Processing Microwave Experimental Data with the Distorted Born Iterative Method of Nonlinear Inverse Scattering *

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1. Introduction

Diffraction tomographic method for the imaging of dielectric bodies is very popular due to its simplicity and speed [1-3]. However, such a theory makes the assumption that the scattered field is linearly related to the dielectric profile of the object. Hence, it does not account for multiple scattering effects within the dielectric body. Multiple scattering effects can give rise to distortions in the linear inverse imaging method. In some extreme cases of strong metallic scatterers, it can give rise to ghost images.

In order to account for the multiple scattering effects, a nonlinear theory has to be developed where the scattered field is nonlinearly related to the object function to be reconstructed [4,5]. In such a theory, a cost function is derived which is a measure of the difference between the experimentally measured field and the calculated scattered field by a predicted object. An ideal object is sought by minimizing this cost function. In the gradient search approach, the cost function can be minimized by Newton-type methods where the gradient of the cost function can be found. It turns out that such a gradient can be easily offered by the distorted Born approximation [5]. In order to execute the distorted Born approximation, the forward scattering problem needs to be solved. Hence, the solving of the forward problem becomes usually the bottleneck in nonlinear inverse scattering problems.

In the past, we have investigated expediting the solution to the forward problem by using fast algorithms. As a result, a number of fast forward scattering algorithms have been developed to achieve this purpose [6,7,8].

2. Born and Distorted Born Iterative Methods

The Born-iterative method (BIM) and distorted Born-iterative method

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(DBIM) have been proposed and verified as methods of solving the nonlinear inverse scattering problem for dielectric scatterers [4,5]. A basic scalar wave equation that appears in 2-D electromagnetic scattering from a line source and also acoustic scattering is

$$\left[\nabla^2 + k^2(\mathbf{r})\right] \phi(\mathbf{r}) = S(\mathbf{r}) \tag{1}$$

where $S(\mathbf{r})$ is a radiating source and $\phi(\mathbf{r})$ represents the total field. A nonlinear integral equation for the total field may be derived as [2]

$$\phi(\mathbf{r}) = \phi_{inc}(\mathbf{r}) + \int d\mathbf{r}' g_b(\mathbf{r}, \mathbf{r}') O(\mathbf{r}') \phi(\mathbf{r}'), \tag{2}$$

where $\phi_{inc}(\mathbf{r})$ is the incident field, $O(\mathbf{r}) = k^2(\mathbf{r}) - k_b^2(\mathbf{r})$ is the object function to be reconstructed and $g_b(\mathbf{r}, \mathbf{r}')$ is the background Green's function. The background Green's function is a solution to

$$\left(\nabla^2 + k_b^2(\mathbf{r})\right) g_b(\mathbf{r}, \mathbf{r}') = -\delta(\mathbf{r} - \mathbf{r}'), \tag{3}$$

for an arbitrary assumed profile $k_b(\mathbf{r})$.

In the Born iterative method [4], k_b is assumed to be that of a homogeneous medium so that it is independent of $\mathbf{r}$ whence $g_b(\mathbf{r}, \mathbf{r}')$ is known in closed form. The internal field $\phi(\mathbf{r}')$ inside the integral of Eq. (2) is initially set to the incident field $\phi_{inc}(\mathbf{r})$ and the object $O(\mathbf{r})$ solved numerically as a linear inverse problem. This value of $O(\mathbf{r})$ is not exact because of the errors in the estimate of $\phi(\mathbf{r})$. However, $O(\mathbf{r})$ can be used to provide a new estimate the internal field $\phi(\mathbf{r}')$ in the integral of Eq. (2) and the process is repeated iteratively until a convergent solution is obtained.

In the distorted Born iterative method [5], the background medium $k_b(\mathbf{r})$ is not constrained to be homogeneous and is updated at each iteration. The added difficulty now is that $g_b(\mathbf{r}, \mathbf{r}')$ is no longer available in closed form and must be sought via a numerical method. However, DBIM can be shown to have second-order convergence as opposed to BIM's first-order convergence and hence is usually better for objects with large contrast. On the other hand, BIM seems to be more robust than DBIM when noise contamination is present [5]. Nevertheless, a convergent solution can be achieved.

Both BIM and DBIM have been implemented for both CW and transient excitation [5]. For the CW case, the recursive-aggregate-T-matrix-algorithm (RATMA) is used for the fast forward scattering solver [6] as well as a CG-FFT method [9]. We have found that the inversion procedure driven by RATMA as a forward solver is more efficient than one driven by CG-FFT as a forward solver. This is because CG-FFT takes more iterations to converge, especially in the case of lossless media and large objects.

3. Processing of Experimental Data and Conclusion

The CW implementation of the DBIM was recently used to process microwave scattering data collected in Barcelona, Spain [10]. Previously, diffraction tomography was used to process the data resulting in an image with a small dynamic range due to the high contrasts present in the human body. Using the DBIM, the processed image was significantly improved and the result is shown in Figure 1. The images are plotted with the same gray levels. The first iteration is equivalent to a linear inverse theory like diffraction tomography. It is seen that upon iterating with DBIM, the contrast of the image is drastically enhanced. The image is discretized with a 64×64 pixels and the processing is about one-half hour on a SPARC workstation.

