

DUSAN PETRIC

# TIME-REVERSED ACOUSTICS

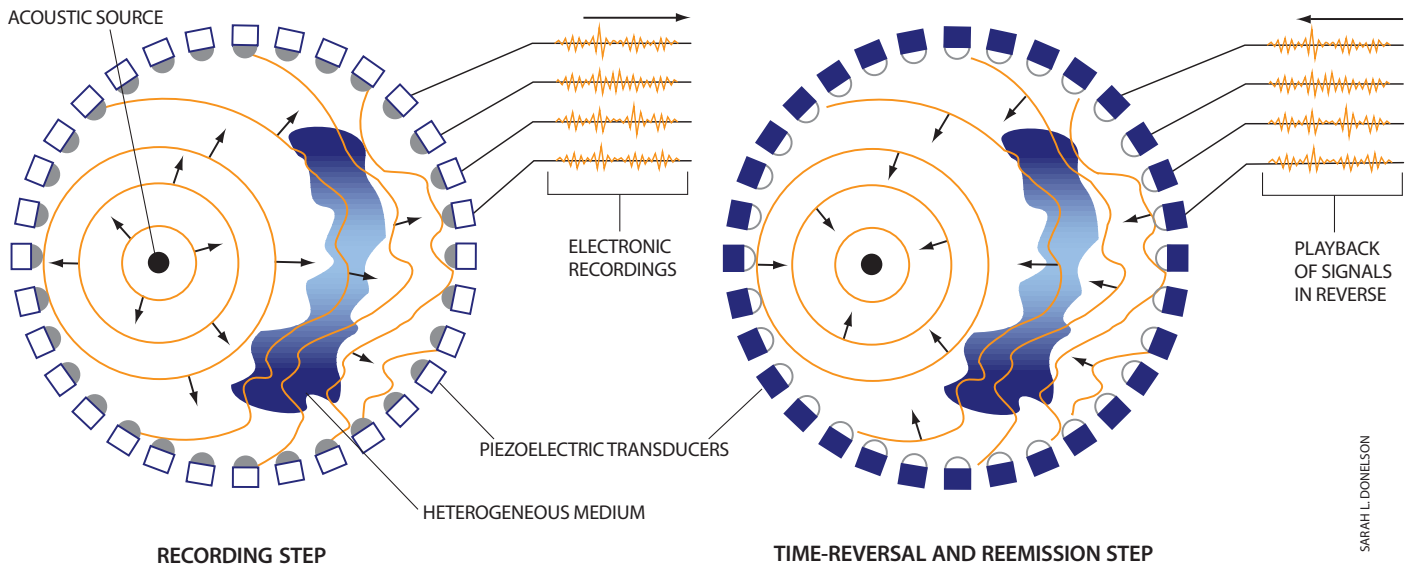
*Arrays of transducers can re-create a sound and send it back to its source as if time had been reversed. The process can be used to destroy kidney stones, detect defects in materials and communicate with submarines*

by Mathias Fink

**I**n a room inside the Waves and Acoustics Laboratory in Paris is an array of microphones and loudspeakers. If you stand in front of this array and speak into it, anything you say comes back at you, but played in reverse. Your “hello” echoes—almost instantaneously—as “olleh.” At first this may seem as ordinary as playing a tape backward, but there is a twist: the sound is projected back exactly toward its source. Instead of spreading throughout the room from

the loudspeakers, the sound of the “olleh” converges onto your mouth, almost as if time itself had been reversed. Indeed, the process is known as time-reversed acoustics, and the array in front of you is acting as a “time-reversal mirror.”

Such mirrors are more than just a novelty item. They have 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.



SARAH L. DONELSON

**ACOUSTIC TIME-REVERSAL MIRROR** operates in two steps. In the first step (*left*) a source emits sound waves (*orange*) that propagate out, perhaps being distorted by inhomogeneities in the medium. Each transducer in the mirror array detects the sound arriving at its location and feeds the signal to a computer.

In the second step (*right*), each transducer plays back its sound signal in reverse in synchrony with the other transducers. The original wave is re-created, but traveling backward, retracing its passage back through the medium, untangling its distortions and refocusing on the original source point.

They can also be used for elegant experiments in pure physics.

back on *exactly* the reversed trajectory, which again would totally alter the final outcome.

The magic of time-reversed acoustics is possible because sound is composed of waves. When you speak you produce vibrations in the air that travel like ripples on a pond spreading out from the point where a stone splashed in. A fundamental property of waves is that when two of them pass through the same location, they reinforce each other if their peaks and troughs correspond, and they tend to cancel each other out if the peaks of one combine with the troughs of the other. This process takes place constantly wherever sound propagates. Echoes reflect back from walls and other obstacles, mixing together different portions of the same wave. Architects of concert halls must pay careful attention to such factors so that their designs result in high-quality sound arriving in the part of the auditorium where the audience sits.

