RESEARCH IN GROUND PENETRATING RADAR IMAGING FOR THE SITE INVESTIGATION ROBOT

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ABSTRACT

The Site Investigation Robot is a cooperative effort between the Field Robotics Center at Carnegie Mellon University and the US Environmental Protection Agency. Its goal is to greatly increase the efficiency of hazardous waste site investigations by integrating advanced subsurface sensing, robotic positioning, automated data acquisition, site databasing, multi-sensor data display, and a uniform system control architecture.

The primary research issue is advanced subsurface sensing using ground penetrating radar (GPR). Ground penetrating radar has be used manually for years for subsurface sensing. It is the only current subsurface sensing technique with high resolution and three dimensional imaging capability. The usefulness of GPR for subsurface identification is currently limited by the properties of the GPR phenomena, GPR equipment technology, and mainly by the operator's skill in accurate data acquisition and interpretation.

The GPR scanning and data acquisition have been automated using robotics technology to provide the accuracy necessary for imaging. Digital signal processing and specialized GPR processing techniques are then used to transform the radar data into a subsurface image. Two different test sites and radar simulation are used in verifying these techniques. Our past work has been in two dimensional imaging. Current work on three dimensional processing will match the three dimensional nature of GPR achieving higher resolutions as well as full volume imaging. Ultimately, a field technician will be able to scan a site and determine the type and locations of objects for excavation.

We will present an overview of the GPR phenomena and properties, the GPR processing techniques used for imaging, future research directions, and current experimental results.

The Site Investigation Robot

In the course of remedial investigations of hazardous waste site, the US Environmental Protection Agency has found manual methods for collection surface and subsurface site information to be tedious, inaccurate, and expensive. Remediation plans cannot be made effectively using sparse site data. In addition, site investigations take so long that conditions may change considerably before remediation can begin.

The Site Investigation Robot (SIR) is applying robotics technology to site data acquisition, databasing, and display. The primary research effort is developing ground penetrating radar (GPR) subsurface sensing.

The SIR is a mobile robot that can be outfitted with a wide variety of sensors. A positioning system on the robot constantly measures the robots position on the site. The SIR can be autonomously driven on uncluttered sites or be teleoperated on overgrown sites. Personal exposure to site hazards can be greatly reduced.

Using simple programming commands, the robot is directed to stop and collect data with specific sensors at intervals. This data is archived with its site position and time. Archived data is written to a non-volatile storage device (e.g. optical or magneto-optical disks) on the robot. Some data may also be transmitted back to the base computer for real time display of site characteristics.

Any sensor that can be made to output an analog or digital value can work with the SIR with little effort. Systems that require constant tuning or range changes may have to be modified to work under computer control. Support for surface contact sensors (e.g. moisture content, ph, or resistivity) will be added in the future. The SIR uses the Modular Autonomous Robot Control Architecture (MARCA) for system control. This allows control modules for special sensors to be easily configured into the system.

When the SIR finishes a data collection run, the disk of information is moved or copied to the base computer for processing and display. The base computer can display sensor data position mapped onto the site map. Multiple types of sensor data can be displayed simultaneously so that correlations between different sensor may be examined. The operator can add notes and drawings to the database to indicate data collection details, theories about site contents, and plans for remediation.

The base computer can apply a toolkit of processing routines to show trends in the collected data. A complete history of operations performed on data is kept in order to insure that all processed results are repeatable.

In short, the SIR's goal is to provide complete information about a site in an non-ambiguous manner to facilitate effective site remediation planning. Through the use of robotic mobility, position determination, databasing, and computer display, this goal is being realized.

Ground Penetrating Radar for Subsurface Imaging

One of the main goals of a site investigation is to acquire information about subsurface objects and the subsurface geophysics that affect the transport of contaminants. Noninvasive direct methods to collect such information include electromagnetic techniques, acoustic techniques, and ground penetrating radar. Invasive methods (e.g. coring or excavation) are very time consuming, expensive, and potentially hazardous. Each technique has advantages, but no single method alone provides complete information, and all are currently limited by to the inaccuracies and inefficiencies of manual deployment.

