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ABSTRACT

Ultra wideband linear array holography is a unique real-time imaging technique for in-situ inspection of buried waste at various DOE sites. The array can be mounted on various platforms such as crane booms, pickup trucks, ATVs, and scanned generating "3-D" subsurface images in real time. Inspection speeds are approximately 0.5 to 2 meters/sec, if the image is viewed in real time, greater for off-line processing.

The Ground Penetrating Holographic (GPH) system developed for inspection of DOE sites employs two 32-element arrays of tapered-slot antenna operating at 5-GHz and 2.5-GHz center frequencies. The GPH system, which is mounted on a small trailer with a computer image processor, display, and power supply, is capable of imaging a wide swath (1 to 2 meters) with its linear arrays. The lower frequency array will be used at INEL (for greater depth penetration) because of high soil attenuation.

Recent holographic "3-D" images of buried waste container lids and dielectrics obtained in Hanford sand and INEL soils at various depths graphically illustrate the unique image resolution capabilities of the system. Experimental results using the 5-GHz array will be presented showing the excellent holographic image quality of various subsurface targets in sand and INEL soil.

INTRODUCTION

Holographic Impulse Theory

Ultra wideband (UWB) linear array radar holography is a unique "real-time" imaging technique for imaging buried waste with extremely high lateral and depth resolution. The large frequency bandwidth, typically 100%, provides excellent depth resolution and the synthetic aperture optimum lateral resolution of one-half wavelength at the center pulse frequency.

The ground penetrating UWB holographic (GPH) system generates high-resolution "3-D" images of buried waste in real time using the most advanced linear array technology. The linear array is attached to a motor vehicle above the surface (air-coupled). It is then scanned over the buried waste, and "3-D" images are generated in real time.

The array is approximately 1 meter in length, producing an image of approximately this width in one scan of the vehicle. The images are scrolled continuously in length as the vehicle scans over the terrain. Large areas can be inspected in a relatively short time compared with conventional ground penetrating radar (single-channel) systems with the linear array.

Let us consider a near-field scanned aperture UWB radar system. The received impulse signal can be expressed as a time-shifted waveform in terms of the target's range and propagation velocity of the medium.

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$$h(t-t_T) = h\left(t - \frac{2r_T}{c}\right) \quad (1)$$

After recording the time-shifted impulse waveforms over the entire aperture, we compute the Fourier transform of each waveform, which decomposes them into their discrete frequency components. These components are simply the holographic signals for each frequency in the impulse and can be expressed by the following equation.

$$FT\left[h\left(t - \frac{2r_T}{c}\right)\right] = H(x,y,f) e^{-j\phi_T(x,y,f)} \quad (2)$$

where

$$\begin{aligned} r_T = r(x,y) &= \sqrt{(x-x_1)^2 + (y-y_1)^2 + z_1^2} &&= \text{distance to target} \\ \phi_T(x,y,f) &= \frac{4\pi r(x,y)}{\lambda} &&= \text{phase of target at frequency (f)} \\ H(x,y,f) & &&= \text{target amplitude at frequency (f)} \\ \lambda & &&= \text{wavelength at frequency (f).} \end{aligned}$$

Equation (2) can be written in terms of its real U_r and imaginary U_i components for all frequencies in the pulse.

$$U_R(x,y,f) = H(x,y,f) \cos\left(\frac{4\pi r_T}{\lambda}\right) \quad (3)$$

and

$$U_I(x,y,f) = H(x,y,f) \sin\left(\frac{4\pi r_T}{\lambda}\right) \quad (4)$$

These expressions are very familiar to radar holographic engineers. They are the holographic signals for each frequency component in the impulse, and they completely describe the target's reflectivity $H(x,y,f)$ and the phase $\left(\frac{4\pi r_T}{\lambda}\right)$. They can be computed from the following equations.

$$H(x,y,f) = \sqrt{U_R^2(x,y,f) + U_I^2(x,y,f)} \quad (5)$$

$$\phi_T(x,y,f) = \frac{4\pi r_T}{\lambda} = \tan^{-1} \left[\frac{U_I(x,y,f)}{U_R(x,y,f)} \right] \quad (6)$$

