SYNTHETIC APERTURE GROUND PENETRATING RADAR IMAGING FOR NONDESTRUCTIVE EVALUATION OF CIVIL AND GEOPHYSICAL STRUCTURES

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ABSTRACT

Synthetic-aperture microwave imaging with ground penetrating radar systems has become a research topic of great importance for the potential applications in sensing and profiling of civil and geophysical structures. It allows us to visualize subsurface structures for nondestructive evaluation with microwave tomographic images. This paper provides an overview of the research program, ranging from the formation of the concepts, physical and mathematical modeling, formulation and development of the image reconstruction algorithms, laboratory experiments, and full-scale field tests.

KEY WORDS

Ground penetrating radar imaging, holographic and tomographic imaging, nondestructive evaluation, backward propagation techniques, synthetic aperture.

INTRODUCTION

High-resolution ground penetrating radar imaging has been regarded as one of the most potential emerging technologies. The applications include the nondestructive evaluation of civil engineering structures and visualization of geophysical subsurface profiles. To produce a high-resolution image of a test area, the operation consists of three major components of microwave illumination, synthetic-aperture scan, and image reconstruction.

Microwave illumination of the area of interest is typically performed with waveforms in the form of either a CW pulse or a sequence of coherent CW signals. The bandwidth of the illumination waveform governs the resolving capability of the imaging system, especially in the range direction. For the case of CW pulse illumination, the bandwidth relies on the spectral spread due to the short pulse period. Step-frequency illumination is also an effective approach to quality data acquisition, which has more well-defined frequency band and involves more complex RF electronics and in return more efficient image formation tasks.

The image formation task is implemented based on the concept of coherent multi-frequency backward wavefield propagation. We first partition the wavefield data into segments according to the frequency index. Thus, each segment is a collection of coherent wavefield over the synthetic aperture. The backward propagation algorithm migrates the coherent received wavefield toward the region of interest to form a holographic image. And the final image is the superposition of all complex holographic images.

In this paper, we first present the concept of synthetic-aperture modality for ground penetrating radar imaging. Then the structure of the backward propagation image reconstruction algorithm is outlined. Subsequently, results from laboratory experiments

and field tests are selected to illustrate the performance as well as limitation of the imaging capability.

SYNTHETIC-APERTURE IMAGING

Synthetic-aperture GPR imaging for nondestructive evaluation of civil structures has been one of the most productive research programs in the Imaging Systems Laboratory. The project has a span over 12 years with great intensity and momentum. In order to provide an accurate overview, it is important to cover the early stage of the research project to review the formulation of the concepts. The project was originated as a research unit within the Advanced Construction Technology Center (ACTC) of the University of Illinois at Urbana-Champaign. The objective of the project was to develop the imaging capability for profiling the interior distribution of the civil structures for the purpose of monitoring the structural integrity as well as inspection for defects.

To perform preliminary experiments, a GSSI Subsurface Interface Radar (SIR) was selected to conduct data-acquisition tasks. The SIR system is a pulse-echo transmission and detection device and its illumination waveform is a gated microwave pulse at the operating frequency of 990 MHz. The relative time delay of the received echo gives the depth of the subsurface reflector. Thus, the SIR system itself is mainly a pulse-echo range detecting device operating in the point-by-point mapping mode. There was no imaging capability especially in the cross-range direction.

To achieve imaging capability, the most direct and immediate approach is to introduce an aperture coverage. To do so, we can utilize a multiple-element receiver array with sufficient aperture span corresponding to the designated resolving capability. Because the GSSI SIR system is a single-transceiver device, the most effective approach is the synthetic-aperture modality. This is to scan the transceiver along a designated path at a steady speed so that microwave echoes can be collected along the scan path. This method requires simpler data-collection electronic hardware and gives better consistency in terms

of signal quality, due to the use of single-transceiver single-channel configuration. The trade-off is the scan time required for data acquisition.

