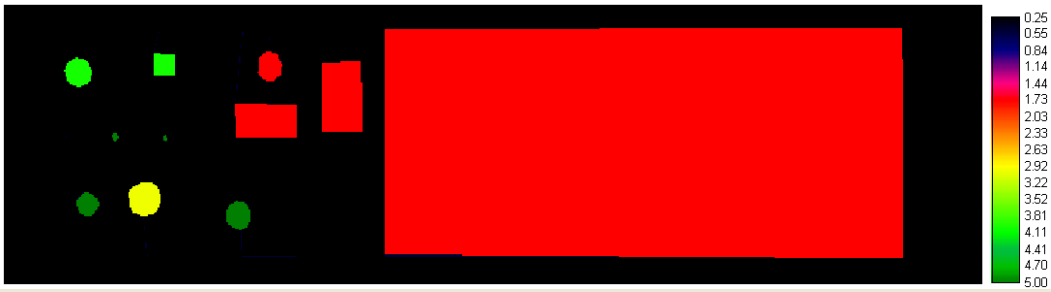


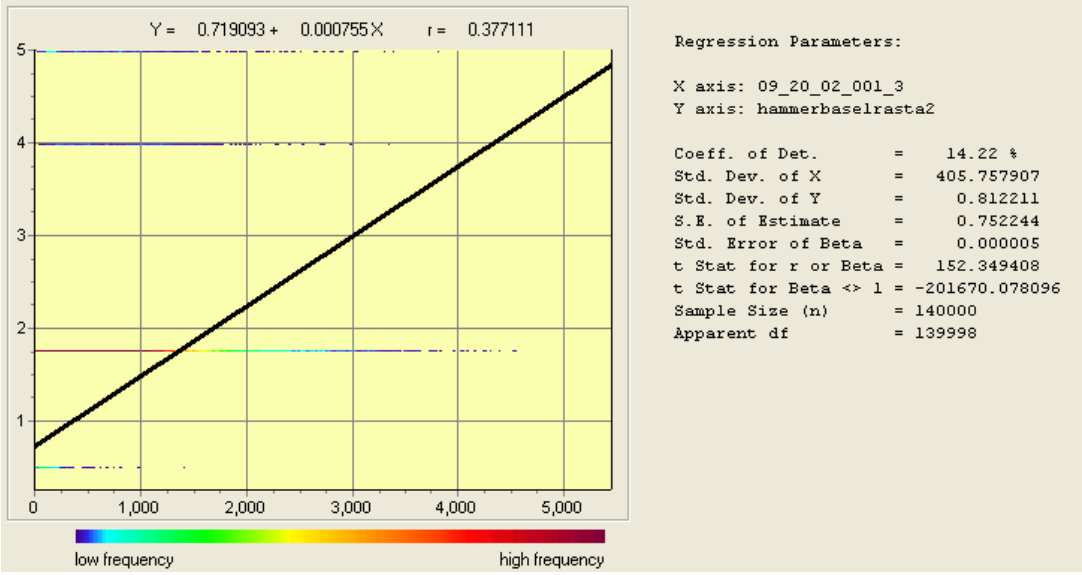



Regression Residual of 8-10nsamendedras
-1.81
-1.40
-1.00
-0.59
-0.18
0.23
0.64
1.04
1.45
1.86
2.27
2.68
3.08
3.49
3.90
4.31
4.72

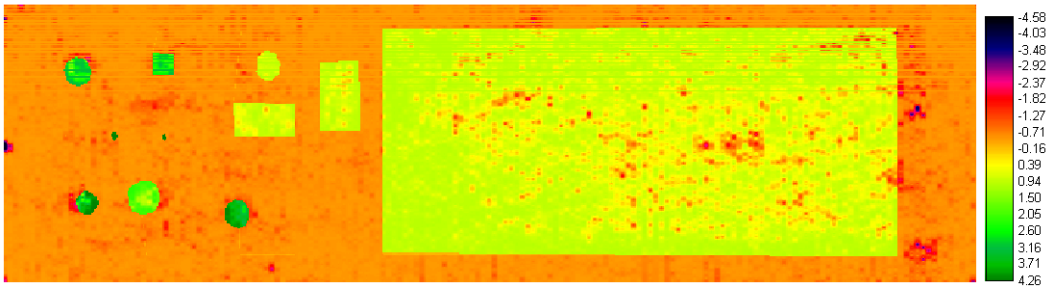
GSSI 900MHz
Hammer 4-6ns
09_20_02.001



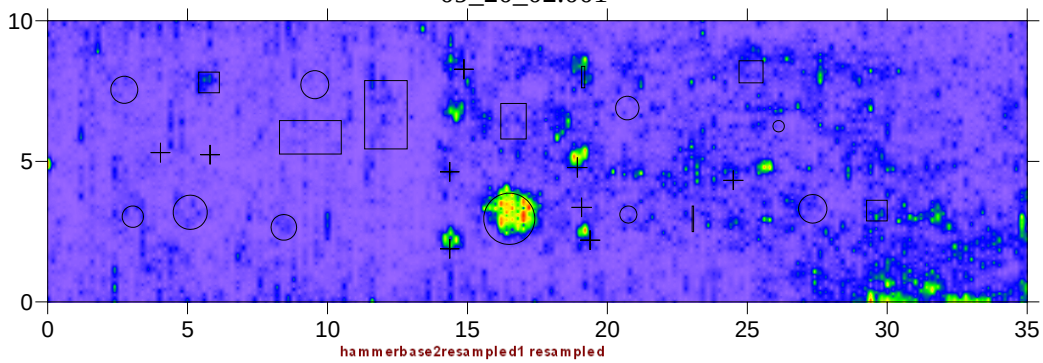


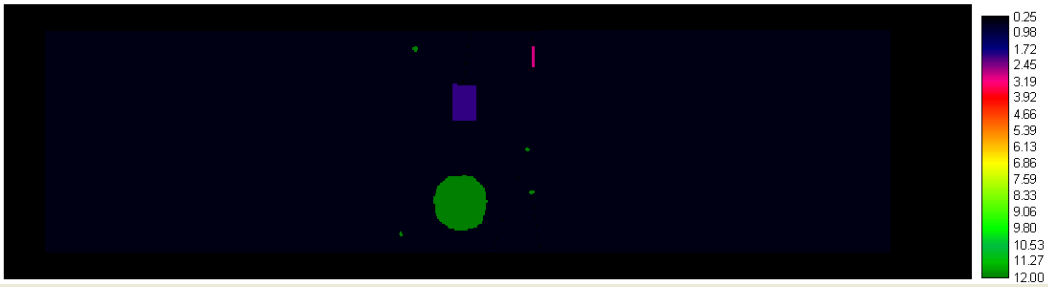


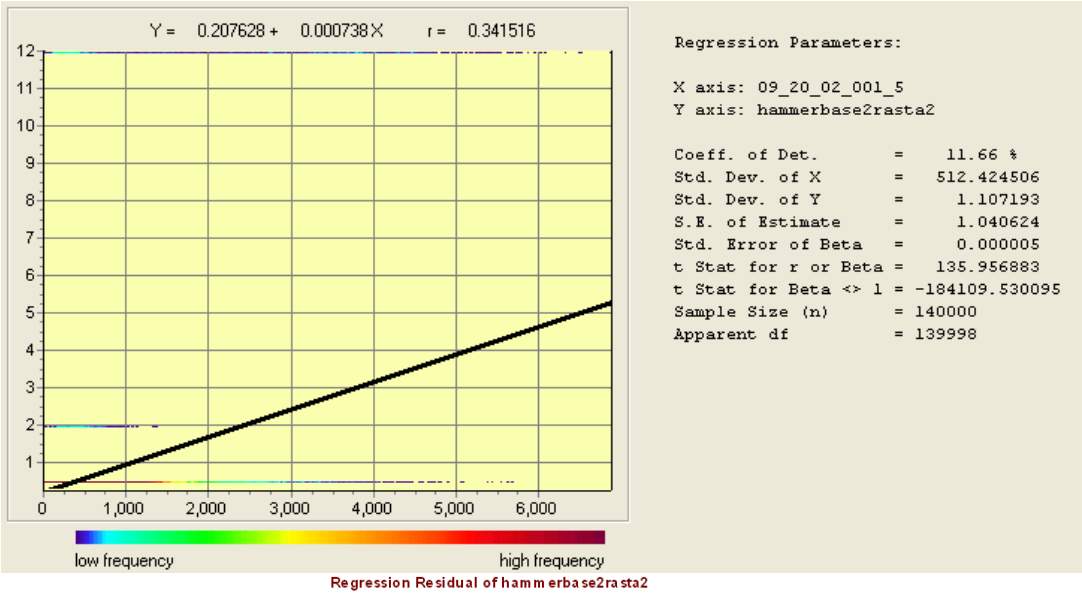
Regression Residual of hammerbase1rasta2