Our main research focus in the SIR program is to develop subsurface mapping using ground penetrating radar. GPR is the most promising of all subsurface sensing technologies for several reasons:

- GPR has sufficient resolution to distinguish multiple nearby or overlapping objects.
- GPR is capable of three dimensional imaging.
- GPR responds to both metallic and non-metallic objects.

The usefulness of GPR for subsurface mapping is currently limited by the physics of the GPR phenomenon, by GPR equipment technology, but chiefly by reliance on a the operator's skill in accurate data acquisition and interpretation.

We have automated GPR sensing using both fixed (Fig. 1) and mobile robots to acquire spatially correlated data and have applied specialized signal processing techniques to transform radar data into a subsurface image. The accurate positioning provided by the robot enables the processing techniques needed for subsurface imaging.

Working Principle

Ground penetrating radar starts by transmitting an electromagnetic (EM) pulse into the earth. When the radar wave reaches a discontinuity in electrical impedance an echo is returned. The strength and the phase of the echo indicate the magnitude and direction of the change. The time of flight of this echo (relative to the transmit pulse) provides a measure of the depth to the discontinuity; Figure 2 schematically illustrates a radar transmit pulse and return echo from a buried drum.

The following equations describe the propagation of an EM pulse through any medium:

$$\alpha = \omega\sqrt{\mu\varepsilon}\sqrt{\frac{1}{2}\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right)} \qquad \text{Eq (1)}$$

$$\beta = \omega\sqrt{\mu\varepsilon}\sqrt{\frac{1}{2}\left(\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}+1\right)} \qquad \text{Eq (2)}$$

$$E(z,t) = E_0 e^{-\alpha z} e^{j(\omega t-\beta z)} \qquad \text{Eq (3)}$$

$\omega = 2\pi f$ (rad/sec)

$\sigma =$ conductivity (mho/m) (10^{-9} - 1.0 for most geologic materials

$\mu =$ magnetic susceptiblity (uo for most geologic materials)

$\varepsilon = \varepsilon_0 \varepsilon_r =$ electric permittivity (ε_r is 1- 81 for most geologic materials)

Equation 1 defines the attenuation component of the signal. Equation 2 defines the phase shift with distance. The wave propagation velocity is ω/β. Equation 3 defines the EM field as a function of time and distance. See references 3 or 4 for more detailed formulations and derivations.

At a discontinuity in the characteristic impedance, a portion of the wave is reflected as described in Eq. 5.

$$Z = \sqrt{\frac{j\omega\mu}{\sigma+j\omega\varepsilon}} \qquad \text{Eq (4)}$$

$$r = \frac{z_1 - z_2}{z_1 + z_2} \qquad \text{Eq (5)}$$

z = characteristic impedance

r = reflection coefficient

The GPR antennas we are working with have a beam angle of 45° from vertical in the X direction and 30° from vertical in the Y direction [2]. The exact location of an echo within this pyramid cannot be determined. To resolve this ambiguity, the antenna is scanned along a line to create an ensemble of return signals. Echo latency is lowest when the antenna is directly over an object and increases as the antenna moves away. When the sequence of recorded echoes at each point along the scan line is displayed as an image, distinctive curves are generated which are currently

