3-D IMAGING OF SUBSURFACE FEATURES USING GPR ARRAY BEAM IMAGING

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ABSTRACT

In this paper, we provide a brief review of standard survey and analysis methods for ground penetrating radar (GPR) and then introduce a new method for producing three-dimensional (3-D) images of the subsurface using GPR. We outline the theory of the new imaging method, called Array Beam Imaging (ABI), by way of a schematic description. We then show results from application of the ABI imaging method to the characterization of a former manufactured gas plant (MGP) site. The 3-D image results are examined using 3-D isosurfaces, 3-D and 2-D volumetric projections, and 2-D tomographic slices. These techniques improve the interpretation of the otherwise standard GPR survey of the relatively complex characteristics of the gas holder and coal tar at the site. Finally, we discuss the relative advantages of the ABI method over traditional methods and summarize some potential future applications of the method.

INTRODUCTION

Historically, the application of Ground Penetrating Radar (GPR) to subsurface geophysical characterization has been limited by its relative effectiveness only for sites with resistive (low conductivity) surface materials. Sites with high clay content soils, saline groundwater conditions, or conductive rock outcrop are not typical candidates for GPR surveys. However, recent developments in GPR hardware, such as shielded antennas and swept frequency systems, have enabled somewhat expanded opportunities to utilize GPR for subsurface investigations. In addition, advances in small, field-worthy computers and specialized algorithms for data processing have increased the potential use of GPR for a broader range of applications.

In this paper, we briefly discuss traditional GPR characterization techniques, including renderings of GPR data as typical "waterfall" displays in a single spatial dimension (1-D) and as two-dimensional (2-D) renderings, where the 2-D format includes both vertical slices (time-to-depth conversion) and plan view maps based on a series of either 1-D data sets or 2-D vertical slices. We then introduce a new processing method that enables true three-dimensional (3-D) GPR imaging. The new method, called Array Beam Imaging (ABI), has been applied to the characterization of a former manufactured gas plant (MGP) site. After outlining the theoretical basis for the ABI method, we show examples of its use for the MGP site characterization. Finally, we discuss its relative advantages over the traditional methods and potential future applications of the method.

ONE-DIMENSIONAL GPR SURVEYS

One-dimensional GPR surveys involve recording and analyzing signal data collected along a set of independent survey lines above a target medium. Survey results can be displayed in the field as a "waterfall" display of signal amplitude as a function of time and horizontal antenna position. Surveys based on such 1-D profiling are routinely applied to environmental, engineering and geologic studies, and for many applications this level of detail is sufficient for the investigation. This is particularly true if additional information is available on a site's geology, geophysics or infrastructure, or if an object that is known to exist simply must be located. Typical applications include identifying the thickness of ice or soil over bedrock, locating buried utilities, and determining the presence or absence of specific subsurface features at a site (e.g., drums, USTs, etc.).

GPR IN TWO DIMENSIONS

In the 1-D GPR recording method discussed above, the time axis can be converted to depth by assuming a velocity function for the host material(s). The velocity can be determined in-situ using a common mid-point (CMP) approach, or by using values derived from empirical data (Balanis, 1989, and Keller, 1987). In-situ CMP measurements are usually preferred, as material conductivities can vary dramatically from site to site. By converting time to depth, one obtains a vertical cross-sectional representation of reflected signal energy as a function of depth and horizontal position. Hence, target depth can be inferred, which for many investigations may be important. However, for large sites where numerous and varied types of subsurface features are potentially present, the purpose of the investigation often shifts from one of depth resolution to one of horizontal detection and resolution. In order to quantify the lateral distribution of buried objects with GPR, a grid is established and GPR 1-D profiles are acquired along independent survey lines. In order to achieve the best spatial resolution of subsurface features as well as to account for lateral variability and electrical property anisotropy within the subsurface, GPR data should be acquired in two directions, say north-south and east-west. The independent north-south and east-west survey lines are analyzed, and particular anomalous features are correlated spatially. In so doing, features that are oriented between grid lines or span multiple grid lines can be distinguished. Such plan view characterization aids in the follow-up phase of subsurface investigation (geoprobe, drilling, excavating, etc.).