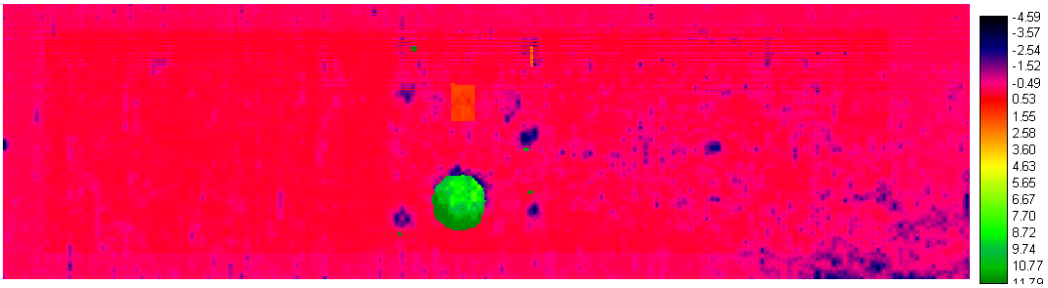


GSSI 900MHz
Hammer 8-10ns
09_20_02.001

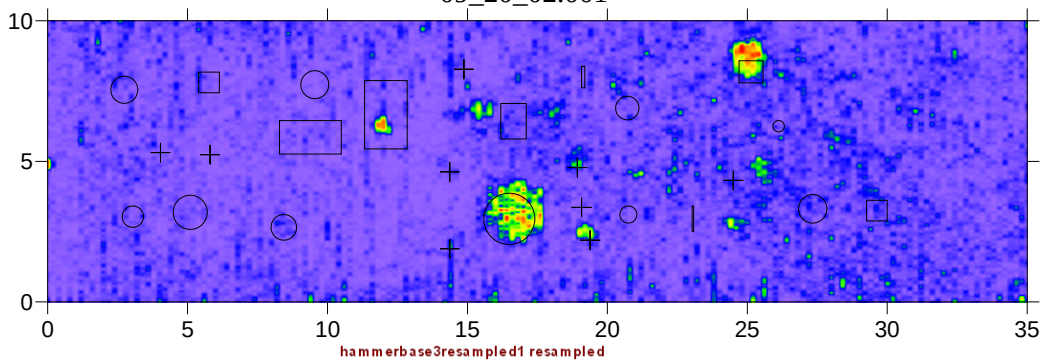


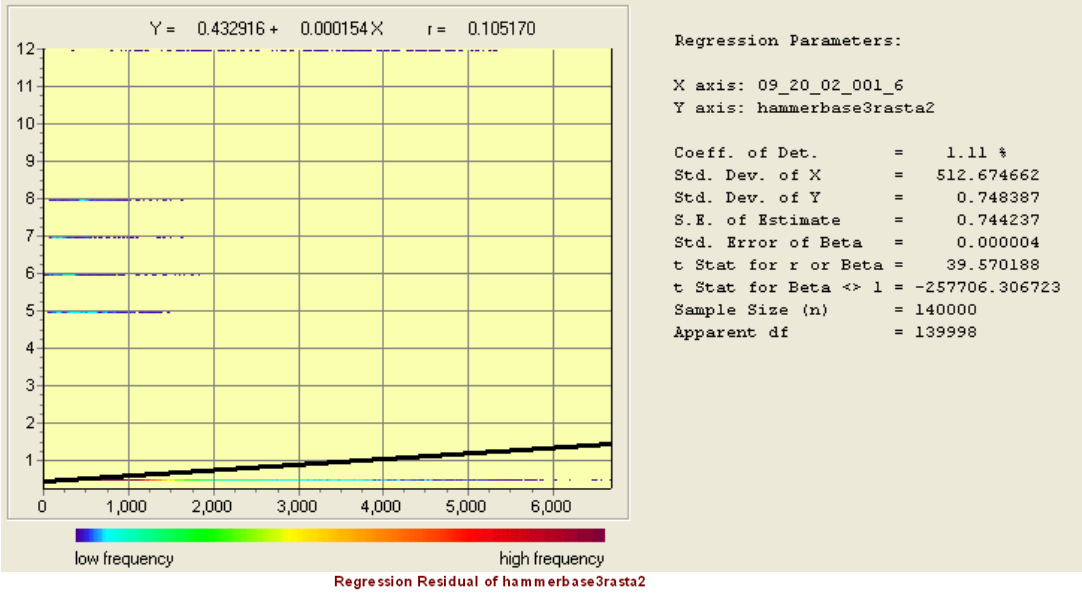


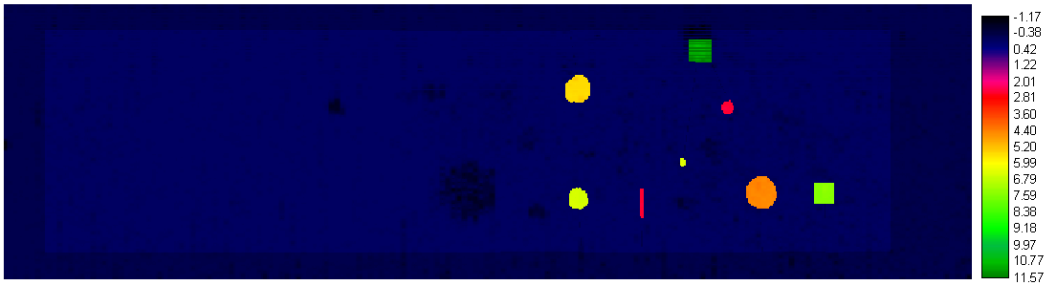




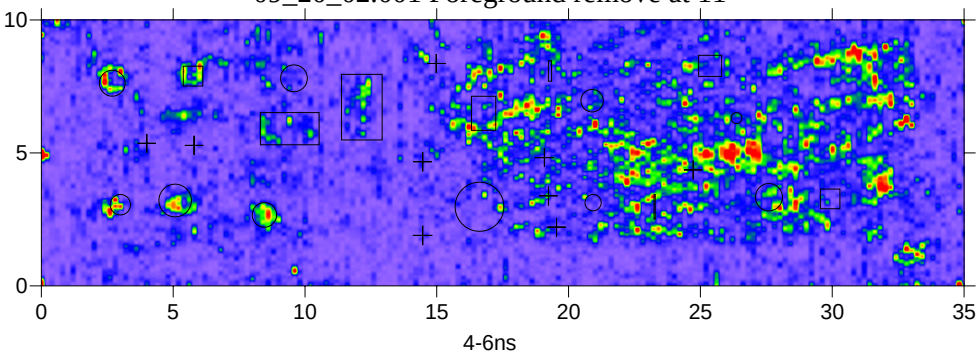
GSSI 900MHz
Hammer 10-12ns
09_20_02.001



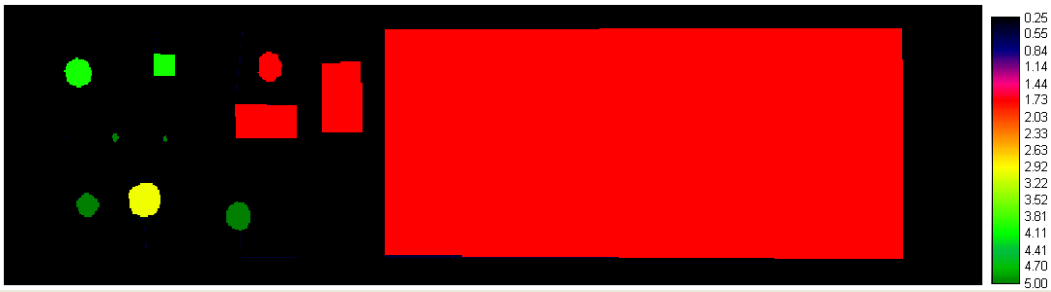


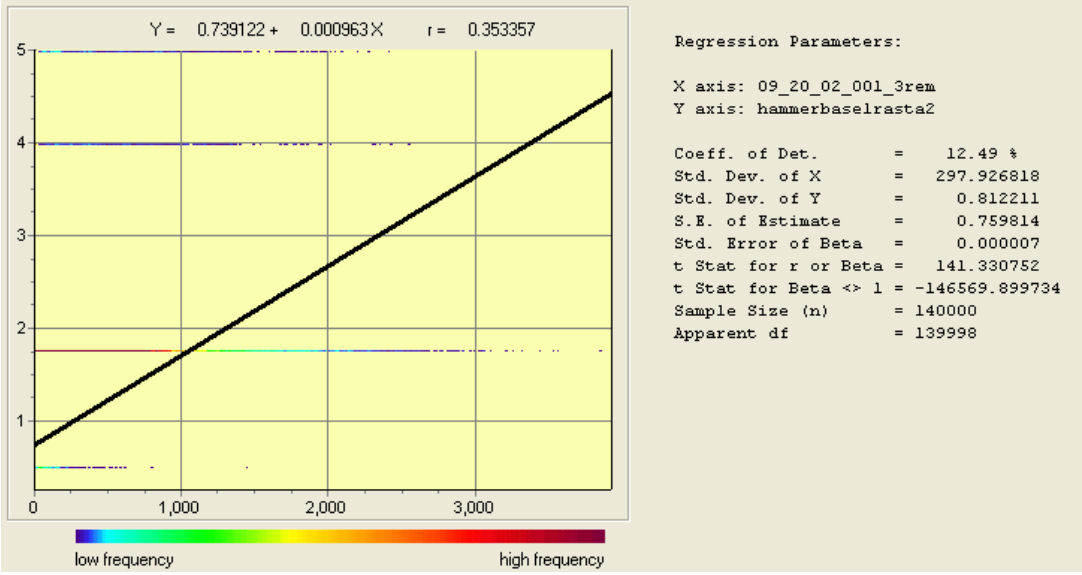


GSSI 900MHz
Hammer 4-6ns
09_20_02.001 Foreground remove at 11

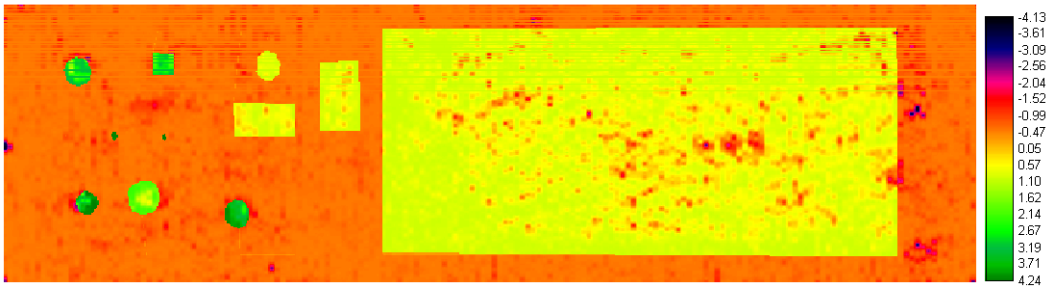


hammerbase1resampled1 resampled

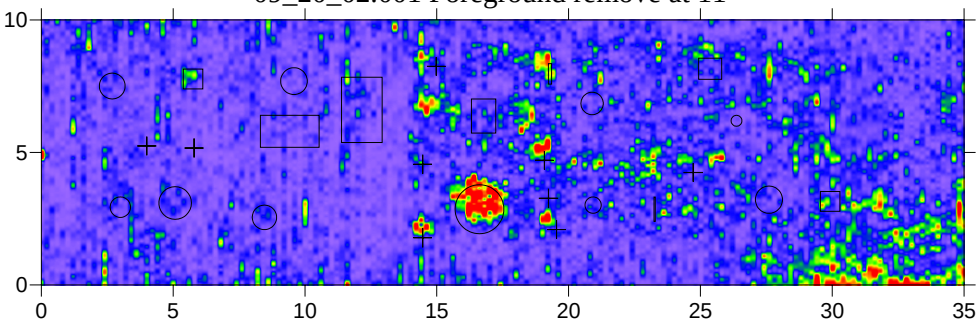




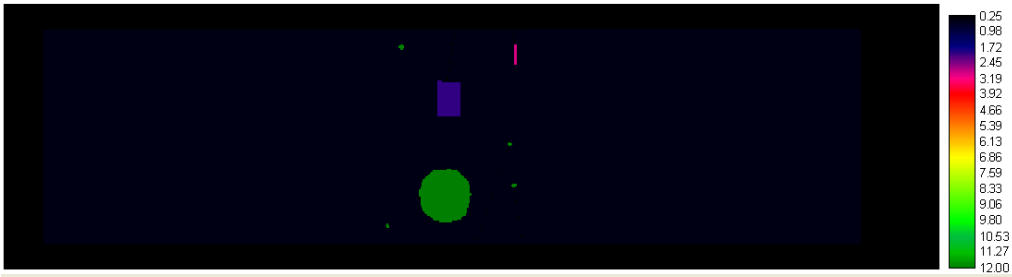
Regression Residual of hammerbase1rasta2

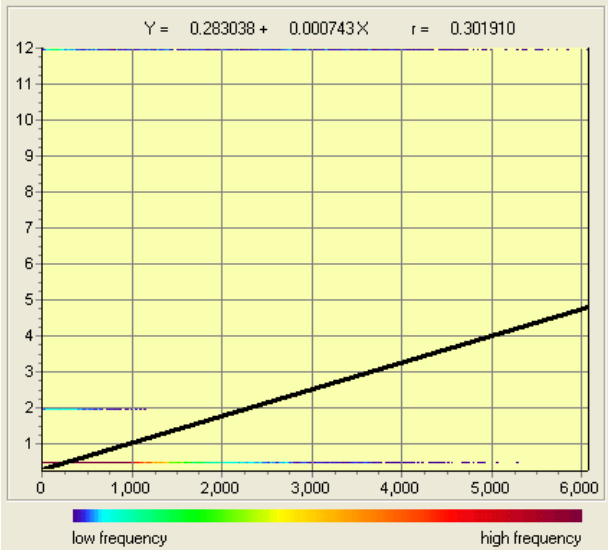


GSSI 900MHz
Hammer 8-10ns
09_20_02.001 Foreground remove at 11



