Ultrasound Breast Imaging using Frequency Domain Reverse Time Migration

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ABSTRACT

Conventional ultrasonography reconstruction techniques, such as B-mode, are based on a simple wave propagation model derived from a high frequency approximation. Therefore, to minimize model mismatch, the central frequency of the input pulse is typically chosen between 3 and 15 megahertz. Despite the increase in theoretical resolution, operating at higher frequencies comes at the cost of lower signal-to-noise ratio. This ultimately degrades the image contrast and overall quality at higher imaging depths. To address this issue, we investigate a reflection imaging technique, known as reverse time migration, which uses a more accurate propagation model for reconstruction. We present preliminary phantom results obtained using data acquired with a breast imaging ultrasound tomography prototype. The original reconstructions are filtered to remove low-wavenumber artifacts that arise due to the inclusion of the direct arrivals. We demonstrate the advantage of using an accurate sound speed model in the reverse time migration process. We also explain how the increase in computational complexity can be mitigated using a frequency domain approach and a parralel computing platform.

Keywords: breast imaging, Helmholtz equation, reverse time migration, ultrasound tomography

Preferred presentation type: oral presentation

Supplementary material

1. Description of purpose:

Ultrasonography is a widely used technique to image internal body structures. In its most common form, known as B-mode, a linear transducer array scans a region of interest by emitting an ultrasound pulse and recording echoes produced by acoustic impedance variations in the body. The basic assumption is that the ultrasound waves travel along ray paths in a medium with a constant sound speed (or velocity) and constant attenuation. The ultrasound image is then formed by combining the received signals using this propagation model. The strongest the coherence of the echoes arising from a particular location, the brighter the pixel.

Ultrasonography provides high resolution imaging capability in real-time, and can be efficiently implemented on a relatively inexpensive hardware. It is a versatile imaging technique that can be used for both diagnonstic and therapy monitoring. However, the image quality degrades quickly with depth due to the high frequencies needed. The assumed propagation model it is based on is a high frequency approximation of the wave equation which neglects multiple scattering events. Therefore, it performs poorly at lower frequencies, in particular in a rich scattering environment.

We explore an ultrasound imaging technique known as reverse time migration (RTM).[1–3] It uses a much more accurate propagation model to reduce the model mismatch introduced at low frequencies. The main advantages of RTM over ray-based imaging methods are its ability to handle multiple ray paths and model wave amplitudes more accurately. If a sharp sound speed model is available, RTM can also image multiple scattering events.

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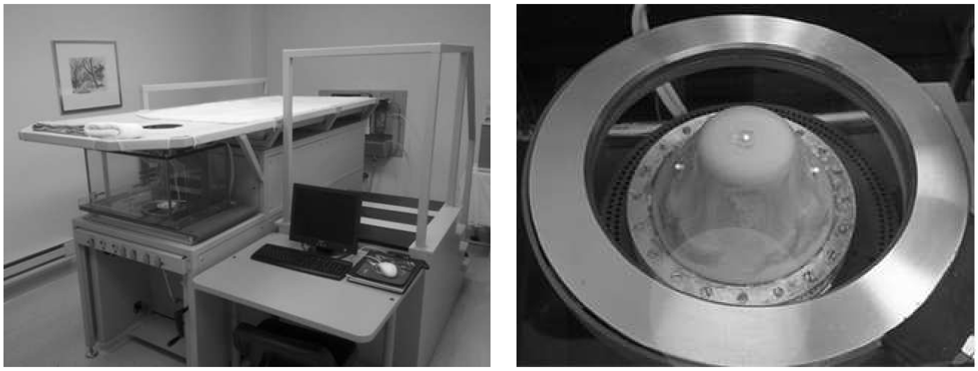


(a) (b)

Figure 1. Ultrasound tomography prototype. (a) Scanner with control computer. (b) Close up of the transducer ring.

We demonstrate preliminary phantom reconstruction results obtained with an ultrasound tomography device used for breast imaging. The computational complexity of the proposed technique is significantly increased over traditional B-mode. However, we show that it can be greatly reduced using a frequency domain approach. Furthermore, the method is non-iterative, and can be easily parallelized.