In conclusion, the nonlinear inversion becomes more practical as computational power increases. The use of fast algorithms in the forward solver can greatly expedite the solution speed of such algorithms. Such algorithm can be used to process real experimental data, and can yield an image with higher contrasts compared to a linear inverse theory.

REFERENCES

[1] A. J. Devaney, *Ultrasonic Imaging*, vol. 4, pp. 336– 360, 1982.

[2] W. C. Chew, *Waves and Fields in Inhomogeneous Media*: Van Nostrand Reinhold, 1990.

[3] J.-Ch. Bolomey and Ch. Pichot, *Int. J. Imag. Sys. Tech.*, vol. 2, pp. 144–156, 1990.

[4] Y. M. Wang and W. C. Chew, *Int. J. Imag. Sys. Tech.*, vol. 1, pp.100–108, 1989.

[5] W. C. Chew and Y. M. Wang, *IEEE Trans. Medical Imag.*, vol. 9, no. 2, pp. 218–225, 1990.

[6] Y. M. Wang and W. C. Chew, *Radio Sci.*, vol. 27, no. 2, pp. March–April 1992.

[7] W. C. Chew and Y. M. Wang, *Micro. Opt. Tech. Lett.*, vol. 3, no. 5, pp. 164–169, May 1990.

[8] W. C. Chew and C. C. Lu, *IEEE Antennas and Propagation Society International Symposium Digest*, pp. 184-187, July 18-25, Chicago, 1992.

[9] D. T. Borup, S. A. Johnson, W. W. Kim, and M. J. Berggren, *Ultrasonic Imaging*, vol. 14, pp. 69-85, 1992.

[10] A. Broquetas, J. Romeu, J. M. Rius, A. R. Elias-Fuste, A. Cardama, and L. Jofre, *IEEE Trans. Microwave Theory Tech.*, vol. MTT–39, no. 5, pp. 836–844, 1991.

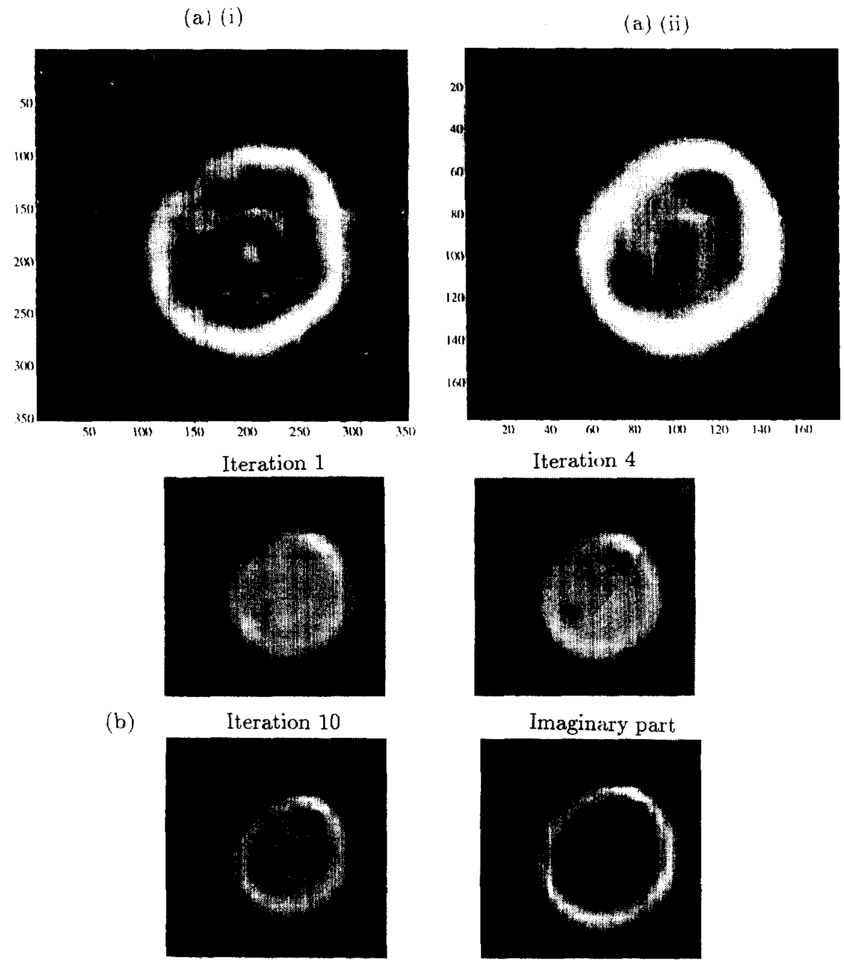

Figure 1. (a) Reconstructed microwave image of a human arm at 2.5 GHz, with 64 transmitters and 33 receivers using (i) the fast recursive algorithm (RATMA), and (ii) the CG-FFT algorithm. The arm is immersed in water. Its shape and bones are clearly visible. (b) Reconstruction of the microwave image at different iterations of the distorted Born iterative method. The first iteration corresponds to a linear theory, and hence, resembles the solution from diffraction tomography. The imaginary part of the reconstruction is shown as well.