TIME REVERSAL

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This article provides an historical overview of Time Reversal (TR), introduces its basic physics, addresses advantages and limitations, and describes some applications of this very active research area of acoustics. In the Geophysics Group at the Los Alamos National Laboratory, we conduct studies of TR of elastic waves in solids. Our work includes application of TR to non-destructive evaluation of materials, as well as to earthquake source characterization, and ground-based nuclear explosion monitoring. We emphasize the term *elastic waves* here to underscore that we include both compression and shear waves, in contrast to purely acoustic waves that are only compressional.

"Reversing time has been a compelling idea for ages. Today we can perform time reversal, leading not to the fountain of youth, but to very interesting physics and applications."

Introduction and a brief history

Imagine the following movie: drop a pebble into a pond, and ripples propagate outward from the location where the pebble strikes the water (see Fig. 1). Now, stop the movie, and reverse it. The ripples propagate backwards and eventually converge upon the original source location reproducing the impulse due to the pebble impact that originally created the ripples. Conceptually, this is TR. Meaning, TR can be thought of as a method that uses backward propagation of waves to focus wave energy onto a specific location in space and time.[1]

Reversing time has been a compelling idea for ages. Today we can perform time reversal, leading not to the fountain of youth, but to very interesting physics and applications. The concept as applied to waves dates back a number of years. In 1965, Parvulescu and Clay[2] studied what they termed a *matched signal technique*. In their experiment, they transmitted a signal from a source to a receiver, time reversed the received signal and broadcast it from the source to the receiver again. Parvulescu and Clay's experiment was the first demonstration of TR. This matched signal technique compensated for the coloration of the received signal due to reverberation (multi-path distortion) thereby improving the signal to noise ratio. In addition, the matched signal technique also focused the arrival of the waves in space. During the 1970s and 1980s, researchers, first in the Soviet Union, and later in the United States, created a unique mirror, called an *Optical Phase Conjugator* (OPC). This mirror provided the means to return an incoming wave back along the same incident ray path.[3,4] Thus OPCs are similar to TR in that they reverse wave energy but they differ from TR in that they function only with quasi-monochromatic waves while TR functions with waves of any frequency bandwidth. TR was again studied in 1991 in underwater acoustics to correct for multi-path distortion and to improve the focusing of transmitted acoustic energy into a narrow beam.[5] An important practical outcome of this work was that TR provided the means to track a moving target. Advances in microelectronics and array technologies during the beginning of the 1990s, coupled with new theoretical tools, led to the development of the acoustic *Time Reversal Mirror* (TRM)[6-8] by Fink and collaborators at the University of Paris VII, Laboratoire Ondes et Acoustique (LOA).

Let us return to the mechanics of how the TR process is conducted experimentally and how it differs from the movie of a pebble dropped in a pond. Normally, TR consists of a forward propagation step and a backward propagation step. In the forward propagation step, a source emits waves that travel through a medium, which are then detected by one or more receivers. The signals detected at each receiver are then reversed-in-time and rebroadcast from their respective receiver positions. The set of receivers makes up what is referred to as a TRM. The wave paths that were traversed in the forward propagation are also traversed in the backward propagation. The back-propagating waves simultaneously arrive at the original source location in phase, producing *a time reversed focus*, which is a reconstruction of the original source, albeit reversed in time.

To perform TR for a pebble dropped in a pond, in an attempt to exactly duplicate the reversed movie playback, one would need to have an infinite set of receivers that surround the drop location to detect the ripple motion. The detected

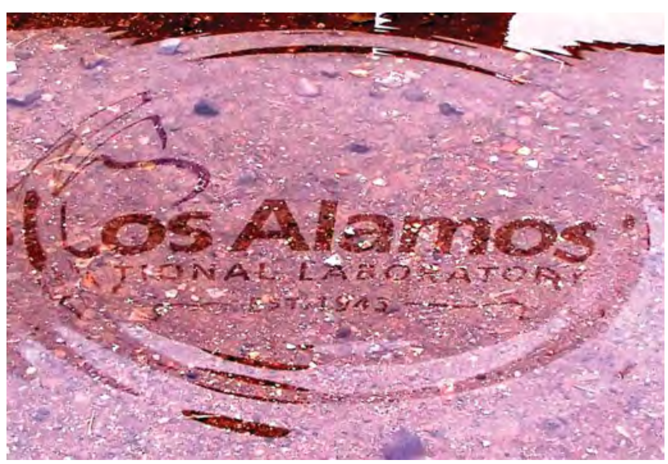

Fig. 1. Snapshot of the ripples created from a pebble dropped into a pool of water.

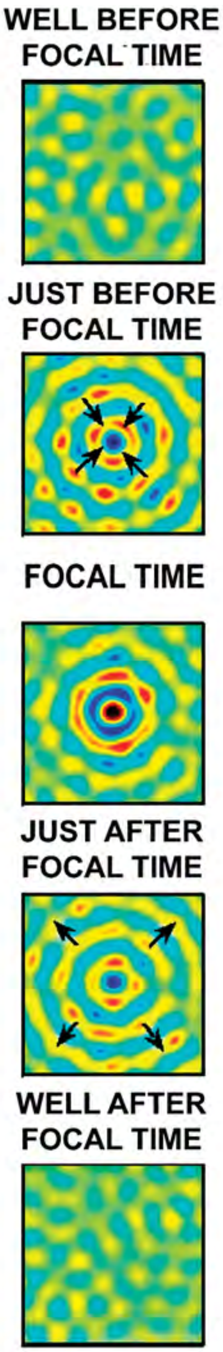

Fig. 2. Spatial map plots showing the progression of the creation of a time reversed focus. The color scale shows the amplitude distribution of the wavefield at discrete moments in time. Note that the image displays the surface velocity (out of plane).

signals would then be reversed in time and the receivers ideally act as highly directional sources to generate the reversed version of the ripples. In practice, Cassereau *et al*. showed that if the receivers in a TRM surround a source that the spacing need not be less than a half wavelength;[8] however, for a *perfect* reversed reconstruction of the movie (including at the nearfield scale) an infinite set of receivers is necessary. If only a few receivers are used (imagine a group of receivers on only one side of the source), the incoming ripples would not be circular and one would expect only a partial reconstruction of the impulse generated by the pebble drop. As a final requirement, when the ripples arrive at the drop location, a pebble would have to emerge from the water at the same time that the ripples converge. Without this final step the converging ripples would simply pass through each other and thereby create outward propagating ripples again. The latter result is similar to what happens in TR acoustic and elastic wave experiments. The incoming waves coalesce at the source position, pass through each other and continue to propagate outward, duplicating the original forward propagation. Source re-emission is one of the main differences between an actual and an ideal TR experiment.