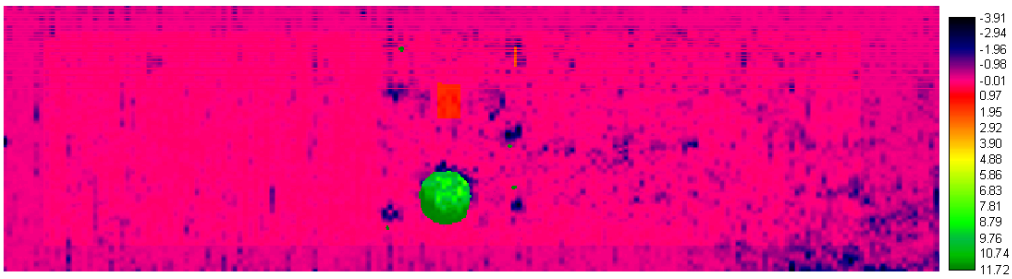
8-10ns
hammerbase2resampled1 resampled



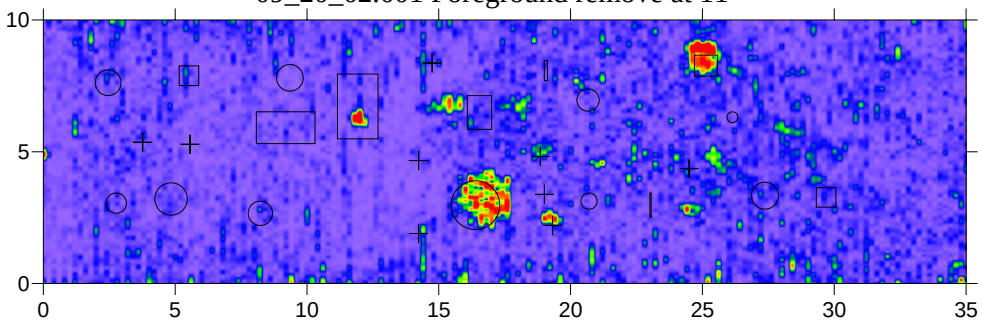



```
Regression Parameters:

X axis: 09_20_02_001_5rem
Y axis: hammerbase2rasta2

Coeff. of Det.        =    9.11 %
Std. Dev. of X        =  450.133858
Std. Dev. of Y        =    1.107193
S.E. of Estimate      =    1.055528
Std. Error of Beta    =    0.000006
t Stat for r or Beta  =  118.492797
t Stat for Beta <> 1  = -159444.804495
Sample Size (n)       = 140000
Apparent df           = 139998
```

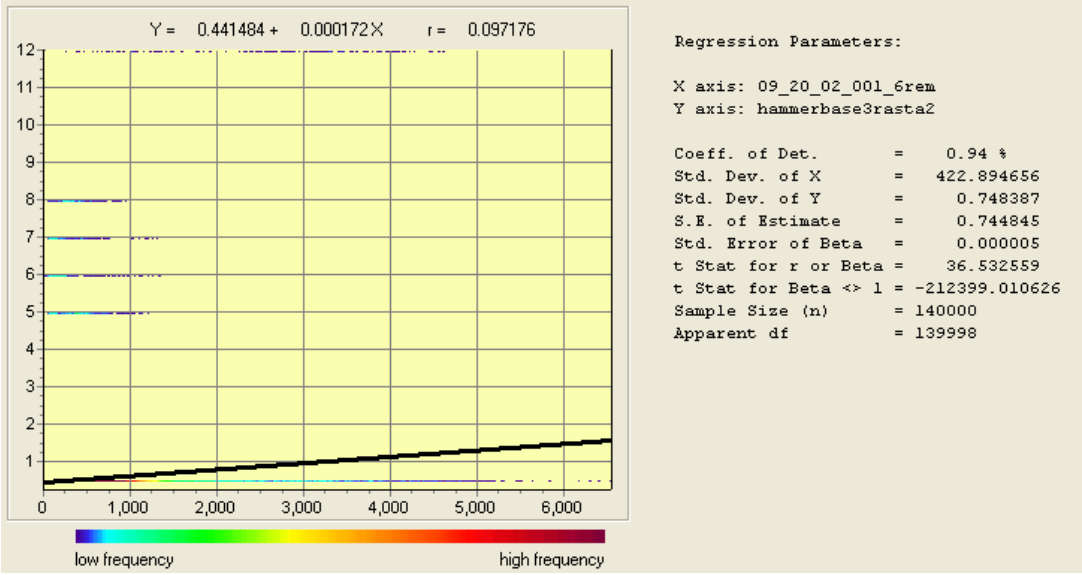
Regression Residual of hammerbase2rasta2



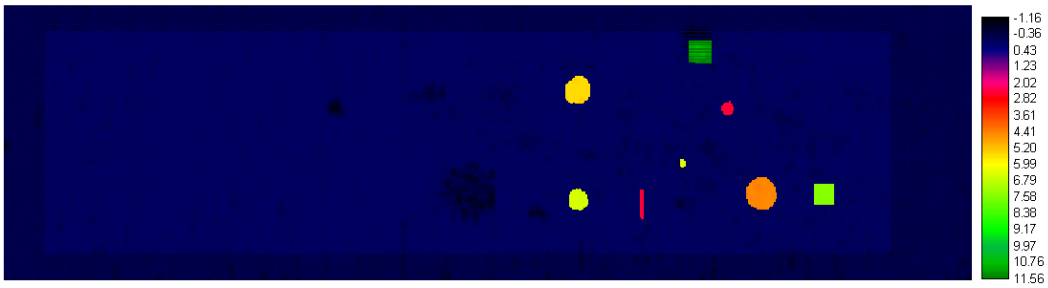
GSSI 900MHz
Hammer 10-12ns
09_20_02.001 Foreground remove at 11



