Ongoing Development of Microwave Breast Imaging System Components

Mark Haynes[1], Line van Nieuwstadt[2], Steven Clarkson[3], John Stang[4], Clare Ward[5], and Mahta Moghaddam[6]

[1-5]Department of Electrical Engineering and Computer Science
3228 EECS, 1301 Beal Ave.
University of Michigan, Ann Arbor, MI 48109, USA
Tel: (734) 764-0500, Fax: (734) 647-2106
[1]mshaynes@umich.edu, [2]linevn@umich.edu, [3]sclarks@umich.edu, [4]johnstan@umich.edu, [5]wardcl@umich.edu,
[6]mmoghadd@umich.edu

Abstract

We present ongoing work at the University of Michigan toward the goal of developing a microwave inverse scattering system for breast cancer imaging. The algorithm is built around the Born Iterative Method with a modified cost function allowing inclusion of a priori information. The calibration is based on a new formulation for S-parameter measurements. The liquid matching medium is an oil-water emulsion with high dielectric constant and moderate loss. Last, we designed a wide-band, linear-phase antenna for both frequency and time-domain applications. Finally, we present numeric studies of a CW microwave breast cancer therapy system.

1. Introduction

Much work has been done in the field of microwave breast imaging. It is based around the assumption that benign and malignant tissues have different dielectric properties, and, if imaged, could provide additional diagnostic information. The two approaches to imaging are time-domain focusing, similar to traditional ultrasound beamforming, and inverse scattering, also called tomography. Beamforming provides fast, qualitative maps of tissue radar backscatter, however, these algorithms assume homogenous backgrounds and rely on the quality of the time domain pulses for resolution. Inverse scattering can provide quantitative maps of tissue permittivity and conductivity, but is computationally expensive, requires full antenna modeling, and are limited by the peak contrast of the object. Our work addresses some of the experimental aspects of breast imaging.

2. Inverse Scattering Algorithm and Calibration

Inverse scattering algorithms have been extensively studied numerically, but most are not readily applicable to experiment. We use the Born Iterative Method (BIM) as the basis of our inverse scattering algorithm. At each step, this algorithm alternates estimates of the contrasts and the object fields. The contrasts are updated by minimizing a least squares cost functional, described below, and we use the Bi-conjugate gradient FFT (BCGFFT) as a forward solver to estimate the fields given the contrasts. This algorithm has been shown in simulation to robustly image objects with contrasts of 3:1.

Traditional cost functions are typically based on least-squares and minimized by solving a large linear system. Instead, we use the covariance based cost function of [1] It is also a least squares functional, but allows us to regularize the inverse problem using the experimental noise and our prior knowledge of the range of pixel values. This avoids the need for tuning parameters which must be changed for different setups. Also, this cost function can be minimized using conjugate gradients avoiding the need to build and solve a large linear system.

One of the outstanding problems in experimental inverse scattering is source characterization. That is, how to link the predicted scattered fields of the volume integral equation (VIE) to antenna voltage measurements. Calibration targets can effectively be used to calibrate far-field systems, but near-fields systems, as in the case of breast imaging, require more complete antenna models. The traditional VIE predicting scattered fields at observation points is given by

978-1-4244-6051-9/11/$26.00 ©2011 IEEE

$$\mathbf{E}_{sca}(\mathbf{r}) = \int \overline{\mathbf{G}}(\mathbf{r},\mathbf{r}') \cdot O(\mathbf{r}')\mathbf{E}(\mathbf{r}')dV' \tag{1}$$

where $\mathbf{E}_{sca}(\mathbf{r})$ is the scattered field, $\mathbf{G}(\mathbf{r},\mathbf{r'})$ is the background dyadic Green's function, O(**r**) is the contrast function containing permittivity and conductivity and $\mathbf{E}(\mathbf{r'})$ is the total field in the object. To make this equation more applicable to Vector Network Analyzer (VNA) measurements, we showed in [2], by using the full wave antenna model, that we can transform Equation 1 into

$$S_{ji,\text{sca}} = \int \mathbf{g}_j(\mathbf{r}) \cdot O(\mathbf{r})\mathbf{e}_i(\mathbf{r})dV \tag{2}$$

$$\mathbf{g}_j(\mathbf{r}) = \frac{iZ_0^j}{2\omega\mu}\mathbf{e}_{inc,j}(\mathbf{r}) \tag{3}$$

where $S_{ji,sca}$ is the two-port scattered field S-parameter diagramed in Figure 1, O(**r**) is the same object function, $\mathbf{e}_i(\mathbf{r})$ is the total object field normalized to the transmit voltage, and $\mathbf{g}_j(\mathbf{r})$ is the vector Green's function kernel for the receiver. It was also shown that the vector green's function is equivalent to the transmitted incident field of the receiver scaled by constants of the system, given by Equation 3.