The TR of a pebble drop in a pond is an example of TR in free space. It is nearly equivalent to creating a phased array, which can also be used to focus energy at a specific location. Phased arrays focus energy at a point in space by introducing appropriate delays to each transducer such that the energy arrives at the desired location at the same time. One of the major advantages of using TR over phased arrays in free space is that one must accurately calculate the delays in applying phased arrays, while the TR process requires no such calculation. With TR, the forward signals are just flipped in time and the proper delays are naturally encoded in the forward propagation signals; however, the proper encoding takes place only if all received, reversed, and re-emitted signals are properly synced in time.

Now let us look at results from an experiment to illustrate the differences between ideal and actual TR. The following experiment was conducted in a thin, rectangular aluminum plate, with a source transducer placed near the center. This transducer emits a pulse consisting of a few cycles of a sine wave. A number of transducers are placed at various other locations on the plate. They are the TRM, detecting the first arrival of the pulse as well as the reflections from the boundaries. The signals detected by the receiving transducers are then time reversed and rebroadcast from these same transducers. Figure 2 displays experimentally-obtained data from the back-propagation experiment, showing only the wavefield relatively close to the source location. A laser vibrometer detects out-of-plane velocity signals of the wavefield at progressively later snapshots in time. Notice that well before the focal time, the field is quite diffuse. Later in time,

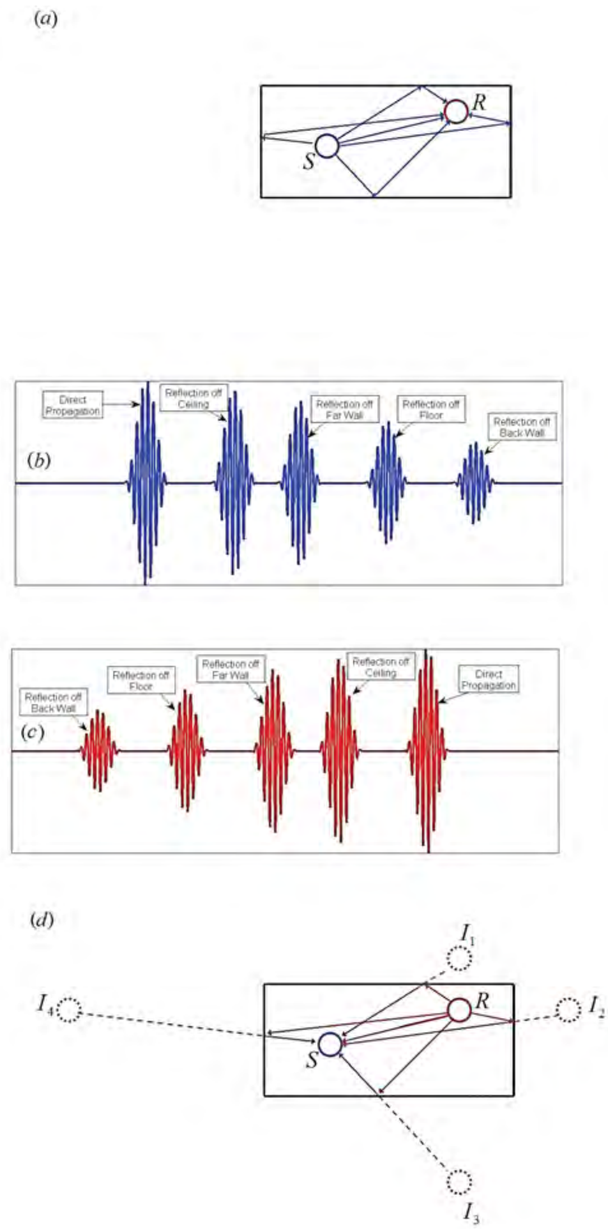

Fig. 3. Illustration of the concept of image (virtual) sources, and how they enhance Time Reversal (TR) focusing in a closed cavity. S, R, and I represent the Source, Receiver, and Image sources respectively. Subplots (a) and (d) depict a spatial illustration of the closed cavity TR process, while subplots (b) and (c) depict the temporal signal recorded at R from the forward propagation and its time reversed version, respectively.

circular rings begin to form that propagate progressively toward the source location. At the focal time, a strong velocity maximum occurs at the source location corresponding to the original input pulse. After the focus, the incoming waves pass through each other, propagating outward until the field becomes diffuse once again [Note that the source transducer is actually located on the opposite side of the plate so as not to interfere with the laser].