2. Method:

The ultrasound data was acquired using the ultrasound tomography prototype[4] shown in Figure 1(a). During an exam, a patient lies prone on the device and places her breast into an ultrasound ring transducer array which is submerged in a water filled chamber. The entire breast is then scanned from the chest wall to the nipple region. The acquired data is then used to produce coronal slices of the breast. The ultrasound transducer, shown in Figure 1(b), has $n = 256$ piezo-electric transducer elements distributed along a ring of approximate radius 100 millimeters.

During the acquisition of a slice, a pulse is transmitted in turn by the emitters and recorded at the receivers' locations. The propagating field is assumed to satisfy the constant density wave equation expressed in the time domain as

$$\left(\nabla^2 - \frac{1}{c^2(\mathbf{x})}\frac{\partial^2}{\partial t^2}\right) u(\mathbf{x},t) = -s(t)\delta(\mathbf{x}-\mathbf{x}_k)\,, \tag{1}$$

where $u(\mathbf{x},t)$ is the field value at position $\mathbf{x}$ and time t, $c(\mathbf{x})$ is the speed of sound, and $s(t)$ is the source signal emitted at transducer element with position $\mathbf{x}_k$ for $k = 0, 1, \ldots, n-1$. In this work, we will use the frequency domain formulation of the wave equation (1), known as the Helmholtz equation. At frequency ω, it is expressed as

$$\left(\nabla^2 + \frac{\omega^2}{c^2(\mathbf{x})}\right) u(\mathbf{x},\omega) = -s(\omega)\delta(\mathbf{x}-\mathbf{x}_k)\,. \tag{2}$$

In order to solve the above equation, the simulation area is discretized on a grid, and the differential operator is approximated using a finite difference method. In its discretized form, the equation can be compactly expressed in a matrix form as

$$\mathbf{S}\,\mathbf{u} = -\mathbf{s}\,, \tag{3}$$

where $\mathbf{S}$ is the propagation matrix, $\mathbf{u}$ the field values, and $\mathbf{s}$ the source values. In the above formulation, the dependency on the frequency ω is omitted for ease of notation. The matrix $\mathbf{S}$ captures all the properties of the propagation medium (sound speed), as well as the characteristics of the numerical scheme (e.g., frequency, finite difference operator, absorbing boundary conditions).[5] The sound speed can be estimated using a travel time tomography[6] or a waveform tomography[7,8] reconstruction algorithm. One main advantage of the frequency domain formulation is that the Helmholtz equation can be efficiently solved using LU factorization.[5] If the matrix $\mathbf{S}$ does not change, the LU factors can be reused to solve equation (3) for different source locations.

RTM is a reflection imaging technique that is commonly used in geophysics.[2] It is a three step procedure: (i) forward propagation of the source signal on the known sound speed model, (ii) back propagation of the

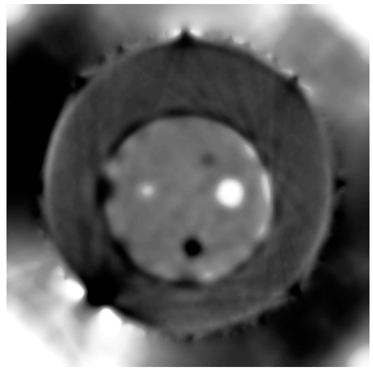
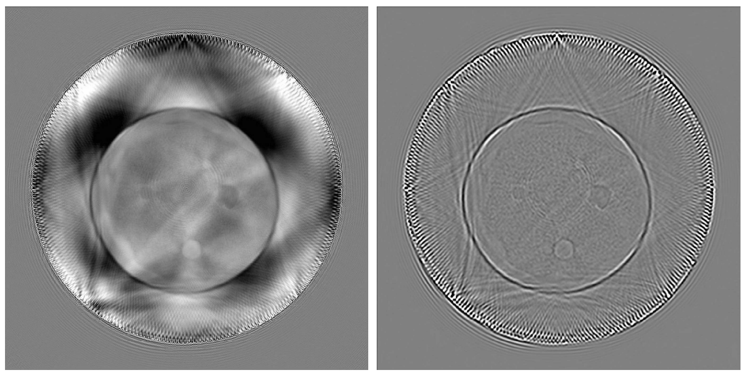


Figure 2. Migration velocity obtained by travel time tomography. The gray scale values range from about 1450 m/s (black) to 1600 m/s (white).