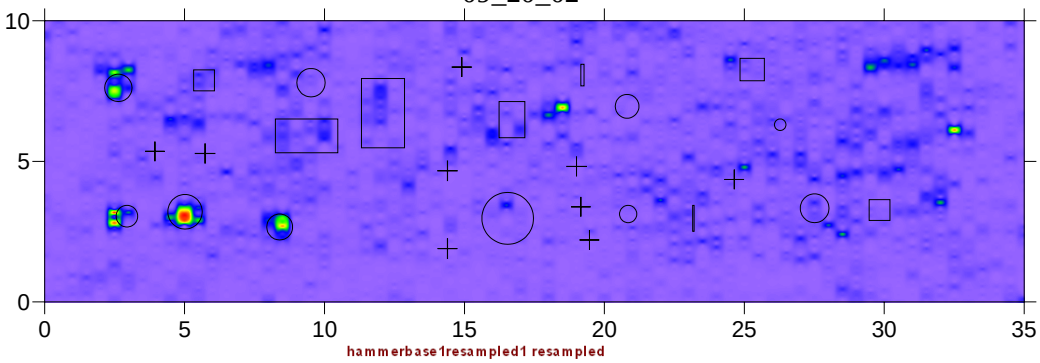
10-12ns
hammerbase3resampled1 resampled

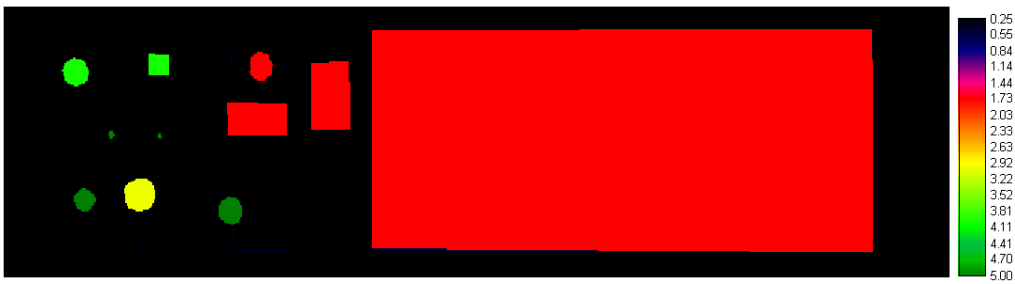


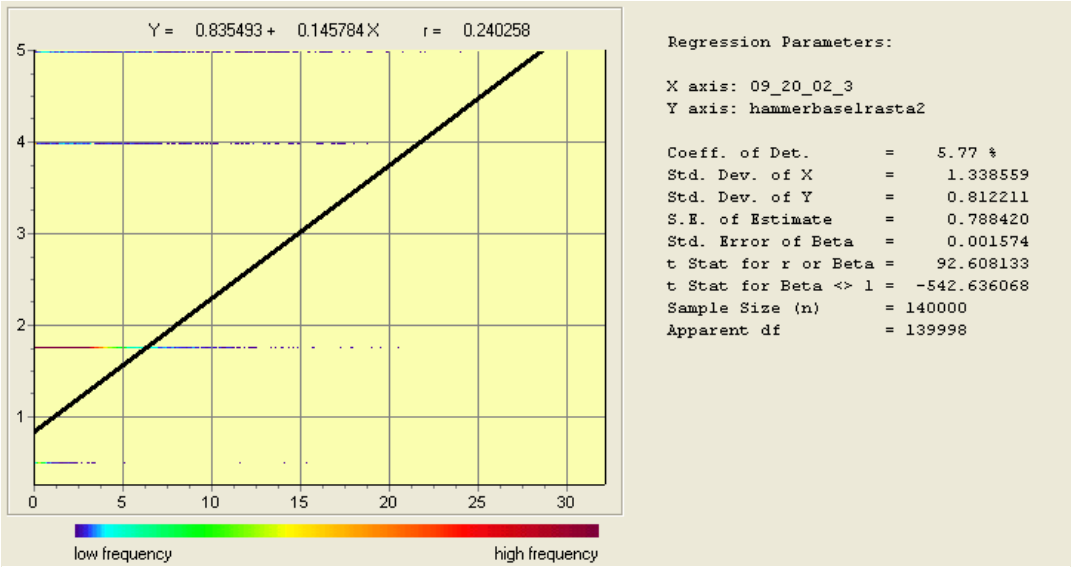
Regression Residual of hammerbase3rasta2



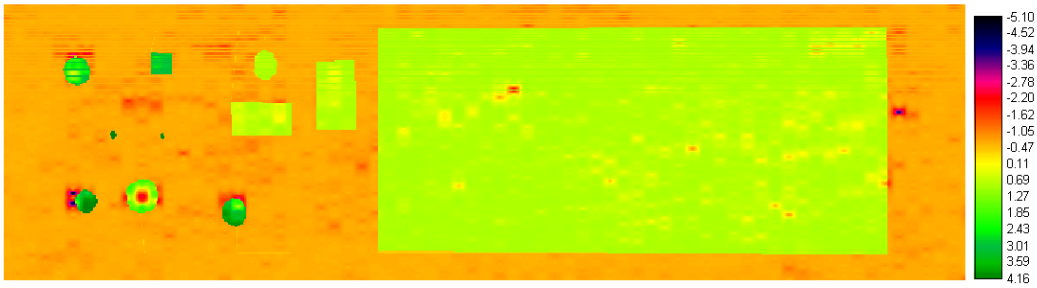
GSSI 400MHz
Hammer 4-6ns
09_20_02



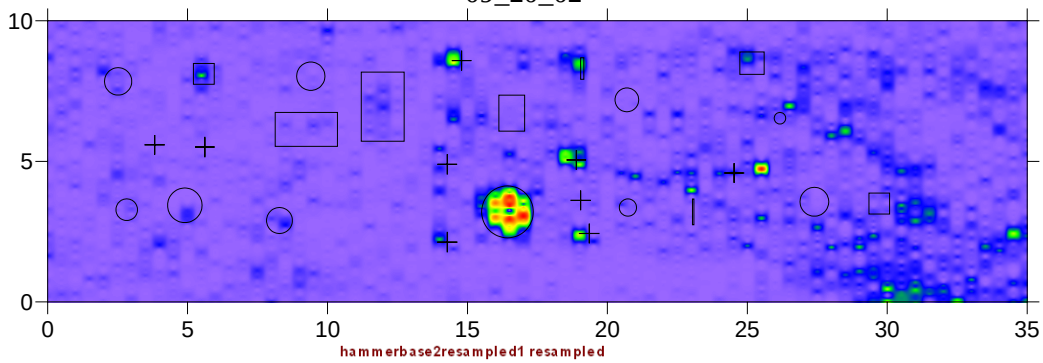


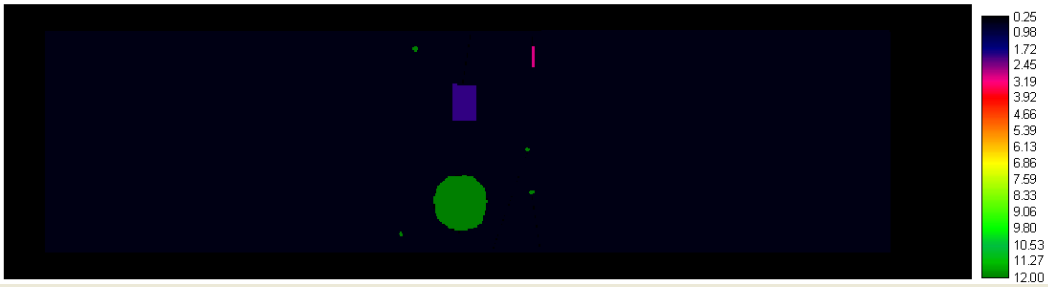


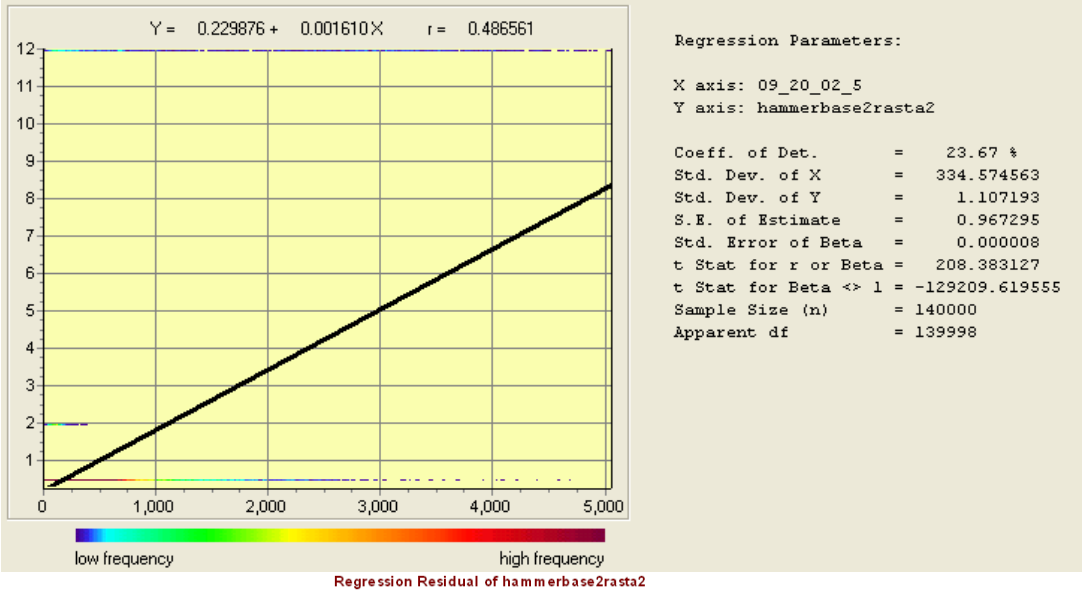
Regression Residual of hammerbase1rasta2



