Session 2P9
Time Reversal Techniques in Electromagnetics

Time Reversal: From Acoustics to Electromagnetism

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Time-reversal invariance is a very powerful concept in classical and quantum mechanics. In the field of acoustics and electromagnetism, where time reversal invariance also occurs, time-reversal experiments may be achieved simply with arrays of transmit-receive antenna, allowing an incident wave field to be sampled, recorded, time-reversed and re-emitted.

Time reversal mirrors (TRMs) may be used to study random media and complex reverberating structures. Common to these complex media is a remarkable robustness exemplified by observations that the more complex the medium between the probe source and the TRM, the sharper the focus. This property is related to the fact that TRMs work with broadband signals, contrary to phase conjugated mirrors. TRMs open the way to new signal processing's that interest imaging, detection and telecommunications.

Due to the limited frequency range of acoustics waves (KHz and MHz), TRMs have been first developed in this field of Acoustics. They have plenty of applications including ultrasonic therapy, medical imaging, non destructive testing, telecommunications, underwater acoustics, seismology, sound control and domotics. An overview of these fields will be presented.

Time reversal within the GHz range is now possible and it is now applied with Electromagnetic waves. A comparison of the TRM possibilities in Acoustics and Electromagnetism will be discussed.

Practical and Theoretical Aspects of Time Reversal of Electromagnetic Waves

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Since 1990, the time reversal of ultrasonic waves is studied at laboratoire Ondes et Acoustique from Paris, France. Experimental as well as theoretical aspects of Time Reversal are explored.

Very recently, the first experiment of time reversal of microwave electromagnetic waves was performed at our laboratory. In this experiment, the time-reversed electromagnetic wave was focused on a single antenna. Since then, we have built two 8-antenna arrays that lead us to measure the spatial focusing. With this new set-up, it was essential to have a better understanding of all the aspects of time reversal of Electromagnetic waves. It exits only a few previous theoretical works on time reversal of electromagnetic waves. However most of the time, they only address a few particular aspects of time reversal of Electromagnetic Waves. Here we would like to propose a theory that makes the link between fundamental and technical aspects of time reversal. Thus in a first part, we discuss general aspects of reversibility of Maxwell Equation. We generalized the concept of time reversal cavity, first introduced in acoustic, to the case of electromagnetic waves. We show that the time-reversed wave is linked to the imaginary part of the dyadic Green's function. However this fundamental approach of time reversal is not sufficient since the electromagnetic wave field is generated and recorded by the way of antenna. Then we describe the time reversal experiment in terms of currents and potentials. The equivalent electric schema of a two-antenna time-reversal experiment is proposed. The influence of the two antennas is taken into account by the way of a 2 by 2 mutual impedance matrix. We recall the link that exists between impedance matrix and dyadic Green's function. The theory is then generalized to linear array of antennas. We show that the time-reversed wave on the array is linked to the real part of the mutual impedance. Technically, an antenna is always loaded, i.e., the antenna is connected to the ground by the way of impedance in order to provide an impedance matching. Therefore we explain the influence of such loads on the focusing. Most of our experiments are performed in a electromagnetic reverberant chamber. We show how the reverberation leads to retrieve the time-reversed Green's function even with a few time-reversal antennas. The presentation will be illustrated with experimental results and numerical results.