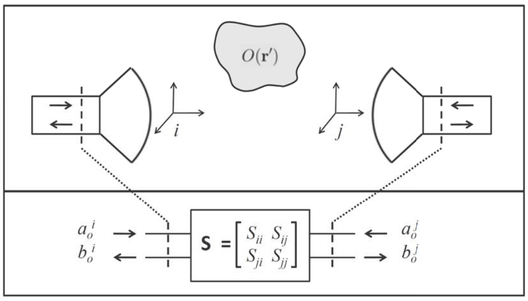


Figure 1: Network model of two antennas and an object. S-parameters are measured between the reference planes of the antenna transmission lines.

By using Equation 2 in place of Equation 1 in the cost function, we effectively modify the forward model which allows us to directly compare model predictions to measured S-parameters from a VNA. The method only requires that we have a properly normalized background incident field and does not require calibration targets. The incident field can be obtained from simulation and include multiple scattering of structures such as antenna mounts or cavity walls.

We have tested the inversion algorithm with this calibration in a free-space experiment, shown in Figure 2, which will be reported in more detail in [3]. The reconstructions of the dielectric profile of a two objects is also shown.

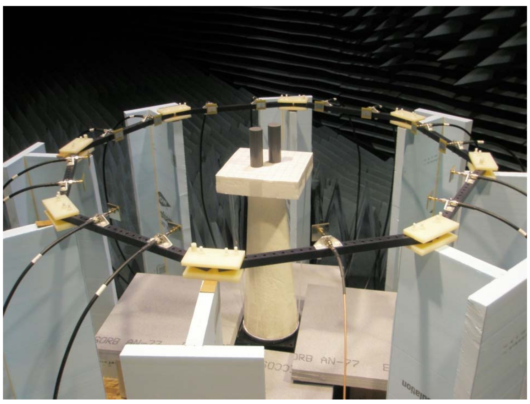
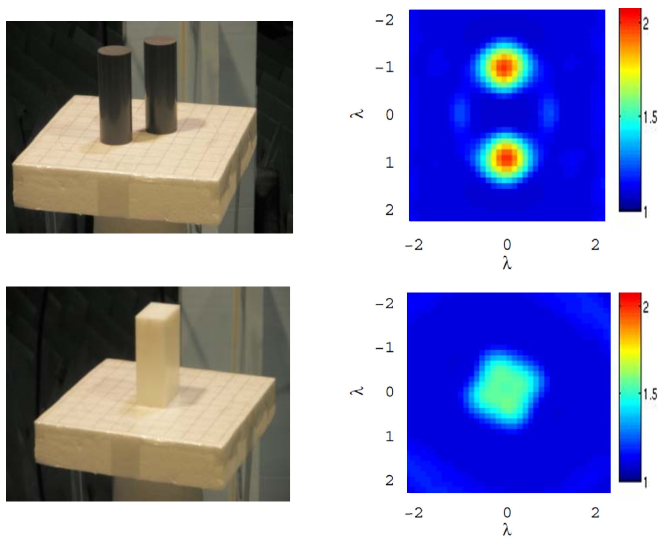


Figure 2: (above) Experimental setup to test the inversion algorithm and calibration. (right) Objects and their reconstructed relative perimittity profiles, the spatial scale is in wavelengths of the operator frequency.



4. Matching Medium

Breast tissue has been reported to have a relative permittivity between 20-60 and a conductivity between 0.5-3 Siemens/m at GHz frequencies. We require a matching medium with similar properties for several reasons. First, it helps minimizes the signal reflection at the skin allowing us to couple energy deeper into the tissue and detect small, imbedded objects. This effectively increases the sensitivity of the measurement system without the need for high power equipment. Second, it lowers the relative contrast of the tissue as compared to the background. For example, tissue with a relative permittivity of 60 in the background with relative permittivity of 20 is a contrast of only 3:1, which is in solvable range of our inverse scattering algorithms. Third, it shrinks the size of the antennas, allowing us to place more sensors around the breast for the same space. Thus, we want a matching medium that has high permittivity and low loss, which is also conformal, non-toxic, and can be inexpensively produced. While solid matching materials have the lowest loss, they are expensive to fabricate, least conformal, and hardest to integrate with antennas. Liquid matching mediums, however, are very conformal, but usually have higher losses.

