DORT Method and Selective Focusing of UWB Electromagnetic Waves

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I. ABSTRACT

This work presents results from the research conducted on time reversal (TR) phenomenon for Ultra Wide Band (UWB) electromagnetic waves. The first part of this work gives an overview on the numerical techniques used in our simulations. Then second part is devoted to the description of standard time reversal process including simulations that shows the process's properties. This is followed by a description and implementation of the time-reversal operator decomposition (DORT) method. An investigation of DORT is provided along with analysis and comparison against the standard TR method.

II. INTRODUCTION

The fact that underlying physical processes of waves would be unchanged if time were reversed in a lossless and stationary media can be exploited for detection and localization of scatters in disordered media. Techniques exploiting TR invariance for remote sensing applications were first developed for acoustic [1]. It has a range of applications, including destruction of tumors and kidney stones, detection of defects in metals, and long-distance communication and mine detection in the ocean [2]. Later, the TR techniques were applied to Electromagnetic (EM) waves using time-harmonic waves and TR array. In this paper, the techniques: standard TR process and the DORT method (DORT is the French acronym for 'décomposition de l' opérateur de retournement temporel') are investigated [1]. The standard TR process, if iterated, provides an elegant way of focusing on the most reflective target in a multiple-scatterer media [6]. On the other hand, the DORT method allows us to focus on any of the targets regardless of its reflectivity.

III. OBJECTIVES

There were three main objectives to be achieved during the two classes (ECE H683 & ECE H783). The following are these objectives which were assigned:

1. Simulation of the propagation of UWB electromagnetic signals using the 2-D Finite-Difference Time-Domain (FDTD) employing Uniaxial Perfectly Matched Layer (UPML) technique.
2. Simulation of the iterated time-reversal process in a homogeneous non-dispersive media.
3. Investigate the time-reversal operator decomposition (DORT).

The first objective was assign to serve as a tool to accomplish the second and third objectives.

IV. FINITE DIFFERENCE TIME DOMAIN

In this research the Finite Difference Time Domain (FDTD) is the main tool for all simulations done in C++ and Matlab programming language (C++ is faster, but Matlab is better for visualization). FDTD is a numerical technique used to solve Maxwell equations. It modifies Maxwell equations into central-difference equations, i.e. discretizes them. Therefore it allows a programmer to implement these equations in a software. The unique feature of FDTD is that it is a Time-domain technique, thus it can cover a wide frequency range with a single simulation [4].

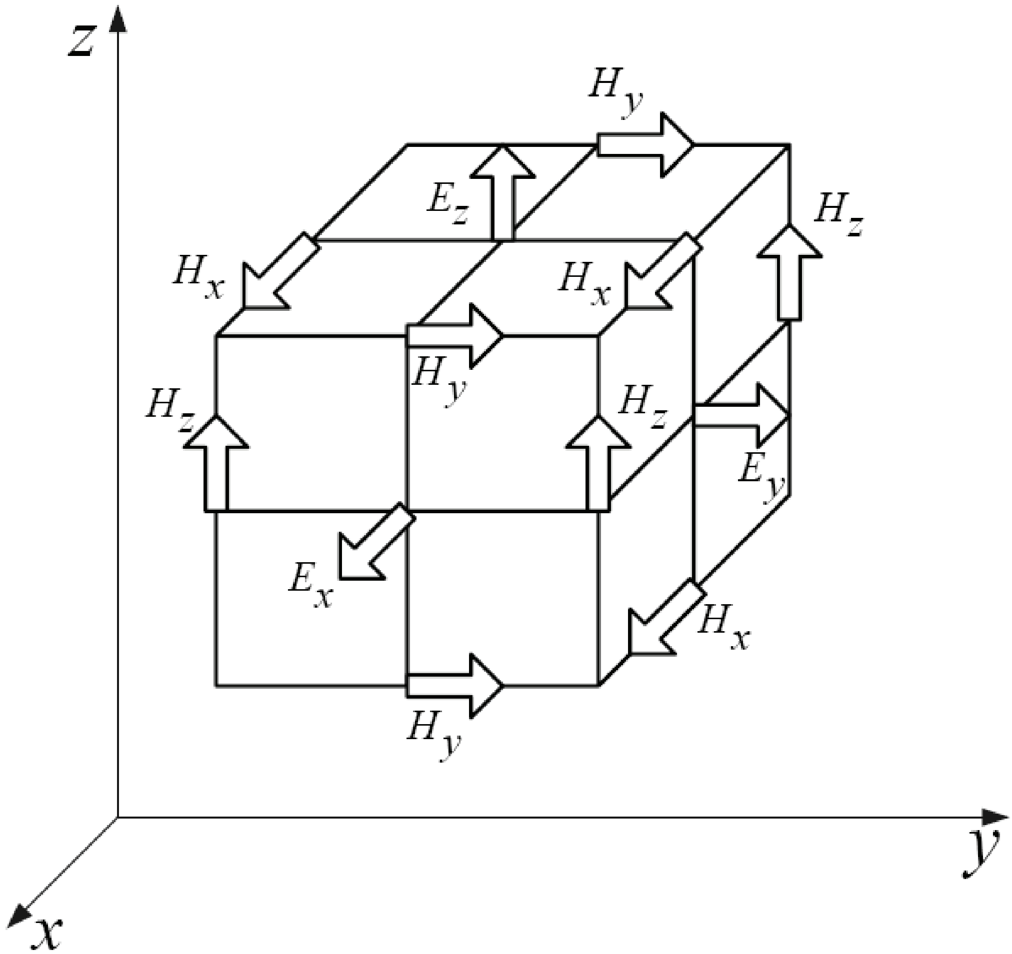

Figure 1: Yee's 3-D FDTD lattice

The algorithm used in the FDTD technique is known as Yee algorithm. This algorithm solves for both electric and magnetic fields in time and space using the coupled Maxwell's equations rather than solving for the electric field alone (or magnetic field alone) with a wave equations [4]. Moreover, the Yee algorithm centers its E and H components in three-dimensional space so that every E component is enclosed by four circulating H components, and every H component is enclosed by four circulating E components. Figure 1 shows how the E and H components are distributed over what is known as Yee's Lattice.

V. PERFECTLY MATCHED LAYER

Another key feature used to perform simulations in this research is the Perfectly Matched Layer (PML). The paragraph below presents some illustration about PML.

As mentioned earlier, in this research, waves are simulated by software using FDTD. Since the wave physically propagates to infinity, the simulation should also reveal such infinite propagation of an electromagnetic (EM) wave. Therefore, due to limitation on the amount of data a computer can store, we need a boundary condition that permits simulation of wave propagating to infinity. Therefore, the boundary condition must suppress spurious reflections of the outgoing numerical EM waves.

As shown in figure 2, the PML is a layer used to surround the simulation computational domain in order to simulate infinite wave propagation. It represents an anechoic cavity providing reflectionless propagation for all impinging waves (for any incident angle) over their full frequency spectrum. Thus, plane waves of arbitrary incidence, polarization, and frequency are matched at the boundary [4].

It should be mentioned that simulations done for this research use the Uniaxial Perfectly Matched Layer (UPML). The UPML plays the same role as PML. The unique feature of UPML is that it is composed of electric and magnetic permittivity tesors [4].