Experimental Wideband Time Reversal of Microwaves

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Time reversal (TR) has been studied for a quite long time in ultrasound, and it has been shown that it is able to focus both in space and time a wave. In a recent paper we have shown that it is possible to time-reverse microwaves without the need to fully digitize the impulse response as it is done with ultrasound. In fact the interesting part of a radio frequency modulated signal being in its complex envelop, one has only to digitize the baseband impulse responses, to time reverse them and phase conjugate the carrier. This allowed the study of such a process with high frequencies using nowadays electronic components, but it was carried with a narrow bandwidth (2 MHz). TR communications have first been successfully performed with acoustic signals in underwater schemes. Recently we have studied the use of ultrasonic TR in a small-scaled indoor environment to characterize its benefits and drawbacks when doing ultra wide band communications. We have underlined that it drastically decreases the time spreading of the signals and allows spacial focusing of the information. The drawbacks are that it also creates inter-symbol interferences due to the fact that the medium is never exactly symmetric in time and that the number of sensor is never infinite. Some of these characteristics have also been addressed theoretically for the electromagnetic case. In this presentation we go further in the study as we developed a wide bandwidth time reversal mirror (up to 250 MHz of bandwidth) in order to have all information on the temporal and spatial focusing properties and to do the first real experiments of wideband TR communications. To that end, we have used separated components that were available commercially. The carrier frequency is generated at 2.45 GHz, the baseband signals come from a dual channel arbitrary waveform generator with 1 GS/s sampling, the modulation is achieved with an IQ modulator with a bandwidth of 250 MHz. The acquisition of the signals is made with a 4-channel 20 GS/s sampling digital scope. The down conversion and processing of the data is achieved numerically with Matlab because nowadays commercial demodulators have smaller bandwidth than the one we needed. In addition to this setup, which stands for a single channel time reversal mirror (TRM), we used two 8-channels switches in order to emulate a 8 channel TRM by linearity, the 8 other antennas being used as receiving antennas. This setup allowed us to study different part of electromagnetic TR process which will be described in this paper. All the experiments were conducted in an electromagnetic reverberating room with a Q factor of 30, because the emitting power of the setup did not allow in-room experiments. Further work will be done in a typical indoor setup, with a more powerful amplifier. In a first part, the temporal compression is investigated as a function of the bandwidth and the number of emitting antennas. A special attention is given to the gain in amplitude that is due to the TR temporal compression in terms of signal to external noise ratio. The effect of the correlation between antennas is also discussed and its effect on the TR sidelobes is shown. In the second part a clear evidence of the spatial focusing of a TR experiment is given. To that end, the 8 channel TRM is used to send a pulse on one antenna of a 8 antenna array receiver. The 8 receiving antennas are quarter-wavelength antennas on a ground plane. That way the field is scanned in the neighborhood of the focus point with model antennas. The result is compared to the analytical functions for spatial correlations of electromagnetic fields in 3 D, while taking the coupling into account. Finally, using the results of the above sections, the 8 channel TRM is used to send information to between 1 and 8 receivers that are 0.5 wavelength apart. It is shown that although no precoding nor error correcting code are used, high data rate communications can be achieved with a significant binary error rate, especially in a noisy environment.

Electromagnetic Super-resolution Time-reversal Nulling

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A novel approach to exploiting multipath for communications and radar detection is time-reversal focusing. In this approach, the multipath is used to focus RF energy on a desired receiver or radar target. In a rich multipath environment, the energy can be focused onto a region roughly the size of 1/2 wavelength even if a line-of-sight is not present.

With suitable modifications to the time-reversed signals, it is possible to create a situation where the multiple paths interfere destructively at a desired location, resulting in a null rather than a focused spot. This technique can be useful for removing the effects of extraneous clutter in radar applications, or to minimize interference to an unintended receiver in communications applications.

In this talk we describe recent experiments in which we have demonstrated time-reversal nulling in both the frequency and time domains, and applied the technique to enhancing the detection of changes in an environment probed by radar. Two types of experiments are presented. The first type consists of frequency domain experiments using multiple antennas or synthetic aperture arrays, and involve bandwidths of up to 2 GHz. These experiments are performed in an open laboratory environment with controlled amounts of clutter. The second type consists of experiments performed in the time domain using a reverberant cavity formed by sections of HVAC duct capped on both ends. These experiments use single transmit and receive antennas and bandwidths up to 36 MHz.

Decomposition of the Time Reversal Operator for a Small Scatterer of General Shape

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Many applications of time reversal to imaging and target characterization require decomposition of the time reversal operator. This is typically accomplished by applying the singular value decomposition to the multistatic response matrix of an array. The number and character of the singular values depends not only on the number of resolvable targets, but also on the particular scattering characteristics of each target. An understanding of how the scattering physics determines the singular values could lead to new methods of characterizing targets when direct imaging is difficult. In this paper we review the decomposition of the time reversal operator for a general planar array and a single small spherical target. We show how the conductivity and permittivity of the sphere can create up to six distinguishable singular values for a fully polarimetric array. We then extend this analysis to a small ellipsoidal scatterer and show how orientation and eccentricity modifies the behavior of the singular values and singular vectors. Results for the limiting cases of a disk and a rod will be presented. We show how orientation could be estimated by rotating an array and tracing the behavior of the singular values as a function of rotation angle.

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Time Reversal Based Multi-tone Imaging Algorithm

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We develop an direct imaging algorithm using an active array. This imaging algorithm is based on time reversal technique and principal component analysis of the response matrix for the active array. The key point is to locate and visualize strong scattering events. The algorithm is very simple and does not need any forward solver. Also multiple-frequencies and multiple-measurements can be superposed naturally. Resolution based thresholding can be used to deal with highly noisy data. Stability and accuracy of of the algorithm for extended target and in random medium will be demonstrated.