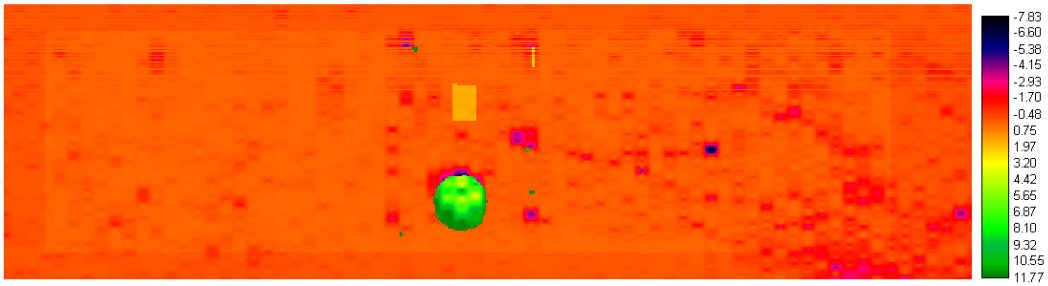
GSSI 400MHz
Hammer 8-10ns
09_20_02



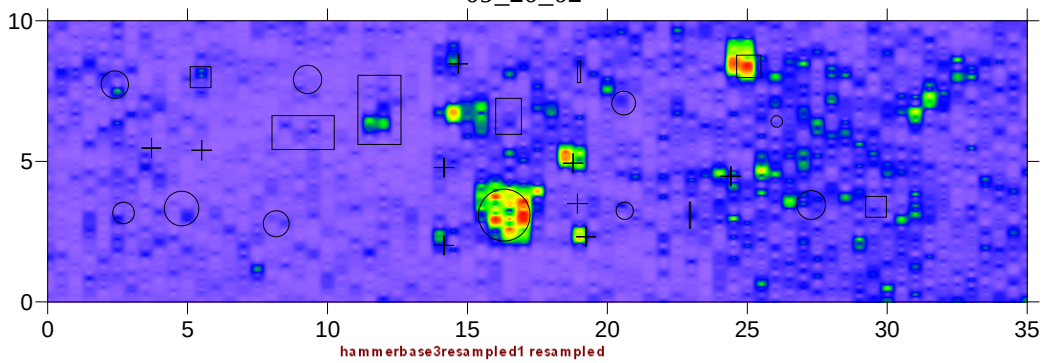


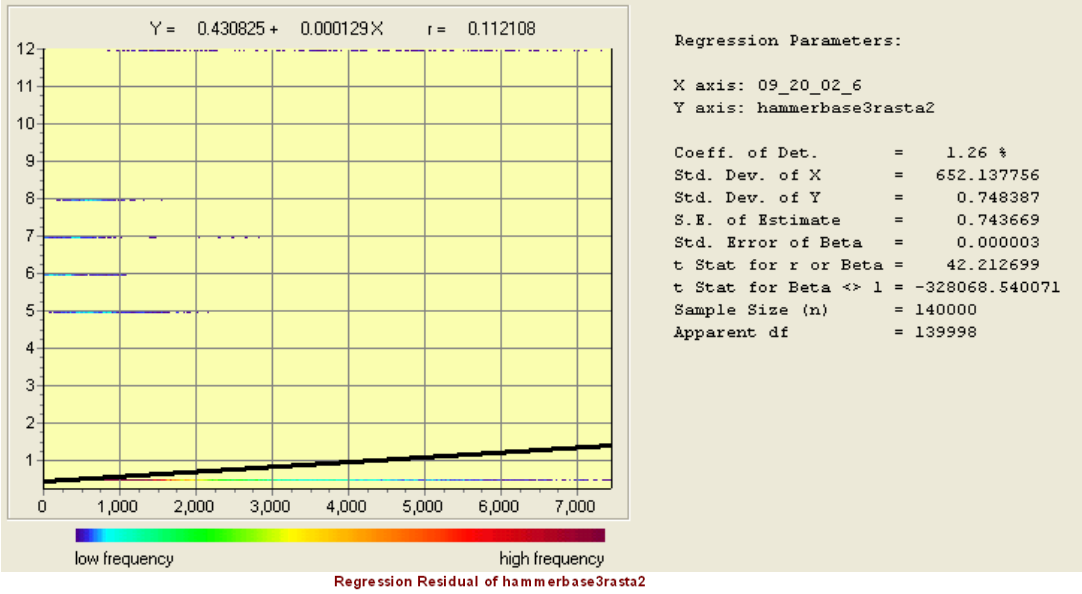


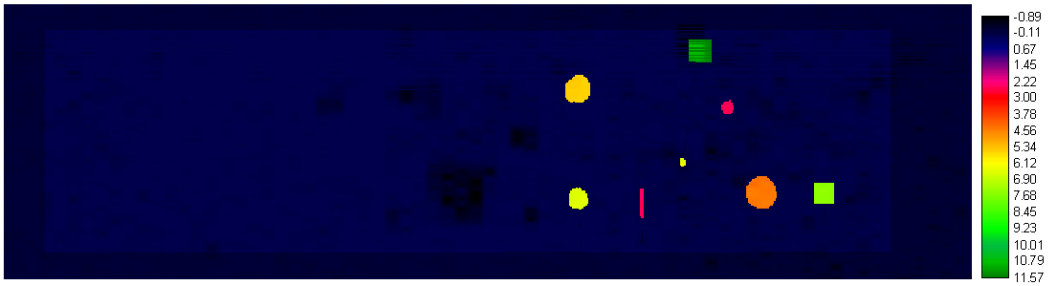
Regression Residual of hammerbase2rasta2



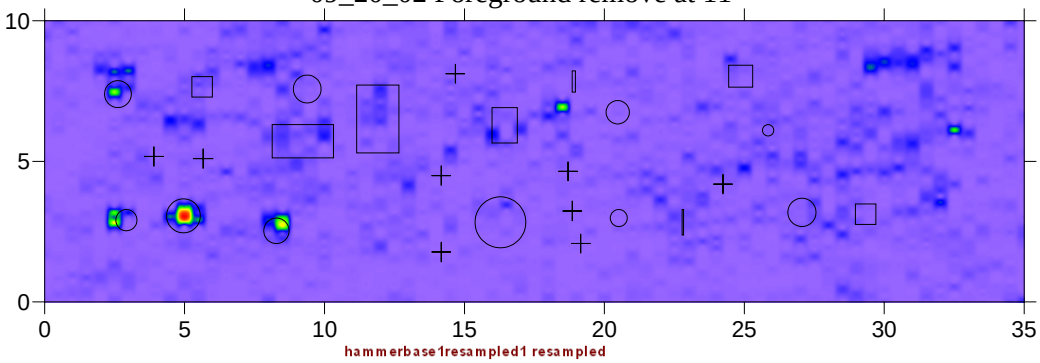
GSSI 400MHz
Hammer 10-12ns
09_20_02

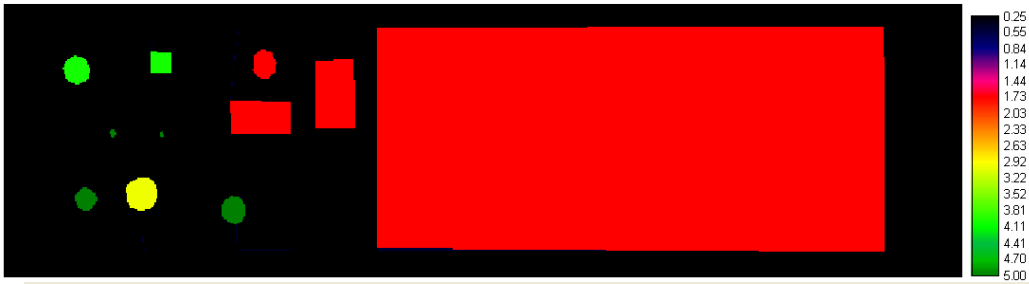


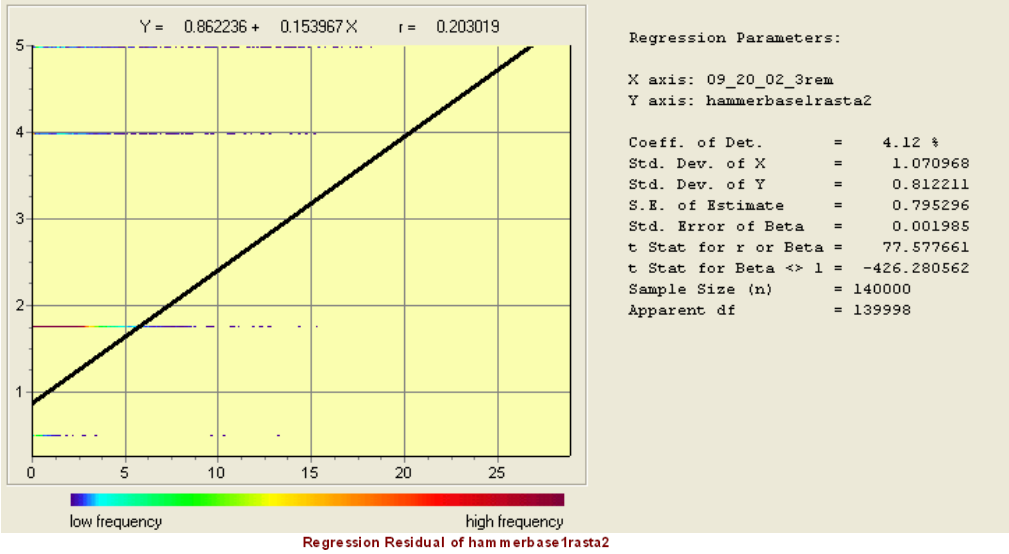




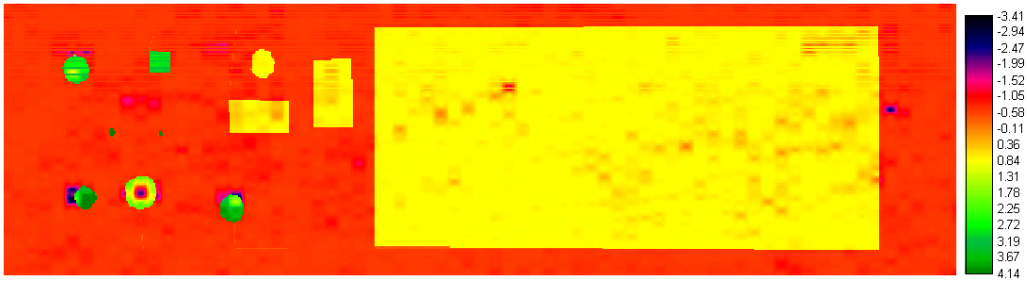
GSSI 400MHz
Hammer 4-6ns
09_20_02 Foreground remove at 11