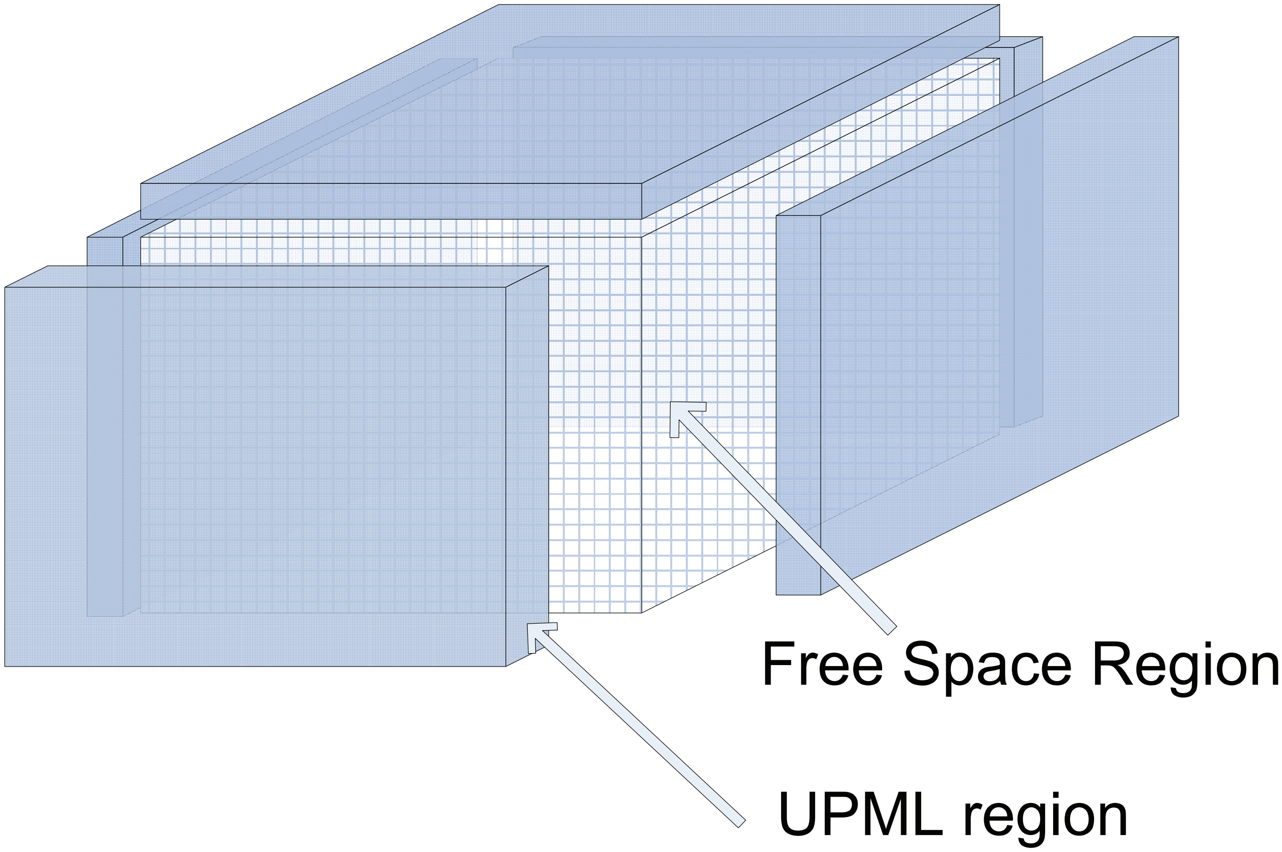

Figure 2: 3-D FDTD computational domain using UPML layer

VI. STANDARD TIME-REVERSAL

The first major technique exploited in this research is the standard time reversal (TR) process. Time reversal was first introduced by Mathis Fink for acoustics. The idea behind time-reversal is that if a wave is sent by a source and recorded by a number of transceivers, then if the data recorded by each transceiver is time reversed (played backward) then the transmitted waves will focus at a point where the source was originally placed. Figure 3 shows an example of time reversal for acoustics. The vertical strip on the right represents a number of transceivers that record the incident "I am here" wave. Then the transceivers time reverse the recorded data and transmit them back. Thus the sent "ereh ma I" signal focuses back to the horn that the person used rather than spreading throughout the space [2]. Physical time-reversal (TR) techniques which were recently introduced by Fink et al. [1] have shown potential for ultra-wideband (UWB) remote sensing applications. Although these techniques were first developed using acoustic waves, they can also be applied to electromagnetic (EM) waves since they are based on the invariance of wave equations under time reversal in lossless media.

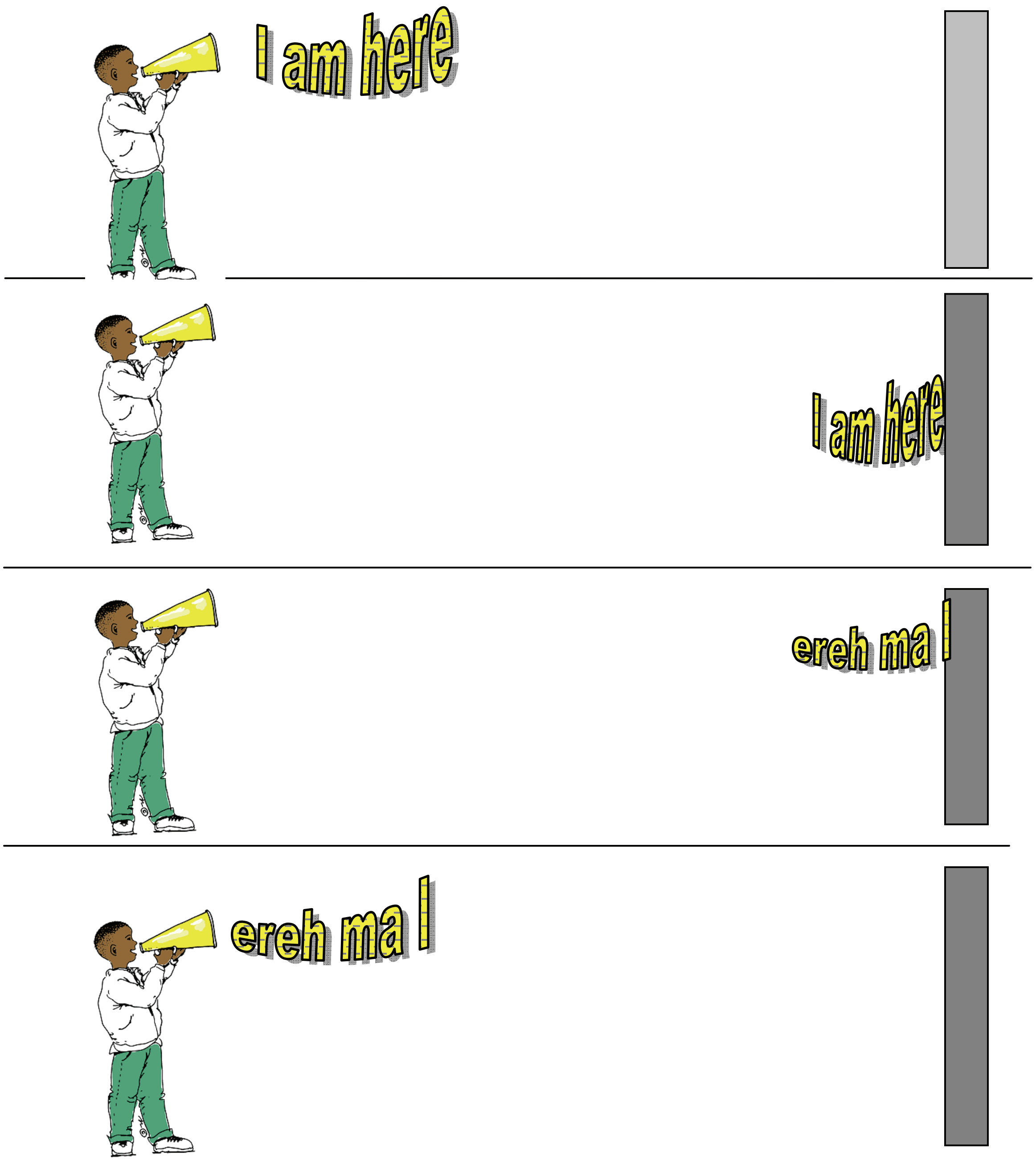

Figure 3: Pictorial example depicting the process of time-reversal acoustics

VII. STANDARD TIME-REVERSAL EXPERIMENT SET UP

In this research, the standard time-reversal process was simulated for a homogeneous 2-D medium. Thus, we can imagine the media as in figure 2, but in 2-D instead of 3-D. The simulation set up and the procedure is summarized in the following steps:

1) A short pulse (UWB) is transmitted from one (or more) of the transceivers. See figure 4 for a clear view.

