Multi-frequency synthetic-aperture imaging with a lightweight ground penetrating radar system

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Abstract

The detection of buried objects, particularly hazardous waste containers and unexploded ordnance (UXO), has gained significant interest in the United States in the late 1990s. The desire to remediate the thousands of sites worldwide has become an increasing concern and the application of radar to this problem has received renewed attention. The US Department of Energy’s Special Technologies Laboratory (STL), operated by Bechtel Nevada, has developed several frequency-modulated, continuous-wave (FM-CW) ground penetrating radar (GPR) units. To meet technical requirements for higher-resolution data, STL and the University of California, Santa Barbara (UCSB) is investigating advanced GPR hardware, signal processing, and synthetic-aperture imaging with the development of an innovative system. The goal is to design and fabricate a lightweight, battery-operated unit that does not require surface contact, can be operated by a novice user, and can achieve improved resolution. The latter is accomplished by using synthetic-aperture imaging, which forms the subsurface images by fully utilizing the data sequences collectively along a scan path. We also present the backward propagation algorithm as the basic structure of the multiple-frequency tomographic imaging technique, and the conventional fast Fourier transform (FFT) method which can be described as a degenerated case of the model where the computation procedure is approximated under the narrow-beam assumption. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Special Technologies Laboratory’s (STL’s) original frequency-modulated, continuous-wave (FM-CW) ground penetrating radar (GPR) unit (Koppenjan and Bashforth, 1993) was designed to meet Naval Explosive Ordnance Division criteria for the detection of buried ordnance and has also been applied to many other areas including hazardous waste containers, site characterization (Koppenjan and Martinez, 1994), utility lines, tunnels, and fossilized dinosaur bones. The unit weighed 40 kg, required intimate ground contact for optimum performance, and
needed a highly skilled operator. The most recent evolutionary development effort is toward a lightweight GPR that operates with minimal or no ground contact and provides a very simple user interface. This paper describes the advances of the latest unit, called the GPR-X (Koppenjan et al., 1998), and the application of synthetic-aperture radar (SAR) image reconstruction algorithms. The multiple-frequency version of backward propagation image reconstruction is presented as the basic framework for synthetic-aperture imaging. For simplicity, the analysis is started from the level of coherent backward propagation, and subsequently the complete algorithm is formulated by modifying the coherent version with multi-frequency superposition and round-trip.

2. System hardware

2.1. System hardware description

The GPR-X is a portable, self-contained unit that weighs 10 kg and consists of four subassemblies: the computer, radar, antenna, and power supply. The unit is illustrated in Fig. 1. It acquires, processes, and displays data in real-time at 30 sweeps per second. The core of the system is a FM-CW radar that operates over the frequency range of 200–700 MHz. A 16-bit analog-to-digital converter (ADC) is used to sample phase coherent (I&Q) data, yielding a system dynamic range of 96 dB. It has the capability to detect targets to depths of 5 m with a range resolution of 20 cm. The overall performance of the GPR is, as always, affected by soil composition, dielectric constant (\(\varepsilon_r\)), and attenuation factors. A block diagram of the system is shown in Fig. 2 and is described in the following section.

2.2. Computer subassembly

The computer subassembly contains the signal processing and display hardware. This unit houses a PC104 bus-based computer, a digital-signal processing (DSP) board, a liquid crystal display (LCD), a PC (formerly PCMCIA) card interface board, a user interface board, and a digital interface module. The PC operates the GPR software, which controls data acquisition, signal processing and depth profile display. This process is performed in parallel, and greatly increases the overall system speed. The DSP is an AT and T WE32DSP which operates at 50 MHz.

The LCD is a low-power, 640 × 480 resolution screen with a 0.19 dot pitch. It is a super-twisted pneumatic type with transflective backing and can be viewed in direct sunlight. The video control board uses a polynomial-based frame rate control and a dithering algorithm to produce 64 gray shades. A split-screen display is implemented to allow scrolling of data at 30 Hz while maintaining a stable user interface display area. This high scroll rate is accomplished by manipulating the screen home position as opposed to shifting video memory.

The PC card sockets accept flash memory cards for saving data. The user interface contains two encoders for display adjustments and a save button. The digital interface module controls the data transfers from the radar section, programs the phase lock loop (PLL) of the RF module, interfaces to the control panel, monitors the power supply, and controls direct memory...
access (DMA) of the digitized radar data with the computer.