THREE-DIMENSIONAL GPR IMAGING

The Array Beam Imaging Method

High resolution, three-dimensional representations of GPR survey data can be obtained by using a new image processing method called the Array Beam Imaging (ABI) method. In the ABI method, signal data is collected over a 2-D grid and combined to produce 3-D images of material reflectance beneath the survey. A schematic of the data collection and signal processing using ABI is shown in Figure 1. Here, a GPR signal is emitted at each gray diamond location in a grid on the ground surface, and reflected electromagnetic energy from the signal is acquired at a receiver that is collocated with the emitter. (Note that in the more general case, the signal from a single emitter is collected at several different receiver locations. However, in the present study the commercial GPR system that was used is configured only for a single, collocated source-receiver pair.) In the ABI method, each discrete point, or cell, in a volume beneath the survey is treated as a reflector. A subset of all scans from the survey is combined to obtain a measure of how much electromagnetic energy is reflected from a particular cell in the volume, relative to all other cells. In Figure 1, one such subset of scans is highlighted using dark diamonds within a circle, and the signals that are used to measure the reflectivity of a buried target are shown as (idealized) signal raypaths.

The measure of reflected energy from a cell is determined by combining the signals such that energy reflected from a particular cell is enhanced while energy reflected from neighboring cells is diminished. The result is a coherent signal, or beam, associated with the target cell. As mentioned above, a real array (as opposed to synthetic) can be configured by using multiple receivers for each source position.

A volume image is constructed by storing the measure of reflected energy from each cell, for all cells in a volume beneath the survey. The resulting 3-D volumes of reflected radar energy, or reflectivity, can be analyzed with the use of a variety of visual displays. These include 3-D renderings of the reflectivity volume, projections of reflectivity from the 3-D volume onto a 2-D plane, and tomographic cross sections through the 3-D volume to display the variations and distributions of reflectivity across 2-D slices. We demonstrate these rendering techniques in the case study discussed in the following section. In all of the following color-coded renderings, warm colors (reds; yellows) correspond to large values of reflectivity, and cooler colors (blues; greens) correspond to lower values of reflectivity. Volumetric display is obtained by plotting isosurfaces of reflectivity. The contours produced by contacts between different colors show surfaces of constant reflectivity. Hence, they (usually) represent the contours of the surface of a material object whose reflection properties are different from those of its surroundings. Therefore, objects and material boundaries can be identified by the shapes of the color contours in the volume images. In addition, the material type (e.g. a metal container, a layer of sand in soil or a coal tar deposit) can be identified by the magnitude of its reflectivity. Of course, rigorous conclusions of the latter type require calibration of the signal intensity using known materials at a particular site.