IMAGE RECONSTRUCTION TECHNIQUES

The development of high-resolution image reconstruction technique is one of the most critical elements of the successful execution of the research goal. For this application, the approach to image formation is based on the concept of the multiple-frequency tomographic backward propagation method. To perform data acquisition for high-resolution visualization, we first illuminate the region of interest with a known waveform. Data detection can be achieved, for greater effectiveness, by scanning an active transmitter-receiver along a known path to form a synthetic aperture. Microwace echoes can then be detected at various receiving positions over the aperture. The echoes received by the data acquisition system at a receiving position can be described as a superposition of delayed versions of the transmitted waveform with coefficients determined by target reflectivity and attenuation in the medium. Because the time delay of the returned signal contains range distance information, time-delay estimation is first performed on the echoes at each receiver location. The accuracy of this estimation process governs the resolution in the range direction. The estimation can be achieved by deconvolving the returned echoes with the known illumination waveform. For simplicity, this step can be replaced by a matched filtering process.

After the time-delay profile is estimated, backward propagation is then performed to obtain the resolution in the cross-range direction. Backward propagation is, mathematically and physically, equivalent to wavefield focusing. It is important to note that backward propagation filters operate by employing specific wavelengths. Thus, we first need to decompose the delay profile at each receiving position into coherent Fourier components and index these components with respect to the wavelength. In this fashion, we partition the spectra of the delay profiles over all the receiving positions into coherent wavefield patterns according to a wavelength index. We then regroup the spectrum data in such a way that each pattern has an identical wavelength index. After re-indexing and

re-grouping, at a specific index value, the signal pattern is the same as the wavefield that would be received if the specimen is illuminated with a coherent CW signal at that wavelength. This is done in such a way that the delay profiles over the synthetic aperture in the frequency domain become a collection of holograms of the specimen at various coherent wavelengths. By using a backward propagation filter corresponding to the appropriate wavelength, we can then backward propagate each of these holograms to the region of interest to form holographic images of the internal structures.

In summary, this holographic reconstruction procedure involves first a spatial-Fourier transformation of the wavefield patterns along the scan direction. Then spatial-frequency domain backward-propagation filters are applied to perform focusing. The backward propagation procedure is applied to all holographic wavefield patterns individually, since the formulation of the backward propagation filter varies with the operating wavelength.

Subsequently, a sequence of holographic images can be formed from the wavefield patterns associated with various wavelengths. The effects due to various illumination wavefield, monostatic or bistatic, will then be removed with a demodulation procedure according to the illumination scheme. The remaining step in obtaining the final image is to superimpose the holographic images for the formation of the tomographic image of the specimen. The superposition can be achieved in either the space domain or spatial-frequency domain. In practice, it would be performed in the spatial-frequency domain for computational efficiency. For systems with one-dimensional synthetic apertures, the resultant images will be two-dimensional cross-sectional profiles, with the additional dimension, that in the range direction, being obtained from the time-delay estimation. Similarly, three-dimensional images can be obtained for systems with two-dimensional apertures.

LABORATORY EXPERIMENTS

Subsequent to the theoretical study, algorithm development, and simulation, a sequence of laboratory experiments were conducted with the GSSI SIR system to demonstrate the

resolving capability, sensitivity, and limitation of the synthetic-aperture imaging technique. For the experiments, large concrete blocks were constructed containing sample test objects such as rebars, air voids, metal pipes, and metal pipes containing water. One important experiment is the imaging of the honeycomb specimen. Honeycomb represents a typical deterioration effect of concrete structures, which has been known to be extremely difficult to detect by traditional sensing systems. To test the resolving capability of the system for this challenging case, we placed a honeycomb specimen in a concrete block similar to the previous experiment. Figure (1) shows the results of this successful experiment. The bottom part is the profile of the microwave echoes from the honeycomb and the top part is the reconstructed image, which clearly shows the location of the honeycomb specimen.