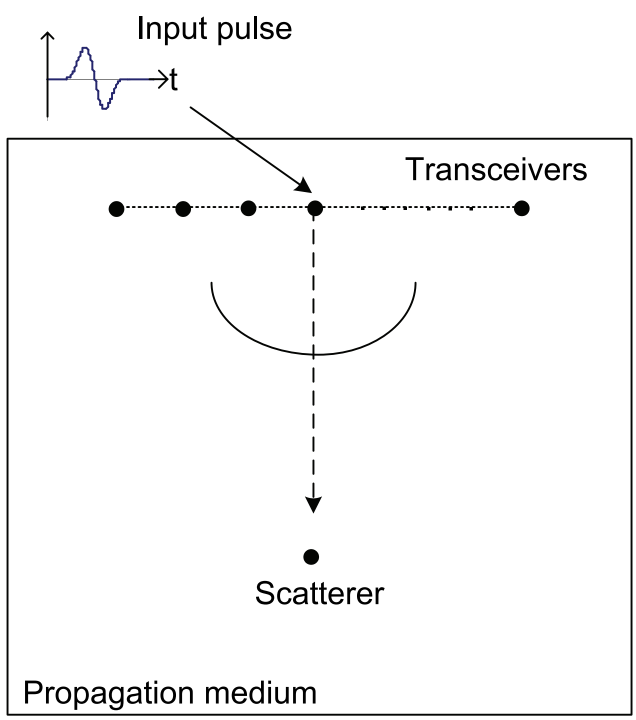

Figure 4: Step 1 in the simulation

2) The signal(s) propagate through a homogeneous medium and got reflected by a scatterer (or more). Figure 5 shows one scatterer for simplicity; however, there could be more.

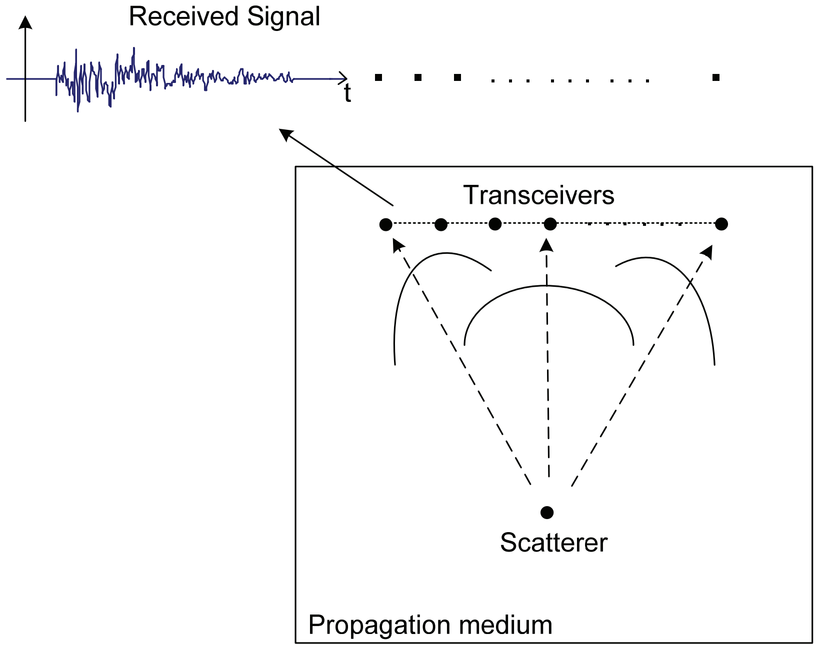

Figure 5: In step 2, the scatterer acts like a point source

3) Received signals at the transceivers are recorded. These recorded signals are time reversed and transmitted back into the same medium.

4) The back retransmitted signals tend to focus near the original source position. Figure 6 shows how steps 3&4 are accomplished.

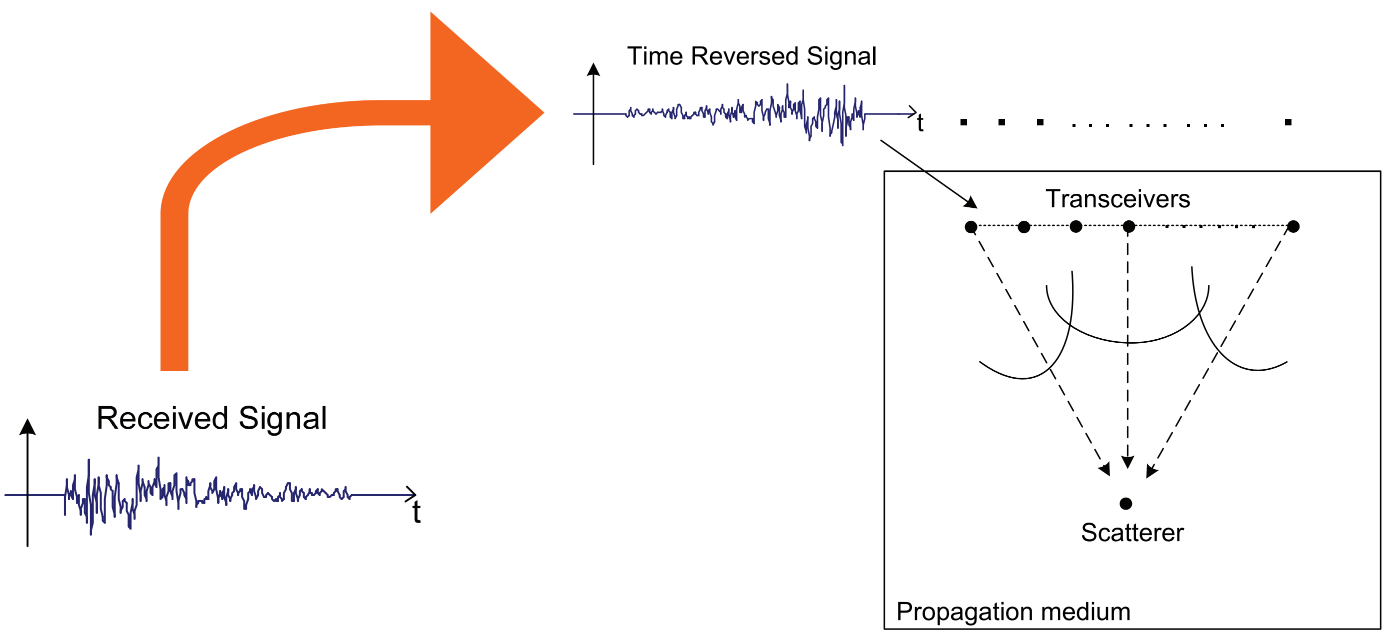

Figure 6: At the end, the back propagating signals focus near the scatterer

VIII. STANDARD TIME-REVERSAL EXPERIMENT SIMULATION

The following Figures are, brought from 2-D Computer simulations, showing the results when a standard Time-Reversal process is applied in a homogeneous media with multiple scatters.

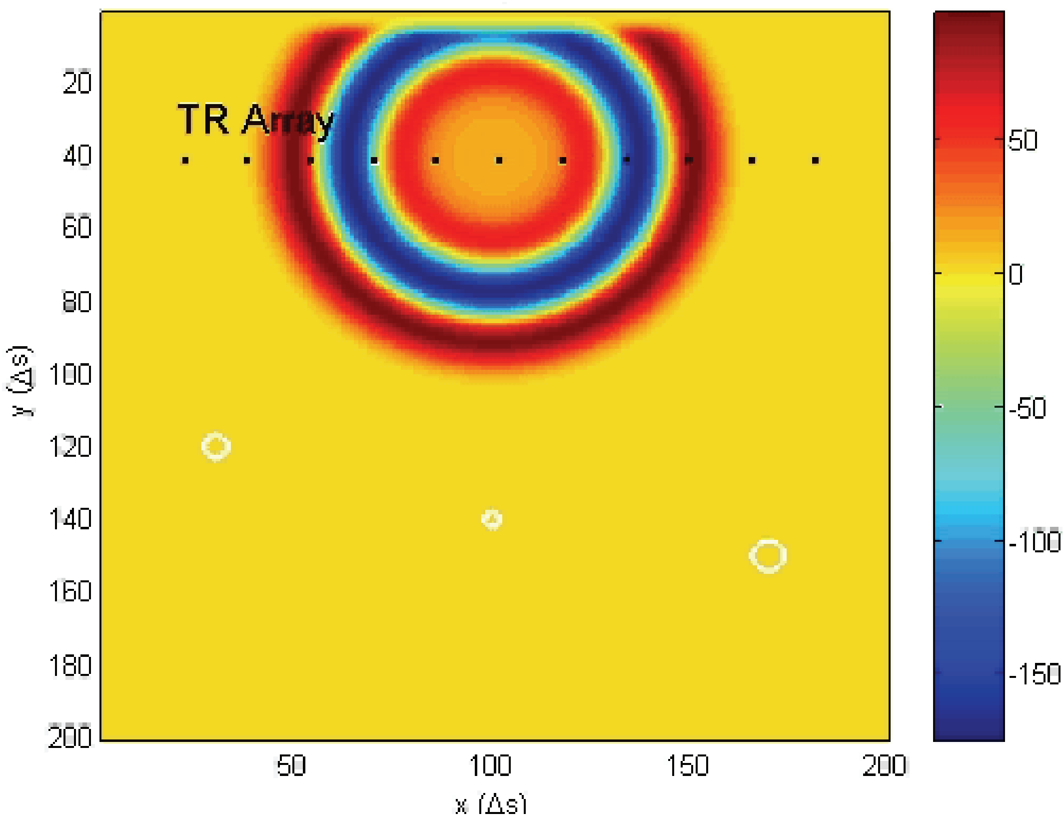

Figure 7: Step1 in the simulation.