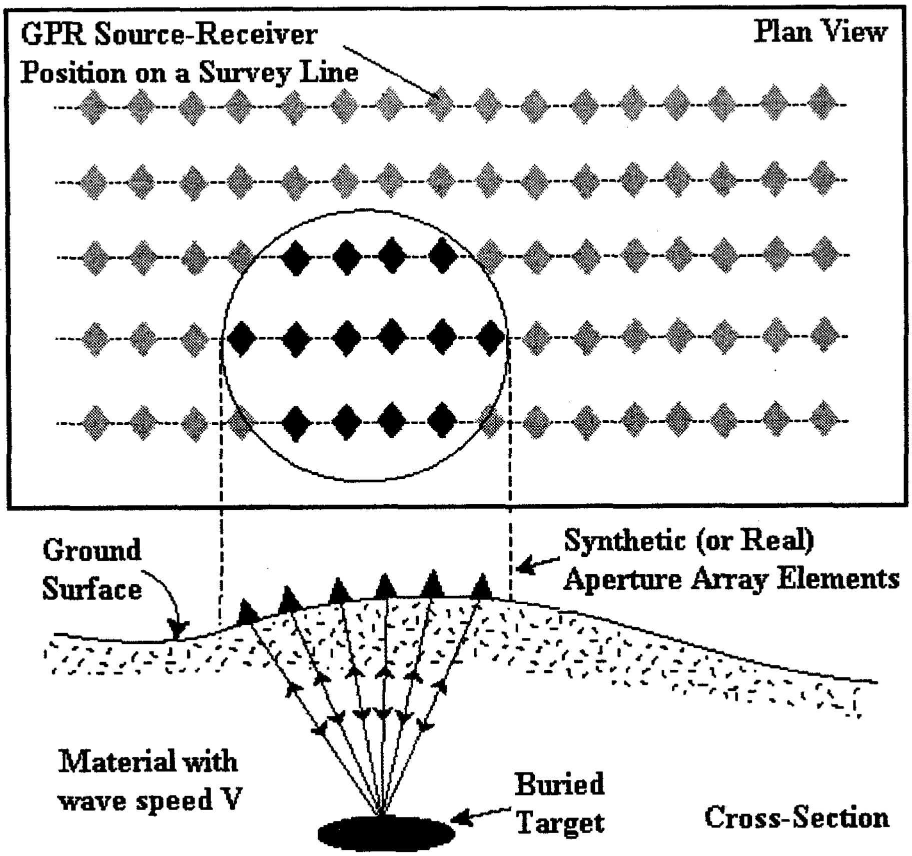

FIGURE 1: Array Beam Imaging schematic. Gray diamonds indicate source-receiver positions along survey lines. Dark diamonds (within circle) represent those receiver signals used to form an image of the buried target beneath them.

ABI Application: A Manufactured Gas Plant Site

GPR data were collected over the site of a former manufactured gas plant, and the ABI processing method was applied. The objectives of the survey were to map the location of an underground gas holding tank with brick walls and to characterize the spatial extent, including location and concentration, of coal tar deposits that were a byproduct of gas production. The plant was located near the bank of a river, and the subsurface material was primarily sand and gravel, with an average water table depth of about 18 feet. A GSSI SIR2 radar system was used with a 300 MHz antenna. Radar data were collected on a grid of parallel profile lines in North-South and East-West directions. These two separate data sets were collected in order to assess the effects on image characteristics of the correspondingly different polarizations of the incident radar waves (which differ by 90 degrees). Differences in the corresponding images are due to differing signal responses from subsurface materials due to the different signal (antenna) polarizations. These differences are generally caused by the inherent dielectric anisotropy of the reflecting material and/or object. Therefore, the following imaging results are labeled either East-West or North-South, depending on the particular profile set used to form a particular image.

GPR data were collected with a spacing of 2 feet between parallel survey lines in one region (Zone 1) and a spacing of 10 feet in an adjoining region to the South (Zone 2). The locations of these fine and coarse surveys with respect to a building on the site are shown in Figure 2. All positions indicated in the figures of this report are based on the GPR grid coordinates shown on Figure 2. Observation wells and bore holes drilled at the site are also shown in the figure.