2.3. Radar subassembly and system operation

The radar subassembly contains the RF electronics and ADC circuitry, and is controlled by the digital interface board in the computer. The digital interface board initiates data acquisition by programming the PLL to step in frequency. The PLL with a crystal oscillator source and RF oscillators are used to synthesize the 200 to 700 MHz signal. The crystal oscillator also generates system reference frequencies used by the timing board, the modulator, and the demodulator. The timing board generates the system clock signals and the 1.25 MHz intermediate frequency (IF) modulation signals.

Before the RF signal is transmitted, it is phase modulated at an intermediate frequency of 1.25 MHz. When a radar return signal is mixed directly to baseband and amplified, a phenomenon known as 1/f noise or flicker noise exists. This noise is also amplified and is very prevalent at low frequencies. It is defined by the noise-temperature ratio of the receive mixer and varies inversely with frequency. Above approximately 500 kHz, the noise-temperature ratio approaches a constant value (Skolnik, 1980). To reduce the effects of 1/f noise, the transmitted RF signal is phase modulated at an intermediate frequency, 1.25 MHz in this case, and amplification takes place at this IF and not at baseband. The receive signal is then demodulated to obtain the baseband signal.

Fig. 2. GPR-X functional block diagram.

Fig. 3. GPR-X being tested.
Each sweep takes approximately 33 ms during which time 85 data samples (85 I and 85 Q) are acquired. The sampling is performed by a 16-bit, dual-channel, simultaneous-sample ADC that serially outputs data at 45 kHz. The DSP board processes the data and this operation is described in Section 3.

2.4. Antenna subassembly

The monostatic antenna subassembly contains a cavity-backed, bowtie element and RF and IF amplifiers. The bowtie was chosen for its good broad-band characteristics. To create a unidirectional single-lobe pattern, the antenna housing is constructed with carbon-fiber absorbing material that shields the antenna and attenuates the back lobes. The typical E-field beamwidth, measured at the 3 dB point, is 120° at 200 MHz and decreases to approximately 90° at 700 MHz. The H-field beamwidth is less than 90° over the 200 to 700 MHz frequency range. Through the use of the absorbing material, the usable bandwidth is increased to a multi-octave range, 200 to 1000 MHz. The return loss is better than −15 dB.

2.5. Power supply subassembly

The power supply uses 14.4-V, 50-W, rechargeable NiCad batteries. These are high quality, commercial off-the-shelf batteries. Typical battery life is 3 h and the recharge time is the same. External power (9–18 V DC) may be used through the auxiliary port with any 10-W source.

Fig. 3 is a picture of the GPR-X being tested. Table 1 contains a summary of technical specifications. The unit’s tubular section folds in the center and the antenna detaches allowing it to fit into two small carrying cases.

3. System software

3.1. System software

The GPR-X records complex, or sampled I and Q, data at 85 linear increments over the 200 to 700 MHz frequency band. This data is converted into its frequency domain representation (time-domain pulse response equivalent) in order to display the radar return as a depth profile. This is accomplished using a narrow-beam image reconstruction algorithm. This algorithm is a simple version of the two-dimensional SAR reconstruction algorithm developed in Section 4, and can be implemented as a FFT.

Real-time algorithms can be implemented on the data because of the system architecture and on-board DSP. Currently a 256-point complex FFT is performed on the radar data to obtain the time-domain pulse response equivalent. A Kaiser–Bessel window is applied to the raw data before the FFT. The GPR-X has a simple interface with only two radar adjustments: a linear ‘‘scale’’ and exponential ‘‘range gain.’’ Other signal processing algorithms, such as auto gain adjustment, are being developed. This will increase the system performance and target detection capability while maintaining minimal user interface, allowing operation by a novice user.

