ADVANCED GPR SYSTEM FOR HIGH-PERFORMANCE TOMOGRAPHIC SUBSURFACE IMAGING

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ABSTRACT
In this paper, the research prototype of a high-performance GPR imaging system is presented. The system is equipped with the capability of synthetic-aperture scan, step-frequency FMCW illumination, and high-resolution tomographic image reconstruction.

KEYWORDS
Ground penetrating radar (GPR), synthetic-aperture imaging, backward propagation methods

INTRODUCTION
Ground penetrating radar (GPR) has been commonly utilized in subsurface imaging in recent years. However, the operating mode has been largely limited to localized mapping with simple CW-pulse waveforms as the illumination signals. To advance the GPR imaging technology, we need to elevate the capabilities in three key areas of (1) optimization of illumination waveforms, (2) formation of aperture coverage, and (3) development of high-resolution image reconstruction algorithms.

One effective approach to the improvement of the illumination waveforms is to utilize step-frequency FMCW signals as the transmitting waveforms. This is to step through a well-organized sequence of coherent signals over a designated frequency band to produce sufficient bandwidth for range resolution. Because of the unique properties of the FMCW signals, it improves the information content of the echoes and simplifies the computation structure of the image formation procedure.
The size of the aperture is the fundamental parameter governing the resolving capability of the imaging system. The formation of an aperture span enables us to elevate from the local-mapping mode to synthetic-aperture imaging, which will significantly improve the resolution of the images.

The Imaging Systems Laboratory at UC Santa Barbara has recently developed a research prototype for high-performance imaging. The system utilizes a step-frequency system, capable of operating with a frequency range from 500 MHz up to 4 GHz, in 1024 frequency steps. The system is also automated with a mobile-scan mechanism for the formation of synthetic apertures. The image reconstruction is conducted by the backward propagation algorithm operating in the multiple-frequency mode. The transmission of illumination waveforms, physical scan for the formation of synthetic aperture, and image formation, are all conducted with a portable computer unit.

This paper consists of an overview of GPR technology, theoretical background, overall design of the system, and results from field experiments.

**GPR IMAGING**

Ground penetrating radar (GPR) has been playing an increasingly important role in many applications in non-destructive evaluation (NDE) and subsurface profiling. Common applications include locating and documenting utility lines, environmental site characterization and monitoring, archaeological and forensic investigation, unexploded ordnance and land mine detection, groundwater detection, pavement and infrastructure characterization, sinkhole detection, and cave and tunnel detection.\(^{[1]}\)

At UC Santa Barbara, significant research has been performed over the years on multiple-frequency topographic imaging algorithms for the elevation of the performance of GPR imaging. More recently, system integration has been conducted for the optimization of system performance.

The performance of the antennas is an important factor in data acquisition, which has been long overlooked. In system integration, the optimization of the antennas can improve resolution, maximize wavefield information content, and minimize signal distortion. With improved data acquisition capability, the quality of image reconstruction can be significantly enhanced.

In addition to the improvement of signal quality through antenna design, the expansion of aperture coverage by synthetic-aperture scan is a critical factor to high-resolution imaging. The formation of synthetic apertures can be achieved by scanning a single antenna element, a dual transceiver pair, or an antenna array.
To maintain the accuracy of the formation of synthetic apertures, dynamic tracking of the transmission-receiving positions is crucial to the precision of the subsequent wavefield migration procedures.

The movement of the transceiver can be conducted either automatically or manually. In either case, the research prototype is equipped with an optical encoder for high-precision tracking of the synthetic-aperture scan. This element has proven to be crucial in practical applications.

**THEORETICAL BACKGROUND**

GPR data acquisition employs microwave illumination as the probing waveforms. The system detects the microwave echoes at various receiving positions. The pulse-echo system, the GPR provides the target range with the estimate of the time delay of the echoes. For CW or FMCW systems, the dual quadrature channels detect the complex waveform and convert into the magnitude and phase of the resulting wavefield. \([2], [3]\)

A common artifact of this far-field assumption in the target range profile is that a point target will produce a hyperbolic pattern. Far-field assumption is often applied for the simplicity of image reconstruction both mathematically and computationally. Because of the far-field assumption, the degradation due to the artifacts remains apparent in many cases. The backward propagation method eliminates the far-field assumption and, as a result, the artifacts are effectively removed.