In this simulation, we used 11 transceivers lined in the top of the grid. In addition, we put three circular scatterers (depicted by white circumference) with different diameter and locations. From figure 7, it is clear that the forward propagation signal was sent from the middle transceiver. This choice was arbitrarily and we could have sent a signal from a different transceiver or even from more than one transceiver. The main goal is to have a signal propagate in the media and gets reflected from the scatterers so that the scatterers work sources.

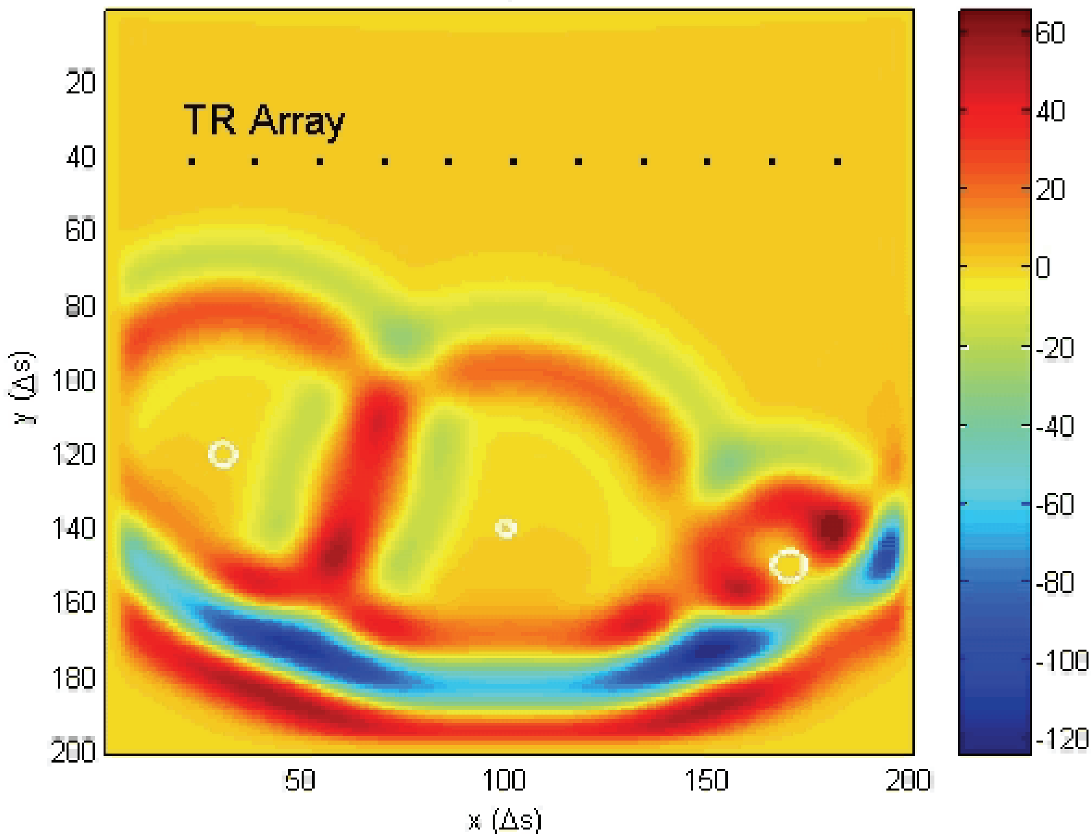

Figure 8: Step 2 in the simulation

As explained earlier, the signal got reflected from each scatterer (scatterers act like sources). The reflected waveforms are recorded in each transceiver and time reversed (step 3).

Figure 9 shows the last step of the process, which is sending back the TR waveforms from each transceiver. The back retransmitted signals tend to focus near the original scatterers' position. An important observation here is that the highest-amplitude wavefront illuminates the most reflective target (larger size and closer to the transceivers), while the weakest wavefront illuminates the least reflective target (smallest size and farther from the transceivers).

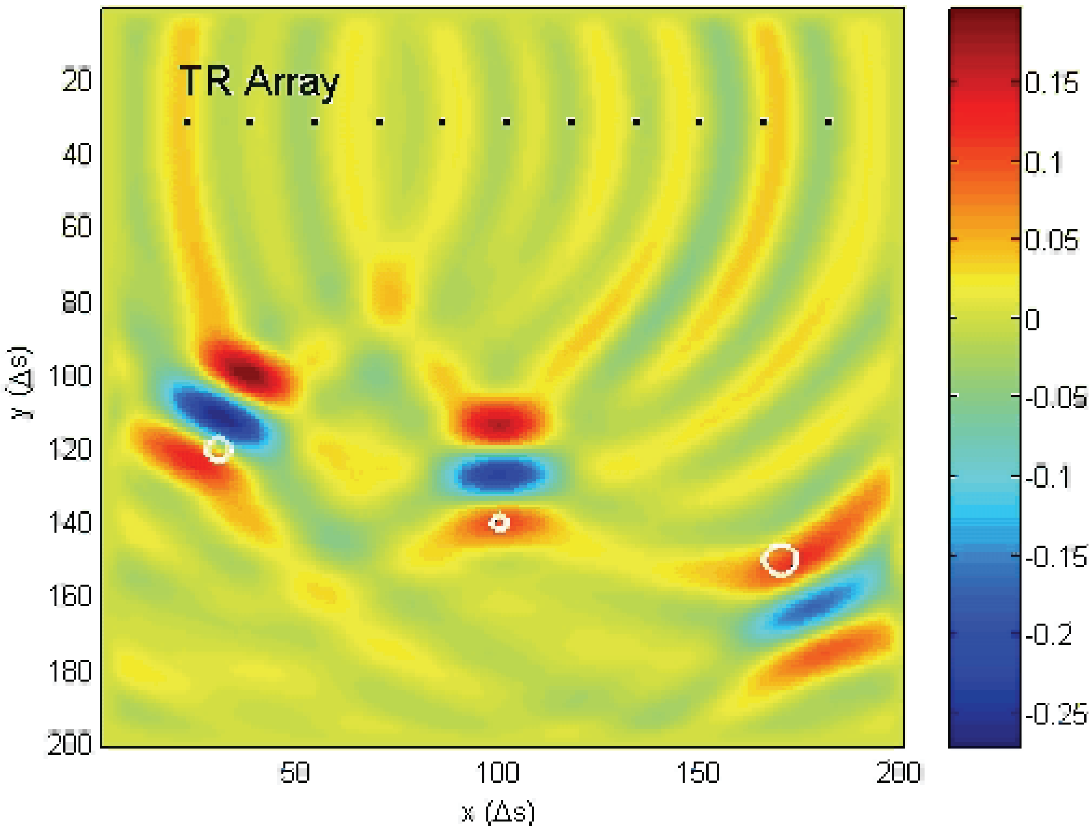

Figure 9: shows the last step of the standard TR process

One might ask, what will happen if we repeat the TR process in a medium containing two targets of different reflectivity? Indeed, if the medium contains two targets of different reflectivities, the TR of the signals reflected from these targets generates two wavefronts focused on each target. The highest-amplitude wavefront illuminates the most reflective target, while the weakest wavefront illuminates the second target. After the first time-reversed illumination, the weakest target is illuminated more weakly and reflects a fainter wavefront tan the one coming from the strongest target. After some iteration, the process converges and produces a wavefront focused on the most reflective target [1].