Selective Focusing of Ultrawideband Fields in Dispersive and Continuous Random Media via DORT

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In lossless and stationary media, invariance of the wave equation under time-reversal (TR) enables optimal refocusing of time-reversed signals. In practice, this can be achieved using a TR antenna array (TRA), where received signals due to a (unknown) scatterer(s)/source(s) are retransmitted back to the original media in a time-reversed fashion. As the time-reversed signals backpropagate in the medium, they interfere constructively (due to phase conjugation) at the original source position(s) resulting in focusing capabilities that can be used to aid in detection and imaging problems. Under certain conditions, focusing obtained by TR can even outperform the classical diffraction limit, characterizing *superresolution*. Ultrawideband (UWB) operation and multiple scattering in the background media are some of the factors that can enhance the focusing resolution in TR applications via frequency decorrelation and spatial decorrelation, respectively. As a result, TR techniques can be particularly attractive in scenarios where strong multiple scattering occurs. Such conditions exist, for example, in subsurface sensing applications where the intervening soil media are in general inhomogeneous. However, information about the soil constitutive parameters is often incomplete and can only be described in a statistical sense via random medium models. A further advantage of TR techniques in this case is that, under UWB operation, they are *statistically stable*, i.e., they do not depend on the particular realization of the random media, but only on its statistical properties.

Here, we apply a method based on the decomposition of the time-reversal operator (DORT) to study a selective focusing approach for UWB subsurface sensing scenarios where the inhomogeneity of soil medium is modeled by *continuous* random medium models with prescribed first and second order statistics (spatially fluctuating random permittivities and correlation functions), and including frequency dispersive effects.

In order to exploit the UWB operation, this method is implemented over the entire available bandwidth in a consistent fashion. While direct TR would produce focusing around all scatterer locations, DORT allows *selective* focusing on the desired scatterer(s). We will study the effects of first and second order medium statistics on the DORT performance and focusing properties. Since frequency-dispersion breaks the TR invariance, several compensation methods for dispersive effects will be compared. Noise sensitivity of the eigenvalues (and corresponding excitation eigenvectors) will be studied towards using it as a criterion to distinguish (distributed) background clutter eigenvalues from those that correspond to distinct (discrete) scatterers. Throughout this study, we restrict ourselves to limited aspect array configurations.

Broadband Time Reversal Scheme for Target Detection in Highly Cluttered Field

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In electromagnetic wave propagation, utilizing time reversal scheme, focus with superresolution has been experimentally demonstrated in highly cluttered environment [1, 2]. Based on such concept, a modified time reversal scheme based on the utilization of antenna array has also been developed to substantially enhance the target detection in highly cluttered environment. The spatial nullifying scheme results in a virtual elimination or substantial suppression of the scattering on the clutter while enabling automatic energy focusing on the target [3, 4]. In this paper, we present a time reversal scheme along using only a single antenna and a broad band illumination of a highly cluttered field for target detection.

Consider a single target in a cluttered field. A short pulse, corresponding to a broad spectral bandwidth, is broadcast from a single transmitter to the field. Echoes from the field with and without the target presence are recorded by a single receiver. The difference signal between the echoes with and without target is time reversed and mathematically rebroadcast to the field. The final received echo is used for an energy detector to assess the presence of the target. Figure 1 shows a 2-D FDTD simulation of a cluttered field along with a target. The scatters and the target are all identical square cross-sectioned metallic objects. AWGN is added to the receiver prior to the mathematical time reversal operation. Figure 2 shows the ROC curve for comparison between results of the broadband time reversal scheme the simple change detection.

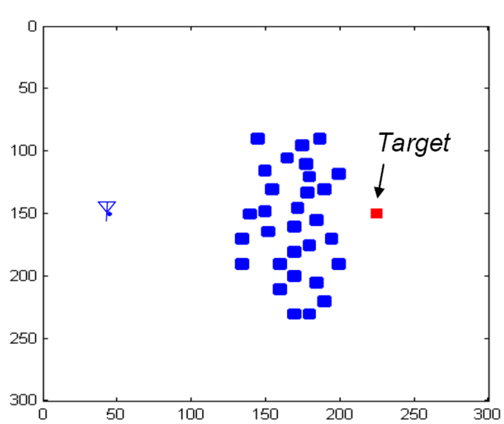

Figure 1: Cluttered field and target used in simulation.

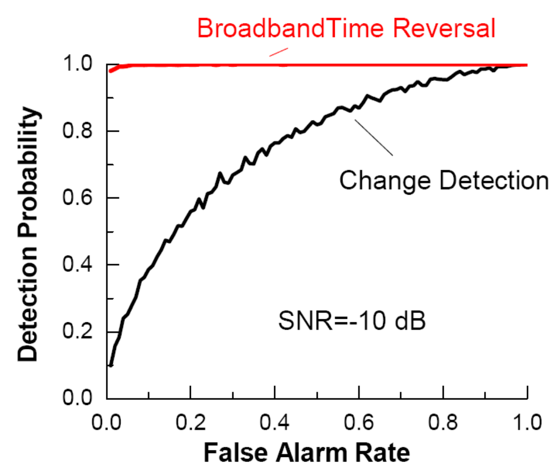

Figure 2: Calculated ROC curve using an energy detector.

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