Coherent Time Reversal Sub-array Processing for Microwave Breast Imaging

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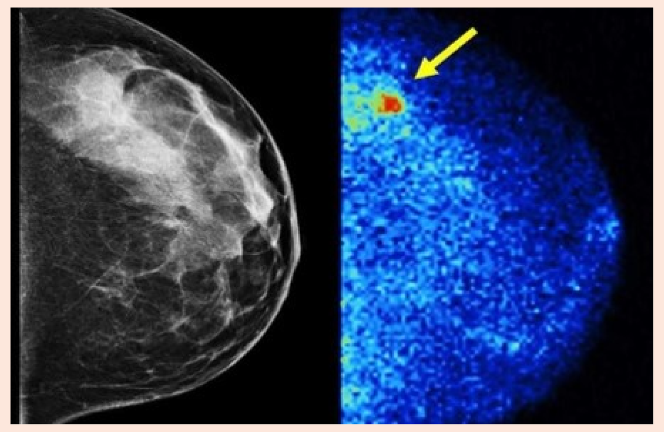
Motivation

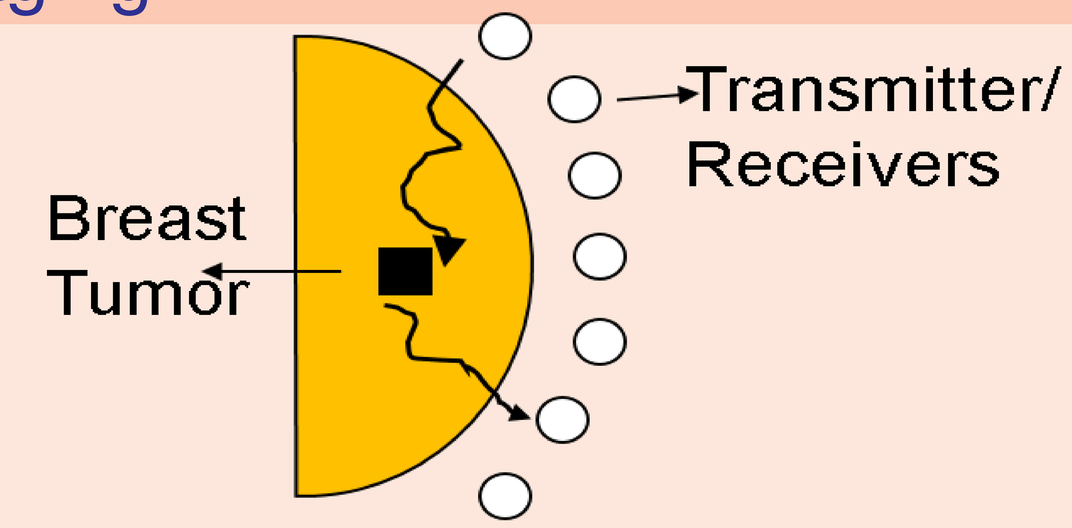
- Lack of precise knowledge of constitutive properties of the breast tissue
- Time Reversal (TR) harnesses multipath propagation to enhance focusing resolution
- TR Clutter Suppression
- Focused frequency time reversal (FFTR) matrices and the TR-based MUltiple SIgnal Classification (MUSIC) algorithm



Conventional MIMO Radar for Breast Imaging

Conventional MIMO Radar Received Signals:

- Assuming all transmitted signals be the same i.e, $F(\omega)$, in the matrix form:
  $$\mathbf{R}(\omega) = \underbrace{\textstyle\sum_{l=1}^{L} X_l \mathbf{K}_t^l(\omega) F(\omega)}_{\mathbf{R}_t(\omega)} + \underbrace{\mathbf{K}_c(\omega) F(\omega) + \mathbf{N}(\omega)}_{\mathbf{R}_z(\omega)},$$
  where $\mathbf{K}_t^l(\omega)$ is the transmit-receive response matrix of the tumor from path l for $1 \le l \le L$ and $\mathbf{K}_c(\omega)$ is the clutter response and the coefficients $X_{ijl} = X_l$.