The matching medium we developed is an oil-water emulsion. Water has a relative permittivity around 80 with a conductivity above 1 Siemens/m from 1-6 GHz, while oil has a low relative permittivity and is very low loss. By combining them in different proportions with a binding agent, we made a liquid with a relative permittivity between 20-40 with moderate conductivity. Figures 3, 4, and 5 show liquid as well as the relative permittivity and conductivity from 1-6 GHz as measured by the Agilent 85070E dielectric measurement probe. For details see, [4].

Figure 3: Photo of liquid matching medium.

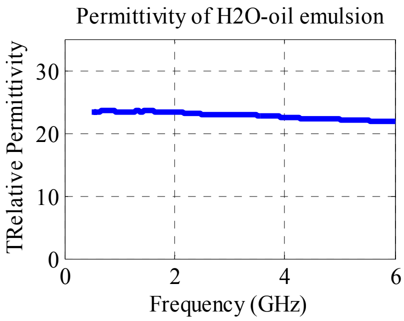


Figure 4: Matching medium relative permittivity.

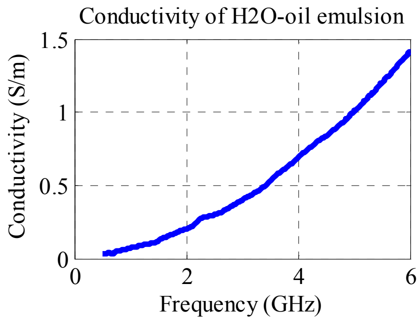


Figure 5: Matching medium conductivity.

5. Wide-band Antennas

There are many challenges associated with designing antennas for breast imaging. The antenna must radiate across a wide band for both inverse scattering and time-domain focusing. The inverse scattering algorithm will use multiple frequencies as data with which to reconstruct the dielectric profile, while the resolution of time-domain focusing is limited by the spatial width of the pulse. In addition, focusing algorithms require pulses with as little distortion as possible, thus we want the phase of the antenna response to be linear. Also, the antenna must have a small form factor in order to increase the number of sensors around the breast. Finally, it must be designed to work in high permittivity, lossy matching medium.

To address these problems, we have developed the elliptically tapered dipole antenna. A pair of antennas and the mount to test them in the matching medium is shown in Figure 6. The antenna dimensions are 3cm x 5cm and fed from behind. Figure 7 shows a measured and simulated time-domain pulse propagate through the matching medium between two antennas separated by 15 cm demonstrating minimal dispersion from the antennas. For details, see [6].

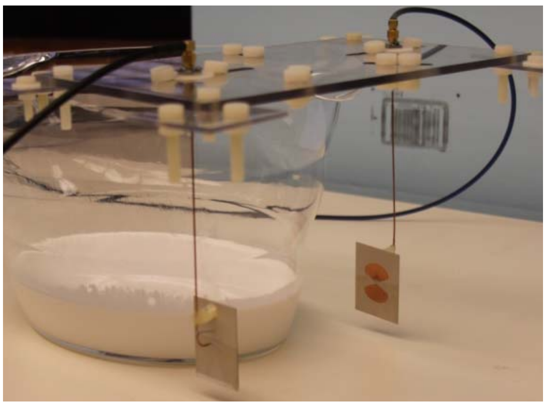


Figure 6: Pair of elliptically tapered dipole antenna and coupling medium.

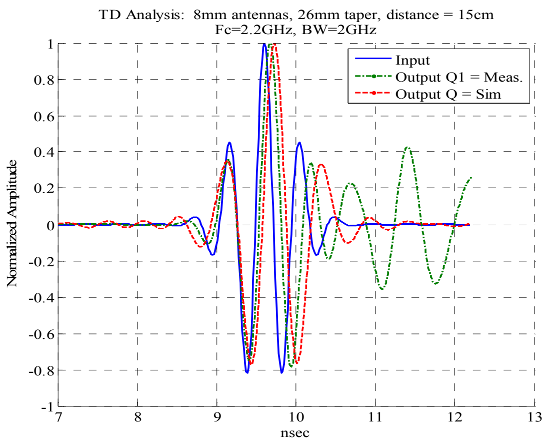


Figure 7: Measured and simulated time-domain pulse propagated through the matching medium.