Most experiments were conducted with two-dimensional configurations that the data acquisition was conducted along a linear scan path and the resultant image is the cross-sectional profile of the three-dimensional specimen. Subsequent to these experiments, we elevated the tasks to the new level of three-dimensional image reconstruction. This involves data acquisition over a two-dimensional synthetic aperture and tomographic image reconstruction in three dimensions. To demonstrate three-dimensional imaging capability, a specimen with three-dimensional variation was constructed and data acquisition was conducted over a two-dimensional planar synthetic aperture. For this experiment, the test specimen contains two layers of rebars at different depths. Figure (2) shows the successful three-dimensional reconstruction of the internal profile of the specimen.

STEP-FREQUENCY DATA ACQUISITION SYSTEM

The GSSI SIR system we utilized for the laboratory experiments was a simple pulse-echo device. The illumination waveform is a single-cycle CW pulse. As the RF electronics becomes more sophisticated and accurate, the pulse-echo devices are now gradually replaced by step-frequency systems.
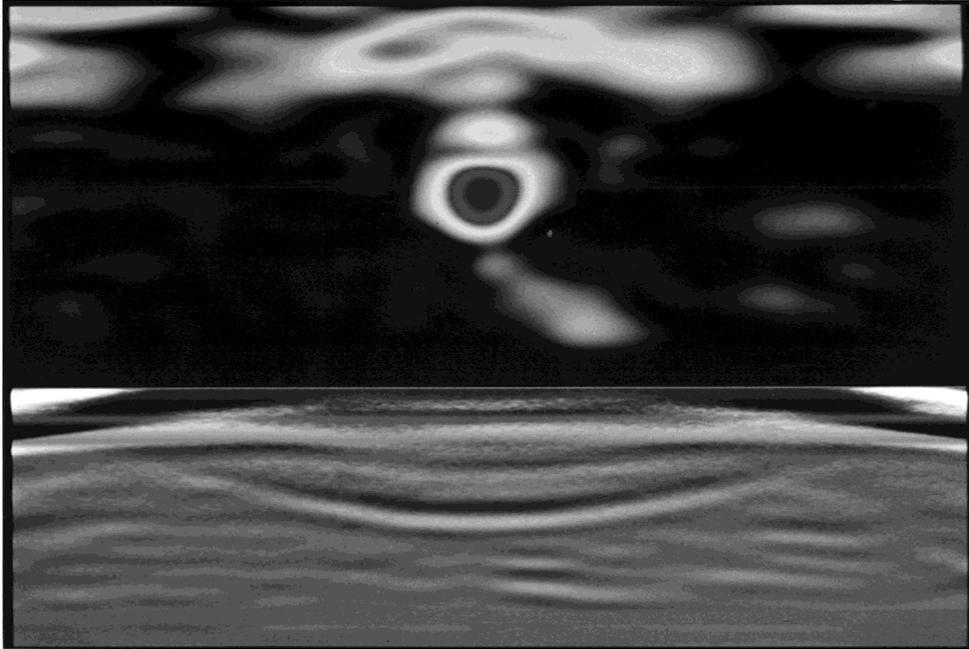
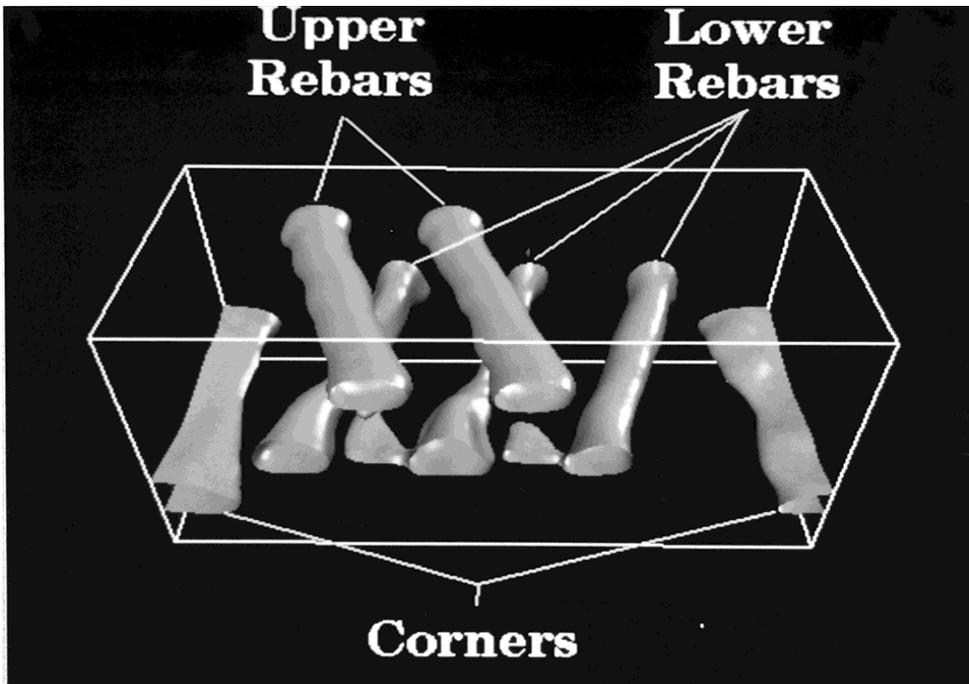Figure (1): Cross-sectional image of a honeycomb void (top) and microwave echoes.