In contrast, wave propagation is linear. That is, a small change in the initial wave results in only a small change in the final wave. Likewise, reproducing the “final” wave, moving in reverse but with the inevitable small inaccuracies, will result in the wave propagating and re-creating the “initial” wave, also moving in reverse and having only relatively minor imperfections.

The other essential property that makes time-reversed acoustics possible is that the underlying physical processes of waves would be unchanged if time were reversed. If you play a movie of waves backward, the waves still obey the correct equations. This is also true of ordinary particle mechanics, which governs objects such as billiard balls, but except in simple cases one cannot “time-reverse” particle mechanics in practice. The problem is the phenomenon of chaos. A small change in a particle’s initial position can result in a large change in its final position.

### Time-Reversal Mirrors

This is how the time-reversal acoustic mirror succeeds in playing back “olleh” onto the mouth of the visitor at the lab in Paris. The final wave is the sound of the “hello” arriving at the array of microphones after traveling outward from the visitor’s mouth. Each microphone detects the acoustic wave (that is, the sound) that arrives at its location and passes the ongoing signal to a computer that stores the data. When the last of the “hello” dies down, the computer reverses each microphone’s signal and plays it back through the corresponding loudspeaker in exact synchrony with the other reversed signals. What emerges from the array of speakers is a close approximation to the final wave, now traveling in reverse, which propagates across the room, retracing the path of the original “hello” back to the speaker’s mouth.

For example, consider a kind of pinball machine where a ball is fired through a fixed array of 100 randomly arranged obstacles. Even in a computer simulation the ball cannot be sent back to retrace its path in reverse: after a dozen or so collisions the ball misses an obstacle that it should have hit (or vice versa), and the subsequent path is utterly different. In a simulation, tiny truncation and round-off errors (which occur when a computer stores numbers and performs arithmetic) are enough to set the time reversal awry. And in a real-life experiment, it would be impossible to start the ball

Each microphone/loudspeaker pair can be combined into a single device, such as a piezoelectric transducer, which converts sound into a voltage when the wave passes, and vibrates like a loudspeaker to produce sound when a voltage signal is applied across it [*see illustration above*].

For time-reversed acoustics to work, the sound wave must propagate without losing too much energy to heat, which consists of the random motion of individual air molecules instead of their collective movement in the sound wave. This

requirement is analogous to having very little friction in a particle-mechanics experiment. For instance, reversing the trajectories of balls on a pool table is impractical because there is no way to make the balls speed up correctly in the time reverse of being slowed by friction and air resistance.

When such energy losses are small enough, the equations governing the waves guarantee that for every burst of sound that diverges from a source, there exists in theory a set of waves that would precisely retrace the path of the sound back to the source. This remains true even if the propagation medium is complicated by objects and variations in density, which reflect, scatter and refract the sound. The reversed waves would follow all these intricate pathways and converge in synchrony at the original source, as if time were going backward. In 1988 my research group built and tested such an acoustic time-reversal mirror with ultrasonic waves in weakly heterogeneous media similar to biological tissues.

You might think that the array of transducers has to have no gaps in it, so that the reversed wave will be re-created without gaps. But because of how waves diffract, gaps as large as half the wavelength will get filled in as the wave propagates. Thus, the transducers can be spaced as far apart as half the smallest wavelength without impairing the quality of the reproduction. For the same reason, however, the waves will refocus to a spot no smaller than half the smallest wavelength. Any details of the source smaller than that are lost.

In the ideal situation, the array of transducers would cover all the walls and even the floor and ceiling of the room, so that the whole final wave could be generated [see illustration on opposite page]. In practice it is often impossible to entirely surround the source with transducers, and the time reversal is usually performed with a limited area of transducers, which we call a time-reversal mirror (TRM). Of course, some information is lost, and as the aperture of the mirror gets smaller, the size of the focal spot gets larger. This is exactly analogous to the case in optics, where a telescope with a large mirror can achieve finer resolution than one with a small mirror. In fact, an analogue of the TRM has been studied for about 20 years in optics: phase-conjugated mirrors. Such mirrors exhibit retroreflectance—the light

reflects back toward the source, wherever it is in relation to the mirror. These phase-conjugated mirrors, however, do not produce the time reverse of a varying light signal.