IX. TIME DOMAIN DORT METHOD

As we have seen in the previous section, backpropagation of TR scattered waves in media containing multiple scatterers results in generation of focal spots on each scatterer. In addition, as the TR process is iterated, the wavefront is increasingly focused on the most reflective target. Therefore, standard TR iteration doesn't allow focusing on other (less reflective) scatterers. The DORT method overcomes this problem and is able to isolate and classify different scattering centers in the medium without any iteration [3]. The DORT method is a little bit harder to understand since it requires some linear algebra manipulation.

X. TIME-DOMAIN DORT EXPERIMENT SET UP

The following paragraphs explain and analyses the DORT method step by step and in more details.

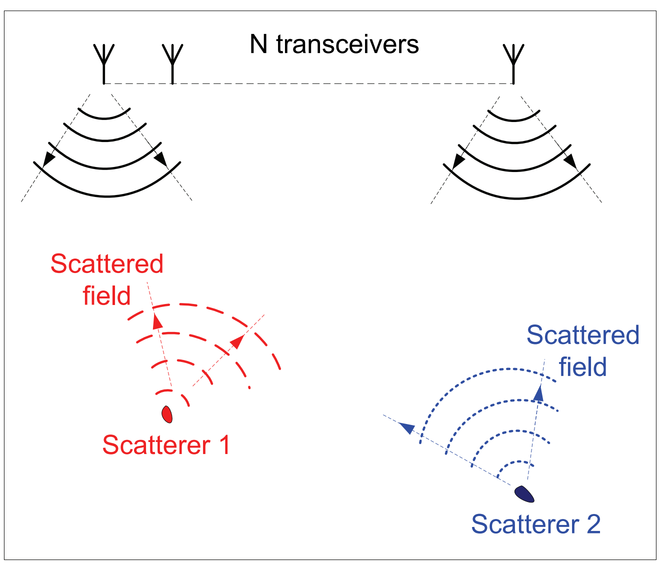

Figure 10: Setup used in the DORT method.

Figure 10 shows a similar setup as we had for the standard TR. *N* transceivers are placed in a homogeneous medium to obtain *NxN* **M**ultistatic **D**ata **M**atrix (MDM) **K**(t). It is also called the Inter Element Impulse Responses. The way this matrix is achieved is as the following: we send an impulse signal from the first transceiver and record the reflected waveform in each transceiver to get the first column of K(t). We repeat this process by sending the same impulse signal from the second transceiver, then third transceiver … and record the received signal to get the corresponding column for each transceiver. Since each element of K(t) matrix corresponds to the signal received (which is a vector by it self), we will end up by 3-D matrix. Then, the Fourier Transform (FFT) of the MDM is taken to obtain **K**(ω) as shown in figure 11.

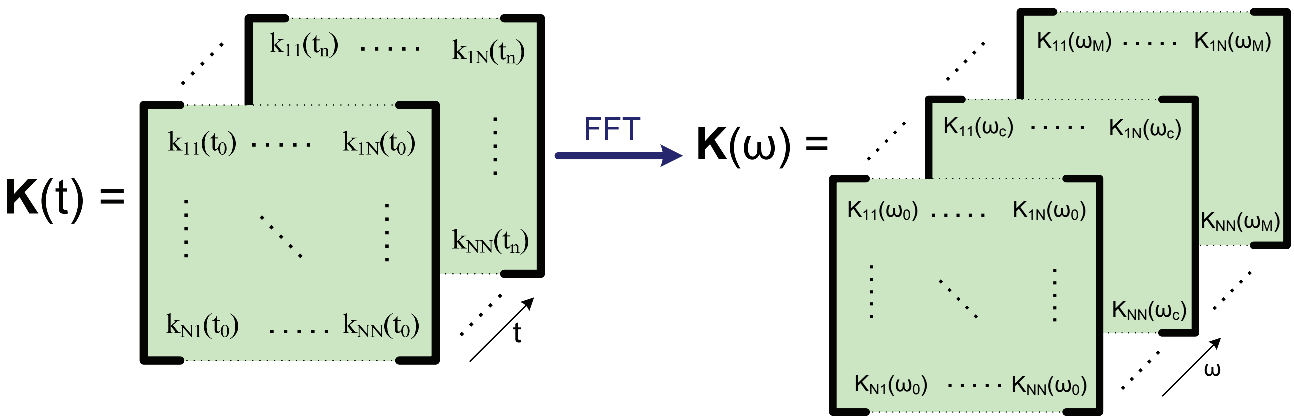

Figure 11: Multistatic Data Matrix K(t) & K(ω)

Since the TR operation is equivalent to a phase conjugation in the frequency domain, it can be represented by its hermitian conjugate **K**†(ω).

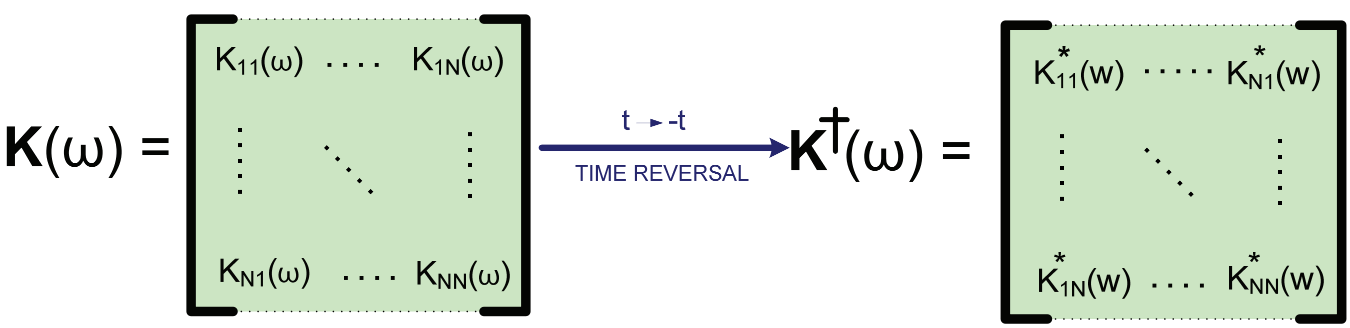

Figure 12: Derivation of **K**†(ω).

The Time Reversal Operator (TRO) is defined as the self-adjoint matrix: $\mathbf{T}(\omega) = \mathbf{K}^\dagger(\omega)\,\mathbf{K}(\omega)$.

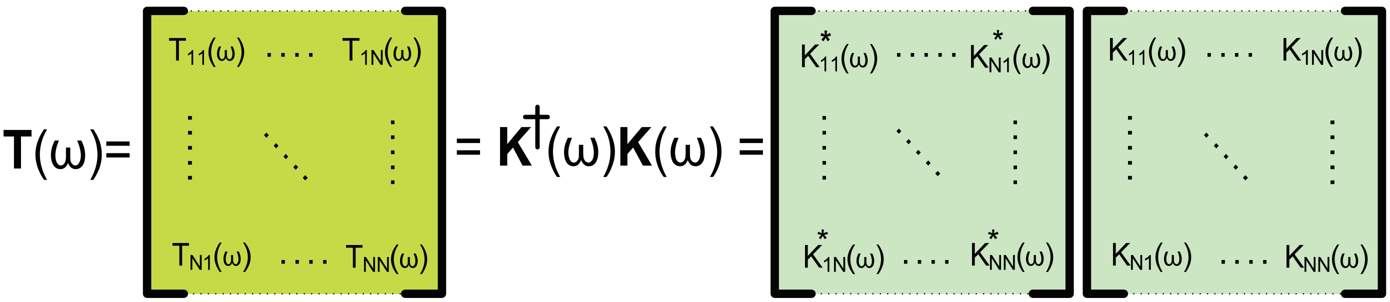

Figure 13: Time Reversal Operator

Then, we apply Single Value Decomposition (SVD) to the MDM matrix to get:

$\mathbf{K}(\omega) = \mathbf{U}(\omega)\mathbf{\Sigma}(\omega)\,\mathbf{V}^\dagger(\omega)$

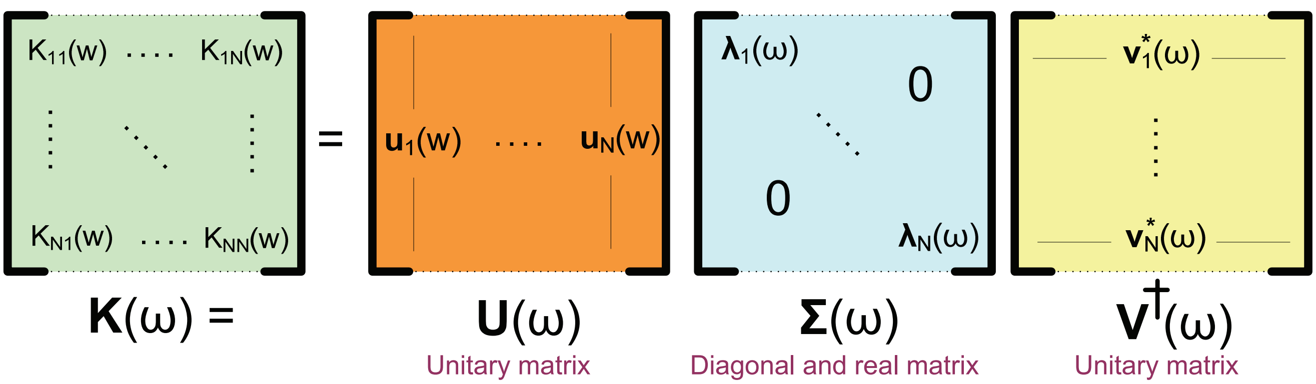

Figure 14: SVD on K(t)

Then, we apply the eigenvalue decomposition of TRO to get:

$$\mathbf{T}(\omega) = \mathbf{K}^\dagger(\omega)\,\mathbf{K}(\omega) = \mathbf{V}(\omega)\,\mathbf{\Sigma}^\dagger(\omega)\,\mathbf{U}^\dagger(\omega)\,\mathbf{U}(\omega)\,\mathbf{\Sigma}(\omega)\,\mathbf{V}^\dagger(\omega) = \mathbf{V}(\omega)\mathbf{S}(\omega)\mathbf{V}^\dagger(\omega)$$

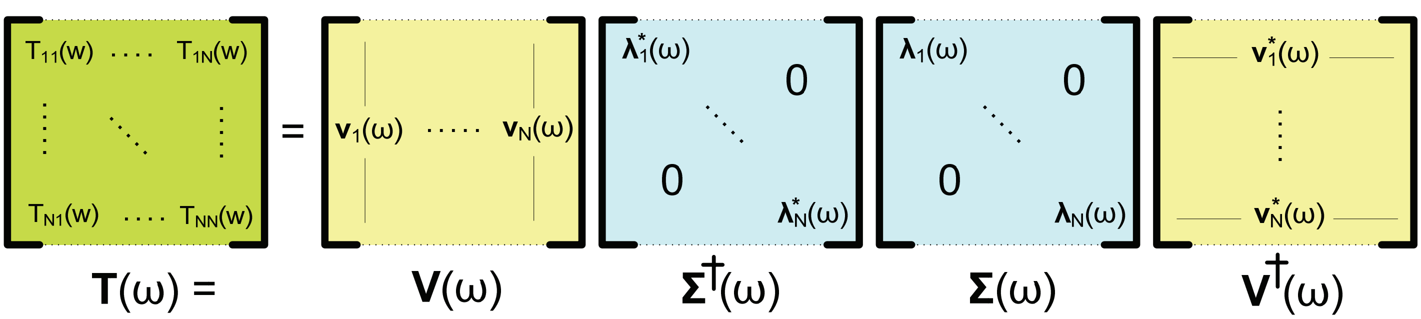

Figure 15: EVD of the TRO matrix

After all this signal processing, we can now using eigenvectors of T(ω) to do selective focusing. For *well-resolved* point-like scatterers, each non-null eigenvector of the TRO is associated to a single scatterer as figure 16 shows.

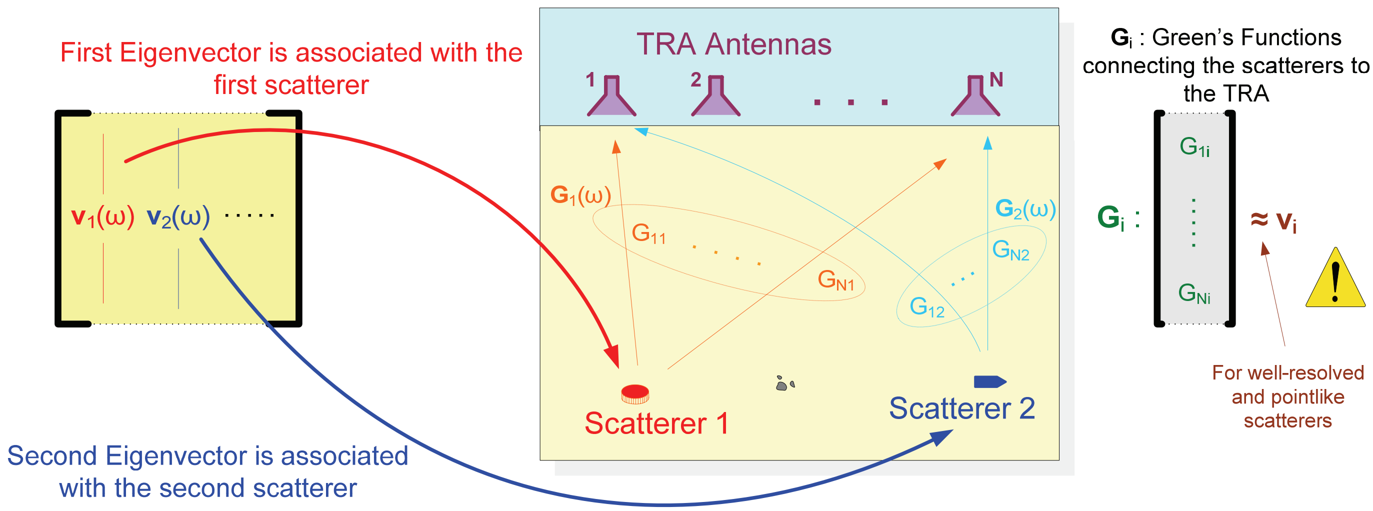

Figure 16: Each non-null eigenvector is associated to one scatterer.

The Green's Functions relate the scatterers to the transceivers (Time Reversal Array). In addition, Green's functions are orthogonal to each other for well-resolved cases.

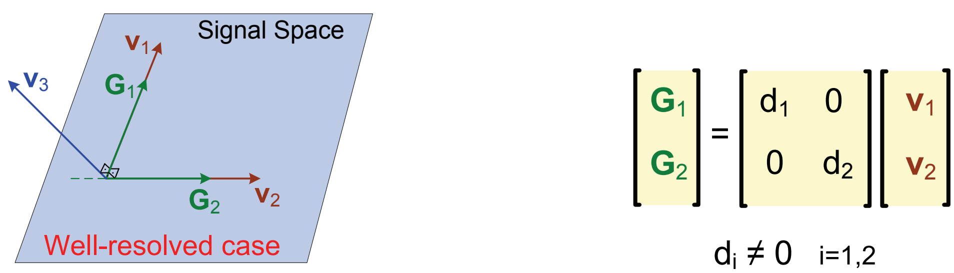

Figure 17: Green's functions for well-resolved cases.

Backpropagation of these eigenvectors creates wave focusing on associated scatterers. The backpropagated signal from the TRA to focus on the pth scatterer is obtained using the associated eigenvector ($\mathbf{v}_p$) and singular value (λ_p) which satisfy:

$$T(\omega_c)\times v_p(\varpi_c)=\lambda_p{}^2(\omega_c)\times v_p(\varpi_c)$$

Components of the *Nx1* column vector $\mathbf{r}_p(\omega_c)$ give the excitation amplitudes for the N element TRA via: $r_p(\omega_c) = \lambda_p^{-1}(\omega_c) \times K^{\uparrow}(\omega_c) \times v_p(\omega_c)$.