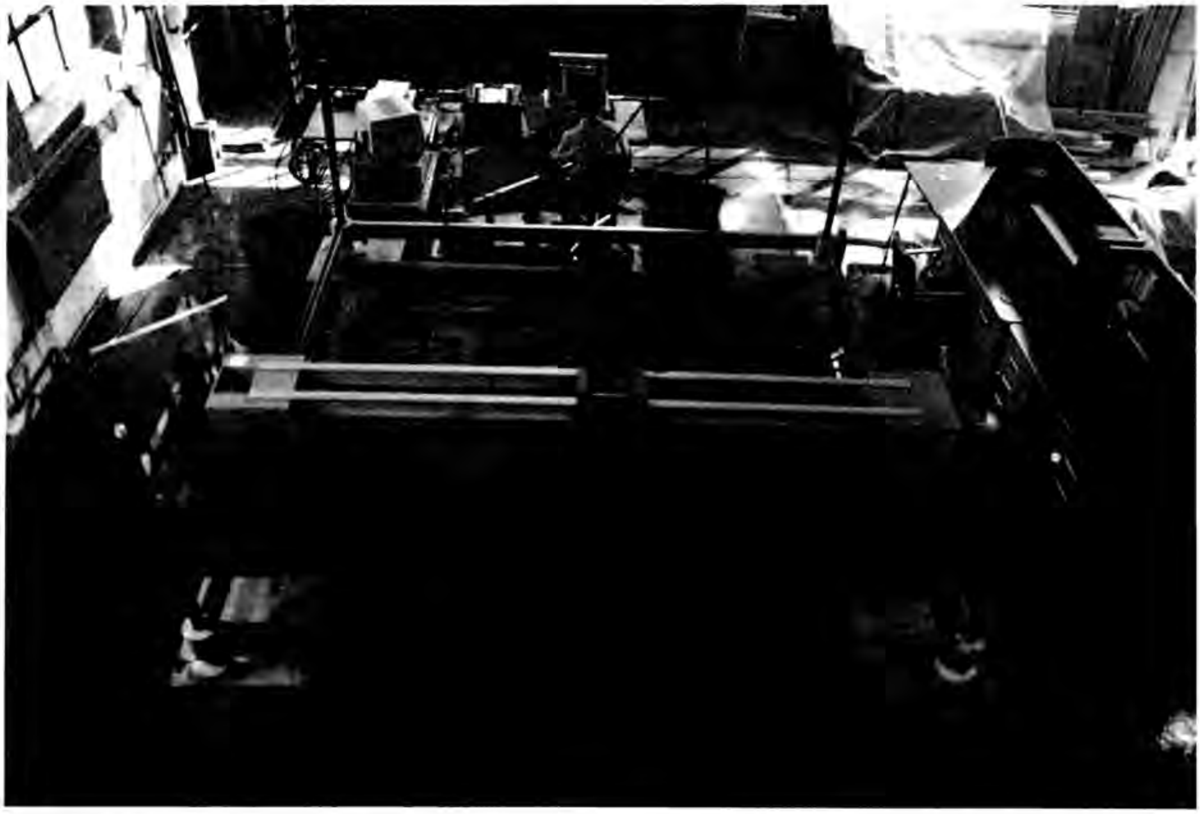

Fig. 1. Buried barrel in our GPR research testbed.

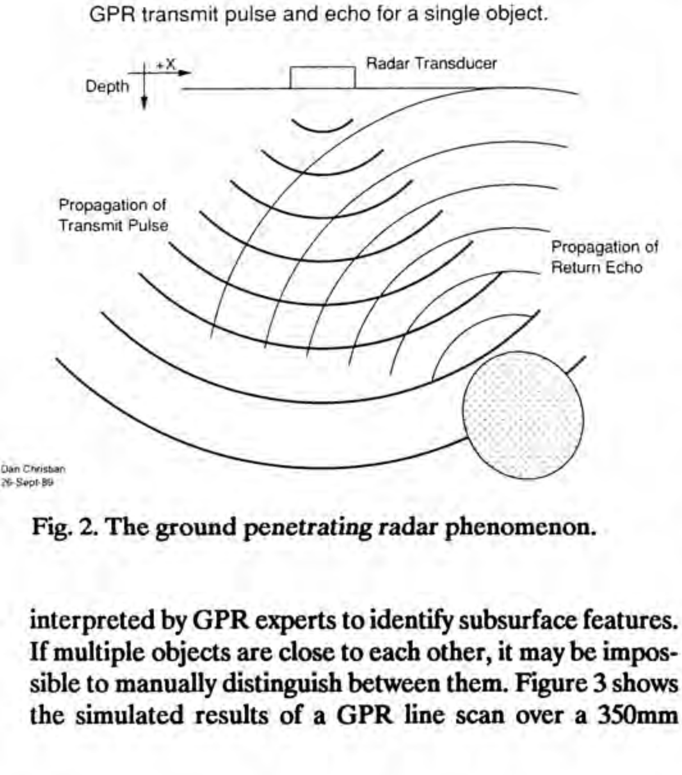

Fig. 2. The ground *penetrating* radar phenomenon.

interpreted by GPR experts to identify subsurface features. If multiple objects are close to each other, it may be impossible to manually distinguish between them. Figure 3 shows the simulated results of a GPR line scan over a 350mm diameter steel barrel buried in sand 710mm deep. Each signal return was simulated at a 5mm intervals.