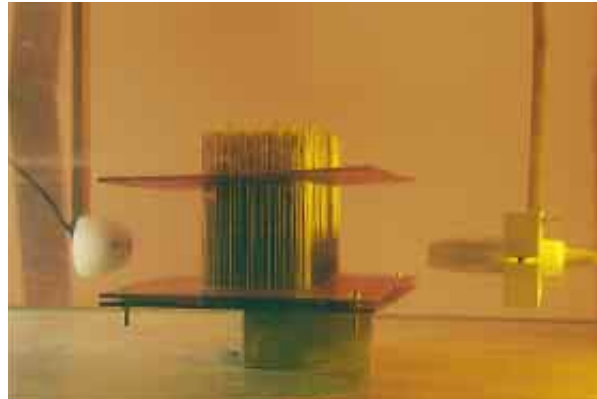
### Chaotic Pinball

In 1994 my students Arnaud Derode and Philippe Roux and I demonstrated ultrasonic time reversal through a medium analogous to the chaotic pinball machine mentioned earlier. The results were surprising. The obstacles were made of a random set of 2,000 parallel steel rods immersed in a water tank [see illustration at left]. The wave started from a small transducer as a pulse lasting one microsecond ( $1\ \mu\text{s}$ ) and propagated through this “forest” of rods to a line of 96 piezoelectric transducers. This array detected an initial wavefront that was the part of the sound that threaded its way directly through the forest, followed by a long chaotic wave lasting up to  $200\ \mu\text{s}$ . The chaotic wave corresponded to the portions of the initial pulse scattered along all possible paths between the rods.

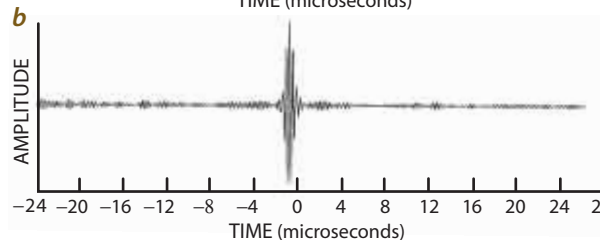
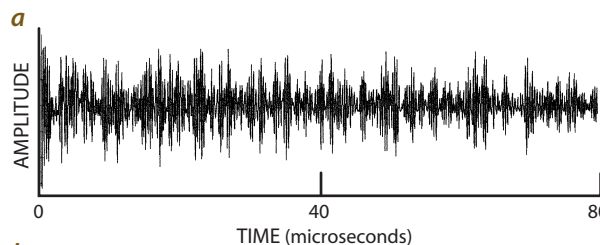
In the second step of the experiment, we time-reversed these signals, and a hydrophone measured the wave arriving at the source location. Even though the array played back a  $200\text{-}\mu\text{s}$  signal through the chaotically scattering forest, at the source location a pulse of about  $1\ \mu\text{s}$  was regenerated. We also carried out both steps of the experiment in the absence of the rods. Remarkably, the time-reversed beam was focused to a spot six times smaller *with* the scattering rods than without them. This paradoxical result is explained by considering that the multiple reflections in the forest redirect toward the mirror parts of the initial wave that would otherwise

miss the transducer array. After the time-reversal operation, the whole multiple-scattering medium acts somewhat like a focusing lens, making the mirror appear to have an aperture six times larger and thus improving its resolution sixfold.

The experiment also showed that the time-reversal process is surprisingly stable. The recorded signals were sampled with analog-to-digital converters that introduced quantization errors. Moreover, if the array and the rods are moved a small fraction of the wavelength (0.5 millimeter, or 0.02 inch) after doing the forward step, the time reversal