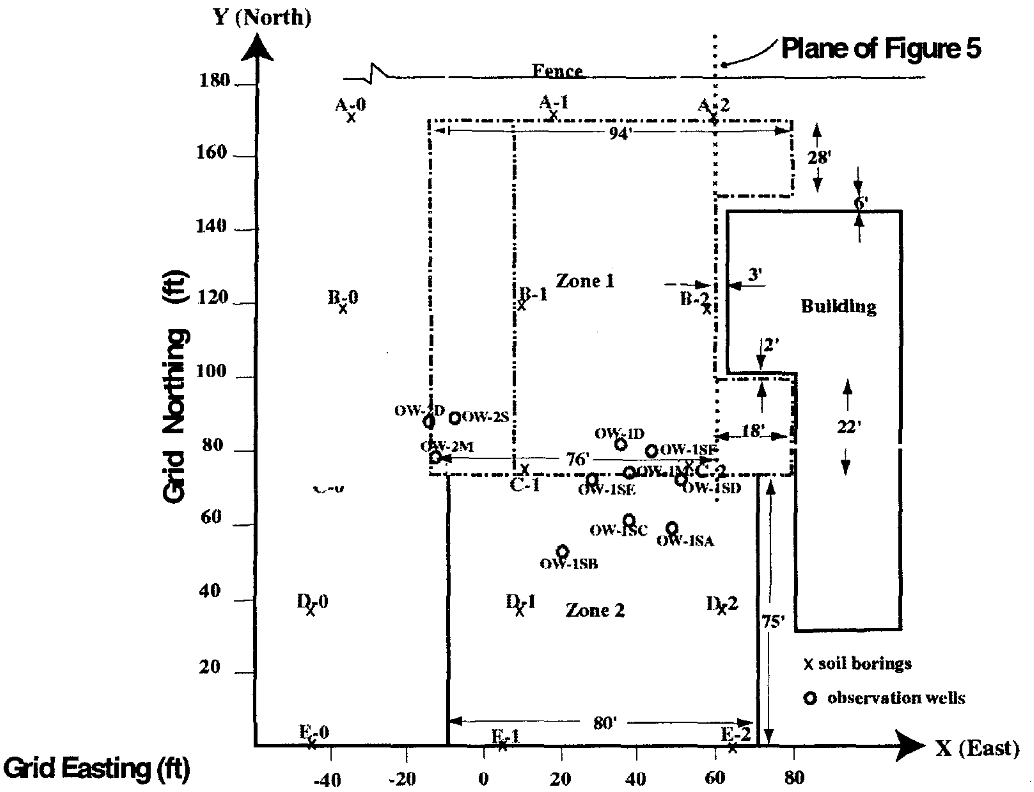

FIGURE 2. GPR survey grid zones for MGP site located in Connecticut. GRP data acquired at 2-foot line spacing on Zone 1, and 10-foot line spacing on Zone 2. A GSSI SIR 2 System with a 300 MHz antenna was used for data acquisition.

3-D Imaging Results at the MGP Site

The GPR data sets were processed with the ABI method, and volume images were formed beneath the entire survey area to a depth of about 22 feet. The resulting volumes were then examined from different angles and by using projection and cross-section views to assess the gas holder and coal tar characteristics. A plan view of the resulting image volumes from both the fine and coarse East-West GPR surveys is shown in Figure 3. The figure is a view of the entire volume, to a depth of 25 feet, as seen from a depth of 2 feet. This reflectivity "map" represents an overlapping projection of all the reflectivity intensity levels, from a depth range of 2 feet to 22 feet below the surface, onto this area plane. This view clearly shows the circular boundary of the gas holder as a narrow zone of very low reflectivity enclosing an area with irregular zones of very high reflectivity (red and yellow) which is most probably nearly pure coal tar. These zones are surrounded by low reflectivity fill material (pale blue) and mixed fill with coal tar contamination (green shades). The Zone 2 image results do not provide much resolution of these variations in reflectivity and are only weakly suggestive of similar features. Since these images are projections, the colors indicate the "sum" of intensities from the volume zones projected onto the plane of the figure. Consequently, red coded intensities projected on blue, and vice-versa, produce green color coding, which are the most common color code in the projections of Figure 3.