Real World Characteristics

In actual use, there are several factors that complicate the radar return. The correlation between the time of flight of return echoes and actual depth depends on the propagation velocity of the EM pulse, which is not a constant but depends on the characteristics of the subsurface material (see Eq. 2). The propagation velocity is currently determined either by calibration from an object of know depth or often by the operator's estimation.

The transmitted EM pulse is not an ideal spike. At GPR operating frequencies (one hundred megahertz through one gigahertz), accurate pulse width control is very difficult. Current systems yield a strong main pulse surrounded by several weaker pulses. These side pulses create additional echoes that confuse the main pulse echo.

The transmitted radar pulse also becomes weaker as it gets further from the antenna due to both the attenuation of the earth and the decrease in energy density as the beam spreads out with depth (see Eq. 1). The conductivity of the soil attenuates the EM pulse faster at higher frequencies than at low ones. In very conductive soils (e.g. clay), the EM pulse will not travel more than a meter. In *slightly* conduc-

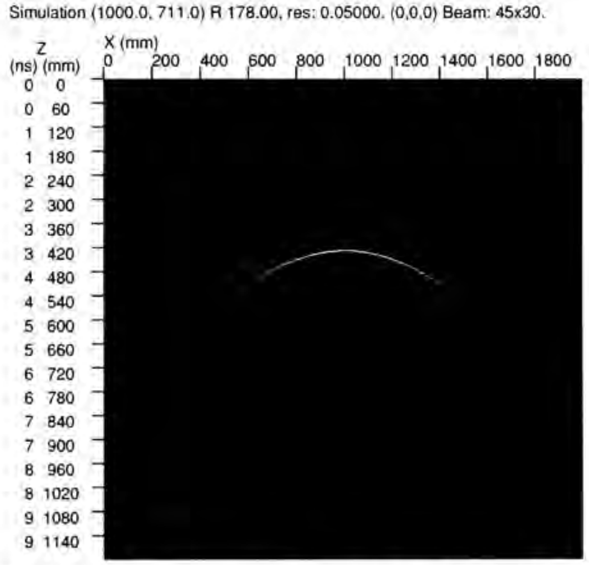

Fig. 3. Data from ground penetrating radar simulation.

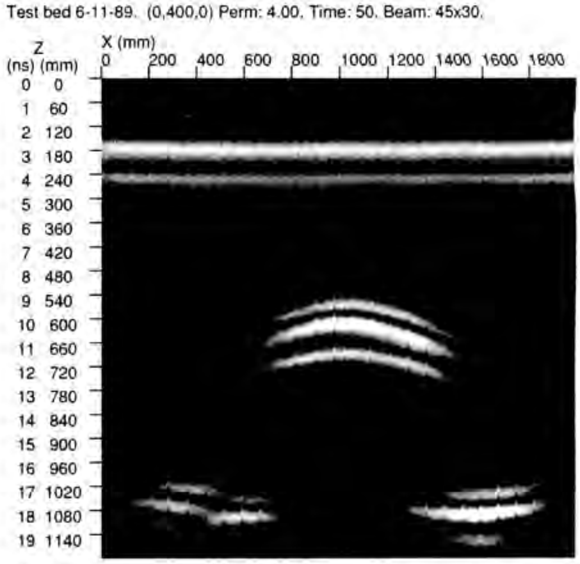

Fig. 4. Unprocessed GPR image of a buried drum.

tive soils (e.g. limestone), the EM pulse may travel twenty meters or more.

To compensate for the signal attenuation with increasing distance, variable gain amplifiers (VGAs) are used to increase the gain as return time increases (i.e. distance increases). In current GPR systems, the gain ramps are set manually by trial and error.

Because the time of flight of the returned echoes is used to calculate distance, the timing resolution of the GPR receiver can directly affect the image resolution. Since GPR uses frequencies through one gigahertz, sampling rates of five gigasample per second or better are required for complete reconstruction. In addition, the VGA must be synchronized with the sampling process to properly strengthen distant signals.

Incremental latency sampling is used to economically record an entire return signal at such a high bandwidth. A radar pulse is transmitted, and a single time sample is taken from the return signal. The next radar pulse is transmitted, and the next later-time sample is taken from the return signal. Successively, later-time samples are taken up to a predetermined maximum time. This completes one complete echo signal. The sample time is returned to zero and the next echo signal is started. At each time step, the VGA can be set to a new gain corresponding to the distance traveled.