The rectangular plate example illustrates the power of the TR process. Instead of multiple reflections/scattering destroying the source reconstruction, they enhance it. Reflectors/scatterers act as *image (virtual) sources* of a TRM. We show conceptually how this works in the illustrations in Fig. 3. Figure 3a shows a closed cavity that contains a source *S*, and a single receiver, *R*. When the source emits a pulse, the pulse travels the paths denoted by the blue colored arrows shown in Fig. 3a [An infinite number of paths actually exist from *S* to *R* , but we limit our consideration to one reflection from each wall for illustration purposes]. The first arrival at *R* will be from the direct propagation followed by the reflection from the top wall and so on, until the reflection from the back wall (on the left) arrives (see Fig. 3b). These five arrivals at *R* (arriving at five different times) can now be time reversed (see Fig. 3c) and emitted re-tracing their forward paths, as shown by the red arrows in Fig. 3d. The later arrivals of energy are emitted first from *R*, and the last emission from *R* corresponds to the direct propagation from the forward step. The four emissions of energy, which reflect from the walls, now arrive at *S* at the same time that the direct propagation arrives (purple colored arrows). Now suppose we remove the boundaries from this experiment and redo the TR broadcast step. To have the focusing that we had inside the cavity, we need sources located at the positions indicated by $I_{1\rightarrow4}$ in Fig. 3d. The sources at positions $I_{1\rightarrow4}$ are called image (virtual) sources and their positions are determined by mirroring the location of *R* about each wall surface. Figure 3 illustrates the advantage of a closed cavity; despite only using a single receiver—it is as if multiple receivers were used. Each unique path between *S* and *R* corresponds to a unique image source location and the more time the receiver is allowed to detect wave arrivals, the better is the focusing in the TR broadcast step due to the increased number of coherent arrivals from the image sources.

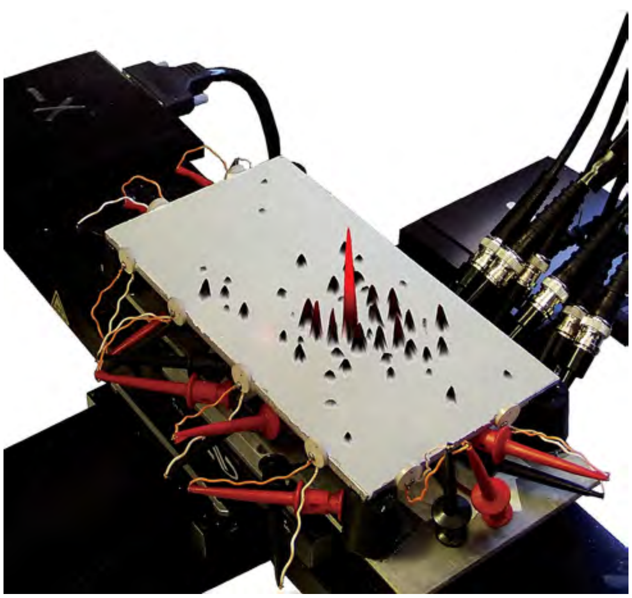

Fig. 4. Photograph of a rectangular aluminum plate used in a Time Reversal study. The overlaid peaks on the plate display the velocity magnitude from actual measurements. The overlay-image was taken at the time of focus and the large-amplitude red-colored peak corresponds to the original source location.

Figure 4 shows a photograph of a rectangular aluminum plate used in a TR experiment with the resulting image obtained at the focal time (specifically, the spatial distribution of the magnitude of the out-of-plane velocity) overlaid. Note the well-defined peak in the overlaid image that corresponds to the original source location. Note also that other energy exists elsewhere at the focal time (just as is in the experiment shown in Fig. 2). This is due to the fact that the experimental TR focusing process is never perfect due to a variety of factors that lead to energy leakage to other locations. We will discuss later why this may happen.

Up to this point, we have described what we will call *standard* TR. We now introduce another method of applying TR, which we term *reciprocal* TR.[2,9] Figures 5 and 6 illustrate the two methods, in time and space, respectively. For illustration purposes, we show only the direct arrival and a single reflection. In both methods, a source emits energy (Figs. 5a [time], 6a [space]) [Note the color scheme of the first and second arrivals in Fig. 5 corresponds to that shown in Fig. 6.]. The time signal is detected by a receiver (Fig. 5b) located at the position *R* shown in Fig. 6a. The detected signal is then reversed in time as shown in Fig. 5c. In standard TR, this (reversed) signal is rebroadcast from location *R* and focuses at location *S*, shown in Fig. 6b. The associated time signal is shown in Fig. 5d. In reciprocal TR, the reversed signal is rebroadcast *from the original source position S* and *focuses at the original detector position R*, as shown in Fig. 6c. This results in the identical focused time signal as in standard TR (Fig. 5d). The reciprocal TR process makes intuitive sense, as the paths traversed in the forward step are retraced in the backward propagation. This is simply a statement of *spatial reciprocity*, i.e., that the propagation from *S* to *R* is the same as that from *R* to *S*. Reciprocity is a fundamental principle to wave propagation and the equations that describe it, and a cornerstone in the TR process (see Limitations section below).

In Fig. 5d, one can see other energy exists that is symmetric about the focal time. Since each emitted pulse propagates outward spherically, the red colored pulse has a direct propagation component that arrives at the focal location *before* the focal time, and the blue colored pulse has a component that reflects from the wall to arrive at the focal location *after* the focal time. These arrivals before and after the time of focus are termed *side lobes*[9] and are inherent in the TR process for closed cavities.

Limitations

As mentioned above, TR relies on the principle of spatial reciprocity,[10] i.e., the ray paths traversed by a pulse from point *A* to point *B* (including reflected paths) will also be traversed if the same pulse is sent from point *B* to point *A*. Spatial rec-

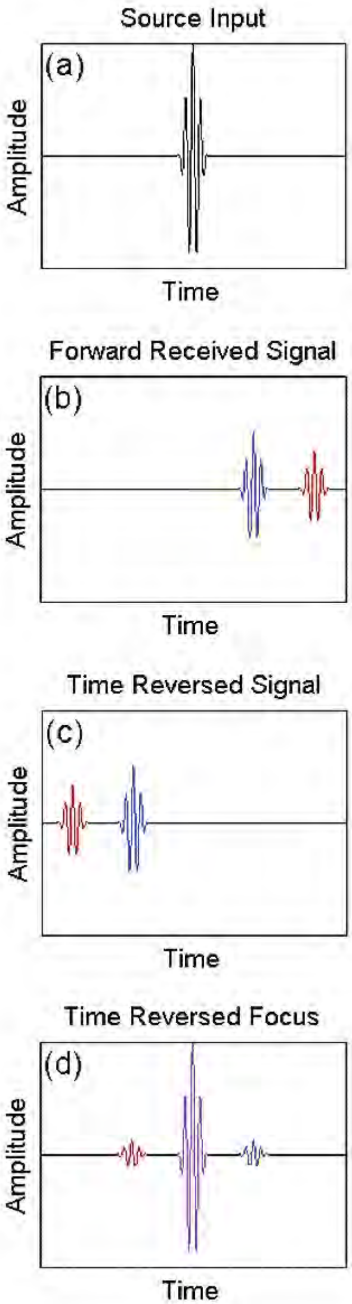

Fig. 5. Temporal representation of the steps used in Time Reversal. Colors correspond to those found in Fig. 6.