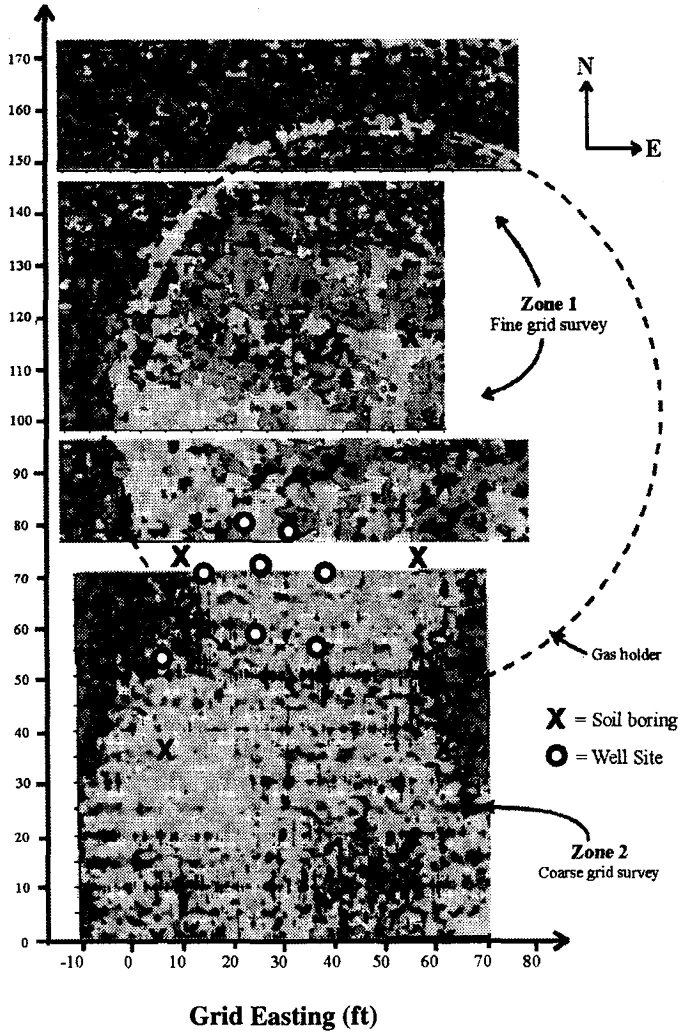

FIGURE 3: Plan view of the image volumes from both the fine and coarse East-West GPR surveys. This reflectivity image is a projection of all the reflection intensity levels below 2 feet onto a horizontal plane at a depth of 2 feet. Location of borehole TW-D2 is shown by a black box (See Figure 6).

Figure 4 shows the 3-D reflectivity images resulting from ABI processing of the North-South survey data in Zone 1 (the fine-scale survey). The three separate volumes correspond to data sets from three separate surveys taken to cover the area of Zone 1. A similar set of volume images was generated from the East-West survey data. From this view, it is clear that the regions of highest reflectivity are near the ground surface, but that the amount of material that is highly reflecting (color-coded red and yellow) in the North-South survey is significantly less than the amount in the East-West survey. This is due to the anisotropy of the highest concentrations of coal tar which are predominantly within the gas holder boundary.

FIGURE 4: 3-D reflectivity images produced from the fine grid North-South GPR survey. Data from the three separate survey sections of Zone 1 were process separately and combined as shown on Figure 3. X is Easting, Y is Northing and Z is depth.

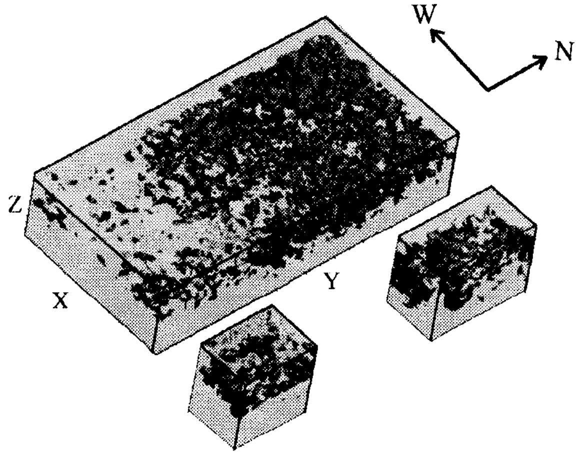

Figure 5 shows another projection of the North-South survey's image volume, onto a vertical north-south plane along the eastern side of the survey area. The extent of the volume that is projected onto the viewing plane is shown in the figure. This projection shows highly reflecting material at depths greater than about 8 feet, with thicknesses varying from about 10 feet in the north to about 4 feet in the south. This section suggests that coal tar/oil residues extend below the base of the gas holder, at 12 or 13 feet, over much of the interior of the gas holder and on the north-eastern side of the survey area. The high reflectivity zone thins to the