3.2. Data and display

Each radar sweep contains 85 data points. The individual data point is displayed as two-

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Summary of GPR-X system specifications</th>
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<tbody>
<tr>
<td>Operating frequency</td>
<td>200–700 MHz</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>500 MHz</td>
</tr>
<tr>
<td>Modulation frequency</td>
<td>1.25 MHz</td>
</tr>
<tr>
<td>Number of sampled points</td>
<td>85</td>
</tr>
<tr>
<td>Scan rate</td>
<td>30 Hz</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>96 dB</td>
</tr>
<tr>
<td>Range resolution ($\epsilon_i = 4$)</td>
<td>20 cm</td>
</tr>
<tr>
<td>Depth penetration ($\epsilon_i = 4$)</td>
<td>5 m</td>
</tr>
<tr>
<td>Antenna type</td>
<td>Monostatic Bowtie</td>
</tr>
<tr>
<td>Weight</td>
<td>10 kg</td>
</tr>
<tr>
<td>Power source</td>
<td>Rechargeable NiCad (3 hr usage)</td>
</tr>
</tbody>
</table>
pixels wide by four-pixels high and equals 5 cm in range, assuming $\epsilon_r = 4$. The strength of the radar return is intensity mapped to a 64-level gray scale. A total of 80 FFT channels are displayed, which equates to a total range of 4 m.

As shown in Fig. 4, the data quality of the GPR-X equals that of the original STL ground-contact GPR as previously reported (Koppenjan and Bashforth, 1993). The data were acquired with an air gap of approximately 5 to 15 cm. The data clearly show the radar returns from seven metal plates buried linearly from 0.3 to 2.2 m deep in a test pit. The plates are $0.3 \times 0.3$ m square and spaced 0.3 m apart.

3.3. Image processing

The FM-CW GPR system described in this paper has been traditionally modeled as a point-by-point strip-mapping device. At each receiving position, an FFT is taken to form the range profile of the subsurface target distribution. The multiple-frequency complex-wave data at each surface location was processed independently and there was no procedure to compensate for diffraction in the cross-range direction.

In Section 4, a different modeling technique is presented. Instead of a simple FFT for range estimation, the system is now modeled as a synthetic-aperture multiple-frequency system operating in reflection mode. A sequence of 128 coherent backward-propagation procedures are conducted to form the composite image, which is the superposition of 128 holographic sub-images, each for every coherent frequency step. As a result, diffraction is fully compensated in both range and cross-range directions, and, hence, overall quality of the images is improved.

4. Synthetic aperture radar image reconstruction

4.1. Synthetic-aperture microwave image reconstruction algorithm

One of the most important components of a high-performance imaging system is the image
reconstruction technique, which directly governs the overall capability of the system. The formulation of the imaging algorithm includes physical and mathematical modeling, design, and implementation, involving the critical elements of computation complexity, parallel processing architecture, and resolving capability. For conventional GPR systems where system hardware is normally the emphasis, the role of image reconstruction algorithm can be easily overlooked. In this section, we present the image formation technique associated with the data acquisition hardware design in a concise manner and then illustrate the resolving capability with an experimental data set.

Traditional GPR systems operate largely in a localized mode, estimating the range information from the time delay of the illumination waveform at a particular location. The resultant image is typically the range profile of a subsurface region over a survey area, a composite image formed by range profiles at various receiving positions. This means the estimation process associated with image formation is effective only in the range direction. If the illumination hardware is a narrow-beam system, the image profile will be sufficiently accurate, since there is no correlation of information contents between data sets collected at different receiving positions. However, most GPR systems operate with one receiving antenna instead of a large physical antenna array, so as a result the beam patterns have significant spread and the narrow-beam assumption is not valid. Therefore, image reconstruction algorithms need to be able to resolve in both range and cross-range directions.

Step FM-CW systems is an alternative to the classical CW-pulse or linear-chirp systems. It steps through a sequence of N frequencies during a so-called illumination period. Within each frequency step, it functions like a coherent CW system. And during the period of one frequency step, the data acquisition system produces the complex amplitude of the returned coherent waveform from the twin output channels.