iprocity is not broken by velocity dispersion,[11] multiple scattering,[12] mode conversion (as happens in solids),[11] anisotropy, nor refraction. Spatial reciprocity is broken when the medium's velocity structure changes. An example is a medium where fluid is flowing thereby creating a disruption of the velocity structure, or a medium that experiences changes in temperature, altering the wave velocity in the medium. Attenuation in a medium does not break spatial reciprocity either, as long as the attenuation is linear with wave amplitude (considered weak attenuation); however, *nonlinear elastic* effects may break spatial reciprocity. This can happen, for instance, in a medium exhibiting amplitude-dependent attenuation that is hysteretic in its stress-strain response. This behavior is seen for instance, with large amplitude waves in rocks or materials with cracks. In all media, as wave amplitudes increase, waves may exhibit distortion. These are known as finite amplitude waves in acoustics.[13] Finite amplitude waves progressively steepen with increasing distance from the source and may eventually form shock waves. Both Cunningham *et al.*[14] and Tanter *et al.*[15] found that, provided shock formation does not occur, wave steepening can be reversed and thus spatial reciprocity is not broken; however, if shock formation does occur then energy is lost to the shock and the wave is no longer reversible.

There are some applications where it is necessary to conduct the TR back propagation in a numerical model, such as in reconstructing an earthquake (see later). To do this, one must create a numerical velocity model that mimics the real velocity structure that the waves encountered in their forward propagation. The accuracy of the velocity model is crucial to the degree of spatial reciprocity between the experimental system and the numerical model, and therefore the quality of the TR reconstruction.

As waves simultaneously arrive at the focal location, they interfere. The spatial distribution of the focus is limited by the *diffraction limit* (see Fig. 7).[12] The diffraction limit is reached when a sufficient number of waves constructively interfere at the focal location. An important consideration regarding the spatial distribution of the TR process is that not all the energy that is broadcast arrives at the focal position at the focal time. Notice the omnidirectional radiation pattern illustrated in Fig. 6. Some of the energy radiated in the rebroadcast step goes elsewhere into the medium. This energy does not retrace the paths traversed in the forward propagation, and equates to noise, diminishing focal quality (note the energy present at other locations in space at the time of focus in Fig. 2 and Fig. 4). Finite sized transducers compound this effect.

In the experimental application of TR, transducers must be used in a TRM to detect and rebroadcast energy. These transducers can "color" the energy they detect and transmit. For instance, frequently, piezoelectric transducers are used.

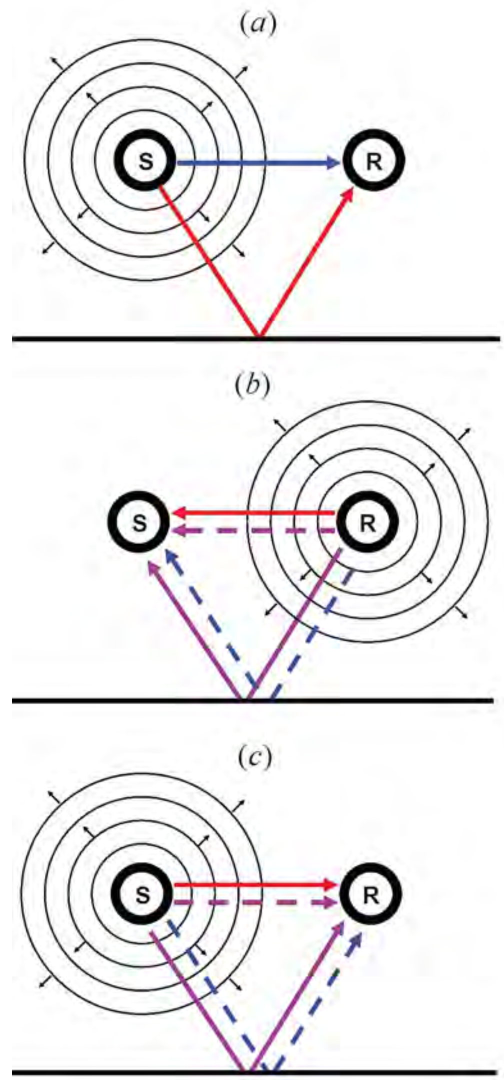

Fig. 6. Pictorial demonstration of two different implementations of Time Reversal (TR): (a) source emission, (b) standard TR and (c) reciprocal TR. Colors correspond to those found in Fig. 5. The solid lines correspond to the first emission of energy (red colored pulse in Fig 5c), while the dashed lines correspond to the second emission of energy (blue colored pulse in Fig 5c).

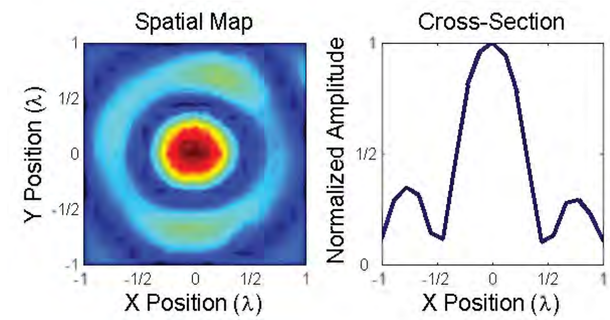

Fig. 7. 2-D spatial distribution and 1-D cross-section view of an experimentally measured time reversed focus which is diffraction limited. Warmer colors correspond to larger amplitudes.