The image reconstruction algorithm was developed based on the concept of coherent backward propagation method. The backward propagation technique is a numerical wave-front migration procedure, operating in coherent mode. For linear or planar apertures, the migration is conducted from the apertures to a collection of parallel lines or planes sequentially. The use of multiple frequencies causes the wavefields from each frequency to be superimposed constructively or destructively, resulting in target formation. \([4]\) The Green’s function of the backward propagation procedure can be written as,

\[
h(r) = \frac{1}{j\lambda r} \exp(-j2\pi r/\lambda) \tag{1}\]

where \(\lambda\) is the wavelength corresponding to the operating CW frequency and \(r\) is the propagation distance from the transceiver position to a point in the target region.\([5], [6], [7]\) One important step in high-resolution GPR imaging is the formation of the synthetic aperture. It is achieved by scanning a transceiver along a designed path at a steady rate to provide uniform spacing of the receiving positions. Wavefield data from a linear synthetic aperture can produce a two-dimensional cross-sectional image. Equivalently, three-dimensional images require a two-dimensional planar aperture.
During image formation process, the properties of the propagation medium need to be provided. \([8], [9], [10]\) The knowledge of the dielectric constant is of great importance. (For example air is close to 1, dry sand is around 4, and wet clay can be as high as 20.) The dielectric constant is directly related to the propagation speed of the microwaves in the medium, which is a governing parameter in the image formation algorithms. Errors in propagation speed can lead to serious image degradation. Also the dielectric constant may not be constant throughout the region. Thus, in order to estimate the dielectric profile, preliminary tests or prior information will be utilized. Alternatively, it can be achieved empirically by observing the focus of the image formation as the dielectric constant is varied systematically. The dielectric level also governs the range capability of the GPR system as higher dielectric values limit the range distance due to greater attenuation loss during propagation.

### SYSTEM OPERATIONS

The Imaging Systems Laboratory of UCSB has recently developed a research prototype GPR for high-performance synthetic-aperture imaging. The GPR unit is designed to optimize the effectiveness of data acquisition. The system is equipped with mechanism for the control for steady scans for the formation of the synthetic apertures. The scan rate is programmable to accommodate various data-acquisition parameters, such as designed frequency band, frequency sweep rate, and desired resolution. Both automated and manual drive mechanisms were constructed and evaluated. Manual drive with tracking proved to be most versatile as monitoring slippage and alignment for various surfaces. The automated system proved to be slower than manual drive. For laboratory experiments, automation proved to be less time consuming but the manual drive will be more adaptable in practical applications.

Two types of apertures, a large scanning array and a scanning transceiver pair, can be utilized. The scanning array is the more effective for three-dimensional imaging from a single pass whereas the scanning transceiver pair requires multiple passes, thus increasing the time required for data acquisition. On the other hand, the single transceiver pair is much smaller and mobile than the array.

Two antennas designs, the Bowtie and Vivaldi, were considered. Under analysis using spectrum and network analyzers, the overall performance of Vivaldi antennas proved superior over the bowtie antennas. The Vivaldi Aerial is a class of an aperiodic continuously scaled antenna structure and has theoretically wide instantaneous frequency bandwidth. It has large gain and linear polarization and has constant gain over the frequency band, which is important to our applications. The key for obtaining constant-beamwidth with the Vivaldi is to maintain a curve of an exponential expansion. \([11]\) Lastly to maximize the power emitted from the transmitter to the air, the antenna must be impedance matched to the transmitter (50 ohms) and the Vivaldi can achieve that with proper slot-line techniques.
The antennas selected for the research prototype were the Vivaldi antennas. The size of the antenna is governed by the longest wavelength of the transmission-receive signal, which is corresponding to the lowest frequency of the designated band. Therefore, low-frequency operations require larger-size antennas. For our system, we utilize a pair of Vivaldi antennas, one for transmission and one for receipt. The data-acquisition electronics can operate up to four antennas simultaneously.