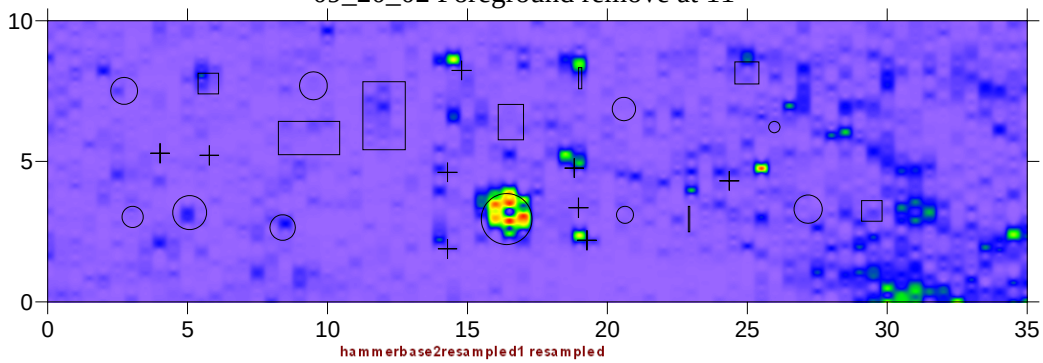


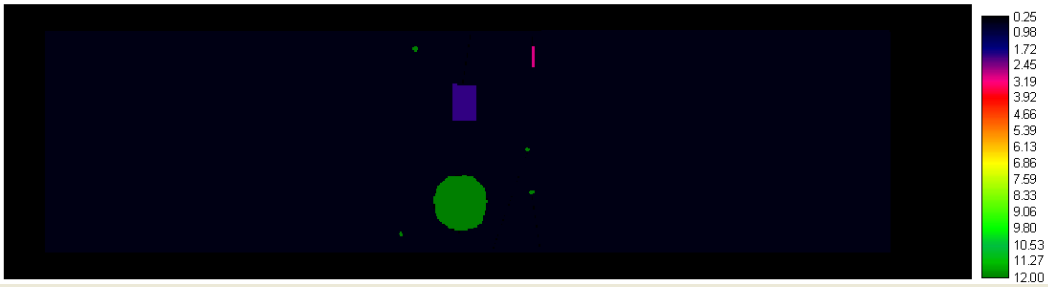


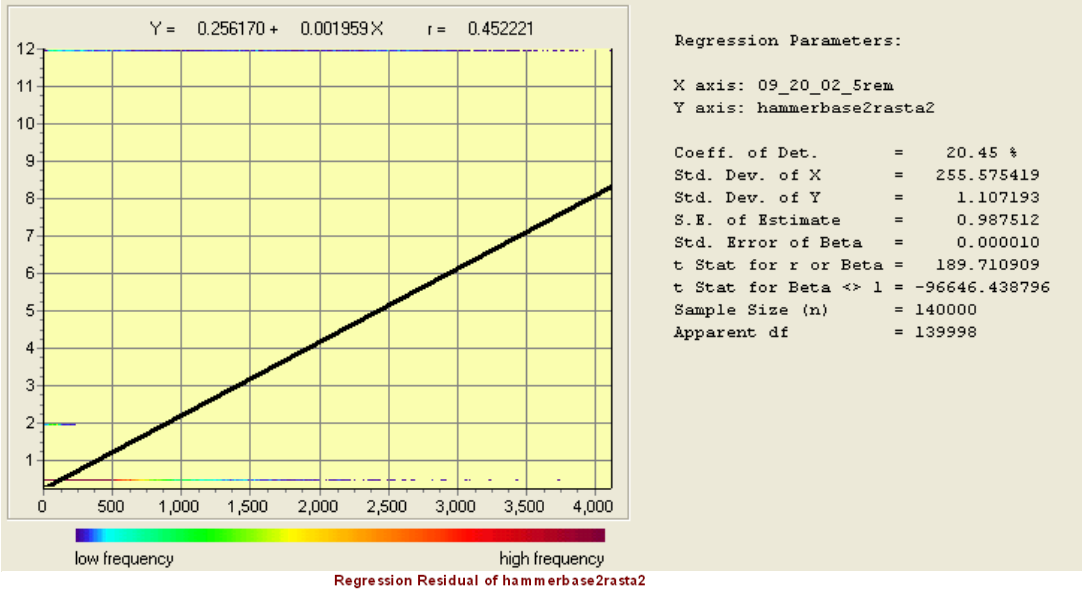
Regression Residual of hammerbase1rasta2



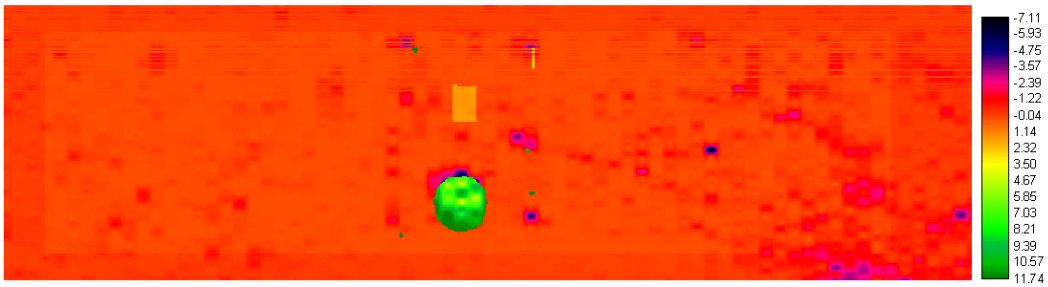
GSSI 400MHz
Hammer 8-10ns
09_20_02 Foreground remove at 11



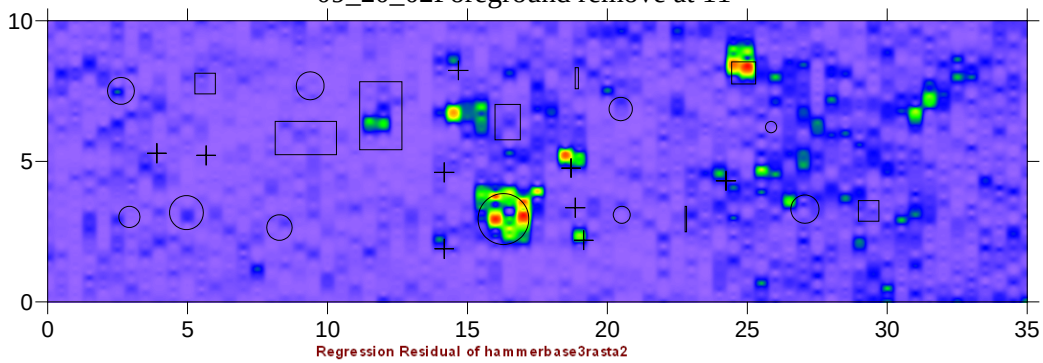


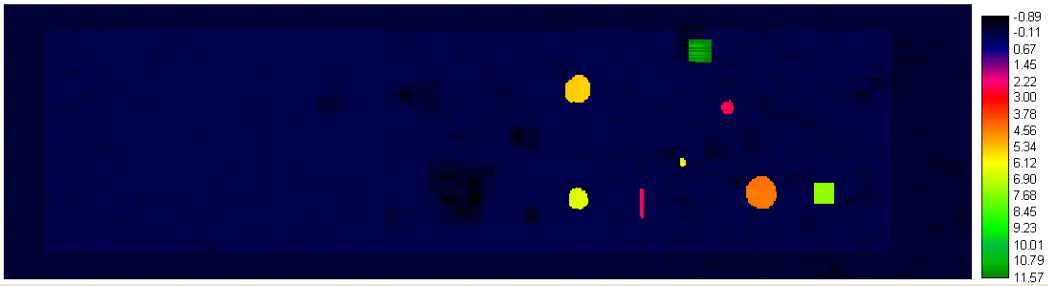


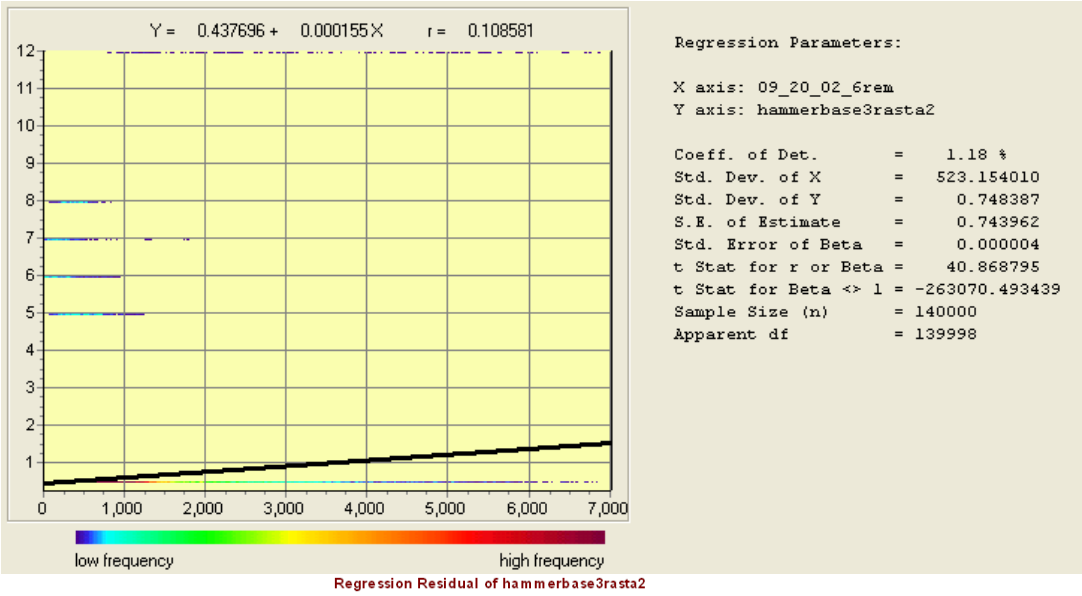
Regression Residual of hammerbase2rasta2