These are often narrow in their frequency-band response. The narrow-band response of these transducers is due to their inherent natural frequencies (resonances). As a result, they *ring down* after wave excitation at their natural frequencies (whether excited electrically as in transmit mode, or acoustically as in receive mode). The net result of the ring down is to temporally broaden the time reversed focus. Figure 8 shows an example of what influence ring down may have on the temporal focus. In Fig. 8a the TRM recreates the source signal quite well, when operating away from a transducer resonance; however, when operating on a transducer resonance, the TRM temporally broadens the recreated source signal as shown in Fig. 8b. While the source reconstruction quality is much improved when operating away from the transducer resonance, the signal to noise ratio is diminished due to the decrease in sensitivity and output efficiency of the TRM transducers. In an experiment, one must address these issues to optimize focusing.

Exploiting TR

Among many other advances made by the group at Laboratoire Ondes et Acoustique in Paris, they have devised the means to use TR to locate individual strong scatterers and to locate multiple scatterers (a scatterer could be a sidewall, an interface, or an object located in the medium). An iterative TR procedure was developed by Prada *et al.*[16,17] to progressively increase the focusing of energy onto an individual, strong wave scatterer (the strongest in the medium under interrogation). The *Iterative TRM* (ITRM) works in a pulse-echo mode. A pulse is sent out and reflects from one or more scatterers. This reflection is detected by the ITRM and then time reversed and rebroadcast. This procedure is repeated and the focal amplitude on the scatterer(s) is thereby progressively increased until the energy is clearly focusing on the strongest scatterer in the medium. ITRM is, in essence, an experimental summation procedure. The ITRM can only focus on the strongest scatterering signal present in the time window used, and thus weaker scatterering signals present in the same time window are not illuminated.

To identify multiple scatterers, Prada *et al.* developed a well-known procedure called the *DORT method*, from the French acronym for Decomposition of the TR Operator.[18,19] Consider a medium with several well-resolved point-like scatterers of varying strengths. The DORT method requires that for a given array of N transducers that, one by one, each transducer emits an impulse and the reflected signals from the scatterers are then detected by all of the transducers within the array. This set of signals can be arranged as a row of a matrix. There are exactly N rows. Distinct rows correspond to different source transducers. Each element of this matrix consists of a temporal signal. A corresponding matrix containing the Fourier transforms of the signals is then calculated. A linear algebra technique called *Singular Value Decomposition* (SVD) can be used to extract, for each frequency, a set of N numbers, called *singular values*, characterizing the *impulse response matrix*. These numbers are like fingerprints of the set of scatterers. In fact, each of these numbers is proportional to the square of the reflectivity of a specific scatterer. More importantly, SVD associates each singular value, i.e. a scatterer, to a set of N signals. This set is called the singular vector of the impulse response matrix relative to that singular value. Physically, it is the set of Fourier transforms of the signals to be applied to the array to focus on that specific scatterer. The DORT theory and method have been

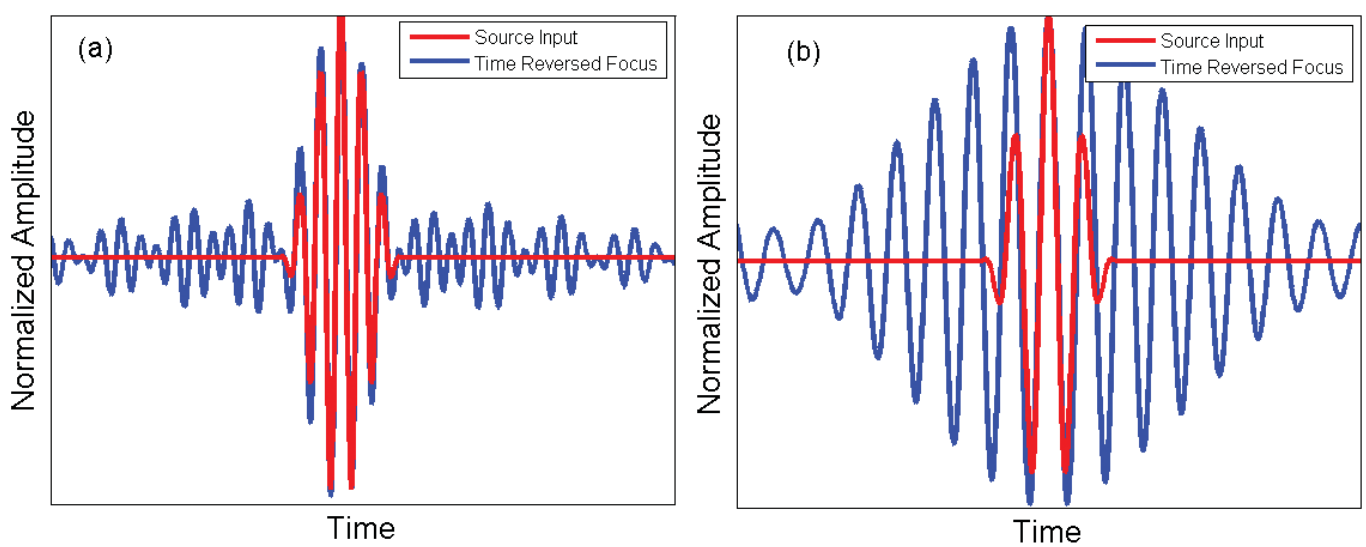

Fig. 8. Experimentally measured temporal signal representing a time reversed focus (in blue) and the source function it attempted to recreate (in red).

investigated in many applications[20-26] and have been additionally refined since they were originally presented, including application to multiple and anisotropic scattering between/by the targets.[27] A different theoretical approach has been developed for the problem of localization and characterization of several extended scatterers in the presence of multiple scattering. This approach is based upon a different mathematical technique, called MUltiple SIgnal Classification scheme (MUSIC), for the SVD analysis of the array response matrix.[28,29]

Super resolution

One major thrust in TR research is to investigate and develop methods to improve resolution of a TR focus by exceeding the diffraction limit. A point source emits a wave field that is composed of two components: a farfield component and an evanescent component, which is only present in the extreme nearfield of a given source. The evanescent waves may have higher spatial frequency content and thus higher spatial resolution information; however, evanescent waves decay exponentially away from the source. Thus a TRM in the farfield cannot directly detect evanescent waves from the source. This means that some information is lost in the forward propagation, resulting in imperfect reconstruction of the source. To have perfect reconstruction, as well as to beat the diffraction limit, one must recreate the evanescent wave field of the source.