Because the propagation speed is constant, the frequency during one particular frequency step corresponds uniquely to a wavelength index, with the relationship

\[ v = f \lambda \]  

where \( v \) is the propagation speed of the media, \( f \) is the frequency, and \( \lambda \) is the corresponding wavelength (Mast et al., 1994). Thus, the index of the output data sequence of a complete illumination cycle can be converted from frequency to wavelength. Then we partition the output data over the entire aperture into groups based on the wavelength index. There will be \( N \) sets of spatial data corresponding to the \( N \) operating wavelengths. Each coherent data set can be considered as a hologram over the aperture at that particular wavelength. Subsequently, a holographic reconstruction of the subsurface profile can be formed by a linear filtering process, known as backward propagation, with the transfer function in the form of

\[ H(f_s) = \exp\left(j2\pi z\sqrt{\frac{1}{\lambda^2} - f_s^2}\right) \]  

where \( f_s \) is the spatial frequency in the \( x \) direction, and \( z \) is the range distance (Goodman, 1968; Lee et al., 1982). This operation is the backward propagation process in the spatial-frequency domain. It is a numerical focusing procedure which corrects for the diffraction effects in both range and cross-range directions to form the holographic image. GPR systems are classified as pulse-echo sensing devices. Thus, the range parameter needs to be scaled by a factor of two to correct for the round-trip effect.

Assuming the characteristics of the targets remains the same over the frequency span, we can reconstruct the overall image by superimposing all \( N \) holographic sub-images.

\[ \hat{s}(x, z) = \sum_k \hat{s}_k(x, z) \]  

The image reconstruction procedure is summarized below.
Step 1: Partition the data based on the frequency index and regroup the data into N spatial data sets. Each spatial data set is associated with one unique frequency index.

Step 2: Convert the index from frequency to operating wavelength.

Step 3: Fourier transform each spatial data set to represent the wavefield in the spatial-frequency domain.

Step 4: Apply the backward propagation filter to the wavefield in the spatial-frequency domain. Since the formula of the backward propagation filter is wavelength dependent, each coherent spatial data set is processed by a unique backward propagation filter corresponding to its wavelength index. The wavefield gains an additional dimension by backward propagating in the range direction. Note that the backward propagated wavefield is now in the space domain in the range direction and in the spatial-frequency domain in cross-range directions.

Step 5: Superimpose N backward propagated wavefields.

Step 6: Inverse Fourier transform in the cross-range directions to form the final image in the space domain.

The backward propagation technique is a linear, space-invariant, and stable filtering procedure. It conducts image formation with consistent performance and resolving capability, and can be implemented in parallel form for high-speed processing. Therefore it has been utilized in a wide range of applications of various imaging configurations and modes. The resolution in the range direction is determined by the spectral bandwidth of the illumination waveforms. In the cross-range direction, the resolution is governed by the span of the aperture (Chang et al., 1994). The unit-magnitude all-phase backward propagation filter is based on the model of the ideal receiver. For data acquisition antennas of various size and shapes, the transfer function can be modified accordingly for optimal image formation.

4.2. Results of the SAR algorithm

The narrow-beam reconstructive algorithm (FFT) as previously shown in Fig. 4 and the synthetic aperture image reconstruction algorithm shown in Fig. 5 were applied to raw data. Both were processed off-line as opposed to the

Fig. 5. Depth profile using synthetic aperture image reconstruction algorithm.
real-time FFT on the GPR unit. No range gain or window functions were applied to the data in order to analyze the results of only the SAR processing. The SAR processed image shows enhanced target resolution when compared to the narrow-beam processed image. The width of the targets in the SAR processed image were an average of 25% sharper than the targets in the FFT processed image and the hyperbolic tails removed. The typical measured target width was 0.54 m when FFT processed and 0.40 m when SAR processed. The target width was measured from the center point of maximum magnitude to the 3 dB points on each side.

5. Conclusions

We have demonstrated the ability to acquire high-quality GPR data without intimate ground contact. The packaging allows the system to be quickly assembled, and by reducing the complex radar adjustments, the operation allows use by a novice operator. Operators have been trained in less than 1 h to successfully detect real-world targets. When operating in the point-by-point mapping mode, the step-frequency illumination scheme significantly reduces the complexity of the profiling process and the range estimation procedure is simplified down to a FFT operation. To develop the resolving capability in both range and cross-range direction, we model the device as a multiple-frequency holographic data acquisition system operating in synthetic-aperture format and utilize backward propagation technique for multi-dimensional image reconstruction. With a combination of high-quality data acquisition hardware and high-resolution image formation technique, this system provides superior imaging capability for subsurface profiling. We are currently researching the implementation of real-time SAR algorithms to be incorporated onto the GPR.

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