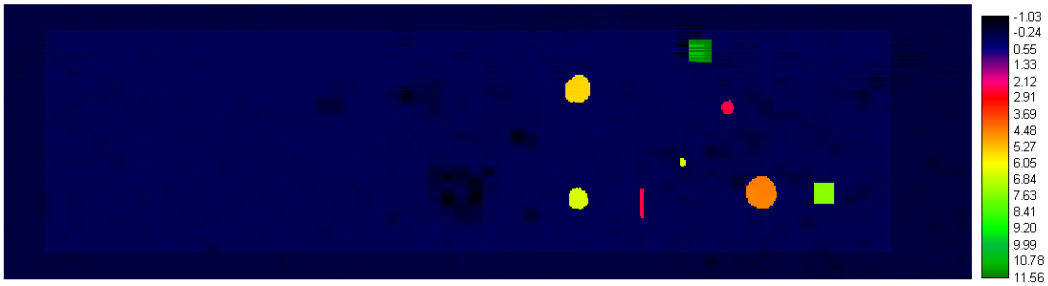


GSSI 400MHz
Hammer 10-12ns
09_20_02Foreground remove at 11

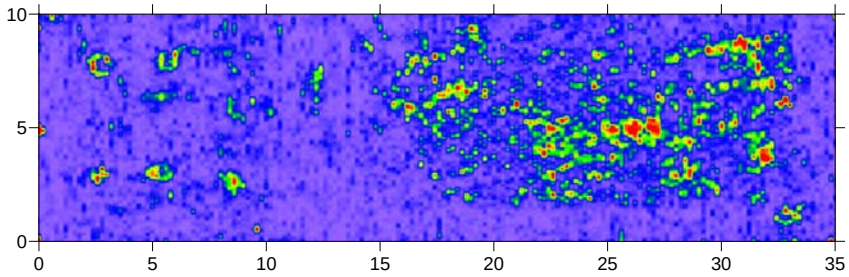




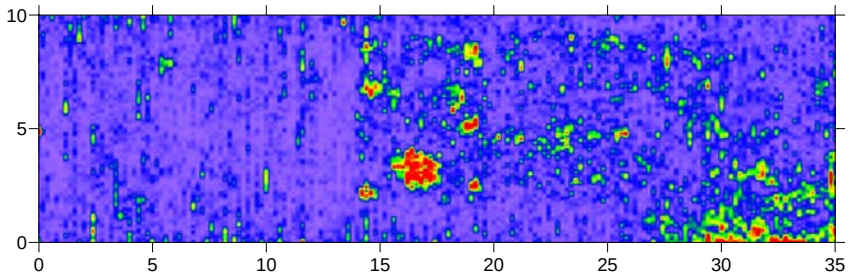




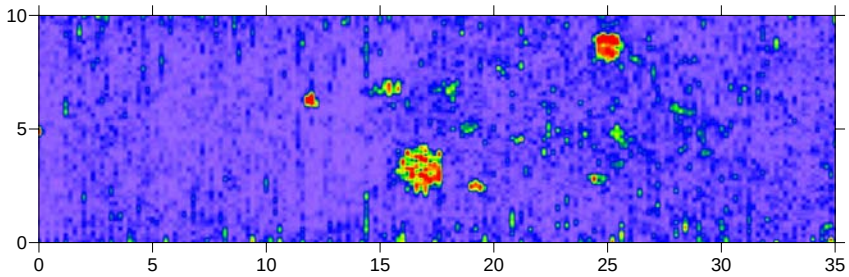
GSSI 900MHz
Hammer .20m spacing
09_20_02.001 Foreground remove



4-6ns



8-10ns



10-12ns

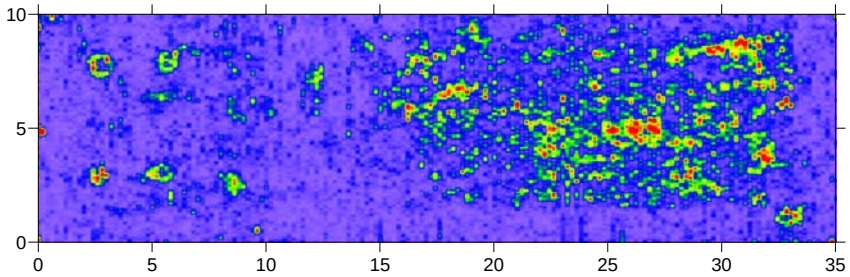
Processing/Slice Parameters

	X	Y	Z
First	-0.1	0	0
Last	35.1	10	20
# Cells	176	400	10
Box Size	.1	.1	2

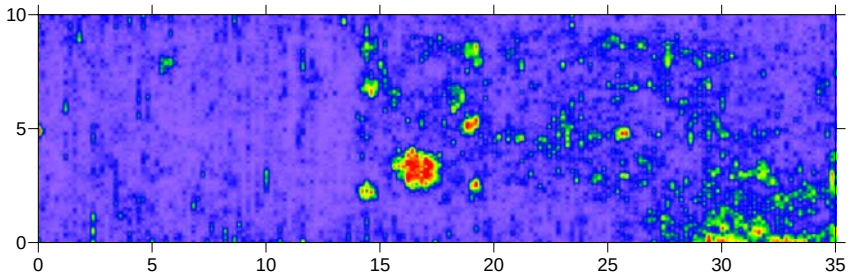
Gridline Geometry

	Min	Max	Spacing	# Lines
X	0	35	0.05	701
Y	0	10	0.05	201

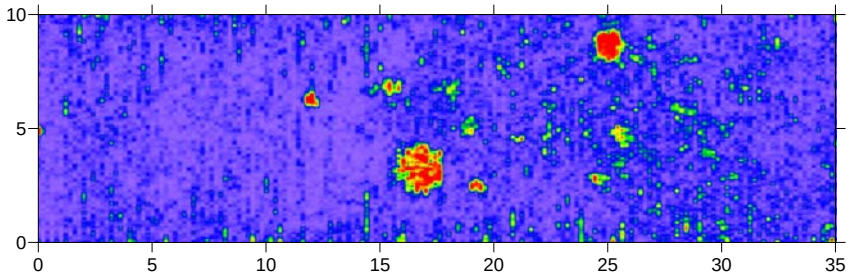
GSSI 900MHz
Hammer .20m spacing
09_20_02.001