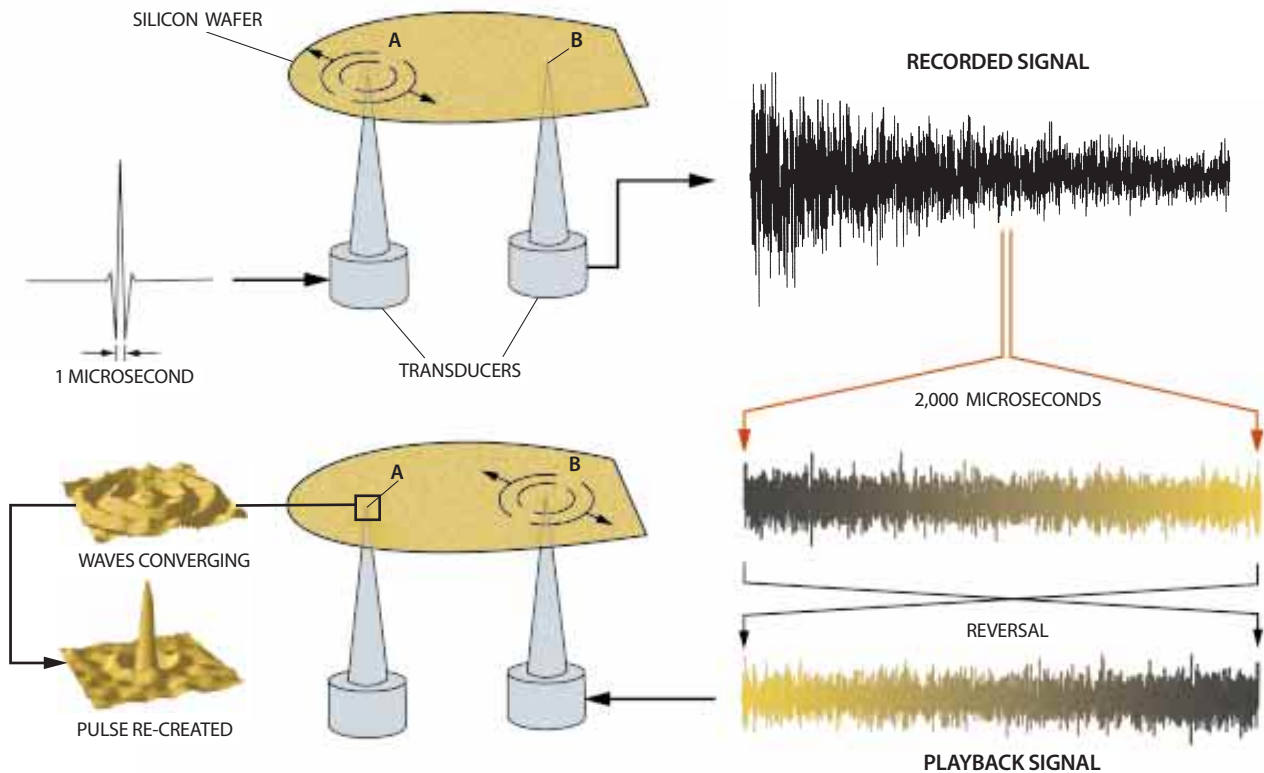


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SARAH L. DONELSON

**ACOUSTIC CHAOTIC PINBALL** occurs when an underwater ultrasonic pulse emitted by the transducer (at left in photograph) ricochets among 2,000 randomly placed steel rods before reaching the 96-element time-reversing mirror at right. Each element of the array receives a chaotic-seeming sound signal (a portion of one is shown in *a*) lasting much longer than the original one-microsecond pulse. When the mirror plays back the chaotic signals, reversed and in synchrony, they ricochet back through the maze of rods and combine to re-create a well-defined pulse (*b*) at the transducer.



SARAH L. DONELSON

**SINGLE TRANSDUCER** can time-reverse a wave in an enclosed “cavity.” A source transducer emits a pulse at location A on a small silicon wafer (*top*). A transducer at location B records chaotic reverberations of the pulse reflected off the wafer edges hundreds of

times. The transducer at B plays back a short segment of that signal in reverse (*bottom*). After many reflections, these recombine to re-create the short pulse focused again at location A, as was revealed by imaging the waves on the wafer near A (*bottom left*).

still works—in absolute contrast to what would happen in a particle experiment. Each particle follows a well-defined trajectory, whereas waves travel along all possible trajectories, visiting all the scattering objects in all possible combinations. A small error in the initial velocity or position makes the particle miss an obstacle and utterly change its trajectory thereafter. The wave amplitude, however, is much more stable, because it results from the interference of all possible trajectories. In chaotic environments, wave physics is much more robust than particle physics, and the focusing properties of TRMs are improved.