Acquired GPR data from an nearly identical test configuration to the simulation is shown in Fig. 4. Although its exact position is hard to determine, the drum shows up in the middle of the image. The multiple bands at the top of the image are the surface reflection of the transmit pulse waveform, and the lines at the bottom are from reinforcing bar in the concrete that the drum rests on. This image is the absolute value of return echo signal. When displaying on a computer screen, color is used to show the polarity of the signal.

Imaging GPR Data

Two processing steps are key to imaging from GPR information. First, the signals is deconvolved to remove the effects of the imperfect EM transmit pulse. Second, the ensemble of echo returns is migrated to create the map of subsurface objects.

Deconvolution creates a filter that transforms an averaged, free-air transmit pulse into an ideal reference pulse. The reference pulse used is bandwidth limited to only contain frequencies below the Nyquist frequency of the receiver sampling rate. When this filter is applied to the GPR data, it removes most of the effects of the transmitted side pulses from the collected data, increasing resolution.

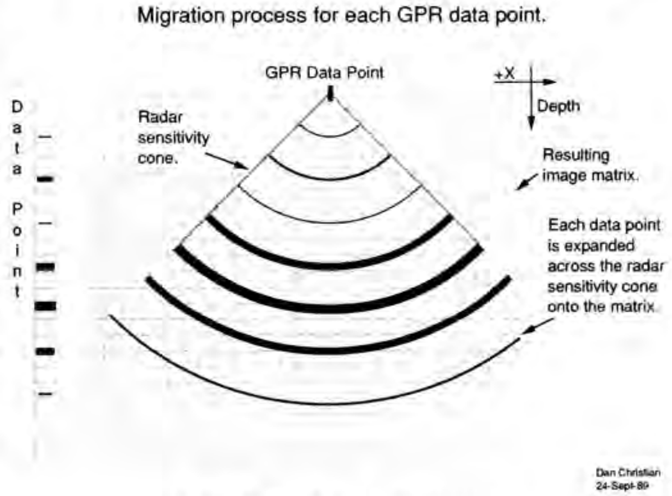

Fig. 5. The migration process.

The deconvolution filter amplifies noise significantly; low pass filtering is used after deconvolution to reduce the amplified noise.

The next step is the key to GPR imaging. A process known as migration converts the deconvolved and filtered data into a representation of the subsurface. This technique is very similar to the Synthetic Aperture Focusing Techniques (SAFT) used for high resolution pipe location [1]. Migration comes from the geophysical field where it is used for seismic processing. Geophysists do not need full subsurface images and often use a number of modified migration techniques for increased processing speed.

Migration is based on the principle that data from adjacent scan points contain echoes from many of the same objects, but from different angles. Migration uses the geometry of the differing positions to correlate all nearby echoes to form a high resolution subsurface image.

First the GPR echo data is stored as an array. Each column contains the GPR echo returned at a specific position. Echoes are usually recorded at fixed distance increments to simplify processing. An identically sized, empty destination array is also created. For each source column, the value in each cell is added to all destination array locations that are equidistant from the transmitter and within the antenna beam angle. This spreads each part of the return signal over an arc that is equal time from the GPR antenna (see Fig. 5). When migration is applied to all data points, the echoes that correspond to a particular array location constructively add to form a strong signal at that position. The destination array now represents the real location of the objects that created the ensemble of radar echoes.

Figure 6 is a gray scale image showing the results of migration on the simulation data of Fig. 3. The drum surface is evident at the strong arc in the center; the light regions to either side are artifacts of the migration process. These error regions can be removed with a simple thresholding operator and, in a real data set, these signals would be lost among other much stronger signals.

Figure 7 shows the results of deconvolution, filtering, and migration of the raw data in Figure 4. This represents the changes in impedance due to a barrel in sand.

The final imaging step is to integrate the changes in impedance to form a map of the actual ground impedance. Figure 8 shows this final result of the scan started in Figure 4. The displayed image shows positive and negative changes from the average impedance identically. When images are shown on a computer screen, color is used to differentiate between positive and negative changes.