Image reconstruction algorithms were developed for all versions of imaging modalities. These algorithms are various versions of the multiple-frequency backward propagation technique. First is the monostatic version, which is the standard backward propagation algorithm with a scaling factor to compensate for the round-trip propagation. When the transmitter is placed adjacent to the receiver, it is often approximated as a monostatic system. If the separation between the transmitter and receiver is small with respect to the range distance of the target, the approximation is valid and the degradation to the reconstructed images is negligible. On the other hand, for near-field applications, the approximation errors can be substantial and the degradation becomes apparent. Thus, a modified version is developed, by replacing the propagation distance in the Green’s function with,

\[
r = \sqrt{(x + d/2)^2 + (z)^2} + \sqrt{(x - d/2)^2 + (z)^2}
\]  \hspace{1cm} (2)

where \(d\) is the separation distance between the transmission and receiver antennas and \(z\) is the depth from the antennas. In our case, the separation is perpendicular to the scan path.
The two versions discussed are mainly designed and developed for post processing. In many applications, it is desirable to have real-time display of the images with sequential updating as additional data samples are collected. In this mode, the two versions of the backward propagation algorithm conduct the wave migration in the spatial-frequency domain and are not computationally effective. A time-space domain version was developed for the capability of instantaneous display. Operating in the time-domain mode proved to be useful in scanning apertures due to its inherent nature of being able to display the image after each collection point whereas in the multiple-frequency mode requires all points to have been already collected. Thus, viewing of the image can occur in real-time rather than post-processing. A side effect though, is a loss of image quality due to the quantization effects of the FFT.

In terms of signaling modality, the research prototype is a step-frequency FMCW system. The waveform-generating device is specified to be able to generate waveforms with a 3.5-GHz bandwidth, covering a spectrum from 500 MHz to 4 GHz. Within the available spectrum, the selection of frequency band is programmable. The system scans through the selected frequency band with a designed scan rate. The scan rate is also programmable, and can be as high as 1028 frequency steps per second. One of the most crucial elements of this system is the tunable waveform-generation capability. It enables us to utilize various segments of the frequency band according to the applications and resolution requirements. It also allows us to skip over certain frequencies to avoid interferences with the local wireless communication and sensitive electronics. In addition, the flexibility makes the system adaptable to in field experiments, interfacing with various antenna sizes.

![RF electronic control unit for waveform generation and data acquisition.](image)

The system for all configurations was equipped with this step-frequency system, and operated with a frequency range from 1 GHz to 2 GHz, in 128 frequency steps. The device was not operated normally at the maximum specification to accommodate the arrangement of the antennas and the speed of data collection and image processing. This step-frequency system was selected due to its availability, suitability and ease of interfacing.
In order to maintain the system portability and flexibility, a laptop computer was used for image reconstruction and display. For this system a laptop with a Pentium4 1.7GHz with 512 Mb of ram was chosen and proved to be adequate.

Both Linux and Windows systems were developed for data collection and Matlab used for image reconstruction and display. It is also planned to move completely over to Matlab allowing a single platform to operate the GPR unit as well as reconstruct and display the images. Matlab was chosen over C development for the rapid development cycle and ease of coding as well as platform portability.

The unit was prototyped using wood because it has a low dielectric and will not effect the wave propagation as much as other materials. Wood also has the advantage of being easy to work with.
RESULTS

The field test included in this paper is a near-field experiment. The operating frequency band is from 1GHz to 2 GHz, with 128 of uniformly spaced frequency steps. Figure (7) shows the subsurface rebar profile. Figure (8) is the reconstruction with the accurate version of the backward propagation based on bistatic configuration. The coverage of the synthetic aperture is 2.5 meters, with 200 uniformly spaced receiving positions.

![Figure 8: Scan area before second set of rebar was placed and concrete was poured](image)

Figure 9: Resulting image formed by backward propagation algorithm operating in the multiple-frequency mode.

CONCLUSIONS

The performance of a GPR imaging system is governed by several important factors. However, research tasks in this area have focused on isolated components on the overall technical problem. The research prototype is the result of the successful system integration efforts, incorporating the optimization tasks of all technical elements, including data-acquisition electronics and waveform generation, synthetic-aperture scan
for aperture expansion, high-resolution image reconstruction, computation complexity, adaptability to various environments, and efficient user interfacing. This research development represents not only the successful execution of a university research program, but also the realization of high-performance GPR imaging technology for the direct industry.

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REFERENCES