### Time Reversal on a Silicon Wafer

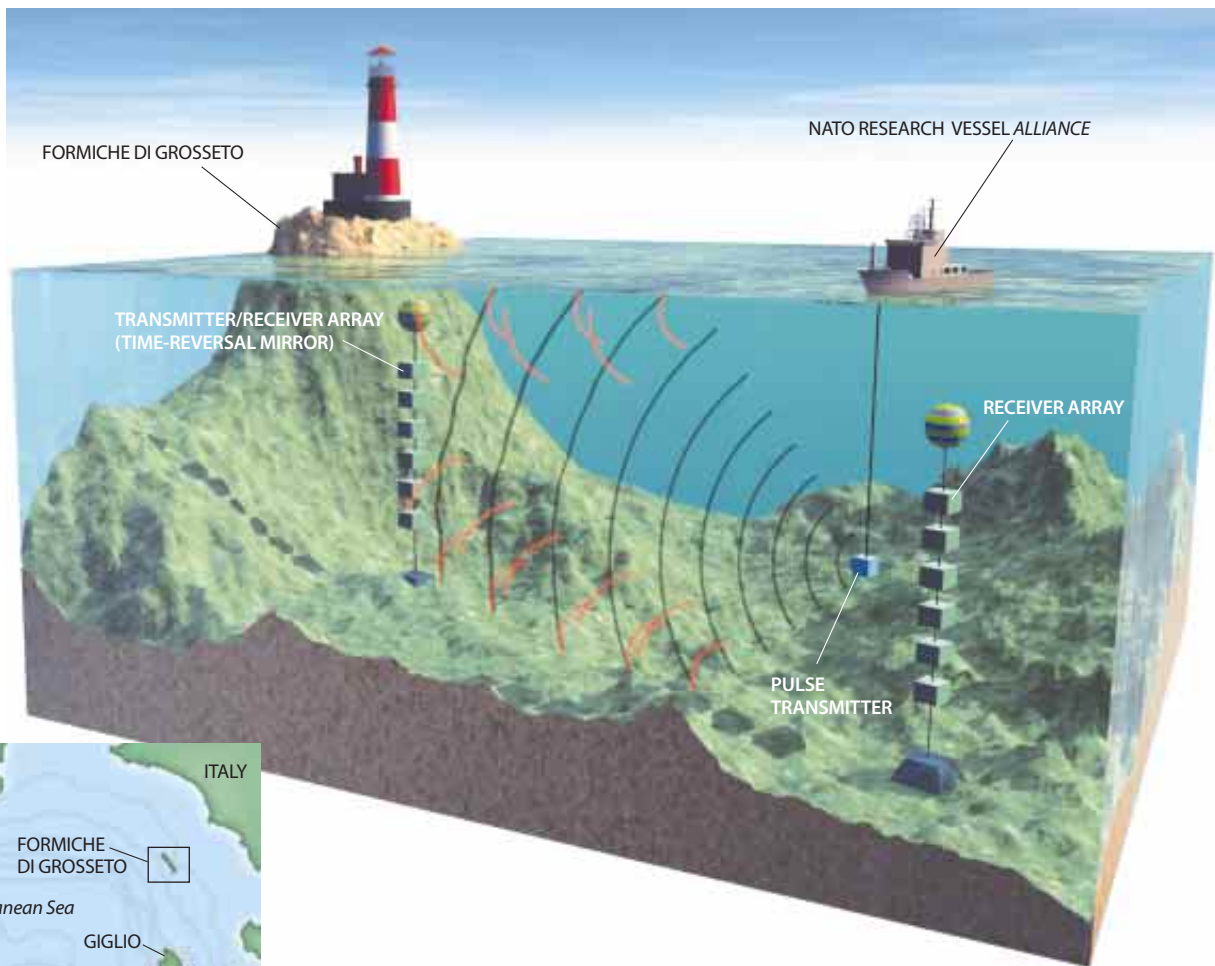
With these ideas of focusing and robustness in mind, we wondered if the number of time-reversal transducers could be decreased to one. How can the information about a source be redirected toward a single time-reversal transducer? We decided to try enclosing the source and the transducer inside perfectly reflective walls, creating a cavity with a peculiar property called ergodicity. A frictionless billiard table shaped with curved ends like a stadium would be ergodic: a ball hit in almost any direction would eventually pass every location on the tabletop. Similarly, in an ergodic cavity all the sound rays emitted by a source will pass by the transducer if we wait long enough.

Three years ago my student Carsten Draeger and I demonstrated one-transducer time reversal using elastic waves propagating on the surface of a silicon wafer [see illustration above]. The source transducer at point A trans-

mitted a circular surface wave lasting 1  $\mu$ s. The time-reversal transducer at point B recorded a chaotic signal that continued for more than 50 milliseconds (50,000 times the initial pulse duration), corresponding to some 100 reflections of the initial pulse from the wafer’s edge. Then a two-millisecond portion of the signal was time-reversed and reemitted by the transducer at point B. The elastic waves induced small vertical displacements of the silicon surface, which we observed by scanning the surface around point A with an optical interferometer.

A very impressive re-creation of the original pulse occurred at point A, focused within a radius of about half the wave’s wavelength with a duration on the order of a microsecond. Using reflections at the boundaries, the time-reversed wave field converged toward the origin from all directions to produce a circular spot. The two-millisecond time-reversed waveform (corresponding to nearly 2,000 complicated oscillations) is the code needed to focus exactly on point A from point B. One can imagine cryptography based on this principle, using signals from point B to generate pulses at different points in the cavity.