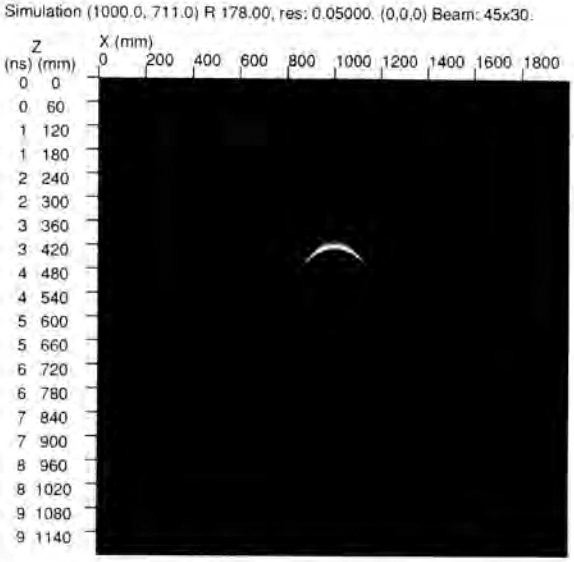

Fig. 6. Synthetic GPR data after migration.

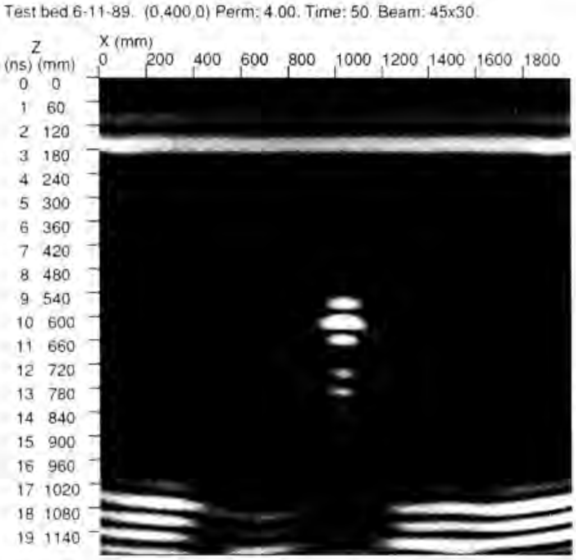

Fig. 7. GPR data after deconvolution, filtering, and migration.

The faint vertical lines near the left and right edges are the walls of the testbed (made of railroad ties). Only the top surface of the drum appears clearly since the bottom surface is always in shadow. The faint area in the middle bottom of the image the GPR shadow of the drum on the floor. The banding in the drums shape is most likely due to transmitted side echos that did not get cancelled by the deconvolution.

Resolution

GPR resolution is primarily limited by the antenna characteristics. The data set shown in Figure 4 was acquired using a transducer with a bandwidth from 250-1000 Mhz. This results in a resolution range of 120cm to 3cm in air (permitivity 1.0) and 60 cm to 1.5cm in dry sand (permitivity 4.0). Since there is a lower bound on the resolution, lower