As was discussed earlier in the example of a time reversed movie of the pebble in the pond, the pebble ascends from the water precisely at the focal time. In this manner the outward propagating ripples are not generated. Now we take the concept of the pebble movie one step further to aid in understanding how super resolution may be achieved. The ascending pebble contains farfield and evanescent components. The incoming, focused-wave, containing only farfield components, is exactly out of phase with the ascending pebble. The net effect is to cancel the farfield component, leaving only the evanescent component. Since the evanescent waves contain higher spatial resolution information than the farfield waves, the diffraction limit may be surpassed, leading to *super resolution*. The pebble ascending from the water is analogous to producing an *acoustic energy sink*, described and first demonstrated by Cassereau and Fink[8] and de Rosney and Fink.[30] Additional examples of achieving super resolution by using TR include an electromagnetic application developed by Lerosey, de Rosney, Tourin, and Fink,[31] and amplification of the nearfield information in acoustics by Conti, Roux, and Kuperman.[32]

Applications

In this section we will review a number of applications in development. As there are so many, the following list is not meant to be exhaustive. Application areas discussed here include underwater acoustics, biomedical ultrasound imaging and therapy, nondestructive evaluation, and seismology. We will also highlight some of the TR work going on at Los Alamos in collaboration with others.

Propagation of acoustic waves in the ocean is complex, due to multiple reflections at the rough bottom surface and at the water–air interface, as well as significant heterogeneity that creates strong scattering. Acoustic wave propagation in shallow water as well as off-shore is usually modeled as propagation in a randomly layered waveguide. Multiple scattering at the boundaries and in the bulk of the waveguide can significantly degrade underwater communications and imaging techniques. With TR, scattering is exploited to improve focusing on specific targets. In fact, Derode, Roux and Fink[12] demonstrated that a random, multiple-scattering material placed between the source and a TRM can increase the effective aperture of the mirror itself, thus improving its spatial focusing. The multiple-scattering material functions as a kind of lens during the back propagation. The same results have been obtained in the case of ultrasonic propagation in a waveguide filled with water.[33] Researchers from the Scripps Institution of Oceanography/University of San Diego, and from the University of Washington (Seattle), have shown not only the feasibility of a TRM for underwater sound and ultrasound focusing[34] but also its robustness[35,36] and potential for target detection[37,38] and underwater communication.[39-42]

TR focusing techniques are in development for biomedical applications as well, for imaging and therapeutic purposes. Inhomogeneity inside the medium greatly affects focusing performance in time and space in standard acoustic imaging methods. For instance, spatial heterogeneity in density and velocity leads to beam spreading, and the presence of interfaces between different materials leads to refraction and scattering of the waves. As already demonstrated, TR naturally compensates for these limits, because the information about the medium is encoded in the forward propagation signals recorded at a TRM. Again, the scattering enhances focusing, acting as a lens during the back propagation. Examples of biomedical applications in development include applying TRM's to localizing kidney stones and focusing high amplitudes on them to destroy the stones (lithotripsy therapy), by the group at LOA in Paris.[43,44] Other applications in development include TR for focusing through the skull for brain tumor hyperthermia therapy, using special corrective techniques to compensate for the high level of attenuation within the skull, [45-47] as well as for brain surgery.[48]

There has been considerable effort devoted to developing TR methods for applications in NonDestructive Evaluation (NDE). To our knowledge, the first work in this field was demonstrated by Chakroun *et al*.[49] In their work, they developed a TRM for focusing on small defects in titanium and duraluminum samples submerged in water tanks. In the presence of multiple defects inside the specimen, the ITRM is used to focus only on the most reflective scatterer.[50] An enhancement of these techniques was described by Kerbrat *et al.* using the DORT method for selective focusing on each of a set of scatterers.[51] DORT was used to improve the selective localization of small defects very close to each other, giving rise to multiple scattering among the defects, and for distinguishing them from the multiple scattering due to the local heterogeneity of the specimen under investigation.[52] TR has been also applied to the detection of flaws and delaminations in thin solid plates.[53-54] The presence of defects inside the plate changes the quality of the TR reconstruction of the source waveform(s). Defects can be detected by comparing the TR reconstruction of the source in the test sample with the TR reconstruction obtained from an intact sample. TR of Surface Acoustic Waves (SAWs) has also been demonstrated in a very wide frequency range from infrasound and high seismic frequencies, to the high ultrasound[55] and phononic range. TR using SAWs include applications in development for characterizing thin films and plates with microscale heterogeneity.[56]

Applications of TR to a variety of geophysical problems are also in development, from the field scale to the global scale. For instance, promising approaches for landmine localization employing both linear and nonlinear elastic methods using TR are being tested.[57-58] The methods generally rely on exciting the landmine from an array located at short distances from the mine, by scanning a detection laser in a raster-like manner, and conducting reciprocal TR at each scan point. The linear methods tend to rely on location by exciting resonances of the mine that give amplified signals compared to the background (the soil), or by acoustic impedance differences. At enhanced wave amplitudes, landmines exhibit a nonlinear response due to the mine's structure, or the interface between the mines and the soil. In the nonlinear methods, the scanning is done to excite the nonlinear response of the mine which leads to localization upon filtering for harmonics for instance.[58] Other geophysical applications will be described below.

We turn now to some applications that are in development at Los Alamos, in collaboration with a number of other institutions. These include applications to NDE as well as studies of the earthquake source (first begun at the Institute of Physics of the Globe [Paris], in collaboration with LOA).