TRMs can also compensate for the multipath propagation that is common in ocean acoustics and that limits the capacity of underwater communications systems. The problem occurs in shallow water where sound travels as if in a waveguide, bouncing off the seabed and the ocean surface, so that a single transmitted pulse generates multiple copies of itself at the receiver, much as in the ergodic cavity. The boundaries of a sea channel are not ergodic, however, so a TRM must contain a significant number of transducers. Re-

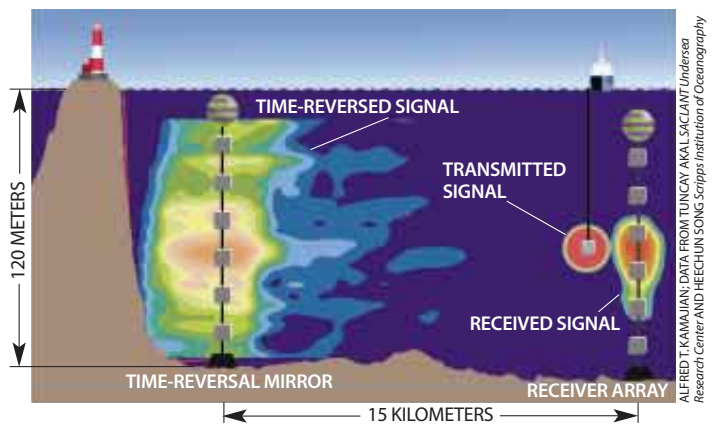


ALFRED T. KAWAJIAN; LAURIE GRACE (inset)

UNDERWATER COMMUNICATIONS can be enhanced by using time-reversed acoustics to focus a signal. This technique was demonstrated in water 120 meters deep near the island of Elba off the coast of Italy. A sound pulse was sent from the target location and recorded up to 30 kilometers away by an array of transponders, distorted by refraction and multiple reflections (red) from the surface and the seabed. The time-reversed signal sent by the array was well focused at the target location.

cently researchers from the Scripps Institution of Oceanography in La Jolla, Calif., and the SACLANT Undersea Research Center in La Spezia, Italy, built and tested a 20-element TRM in the Mediterranean Sea off the coast of Italy [see illustration above]. Led by Tuncay Akal, William Hodgkiss and William A. Kuperman, they showed in water about 120 meters deep that their mirror could focus sound waves up to 30 kilometers away. In a result similar to the sixfold enhancement in the scattering rod experiment, the time-reversed beam was focused onto a much smaller spot than the one observed with standard beam-forming sonar. Roux and I have conducted similar studies using ultrasonic waveguides, in which multiple reflections occur. The focusing and the strong time recompression of the time-reversed wave let us create a very high power acoustic pulse that can be used for shock-wave generation.