The previous way of backpropagation is called Central-Frequency DORT since it uses only the components of the central frequency. One the other hand, there is another way to do backprobagation which is the Time-Domain DORT. For UWB signals, decomposition over the entire bandwidth is possible and the time-domain signals to be fed to the TRA can be obtained by an inverse Fourier transform: $r_p(t) = F^{-1}\left\{\lambda_p^{-1}(\omega) \times K^{\uparrow}(\omega) \times v_p(\omega)\right\}$.

XI. TIME-DOMAIN DORT EXPERIMENT SIMULATION

2-D Computer simulations show what happens when a Time-Domain DORT method is applied in a homogeneous media with multiple scatters:

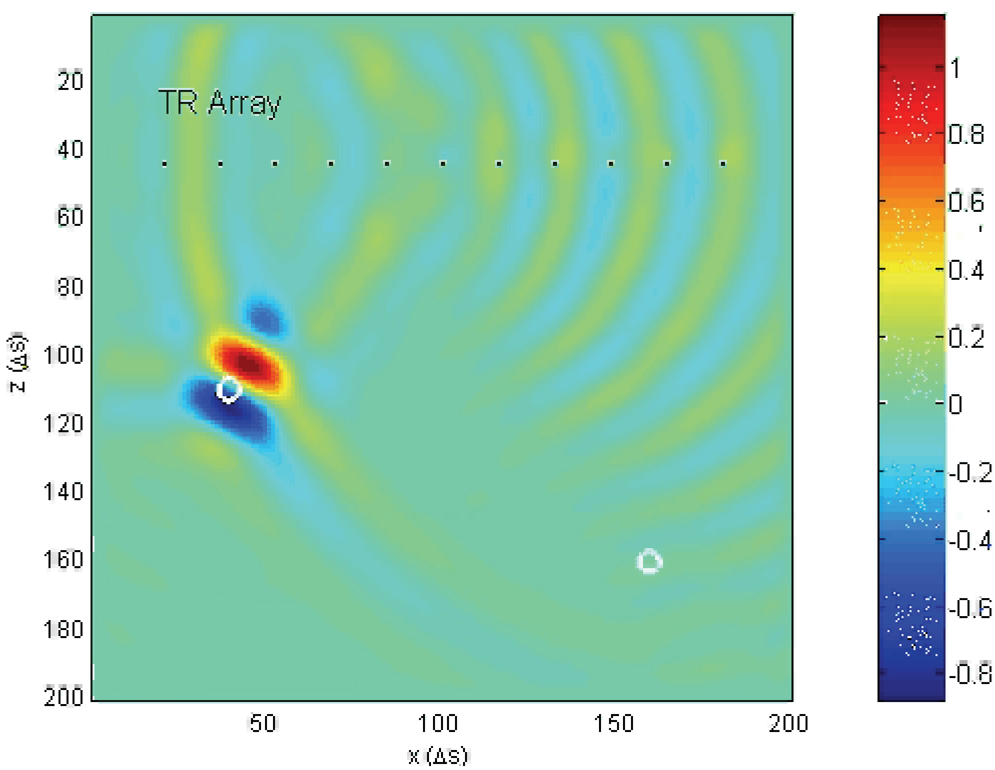

Figure 18: Using the first eigenvector

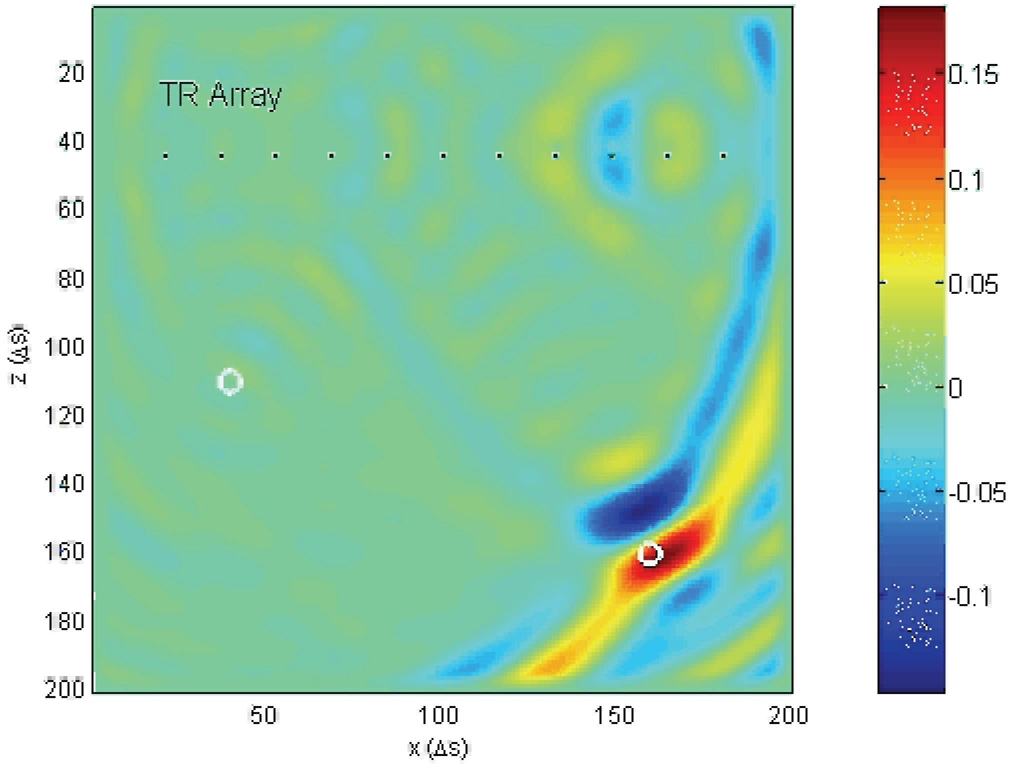

Figure 19: Using the second eigenvector

First, we used the first eigenvector to produce the backpropagating signal. Figure 18 shows how we could focus the signal selectively on the first scatterer using the DORT method. Then, we used the second eigenvector to generate the backpropagation signal and the result is shown in figure 19. The backpropagated signal could focus on the second scatterer.

XII. SINGULAR VALUES VS SEPARATION DISTANCE

If the case wasn't well-resolved, eigenvectors will be linear combination of the Green's function connecting the scatterers to the TRA. Hence, the focusing will be on the linear combination of the scatterers. A question appeared here, how would the distance between two scatters affect the singular values? A simulation was performed to exploit that question and the configuration in figure 20 was used.

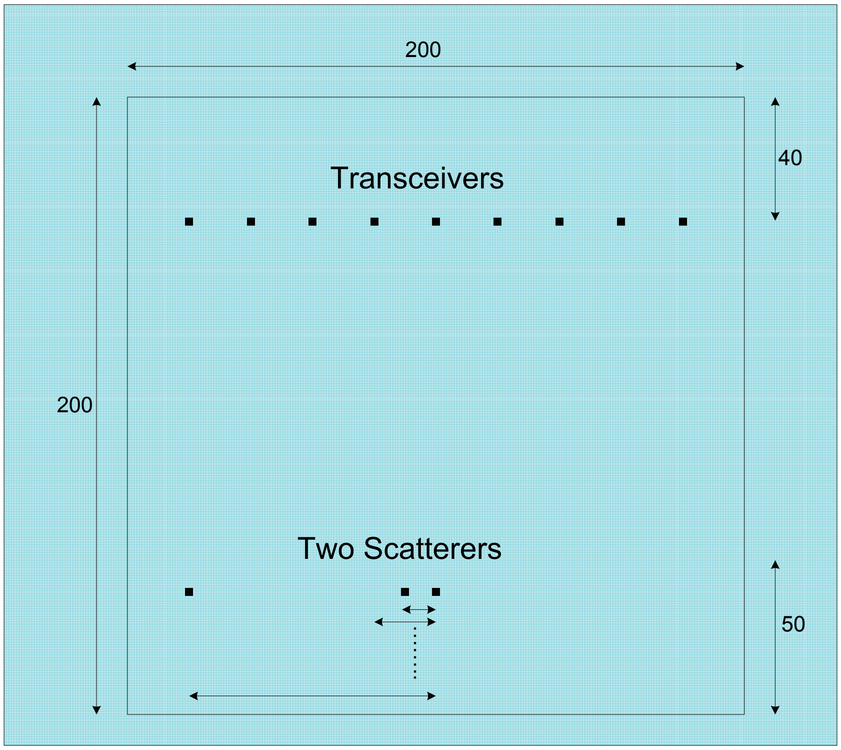

Figure 20: The distance was increased with each simulation

We used a similar simulation setup and we kept increasing the distance between the two scatterers each time we run the simulation. We compared the resulting singular values in each case for two frequency components (small frequency and high frequency). For small frequency, the first observation was that for small distance (less than half the central wavelength) there was only one significant singular value. This means that the two scatterers are acting like one big scatterer when there two close. As the distance increased, the second singular value start to increase significantly as it is shown in figure 21. On the other hand, high frequency components could distinguish between the two scatterers and the second singular values were valuable even for a small distance between the scatterers as figure 22 shows.