Figure (2): Tomographic image of three-dimensional internal profile of rebars.

During the collaboration with the U.S. Department of Energy's Special Technologies Laboratory, a step-frequency system was utilized for the experiments. It is a transceiver system, illuminating 128 steps of coherent waveforms, ranging from 200 MHz to 700 MHz. The span of the synthetic aperture is 7 feet. Figure (3) shows the reconstructed image of six buried metal plates. The size of the plates is 1 foot and the spacing in range direction is also 1 foot. For systems with step-frequency illumination, the decomposition of the received time-domain signals and repartitioning into subsets of coherent wavefield patterns become unnecessary and can be eliminated. The final image is simply the complex superposition of all the coherent holographic sub-images, which substantially simplifies the computation complexity. On the other hand, the RF electronics is more complicated for the generation and switching of the illumination frequency.
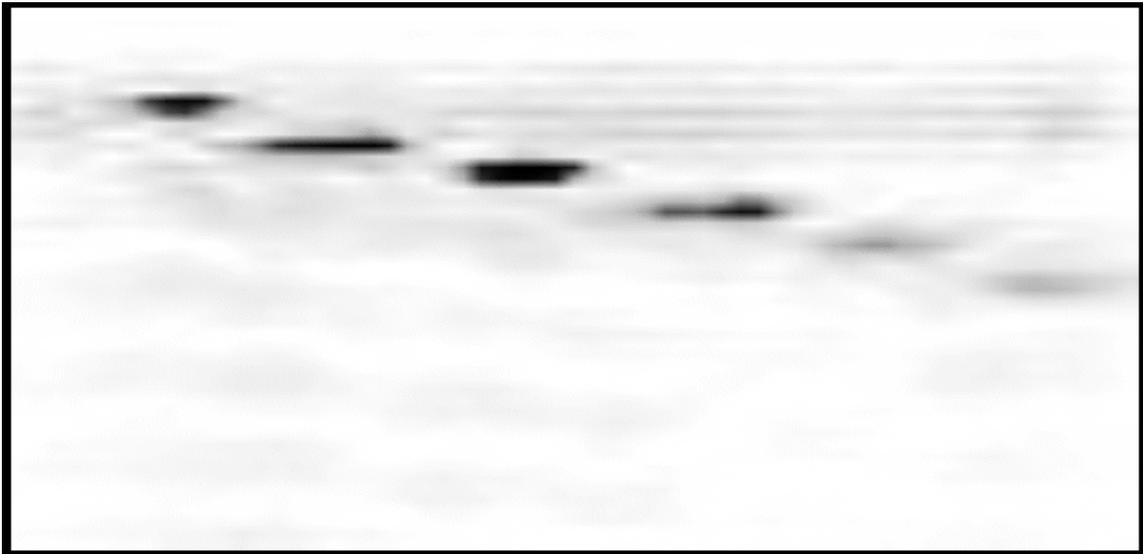

Figure (3): Multiple-frequency reconstruction of six metal plates.