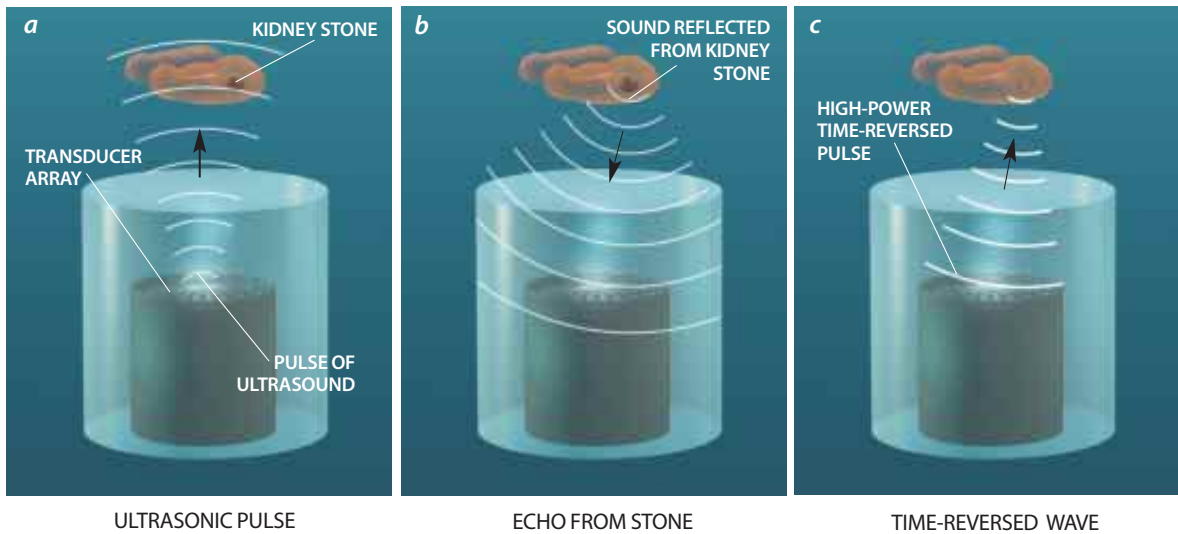
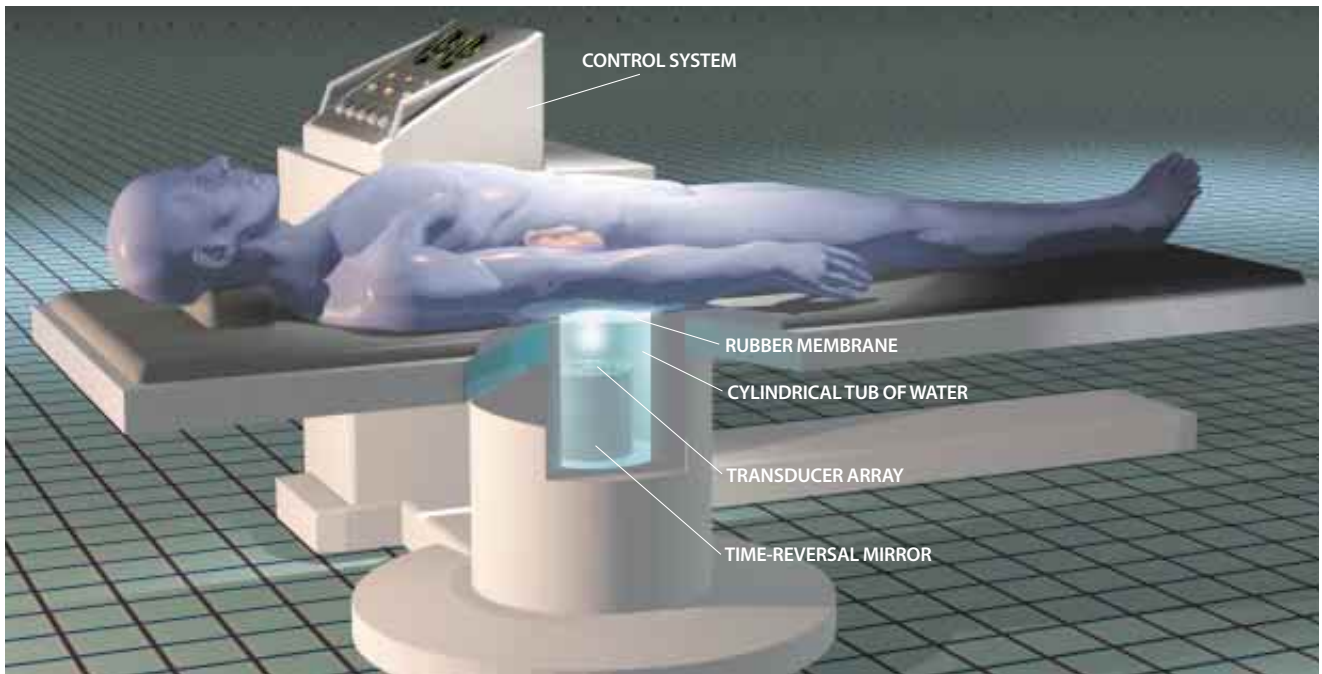
A particularly rich field for applications of TRMs is pulse-echo detection, in which one sends out a short pulse and de-



ALFRED T. KAWAJIAN; DATA FROM TUNCAY AKAL, SACLANT Undersea Research Center AND HEECHUN SONG, Scripps Institution of Oceanography

RESULTS from an underwater experimental run. Color contours indicate intensity of sound. The transmitted signal pulse (red circle) is greatly distorted at the time-reversal mirror, but when the time-reversed signal is played back (at left) it reproduces a focused pulse at the receiver array (at right).

fects the echoes from one or more targets. The possible scenarios are diverse, ranging from medical imaging to nondestructive evaluation (inspecting materials such as industrial components for cracks and defects) to underwater acoustics (searching for mines, submarines or buried objects). The common element needed for high-quality detection is a sharp acoustic beam, and in each application the intervening medium makes it difficult to achieve this at the target location. The problem is perhaps most evident in the case of



**KIDNEY STONES** can be targeted and broken up with ultrasound by using the self-focusing property of a time-reversal mirror. An ultrasonic pulse emitted by one part of the array (a) produces a distorted echo from the stone (b). A powerful time-reverse

of this echo passes through intervening tissues and organs, focuses back on the stone (c) and breaks it up. Iterating the procedure improves the focus and allows real-time tracking as the stone moves because of the patient's breathing.

medical imaging, where one wishes to send the ultrasound through fat, bone and muscle to targets such as tumors or kidney stones. Pulse-echo detection with a TRM can circumvent this problem.

### Pulse-Echo Detection

First, one part of the array sends a brief pulse out through the distorting medium to illuminate the region of interest. Next, the wave that is reflected back to the array by a target is recorded, time-reversed and reemitted. The time-reversal process ensures that this reversed wave focuses on the target despite all the distortions of the medium.