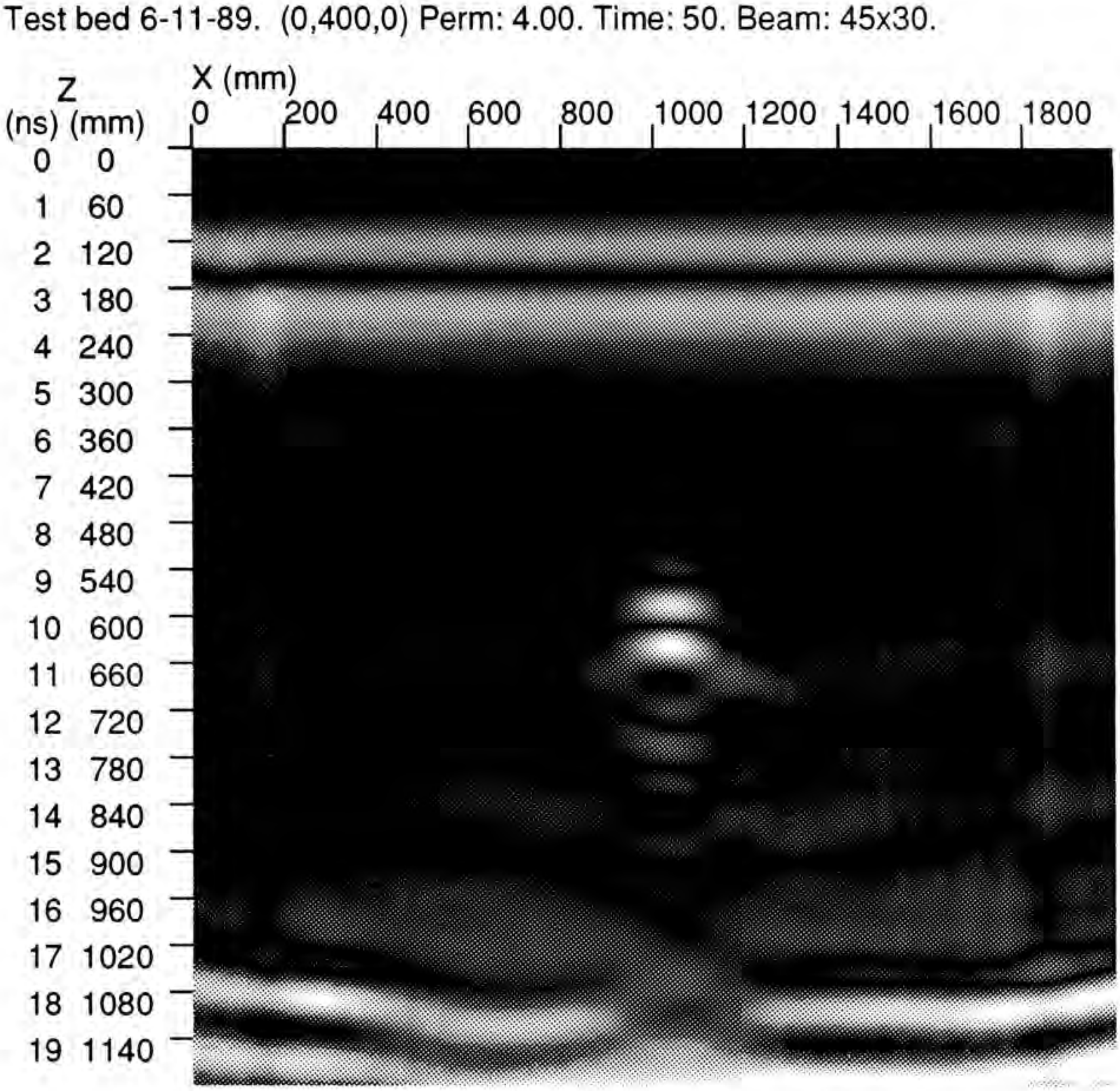

Fig. 8. GPR data after deconvolution, filtering, migration, and integration.

frequency antennas will be needed to investigate large objects or geophysical features.

Advanced Processing

When migrating the GPR data, the propagation velocity is not known exactly; and an assumed value is applied uniformly over the entire map. However, once the migration is complete, a better estimate of propagation velocity may be made from the resulting image. An iterative process could improve imaging resolution using propagation velocity estimates based on a previous migration. This process is very computationaly expensive; migration with varying propagation velocity could increase processing time by an order of magnitude.

So far, only 2D GPR processing and display have been shown. However, GPR is a 3-D phenomena and requires 3-D processing to achieve its full imaging potential. The extension from 2-D to 3-D is very straightforward; however, the data sets and processing requirements become huge. At 0.5 cm resolution, 3-D processing of a 2mx2m area requires 64 million entries and as many calculations. Modern high density storage devices and advanced digital signal processors have made 3-D processing practical.

Current Research Areas

Current GPR receivers use manually-set, fixed gain ramps to correct for loses due to distance and soil characteristics. In order to fully automate GPR imaging, the gain ramps must adaptively adjust to the current soil characteristics. A digital signal processor based receiver with digitally controlled gains is currently under development.

The non-ambiguous display of the translucent 3-D solid produced by 3-D migration is a difficult problem. Since GPR images are not normal geometric solid objects, most 3-D graphics techniques are useless. Techniques borrowed from medical and chemical imaging are being applied.

CONCLUSIONS

By combining ground penetration radar, robotics, and specialized signal processing, high resolution images of the subsurface are within reach of this project. Future improvements on this technology should improve range, resolution, and user interaction.

ACKNOWLEDGEMENTS

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