6. Microwave Therapy

Interest is growing in the use of microwaves for breast cancer treatment. Hyperthermia is one technique that can be used to raise the bulk temperature of tissue. Tissue ablation therapies set out to destroy selected tissue. Probe-based invasive RF tissue ablation techniques exist, however, with proper system modeling, non-invasive tissue ablation is possible through the use of CW focused microwaves.

Figure 8 shows COMSOL simulations of a concentric array of ten antennas where the radiation is focused into heterogeneous breast tissue that is suspended in the matching medium. The antennas are planar bow-tie with an operating frequency of 915 MHz. The focal spot is steered off center and has a size of approximately half a wavelength demonstrating the potential use of this system. These results are described in more detail in [6].

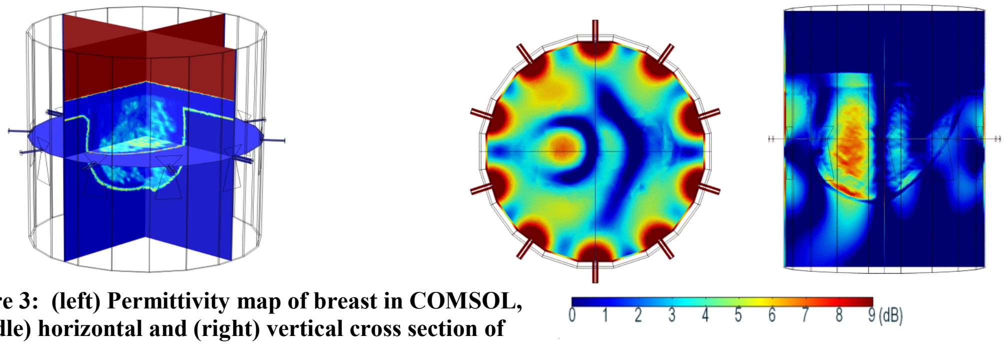


Figure 3: (left) Permittivity map of breast in COMSOL, (middle) horizontal and (right) vertical cross section of the relative strength of the focused electric field in dB.

4. Conclusion

We have presented our ongoing work in developing system components for microwave breast imaging. We have developed an inverse scattering algorithm that is fully integrated with our calibration method and have demonstrated it with a free-space experiment. We have developed an oil-water matching medium with high permittivity and moderate loss. Also, we have designed and tested a wide-band antenna for operation between 1-4 GHz in the matching medium. Last, we have started investigations into microwave therapy techniques. Future work includes building a clinical scale prototype integrating the inverse scattering algorithm, calibration technique, matching medium, and antenna in order to test the limits of these methods on breast phantoms. We also plan to build and test the therapy system to evaluate its potential as a treatment method.

6. Acknowledgments

These projects were sponsored in part by the Department of Defense, BCRP, Predoctoral Traineeship Award, the National Science Foundation CBET program, and the NASA Harriett Jenkins Pre-doctoral Fellowship Program

7. References

[1] M. Haynes, M. Moghaddam, "Large-domain, low-contrast acoustic inverse scattering for ultrasound breast imaging," *IEEE Transactions on Biomedical Engineering*, vol.57, no.11, pp.2712-2722, Nov. 2010.

[2] M. Haynes, M. Moghaddam, "Vector Green's function for S-parameter measurements of the electromagnetic volume integral equation," *IEEE Transactions on Antennas and Propagation, in review.*

[3] M. Haynes, S. Clarks, M. Moghaddam, "Electromagnetic inverse scattering algorithm and experiment using absolute source characterization," *IEEE Transactions on Antennas and Propagation, to be submitted.*

[4] L. van Nieuwstadt, "Microwave measurement system for breast cancer imaging: an experimental prototype towards time-domain inverse scattering" Ph.D. dissertation, Dept. Elec. Eng., Michigan Univ., Ann Arbor, MI, 2011.

[5] L. van Nieuwstadt and M. Moghaddam, "Planar UWB antenna for Microwave Imaging: Design and Parametric Dispersion Study", *in preparation*.

[6] J. Stang, M. Moghaddam, O. Kripfgans, J. B. Fowlkes, P. Carson, "Image based time-reversal focusing for transcutaneous microwave thermal therapy," in *Proc. USNC/URSI*, Boulder, CO, January 2011, 1 page.