When the region contains only one target, this self-focusing technique is highly effective. If there are several targets,

the problem is more complicated, but a single target can be selected by repeating the procedure. Consider the simplest multitarget case, in which the medium contains two targets, one more reflective than the other. The echoes produced by the initial pulse will have a somewhat stronger component from the brighter target than from the weaker one. Therefore, the first time-reversed signal will focus a wave on each target but with a more powerful wave on the brighter target. The echoes from these waves will have an even greater bias toward the brighter target, and after a few more iterations one will have a signal that focuses primarily on that target. More complex techniques let one select the weaker reflectors.

Among the medical applications of pulse-echo TRM, the closest to fruition is the destruction of stones in kidneys and

gallbladders [see illustration on opposite page]. Conventional ultrasonic or x-ray imaging can accurately locate such stones, but it is difficult to focus ultrasonic waves through the surrounding tissues to destroy the stones. Also, the movement of stones during breathing is hard to track. Only an estimated 30 percent of the shots reach the stone, and it takes several thousand shots to destroy one. Ultrasonic time-reversal techniques can solve these problems.

After several iterations of the pulse-echo time-reversal process, the ultrasonic beam focuses tightly on the most reflective area of a stone. Intermittent amplified pulses can then be applied to shatter the stone. This process can be repeated to track the stone in real time as it moves. Jean-Louis Thomas, François Wu and I have developed a TRM 20 centimeters in diameter for this application. The tracking procedure and in vitro stone destruction have been demonstrated in two French hospitals.

Another promising application is ultrasonic medical hyperthermia, in which high-intensity ultrasound heats up tissues. Temperatures above 60 degrees Celsius (140 degrees Fahrenheit) can destroy tissues within seconds. Devices that use conventional techniques to focus ultrasound are already on the market but only for static tissues, such as a cancerous prostate gland. Abdominal and cardiac applications are limited by the motions of breathing and heartbeat. At the University of Michigan, Emad Ebbini and his group are developing self-focusing arrays to solve this problem. My group is working on brain hyperthermia. The challenge is to focus through the skull, which severely refracts and scatters the ultrasonic beam. The porosity of the skull produces a strong dissipation—absorbing energy from the wave—and thus breaks the time-reversal symmetry of the wave equation. We have developed a new focusing technique that adds a correction of these dissipative effects to standard time-reversal. It allows us to send an ultrasonic beam through the skull and focus it on a 1.5-millimeter spot [see illustration above].

Another important application of TRMs is flaw detection in solids by nondestructive evaluation. Small defects are

hard to find in an object with a complicated geometry or one made of heterogeneous or anisotropic material. Usually the sample and the ultrasonic transducers are immersed in water, but refraction can alter the beams at the water-solid interface, making it even harder to detect small defects. Furthermore, the ultrasound can produce a variety of wave polarizations and types in the solid. We have demonstrated that self-focusing techniques using TRMs can automatically compensate for these problems. In a joint program with the

French National Society for the Study and Construction of Aircraft Engines, we have developed a 128-element time-reversed mirror to detect low-contrast defects in the titanium alloys used in jet engines. Titanium has a highly heterogeneous microstructure that produces a lot of scattering noise, which can hide the echo of a defect. We have shown that the iterative pulse-echo method can detect defects as small as 0.4 millimeter in 250-millimeter-diameter titanium billets and offers a better signal-to-noise ratio than the alternative techniques do.

The process of acoustic time-reversal is now readily achievable in the laboratory, and the challenge is to perfect its application in real-life clinical and industrial settings. Reversing a person's "hello" is a bit like a party trick, but the same principles that focus the "olleh" on the speaker's mouth can be used, with a little more computer processing, to generate acoustic holograms in the room. For example, the transducers can be programmed to focus the sound "hello" near one person and "bonjour" near another, simultaneously.

Time-reversal techniques may also be extended to types of waves other than sound waves. Some researchers in the radar community are exploring their possible application to pulsed radar, using electromagnetic waves in the microwave range. Another type of wave occurs in quantum mechanics: the quantum wavefunctions that describe all matter. Indeed, a type of retroreflection can occur when an electron wavefunction hits the boundary between a normal conductor and a superconductor. One can only speculate on what kinds of tricks would be possible if time reversal were applied to the waves of quantum mechanics. SA



**POROUS BONE IN THE SKULL** presents an energy-sapping challenge to focusing ultrasound waves on a brain tumor to heat and destroy it. A time-reversal mirror with a modified playback algorithm can nonetheless focus ultrasound through skull bone onto a small target.

### The Author

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### Further Reading

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