Recently, tests of the feasibility and robustness of applying TRM transducers directly to the surface of a solid specimen (a typical configuration in NDE) were reported.[59] These studies, illustrate that TR works very well without submerging the test specimen, and in the presence of the fully elastic wavefield. They also confirm the efficiency of TRMs composed of a small number of elements. These studies consist of a solid sample with reflecting boundaries, including the case of a simple geometry, which does not lead to *chaotic/ergodic ray path dynamics* [in an ergodic cavity, a wave originating at any point reaches all other points]. Ergodic ray path dynamics have been shown to be the ideal case when only using a single channel TRM because the virtual aperture on a TRM is increased dramatically.[12,60] Meaning, ergodic cavities are of great value when using a single transducer and recording for a long time because of the large number of reflections one obtains.

Crack detection and imaging exploiting nonlinear elasticity is a topic of significant interest, and much work in NDE of solid materials has been conducted over the last 10 years or so. The general approach is known as Nonlinear Elastic Wave Spectroscopy (NEWS). NEWS encompasses all nonlinear methods that employ spectral analysis.[61,62] As noted, cracks can be the source of significant elastic nonlinearity, generating wave distortion in the form of harmonics, sum and difference frequencies (intermodulation distortion) in the presence of relatively large amplitude elastic waves.[61-64] We describe two methods below (Note much of this work was developed in collaboration with A. Sutin [Stevens Institute of Technology, Davidson Laboratory], R. Guyer [University Nevada Reno and LANL], the group of P. P. Delsanto and M. Scalerandi [Turin Polytechnic Institute], and with K. Van Den Abeele [Catholic University Leuven, Belgium (Kortrijk campus)]).

The first method we describe is called the Time Reversal Elastic Nonlinearity Diagnostic, known as TREND,[65,66] and uses TR and NEWS to image surficial or near-surface, nonlinear scatterers (normally cracks or near-surface disbonding). This is accomplished by conducting the TR process repeatedly in a raster-type scan of a region of interest. At each scan position, harmonics and/or sidebands are extracted from the focal signal by Fourier analysis. In this manner, a map of the nonlinear response is created. The method provides the means for isolating mechanical damage features by scanning, and directly probing crack complexity at very high resolution. Typically TREND is performed using a laser vibrometer or other non-contact detector to facilitate the ease and speed of measuring many points on the surface of an object and applying reciprocal TR. The limitation of this method is that one can only measure at locations where a detector can be placed. TREND is also time intensive as the entire forward-propagation/time-reversal/back-propagation procedure must be performed at each scan point. The resulting signals require little processing to be analyzed. Figure 9a

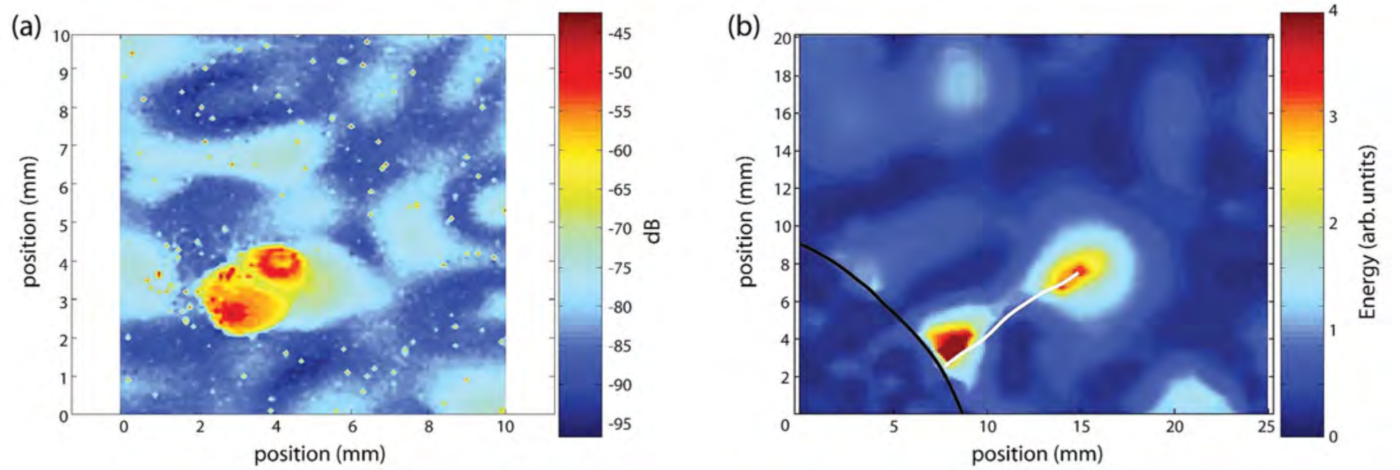

Fig. 9. Nonlinear imaging of cracks in solids. The TREND image (a) shows the extent of the damage region of a highly complex surface crack resulting from a hammer impact onto a glass sample. The difference frequency (sideband) is used to create the scan. The image in (b) illustrates the focusing of elastic energy (again using the difference frequency) onto a fatigue crack. The white line approximates the crack while the black curve is the edge of the sample (a steel bearing cap).

shows a result of TREND in a glass sample with a highly complex surficial crack. The very bright red regions in the figure show the highest nonlinear response, corresponding to the regions of highest damage intensity.