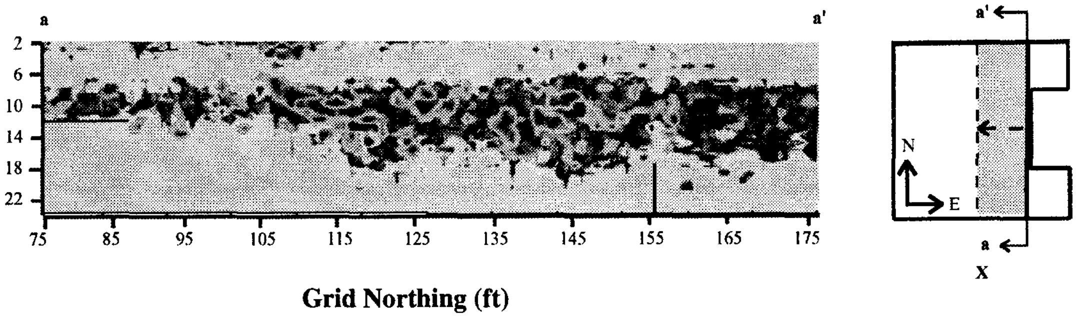

Figure 5: Volume projection of the reflection intensity levels onto a north-south vertical plane from the North-South GPR data imaging. The projected volume is indicated by the shaded zone in the inset to the right. The northern boundary of the gas holder is at about 155 ft Grid Northing (shown with a vertical line), and the base of the gas holder is at about 12 to 13 ft below ground surface (shown with the horizontal line).

south so that migration much below the base of the gas holder is not evident for this area.

Ground Truth through Image Volume Coring

Given the limited application, to date, of GPR surveys to subsurface coal tar imaging, particularly with the new ABI imaging method, it is difficult to correlate the imaging results with coal tar concentrations. Also, the imaging results are highly dependent on host material properties, including soil and rock constituents and moisture content. A stronger correlation between image characteristics and subsurface material properties is obtained by comparing those sections of the image volume that correspond to samples obtained in boreholes.

Once such borehole comparison is shown in Figure 6. The 3-D image volumes from both the East-West and North-South surveys have been "cored" for comparison to the material properties logged from samples obtained in the borehole at the corresponding volume location. The volume cores represent a 2-foot by 2-foot width to the bottom of the volume. As shown in Figure 6, the North-South and East-West data sets did produce different image results, indicating a high degree of anisotropy in the subsurface material properties. The reflectivity levels in the image volume cores are compared to the material properties in the borehole, as indicated by the geologic log (field notes) on the right-hand side of Figure 6. As was expected, there seems to be rather strong correlation between high levels of reflectivity and the presence of hydrocarbons. In particular, regions of highest reflectivity in the cored image volume correspond to borehole samples containing oil, naphthalene odor, and coal tar.