The utilization of the frequency band is important to the applications of GPR imaging. The GSSI SIR system, operating at 990 MHz is considered a mid-frequency system and

The STL step-frequency system with bandwidth between 200 MHz and 700 MHz is a low-frequency device. High-frequency systems give superior resolving capability because the resolution limit of an imaging system is in general governed by the operating wavelength. On the other hand, high-frequency illumination also introduces greater attenuation, which represents a reduction of penetrating capability. In comparison with the GSSI system, the STL system is operating in a lower frequency domain to gain range capability by trading off resolution.

CONCLUSION

Synthetic-aperture ground penetrating radar imaging for civil and geophysical structures has been one of the most exciting applications in the recent years. The effort represents an integration of the technical areas of signal processing, RF electronics, mathematical and physical modeling of wave propagation, and hardware and software integration and optimization. This paper provides a brief overview of the development of the imaging capability from the formation of the concepts, mathematical and physical modeling, structure of the imaging algorithms, laboratory experiments, and field tests. In the early part of the paper, the focus was on the description of the signal-processing procedure as the inverse scattering process responding to the physical interactions of the microwave illumination and the subsurface structures of the specimens. Then, out of a long sequence of laboratory experiments, two were selected for illustration to demonstrate the capability of this new sensing technology. Subsequently, we moved from the pulse-echo mid-frequency system to the low-frequency step-CW system. The image reconstruction algorithm was modified to accommodate the change of illumination configuration and the result of a full-scale field test was presented.

ACKNOWLEGMENT

REFERENCES

1. Hua Lee and Glen Wade, *Imaging Technology*, IEEE Press, New York, 1986.

2. Hua Lee and Glen Wade, *Modern Acoustical Imaging*, IEEE Press, New York, 1986.

3. Albert Mocovski, *Medical Imaging Systems*, Prentice-Hall, Englewood Cliffs, 1983.

4. Hua Lee, "Formulation of the Generalized Backward Projection Method for Acoustical Imaging," *IEEE Transactions on Sonics and Ultrasonics*, vol. SU-31, no. 3, pp. 157-161, May 1984.

5. Hua Lee, "Acoustical Image Reconstruction Algorithms: Structure, Performance Sensitivity, and Limitation," *Proceedings of 1987 SPIE International Symposium on Pattern Recognition and Acoustical Imaging*, vol. 768, pp. 34-43, 1987.

6. Jeffrey Mast, Hua Lee, Weng Chew, and Joseph P. Murtha, "Pulse-Echo Holographic Techniques for Microwave Subsurface NDE," *Proceedings of the Conference on Nondestructive Evaluation of Civil Structures and Materials*, pp. 177-191, 1990.

7. A. D. Whalen, *Detection of Signals in Noise*, Academic Press, New York, 1971.

8. Joseph W. Goodman, *Introduction to Fourier Optics*, McGraw-Hill, New York, 1968.

9. Jeffrey E. Mast, Hua Lee, and Joseph Murtha, "Application of Microwave Pulse-Echo Radar Imaging to the Nondestructive Evaluation of Buildings," *International Journal of Imaging Systems and Technology*, 4(3), pp. 164-169, 1992.

10. Jeffrey E. Mast, Hua Lee, and Joseph Murtha, "High-Resolution Microwave Subsurface Nondestructive Evaluation of Civil Structures and Materials," *International Advances in Nondestructive Testing*, Vol. 17, pp. 207-250, 1994.

11. Stephanie J. Lockwood and Hua Lee, "Pulse-Echo Microwave Imaging for NDE of Civil Structures: Image Reconstruction, Enhancement, and Object Recognition," *International Journal of Imaging Systems and Technology*, 8(4), pp. 407-412, 1997.

12. Steven K. Koppenjan, Curt M. Allen, Duane Gardner, Howard Wong, Hua Lee, and Stephanie J. Lockwood, "Multi-Frequency Synthetic-Aperture Imaging with Lightweight Ground Penetrating Radar Systems," *Applied Geophysics*, 43, pp. 251-258, 2000.