4-6ns



8-10ns



10-12ns

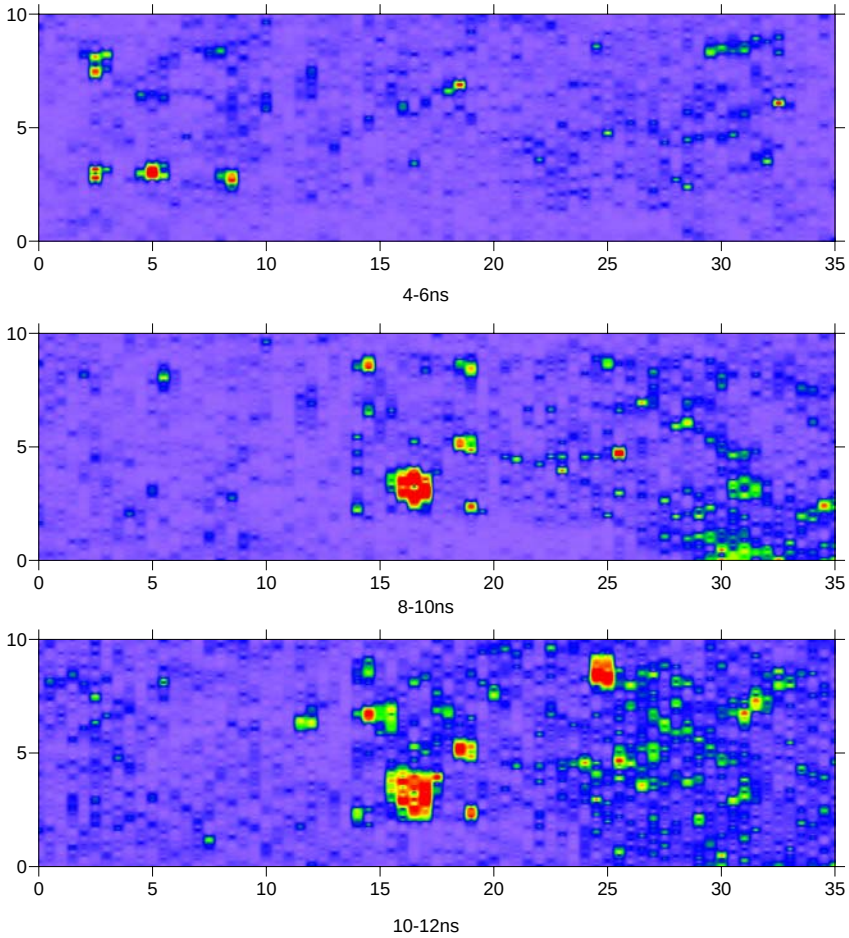
Processing/Slice Parameters

	X	Y	Z
First	-0.1	0	0
Last	35.1	10	20
# Cells	176	400	10
Box Size	.1	.1	2

Gridline Geometry

	Min	Max	Spacing	# Lines
X	0	35	0.05	701
Y	0	10	0.05	201

GSSI 400MHz
Hammer .50m spacing
09_20_02



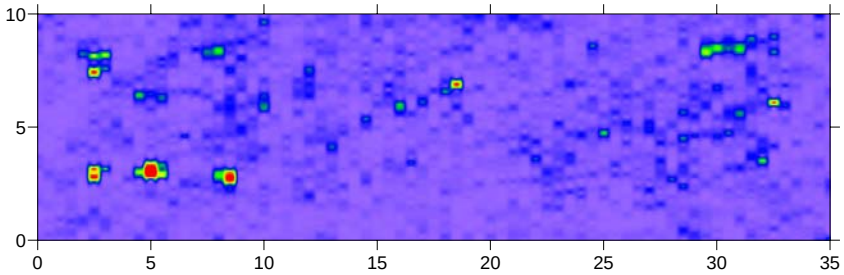
Processing/Slice Parameters

	X	Y	Z
First	-0.25	0	0
Last	35.25	10	30
# Cells	71	400	15
Box Size	.1	.1	2

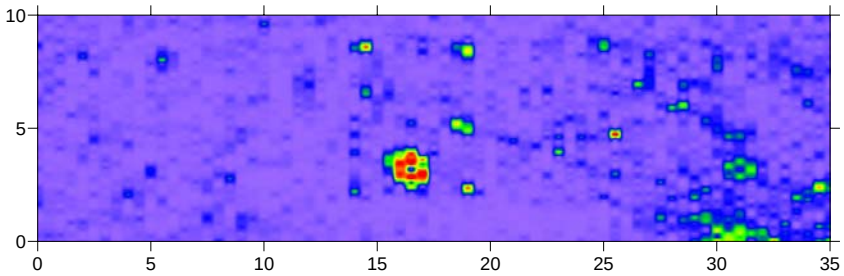
Gridline Geometry

	Min	Max	Spacing	# Lines
X	0	35	0.05	701
Y	0	10	0.05	201

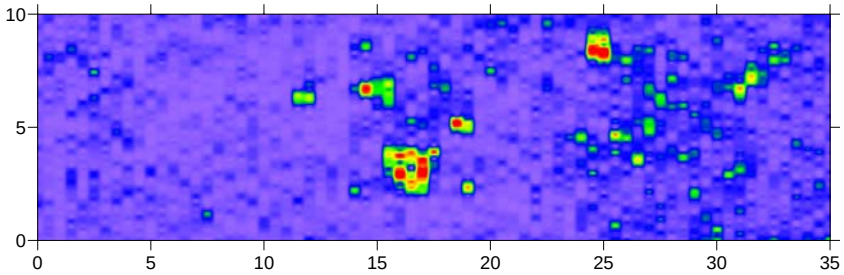
GSSI 400MHz
Hammer .50m spacing
09_20_02 Foreground remove



4-6ns



8-10ns



10-12ns

Processing/Slice Parameters

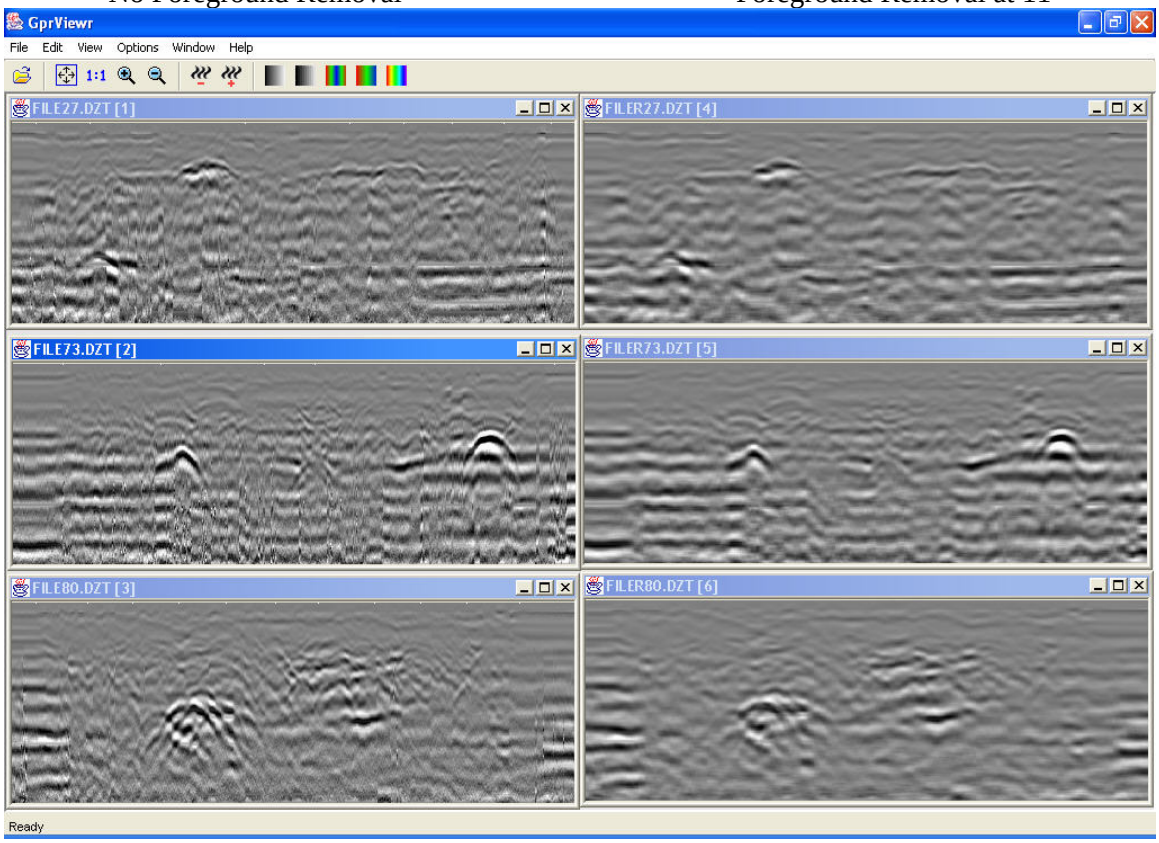
	X	Y	Z
First	-0.25	0	0
Last	35.25	10	30
# Cells	71	400	15
Box Size	.1	.1	2

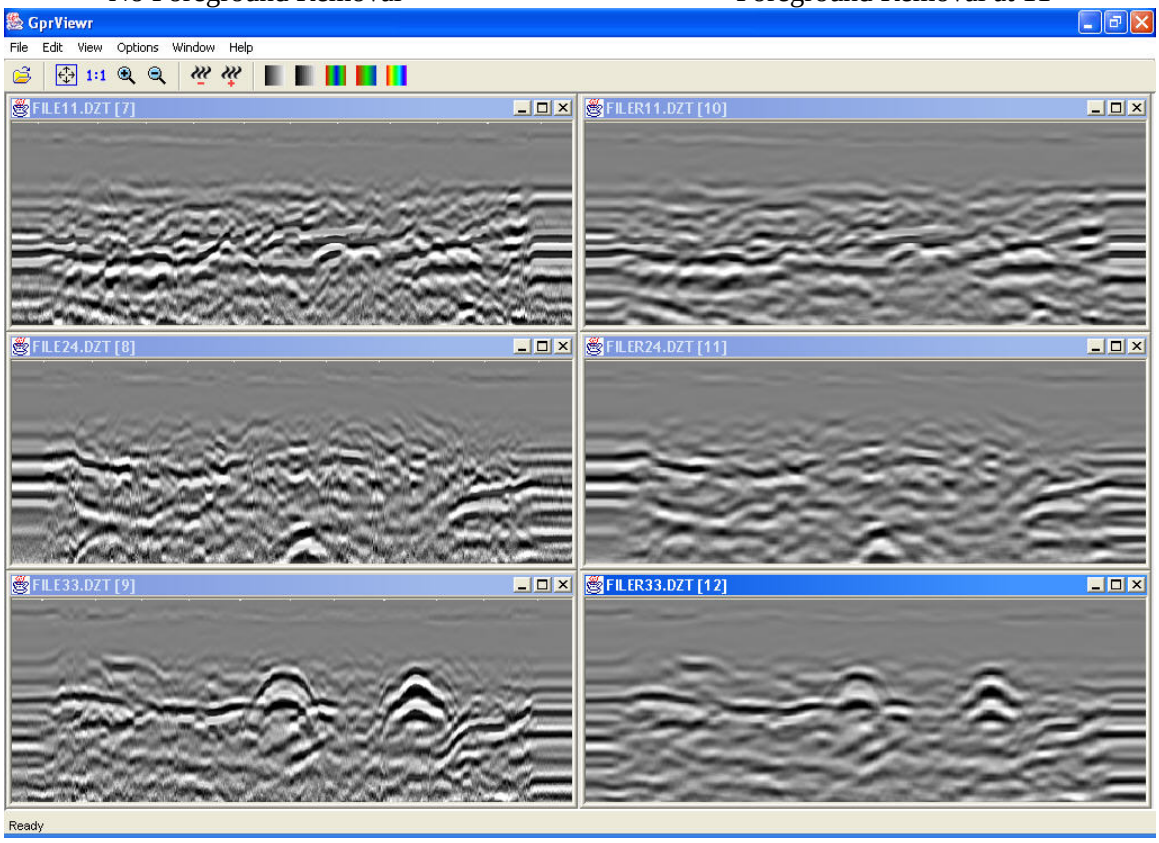
Gridline Geometry

	Min	Max	Spacing	# Lines
X	0	35	0.05	701
Y	0	10	0.05	201

GSSI 900MHz
Hammer
09_20_01.001

No Foreground Removal | Foreground Removal at 11



GSSI 400MHz
Hammer
09_20_01

No Foreground Removal | Foreground Removal at 11