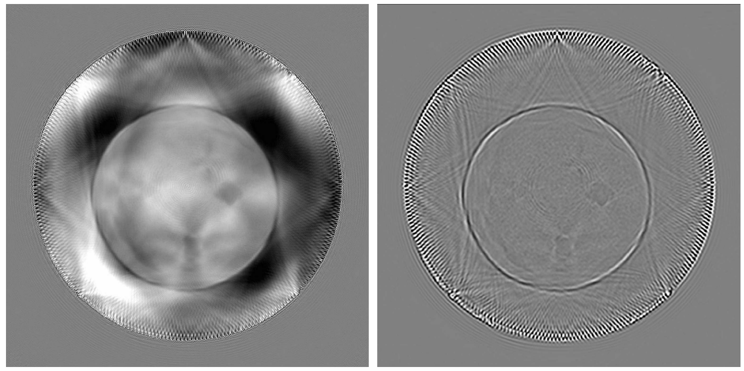
(a) (b)

Figure 3. RTM images using the migration velocity shown in Figure 2. (a) Raw image. (b) Post-processed image.

experimental data through the same model, and (iii) cross correlation of the forward and back-propagated fields. While RTM is conventionally performed in the time domain, we use a frequency domain approach to benefit from the LU factorization strategy mentioned above. These steps are repeated for all the emitters and a selected set of frequencies. The individual contributions are summed up to form the final image. Since the algorithm is not iterative, the contributions can be computed simultaneously. The algorithm is thus well suited to a parallel computing architecture (e.g., multiple CPUs and/or GPUs, multiple cores). Moreover, as shown in the results presented in the next section, only a few frequencies need to be migrated to obtain an image of reasonable quality.

3. Results:

Frequency domain RTM was performed for a breast mimicking phantom on the data acquired using the ultrasound tomography prototype. The frequency range used was 400–900 MHz with a spacing of 10 MHz (51 frequencies). Migration velocity for RTM is shown in Figure 2, which was obtained using travel time tomography. This migration velocity was used to obtain the RTM image shown in Figure 3. Post migration processing (Laplacian filter and a spatial bandpass filter) was applied to the raw image (Figure 3(a)), to obtain the final RTM image shown in Figure 3(b). The raw image has low-wavenumber artifacts (removed by post processing), which are a typical feature of RTM, albeit the cause of these low-wavenumber artifacts is very different here than that in RTM of geophysical surface seismic data. Here the low-wavenumber artifacts appear due to the direct arrivals. It is logical then, that direct arrivals should be removed for back-propagation in RTM, but tests so far have shown lower signal-to-noise ratio (SNR) for the scatterers to be imaged. This could be because most of the useful information about target scatterers is contained in diffractions, which are close to direct arrivals. Thus, removing the direct arrivals might be eliminating some of the diffracted events as well, especially the weaker ones. Figure 4 shows RTM results using a constant migration velocity of 1520 m/s. Figure 4(a) shows the raw RTM image and Figure 4(b) the post processed image. Although a constant velocity RTM does image the velocity anomalies, they are not as sharp as in the case of variable velocity RTM. Using a constant velocity for RTM



(a) (b)

Figure 4. RTM images using a constant velocity model of 1520 m/s. (a) Raw image. (b) Post-processed image.

is kinematically equivalent to using the straight-ray approximation. Therefore, a comparison of RTM images in Figures 3 and 4 shows the importance of honoring ray bending in imaging. Besides ray bending, RTM can handle multiple ray paths because it uses a more accurate modeling of the wave equation (3). Further testing is in progress to improve the SNR and resolution of the RTM images.

4. New or breakthrough work to be presented:

We show that reasonable reflection image quality can be obtained using low frequency content provided that ultrasound propagation is more accurately modeled. The proposed technique uses a frequency domain approach which can be easily parallelized. We present some preliminary breast mimicking phantom image reconstruction results.

5. Conclusions:

Reflection imaging techniques that use a more accurate propagation model have the potential to image at higher depth using signals with a lower frequency content.

6. Indicate whether the work is being, or has been, submitted for publication or presentation elsewhere, and if so, indicate how the submission differ:

The work has not been submitted elsewhere for publication or presentation.

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