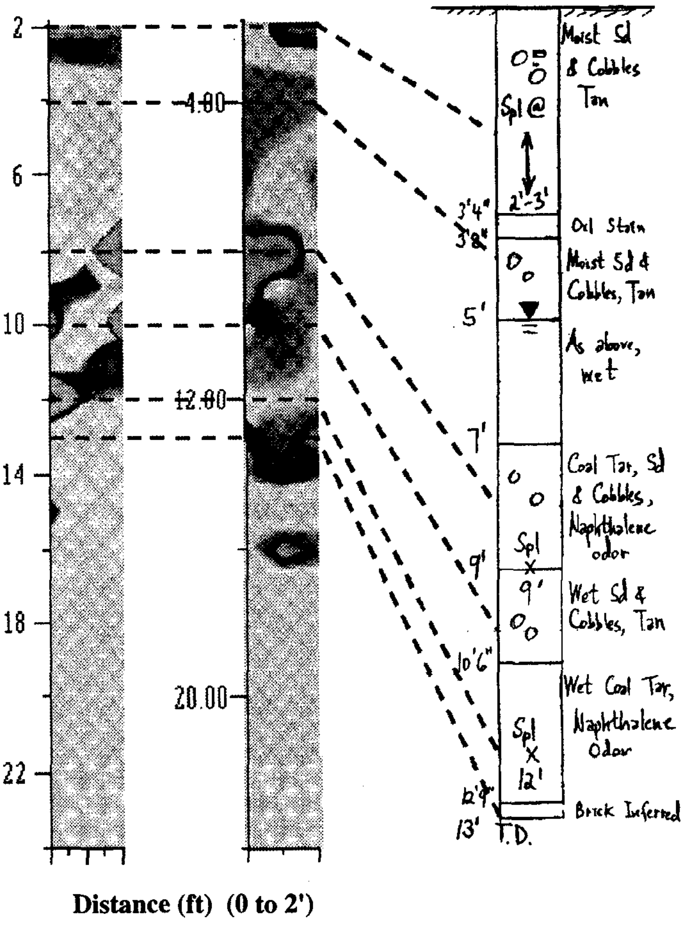

FIGURE 6: Comparison of geologic field log with "cored" image volume for ground truthing. A column of the volume images (2' by 2') for both the North-South and East-West GPR data sets is compared to the material properties of samples obtained in borehole TW-D2. The cored volume images are located at the same position within the GPR grid (X=64'; Y=88') as the drill hole. The highest reflectivity levels correlate well with the hydrocarbons encountered in the boring.

SUMMARY AND CONCLUSIONS

Array Beam Imaging, a new 3-D image processing method, has been applied to standard ground-penetrating radar data acquired at a former manufactured gas plant site. Quick interpretation and characterization of the spatial extent of coal tar deposits at the site was achieved by rendering of the image processing results as 3-D isosurfaces, 3-D and 2-D volumetric projections, and 2-D tomographic slices. Collection of the GPR data along perpendicular survey lines was important for interpretation of the surface material. In particular, we have inferred the presence of material with high hydrocarbon content as located in those regions of the image volumes that exhibit strong dielectric anisotropy as well as high reflectivity.

Specifics of the interpretation of the site based on the GPR survey and data processing are as follows: The base of the gas holder appears to be at a depth of about 12 feet below the present surface. The water table appears to be at an average depth of about 18 feet, based on the reflectivity cutoff at this level. The low intensity reflectivity observed in the image volumes is considered to be a mix of coal tar and soil material, with lower concentrations of coal tar (or other hydrocarbon bi-products) than that associated with the high intensity reflectivity zones. The presence of lower concentrations of coal tar and oil residues is more pervasive than at higher concentrations, as might be expected. This is particularly the case in the areas just outside the gas holder, suggesting that the residues were removed from the gas holder, dumped just outside of it and mixed with fill material or native soils.

It is apparent that applying the ABI method improves the interpretation of otherwise standard GPR surveys performed at sites such as the MGP site presented herein. In particular, the boundary of the gas holder is well defined in the imaging results and is easily mapped with respect to other surface features. Also, the highly heterogeneous distribution of subsurface reflectors associated with the coal tar is easily interpreted using isosurface renderings and volume projections.

Several new features of the ABI imaging system are in progress that will increase imaging efficiency and resolution. Ultimately, the ABI processing system will be used for "real time" interpretations to be integrated with other site-specific information on a daily basis. In the present study, limited interpretation was performed in the field, and correlation of signal characteristics with subsurface structures was performed in the office. However, the total time requirement of the image generation was a small fraction of the overall interpretation process. Consequently, the entire interpretation process can be performed in the field. A future release of the image processing system will provide this in-the-field processing capability. Volumetric image results can be integrated with geographic, geophysical, hydro-geological, as well as other information via a Geographic Information System (GIS). One advantage of a real-time approach is that the resolution of the survey and the field parameters (i.e., survey line spacing, antenna frequency, gain ranging, etc.), can be determined and/or adjusted in the field to optimize the investigation for the site-specific conditions. Also, interpretation of volume imaging results can be combined with other geophysical, hydrological, or geological interpretations to maximize the efficiency of site characterization.

ABI imaging is not limited to electromagnetic (radar) wave signals. A similar processing system is being designed for application to acoustic/seismic data. Such a system can be used in conjunction with a radar survey for cross-correlation of imaging results. Also, a small-scale seismic survey using inexpensive, light-weight sources of seismic energy and geophones could be configured for efficient earthquake fault location, contaminant characterization in saturated soils, and unexploded ordnance detection. Many applications should be realized in civil, environmental and geotechnical engineering as the ABI technique becomes state-of-the-practice for high-resolution, real-time, 3-D subsurface imaging.

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