Computer Reconstruction of Impulse Data

Assume the radar holographic system operates in a mono-static mode and the UWB signal received at the scanned aperture is expressed by the following equation:

$$s(x',y',o,f) = \iint f_T(x,y,z,f) e^{j2kR} dx dy \quad (7)$$

where $f_T(x,y,z)$ = target reflectivity
 k = the wave number
 x,y,z = target coordinates
 x',y',o = receiver coordinates

$$R = \text{distance to target} = \sqrt{(x'-x)^2 + (y'-y)^2 + z^2}$$

$$e^{j2kR} = \text{spherical wave} = \iint e^{jk_x(x'-x) + jk_y(y'-y) + jk_z(o-z)} dk_x dk_y \quad (8)$$

The spherical wave can be expressed as a vector summation of plane waves. If we substitute this expression into Equation (7), the received signal is given by the following equation.

$$s(x,y,o,f) = \iint \left\{ \iint f_T(x,y,z,f) e^{-j(k_x x' + k_y y')} dx dy \right\} e^{j(k_x x' + k_y y')} e^{jk_z z} dk_x dk_y \quad (9)$$

The term in brackets is the target's plane wave angular spectrum (i.e., Fourier transform of target's activity). We can express it by the following equation.

$$A_T(k_x, k_y, z, f) = \iint f_T(x, y, z, f) e^{-j(k_x x' + k_y y')} dx dy \quad (10)$$

We can then write Equation (7) as

$$s(x', y', o, f) = \iint A_T(k_x, k_y, z, f) e^{j(k_x x' + k_y y')} e^{-jk_z z} dk_x dk_y$$

$$= FT^{-1} [A_T(k_x, k_y, z, f) e^{-jk_z z}] \quad (11)$$

The result of taking the Fourier transform (both sides) of Equation (11) is

$$FT[s(x', y', o, f)] = A_T(k_x, k_y, z, f) e^{-jk_z z} = A_O(k_x, k_y, o, f) \quad (12)$$

This expression uniquely defines the target's angular spectrum in terms of the angular spectrum computed from the recorded aperture data $s(x', y', o, f)$ and the back propagation factor $e^{jk_z z}$.

$$A_T(k_x, k_y, z, f) = \sum A_O(k_x, k_y, o, f) e^{jk_z z} \quad (13)$$

UWB Holographic Image

The UWB image of the target is simply the absolute value of the inverse Fourier transform of its multi-frequency angular spectrum.

$$IMAGE = f_T(x, y, z, f) = FT^{-1} [A_T(k_x, k_y, z, f)] = FT^{-1} \left[\sum A_O(k_x, k_y, o, f) e^{jk_z z} \right] \quad (14)$$

$$\text{where } k_{z'} = \sqrt{4k^2 - (k_x)^2 - (k_y)^2}$$

EXPERIMENTAL RESULTS

A 5-GHz center frequency UWB impulse with a 100% bandwidth radar system was used to construct holographic images of shallow subsurface targets in INEL and dry sand soils. The targets simulated small circular waste canisters (metal and dielectric), and varied in diameter from 10 cm to 22 cm, and were buried at a depth of approximately 1 meter. The metal letter "F" is approximately 30 cm in width and 52 cm in length and is used as a resolution target.

Figure 1 is the holographic image and "3-D" amplitude profile of the letter "F" and three simulated canisters buried approximately 1 meter in Hanford sand. The images are of excellent quality and graphically illustrate the resolution capabilities of the system.

Figure 1. Holographic Images of Buried Targets (1 meter in sand): (a) top view and (b) intensity "3-D" view

Figure 2 is a picture of the UWB holographic 5-GHz linear array buried waste imaging system mounted on a small trailer for DOE/BWID project at Idaho Falls.

Figure 3 is the holographic image of a 55-gallon drum lid buried approximately 20 cm in INEL soil.

CONCLUSIONS

Real-time UWB holographic linear array imaging is a viable technique for imaging subsurface targets in low conductivity soils. The center frequency and bandwidth of the impulse should be selected with respect to soil penetration depth (target range), radar cross section, and size of targets to be imaged.

One of the most important soil attenuation factors appears to be moisture content, and successful surveys with radar must include selecting the optimum penetration frequency. In our experiments, we used a 5-GHz center frequency linear array (1 meter in length) with a 100% bandwidth for imaging small targets (10 cm to 52 cm) both metal and dielectric at penetration depths between the surface and 1 meter depth in dry sand. A 2.5-GHz linear array (meters in length) is under construction and will be used in imaging shallow buried waste at a INEL/BWID demonstration this year.

Figure 2. Holographic Array System on Trailer

Figure 3. Holographic Image of Waste Drum Lid