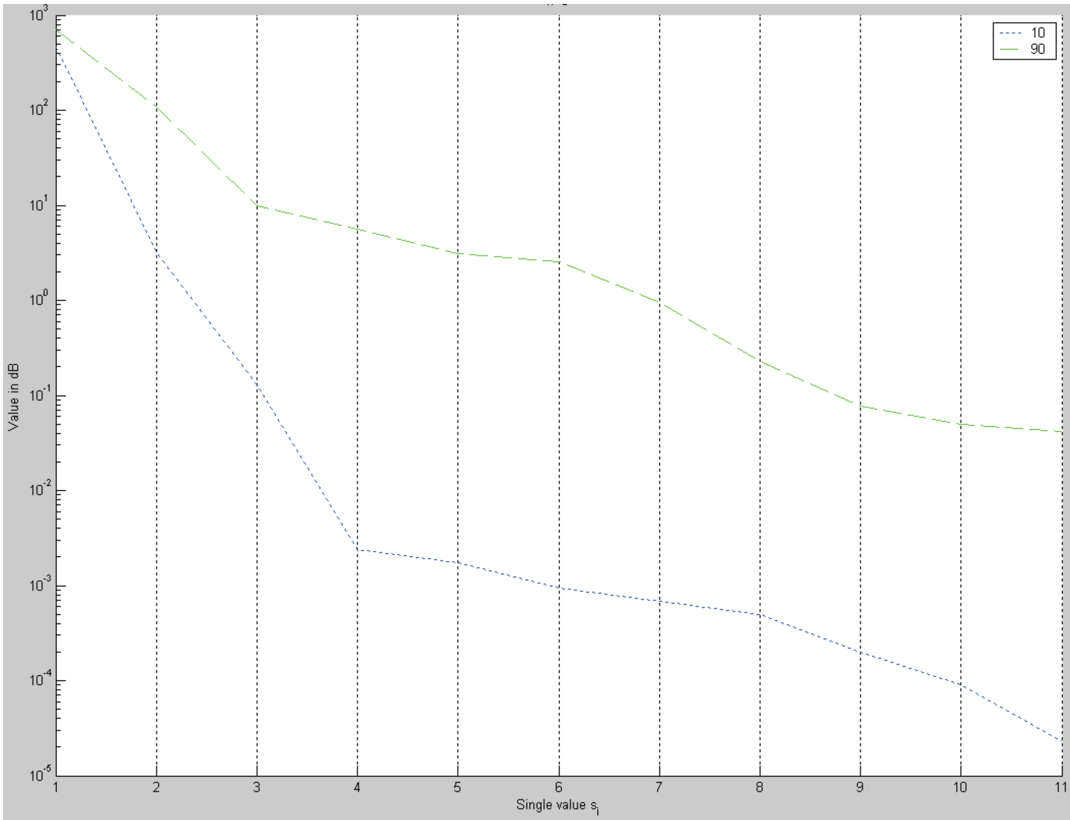

Figure 21: Singular values for lower frequency

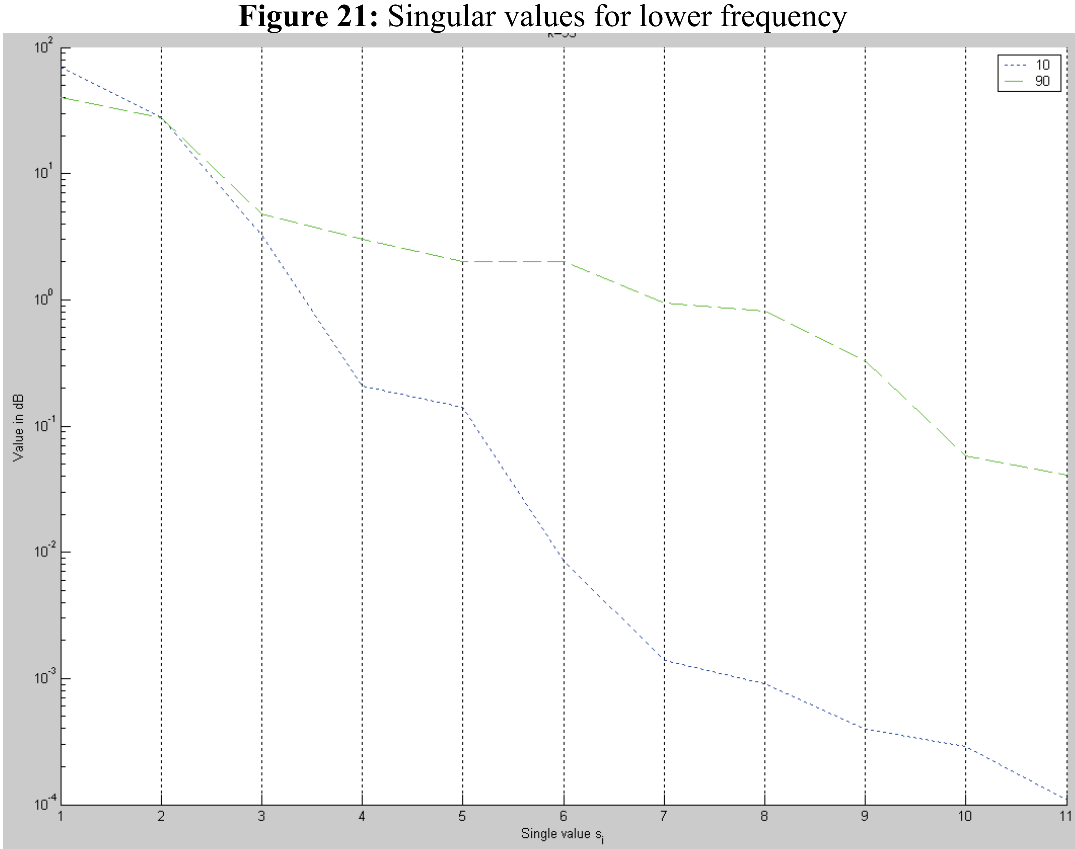

Figure 22: Singular values for higher frequency

XIII. STANDARD TR VS. DORT

For the purpose of making a comparison between standard TR and DORT method, we used a similar configuration for both methods simulations. After investigating the two methods (Standard Time-Reversal and Time-Domain DORT) and looking at the simulation results, we can conclude two major differences between them:

- Iterative TR allows focusing *only on* the strongest scatterer whereas DORT allows *selective* focusing on any of the scatterers.
- In Standard TR, we are only time reversing the received signal. On the other hand, DORT requires signal processing the received data before we send it back.

IXV. CONCLUSIONS

This research has accomplished its objectives. EM waves propagation was simulated using FDTD technique as well as UPML. FDTD allowed us to implement Maxwell equations in software. UPML layer suppressed spurious reflections of the outgoing numerical waves. In media containing multiple scatterers, back propagation of time reversed (TR) scattered waves results in generation of focal spots on each scatterer. After some iteration, the process converges and produces a wavefront focused on the most reflective target. For well-resolved cases, Time-Domain DORT method allows us to isolate and classify different scattering centers in the medium without any iteration. Standard TR simulation and Selective focusing using time-domain DORT was demonstrated. The future work for this project is to consider scattering effects on focusing and develop techniques accounting them to improve the selective focusing.

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