- Conventional Clutter Suppression: The clutter is characterized in the spatial and spectral domains as a multivariate complex Gaussian random process. Then, after whitening the clutter + noise, we have $\tilde{\mathbf{R}}(\omega) = \underbrace{\mathbf{R}_{\mathbf{r}_z}^{-\frac{1}{2}} \mathbf{K}_t(\omega) F(\omega)}_{\tilde{\mathbf{R}}_t(\omega)} + \underbrace{\mathbf{R}_{\mathbf{r}_z}^{-\frac{1}{2}} \mathbf{R}_z(\omega)}_{\tilde{\mathbf{R}}_z(\omega)}$, with the whitened clutter-noise term $\tilde{\mathbf{R}}_z(\omega) \sim \mathcal{CN}(0, \mathbf{I}_{N^2})$.

TR-MIMO Radar for Breast Imaging

TR Probing: The whitened backscatters $\tilde{\mathbf{R}}(\omega)$ are time-reversed, energy normalized, and are used to probe the medium a second time. Considering that the no. of multipath is large, the TR response matrix is given by

$$\mathbf{P}(\omega) = g \textstyle\sum_{l=1}^{L} |X_l|^2 \mathbf{K}_t^l(\omega) \mathbf{R}_{\mathbf{r}_z}^{-1/2^*} \mathbf{K}_t^{*l}(\omega) F^*(\omega) + \mathbf{P}_c(\omega) + \mathbf{P}_z(\omega)$$

TR Clutter Suppression: Using a sub-aperture of length M of the antenna array and study the SVD of each sub-aperture and the correlations to the neighboring sub-arrays: $\mathbf{P}_i^{\text{sub}}(\omega)\mathbf{v}_{i,m}^{\text{sub}}(\omega) = \lambda_{i,m}^{\text{sub}}\mathbf{u}_{i,m}^{\text{sub}}(\omega)$, then the clutter can be modeled as:

$$\mathbf{P}_c(\omega) = \textstyle\sum_{m=1}^{P} \lambda_{i,m}^{\text{sub}} \mathbf{u}_{i,m}^{\text{sub}}(\omega).$$

Coherent FFTR-MUSIC Imaging: Finding focusing matrices to transform the TR operator at different frequency bins onto a single reference frequency as

$$\min_{\mathbf{B}(\omega_q)} \|\mathbf{P}_t(\omega_0) - \mathbf{B}(\omega_q)\mathbf{P}_t(\omega_q)\|_F$$

subject to $\mathbf{B}^H(\omega_q)\mathbf{B}(\omega_q) = \mathbf{I}$, and then $\tilde{\mathbf{P}}_t(\omega_0) = \sum_{q=0}^{(Q-1)} \beta_q \mathbf{B}(\omega_q)\mathbf{P}_t(\omega_q)\mathbf{B}^H(\omega_q)$.

Simulations Using FDTD Method

The final step will be to form the pseudospectrum of FFTR-MUSIC as follows. $A(\omega_0, \mathbf{r}) = \frac{\mathbf{g}^H(\omega_0,\mathbf{r})\mathbf{U}_{\text{Sig}}(\omega_0)\mathbf{U}_{\text{Sig}}^H(\omega_0)\mathbf{g}^*(\omega_0,\mathbf{r})}{\|\mathbf{g}(\omega_0,\mathbf{r})\|^2}$, where $\mathbf{U}_{\text{Sig}}(\omega_0)$ is the signal subspace matrix at the focused frequency resulted from the SVD of $\tilde{\mathbf{P}}_t(\omega_0)$ and $\mathbf{g}(\omega_0, \mathbf{r}) = [G(|\mathbf{r} - \mathbf{x}_1|, \omega_0), \cdots, G(|\mathbf{r}_l - \mathbf{x}_N|, \omega_0)]^T$. Finally, the FFTR-MUSIC image is given by $I(\mathbf{r}) = (1 - A(\omega_0, \mathbf{r}))^{-1}$.

