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High-resolution imaging of dielectric profiles by using a time-domain ultra wideband radar sensor

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ABSTRACT

This paper describes the development of an imaging instrument that capitalizes on high-resolution phenomenon in inverse scattering using a time-domain ultra wideband (UWB) sensor. The image reconstruction algorithm that accounts for the band-limited view of the UWB data is based upon the TM-mode wave equation, the Born approximation, and the adjoint method for computing the Fréchet derivatives. The computation of the sensitivity function requires the forward propagation of the UWB wavefield, as well as the reverse propagation of the residual wavefield. The electromagnetic and adjoint fields are calculated using the finite-difference time-domain (FDTD) method, implementing the first and second orders Mur's absorbing boundaries. The overall performance of the instrumentation system is demonstrated using computer simulations and experimental measurements. Results indicate that the equipment can reconstruct fairly complicated dielectric profiles at near millimeter resolution even with the presence of large amount of noise.

1. Introduction

The goal of ultrawide band microwave tomography is the reconstruction of a dielectric model for a part of host medium resulting from the propagation of electromagnetic energy in different orientations and angles. The inverse problem can be formulated as an optimization problem that requires minimization of the least square error functional between the observed and computed electrical fields strengths. In this case, the fields are measured as a function of time, and therefore, the resulting inverse problem requires full-waveform data inversion. Recently, it has been demonstrated that this technique is capable of providing reliable information on broad range of inhomogeneities, reaching the resolution as good as one half to one third of a wavelength [1,2]. With the given safety advantage and super-resolution phenomenon, there has been growing interest among scientific community in developing UWB radar as an alternative imaging strategy. Among many promising applications, the detection of early stage breast cancer is the most researched topic as evident by the number of published papers in the literatures [3–5]. Popular scanning geometries used to capture UWB data include: (i) the full viewing and (ii) the limited viewing angles [6]. In the former, the region of interest is investigated from multiple viewing points whereas in the later, it is investigated from lateral boundaries only. Consequently, the reconstruction arising from limited-view measurement is expected to be more difficult. The use of gigahertz frequency sensors complicates the problem since a search region in the imaging plane is relatively large compared to the operating wavelength. Such a problem is more prominent with the iterative reconstruction scheme since the solution requires the inversion of a large-size optimization matrix. The method is not only computationally intensive, but also converges very slowly, and depending on the quality of first guess values, the problem associated with local minima arises. In spite of these difficulties, a number of acceptably accurate solution methods have been developed [7–10]. In particular, the distorted-Born iterative

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method [7] was attempted to provide inversion solution using experimental data collected from limited view angles. This method offers the advantage as it allows reconstruction of a target at super-resolution when illuminated by UWB signals. In order to effectively reconstruct the unknown profiles, the first order method employing the gradient information was a preferred choice [11]. Reformulation of the inverse problem as a non-linear optimization function, and its solution using various optimization strategies and data collection geometries was suggested [8–10]. In most cases, the direct scattering problem was treated by means of the finite-difference time-domain (FDTD), whereas the inverse techniques used gradient-based algorithm to minimize the appropriate cost function. The forward and backward time-stepping algorithms are frequently employed in calculating and updating the solutions at successive instants of time. Therefore, these inversion procedures are very time consuming and require higher-end workstations or supercomputers. Thus it is commonly accepted that these inversions are too expensive and cannot be a practical tools for most industrial applications.

The concept of system sensitivity analysis implementing the Landweber regularization strategy was introduced for applications in process tomography [12]. Following this, the FDTD approach of the inverse-scattering problem using sensitivity coefficient solution was recently proposed [13,14]. This method is similar to the well known back projection algorithm in which the reconstruction is based on first obtaining the sensitivity distributions for all transmitter and receiver pairs, and second, superimposing the normalized field using the sensitivity maps as weighting factors to produce an image. One particular shortcoming of this inversion strategy is that the sensitivity calculations are computationally intensive and are not yet efficient enough for large tomographic problems. Furthermore, the quality of the image depends strongly on the threshold values used to map the scattered field vector to the permittivity space and, subsequently, updating these parameter in response to a convergence or divergence becomes an issue. In most cases, these values are determined by a trial-and-error method even though some practical guidelines have been published [15]. Moreover the sensitivity kernels were computed using first arrival time, which can be difficult to measure if the first arrival is very small due waveform scattering. Clearly, a more realistic model which focuses on the information in the full waveform is needed in order to improve the accuracy of the inversion scheme. In this paper we employ the formal approach in calculating the sensitivity or gradient of the scattered fields with respect to the model parameter by using Fréchet derivatives and the adjoint-state method [8,10]. This analytical form of the sensitivity functions retains the true linearized solution to the forward problem, and with adequate preconditioning and smoothing, the tomographic imaging can be accomplished in a single step. All measurements and reconstructions are performed in the time-domain because this approach is more accurate in handling pulse type incident waves compared to frequency-domain solutions. Moreover, this approach does not suffer from phase wrapping artifact associated with conventional frequency-domain reconstruction [16]. This paper demonstrates the usefulness of this relatively new inversion technique using both simulated experiments and real data measurements.

2. Mathematical formulation

2.1. Inverse problem

The geometry used in the reconstruction is the scanning cross-borehole radar measurements and the details are described in an earlier publication [14]. A summary is provided here for the sake of completeness. In this arrangement, the medium Γ is illuminated successively by short pulse UWB wave generated by point source current located at point $p_n^r; n = 1,2,3,\cdots,N$. Mathematically:

$$\vec{J}^n(t) = \vec{J}(t)\delta(p - p_n^r) \tag{1}$$

where $p = (x, y)$, p_n^r is the nth transmitter position, $\delta(p)$ is the Dirac delta function, and the time factor $\vec{J}(t)$ is assumed to be zero before $t = 0$. The total electromagnetic fields under excitation of the nth current source satisfy Maxwell's curl equations and constitutive parameters [17]. For limited-view cross-sectional profiling, where antennas are oriented parallel to z-plane, the TM mode equations were used. Hence, the Maxwell equations reduce to:

$$\Im\vec{B} = 0 \tag{2}$$

where

$$\vec{B} = \begin{bmatrix} \vec{H}_x \\ \vec{H}_y \\ \vec{E}_z \end{bmatrix} \tag{3}$$

and the differential operator $\Im$ is given by:

$$\Im = X_1\frac{\partial}{\partial x} + Y_1\frac{\partial}{\partial y} + C\frac{\partial}{\partial t} - D \tag{4}$$

and the constants A, B, C and D are defined as:

$$X_1 = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}; Y_1 = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{bmatrix};$$
$$C = \begin{bmatrix} \mu & 0 & 0 \\ 0 & -\mu & 0 \\ 0 & 0 & -\varepsilon \end{bmatrix} \text{and } D = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \sigma \end{bmatrix} \tag{5}$$

Here μ, ε and σ are the electrical permeability, permittivity and conductivity of the medium. Eq. (2) is solved with zero initial conditions as follows:

$$\vec{E}(p, 0) = \vec{H}(p, 0) = 0 \tag{6}$$

For a given transmitter position, electric field signals $\vec{E}^m$ are measured in a time interval $[0, T]$ and at receivers located at points $p_m^r; m = 1,2,3,\cdots,M$ such that:

$$\vec{E}^m(p_{m,}^r, t) = \vec{E}(p, t)\delta(p - p_m^r) \tag{7}$$

Using (1), (2) and (7), a multitude of transmitter and receiver locations are used to effectively sample the region of interest with a large number of orientations of