TR and NEWS are also combined in another method potentially not restricted to detecting only surface/near-surface features.[67-69] In this method, the initial source signal(s) propagate to a crack in a sample, where new frequencies are produced (e.g., harmonics/sidebands). The crack acts as a nonlinear scattering source. The combined signals (linear and nonlinear) are detected at a TRM. Before performing TR one filters the signals, leaving only the nonlinear frequency content of the wave. The filtered signals are time reversed and rebroadcast from the TRM. These signals then focus back *only* on the nonlinear scattering source, i.e., the crack. The signals are back-propagated repeatedly as a detector (a laser) scans stepwise in a raster-type manner around the entire sample, or in a region of interest. In this manner, one can isolate the nonlinear scatterer from the background. An advantage of this method is that only a single forward propagation step is required. Figure 9b shows an example of the method, in a steel bearing cap sample that has a narrow but deep, surface breaking crack. The interaction of the crack with the back propagating waves is extremely complex.[69] While in principle it is possible to focus the energy on buried features or surface features without a priori knowledge of their existence/location, it is only possible to experimentally verify this with surface features, to date.[69] The back propagation to find a buried feature has been successfully demonstrated in 2-D and 3-D numerical models.[67]

The last topic we describe is TR applied to earthquake source localization and study of earthquake source complexity. In earthquake source localization, identifying individual arrivals on seismograms is a challenging and time-consuming task, particularly when dealing with the large volume of data currently recorded on a daily basis by the stations which make up the Global Seismic Network (GSN) [http://www.iris.edu/about/GSN/]. The arrivals, comprised of a variety of body waves, both compressional and shear, as well as surface waves, are used to locate a seismic source via sophisticated triangulation methods. TR was suggested as an alternative method for earthquake localization and imaging beginning in the 1980s.[70] Sources of earthquakes are described physically using what is known as *double couple*. A double couple source generates a displacement wavefield that contains complex radiation patterns for the shear, compressional, and surface waves, making the source localization problem additionally challenging.

By applying a TRM, earthquake source locations can be found by taking the recorded seismograms, time-reversing them, and back propagating them through a numerical velocity model. In the example described here, seismograms were recorded worldwide from a well-known earthquake in central California, known as the 2004 Parkfield Earthquake. Figure 10 shows progressive snapshots of the back propagation of the velocity wavefield. Note the energy observed at the focal time located elsewhere is due, primarily, to an insufficient distribution of receivers and is due, secondarily, to mode conversion (for example, conversion of body waves to surface waves).

The accuracy of reconstructing an earthquake source using TR relies upon the accuracy of the numerical modeling. The first attempts of seismic source localization using TR were conducted by McMechan and were limited to simple velocity models[70,72] or restricted to the acoustic case[73] (using only compression waves). With the development of efficient wave-propagation methods which can handle complex geologic models, the TR method is now an alternative to other source location methods as demonstrated numerically by Gajewski.[74] The first global scale TR reconstruction of an earthquake using surface waves was performed by Larmat *et al.* to image the rupture of the 2004 great Sumatra earthquake.[75] This work first began at the Institute of Physics of the Globe and LOA.

Summary

This article presents a brief overview of Time Reversal (TR), an extremely active area of acoustics. We described TR and the mechanics of how it works. We also described benefits and limitations inherent in TR, relative to standard meth-

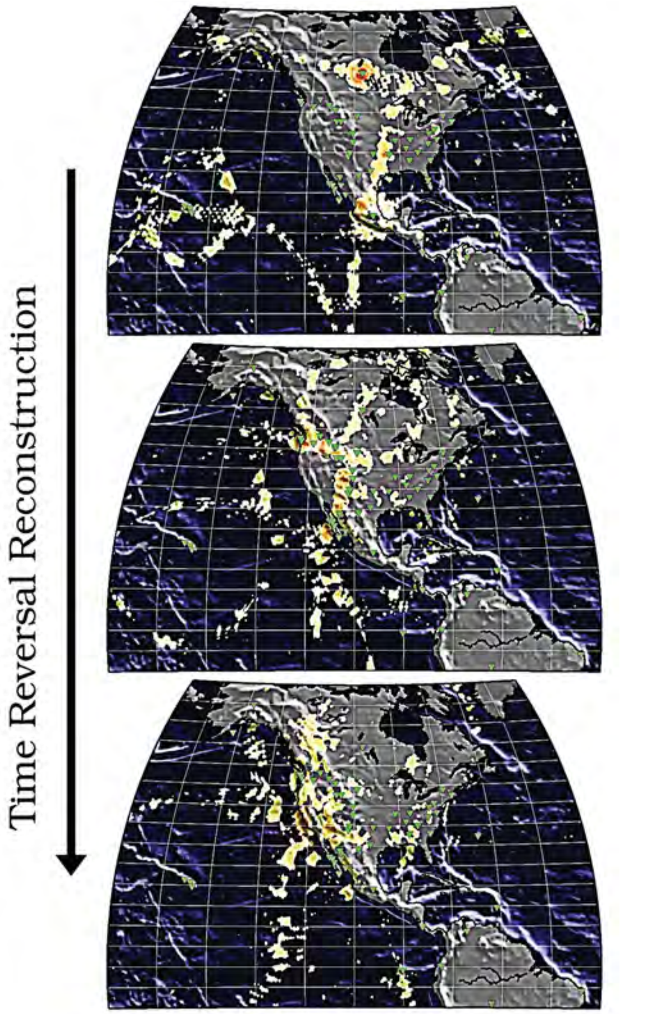

Fig. 10. Images displaying the Time Reversal reconstruction of the 2004 Parkfield, CA earthquake. From top to bottom the images show the progressive reconstruction of the earthquake as the back propagated wave fronts coalesce at the original source location. This figure was made with the help of GMT software.[71]

ods. Linear and nonlinear methods of exploiting TR were outlined, including methods to improve TR imaging by achieving super resolution. Finally, some of the primary application areas of TR were summarized.

TR has proven to be a very robust method of detecting and characterizing sources and scatterers, despite its limitations. The frontiers of the science of TR will likely focus on developing practical methods of beating the diffraction limit to improve the resolution of TR. Additional frontiers of TR will include characterizing and understanding complex source events such as earthquakes and acoustic emission in the laboratory, further exploiting TR to identify and locate cracks in NDE applications especially by applying Nonlinear Elastic Wave Spectroscopy (NEWS), a large number of potential medical applications, as well as many more applications currently being studied and those yet to be discovered.

Acknowledgments

We would like to acknowledge the discussions with Robert Guyer, Jim Ten Cate, Pierre-Yves Le Bas, Donatella Pasqualini, Alexander Sutin, Marco Scalerandi, Antonio S. Gliozzi, Koen E.-A. Van Den Abeele, and Francesco Simonetti.**AT**

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