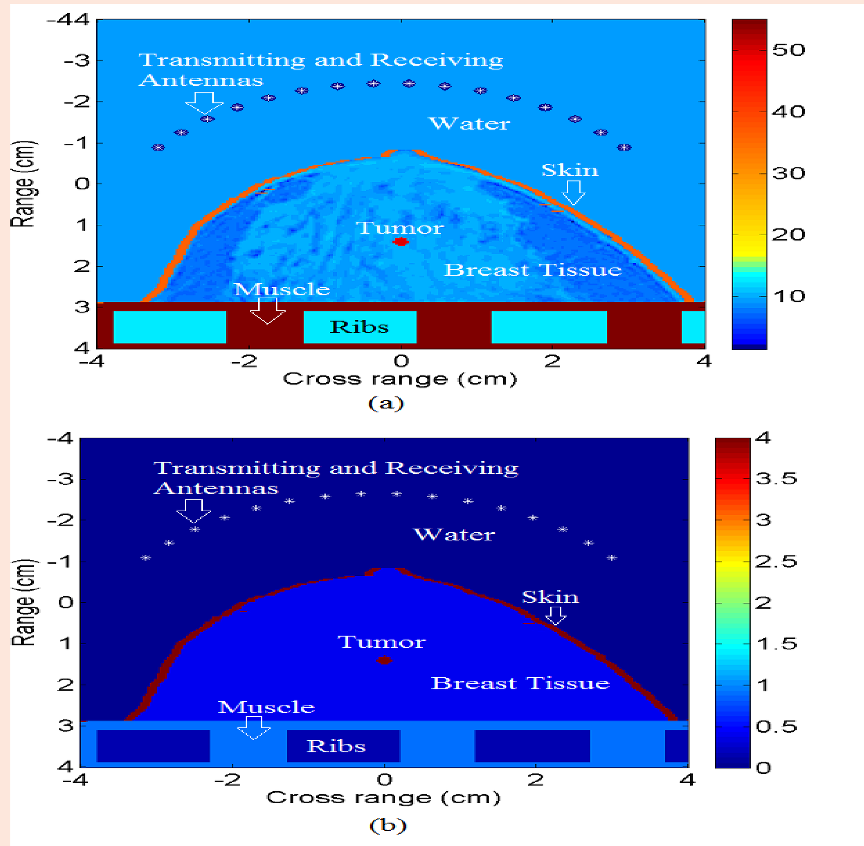
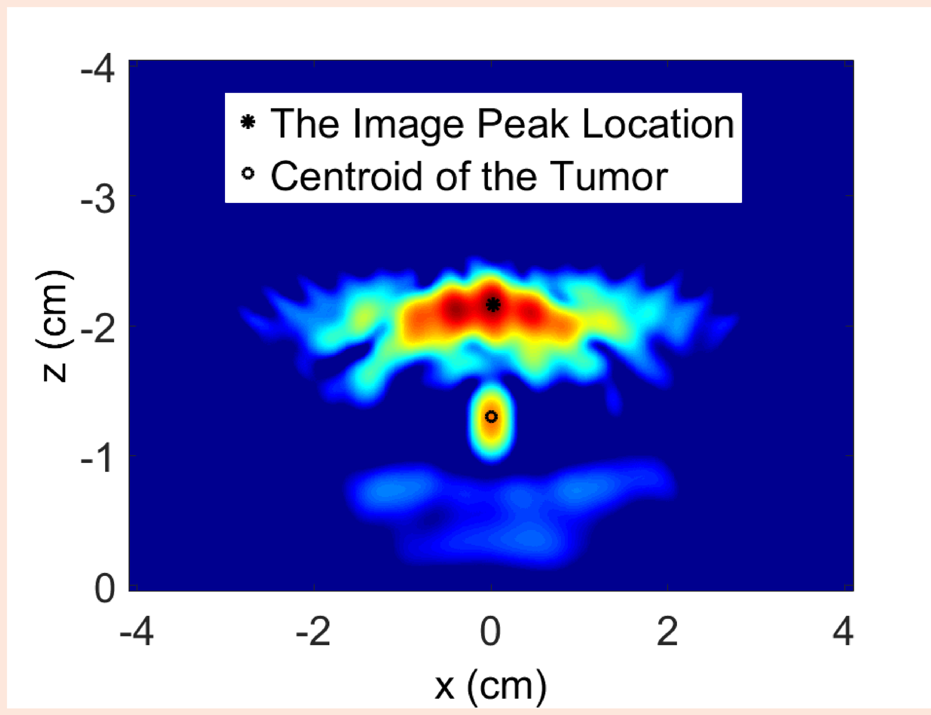
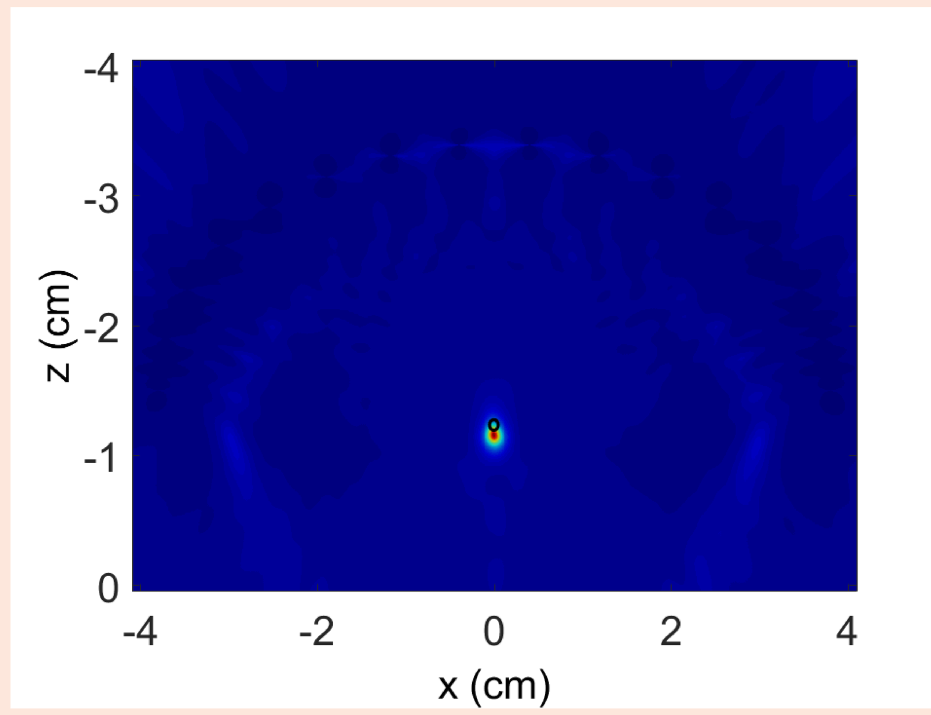


TABLE I
ELECTROMAGNETIC PARAMETERS AND VALUES

Component in FDTD domain	Permittivity (ε) × 8.854e-12 farad/meter	Conductivity (σ) Siemens/meter
Water	9	0
Skin	36	4
Tumor	50	4
Breast Tissue	Derived from MRI	0.4
Ribs	12.48	0.1395
Muscle	55.11	0.9329

MRI-based breast model: (a) Permittivity of the numerical domain comprised of transmitting and receiving antennas, water, breast skin, breast tissue, tumor, ribs and muscle between ribs. (b) The corresponding conductivity, and(c) Electromagnetic parameters and values.





MIMO radar imaging to detect the tumor location: (a) Conventional MIMO radar where the clutter is subtracted from the complete FDTD results with tumor. Symbol "o" represents the centroid of the tumor and ∗ represent the peak of the image; and (b) Coherent FFTR-MUSIC with the TR clutter suppression method.

References

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2018 IEEE ICASSP Conference.