

TIME REVERSED ACOUSTICS

The irreversibility of time is a topic generally associated with fundamental physics. Imaging techniques, on the other hand, are usually related to engineering sciences. Remarkably, however, these two domains can be fruitfully connected to yield many applications in medicine, undersea communications, hydrodynamics and material analysis, as well as elegant experiments in pure physics.

The objective is to exploit time reversal invariance, a fundamental symmetry that holds everywhere in fundamental particle physics except in an esoteric corner of the weak nuclear interactions, to create a variety of useful instruments. What one wants for these purposes is *macroscopic* time-reversal invariance, a symmetry generally thwarted by thermodynamics. Happily this symmetry does hold in acoustic-wave phenomena, to the extent that everything is adiabatic.

Although the equations of classical mechanics are time-reversal invariant on the microscopic scale, it is difficult to test this invariance in a complex system of particles. Such a test requires a time-reversal mirror. In the world of images, we have such mirrors: one simply makes a movie and then runs it backwards. In the real world, the reversal of the motion in a complex system can be ascribed to a change in initial conditions. If we want to reconstruct an exploded block from the various scattered pieces, a time-reversal mirror would be a device that precisely reverses the velocity of each debris particle as it crosses a closed surface surrounding the initial block. But before being sent back, each particle must be held for an appropriate delay time: To reconstitute the block, one has to send back first the slowest pieces, which had arrived last. Such a device, however, would rely on its ability to resolve the details of every particle's dynamics with "adequate" precision. But the extreme sensitivity to initial conditions that lies at the heart of chaotic phenomena in classical mechanics renders any such particulate scheme impossible.

Waves are easier

Classical wave physics is more amenable. The amount of information needed to describe a wave field without am-

Nowadays we can intercept a spreading sound wave, time-reverse it and send it back to the source. That should greatly enhance our ability to locate gallstones and submarines.

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biguity is limited; it depends on the shortest wavelength of the field. The smallest scale of the wave-field fluctuations is on the order of the wavelength in question. That's essentially why one can do time-reversal experiments with wave fields, given adequate reversible-sensor technology. Instead of measuring the velocities of

discrete particles and applying the individual forces needed to reverse them, one measures only the wave field and radiates an appropriately reversed wave. One can realize such conditions in acoustics by using reversible acoustic retina arrays of piezoelectric transducers that combine the functions of microphone and loudspeaker. Within the range of sonic or ultrasonic frequencies, where adiabatic processes dominate, the acoustic pressure is described by a scalar field p in a heterogeneous propagation medium of density $\rho(\mathbf{r})$ and compressibility $\kappa(\mathbf{r})$, satisfying the equation

$$\kappa(\mathbf{r}) \frac{\partial^2 p}{\partial t^2} = \nabla^2 (p / \rho(\mathbf{r}))$$

This equation is time-reversal invariant, because it contains only second-order time derivatives. This means that for every burst of sound $p(\mathbf{r}, t)$ spreading from a source and later possibly reflected, refracted or scattered at various locations in the medium, there exists, in theory, an extended waveform $p(\mathbf{r}, -t)$ that precisely retraces all of these complex paths and converges in synchrony at the original source, as if time were going backwards.

Just as in the idealized experiment I described above, this time-reversed wave can be obtained by measuring the field $p(\mathbf{r}_s, t)$ on a closed surface S surrounding the experimental volume. This surface would be covered with transducers that sense the pressure field over a time interval T long enough for the wave to vanish. Once this field has been recorded, the surface remits the time-reversed signal $p(\mathbf{r}_s, T - t)$. The resultant field emerging from the surface converges back toward the initial source.

David Dowling and Darrell Jackson in the US and Didier Cassereau in our Paris laboratory have theoretically studied the conditions necessary to ensure this convergence.¹ They show that, in addition to time-reversal invariance, one also needs spatial reciprocity. An acoustic phenomenon is said to satisfy spatial reciprocity if interchanging the positions of source and receiver does not alter the resulting field. One needs spatial reciprocity if one wants to construct the exact time-reversed wave in the whole volume by means of a two-dimensional time-reversal operation. Mathematically, spatial reciprocity is

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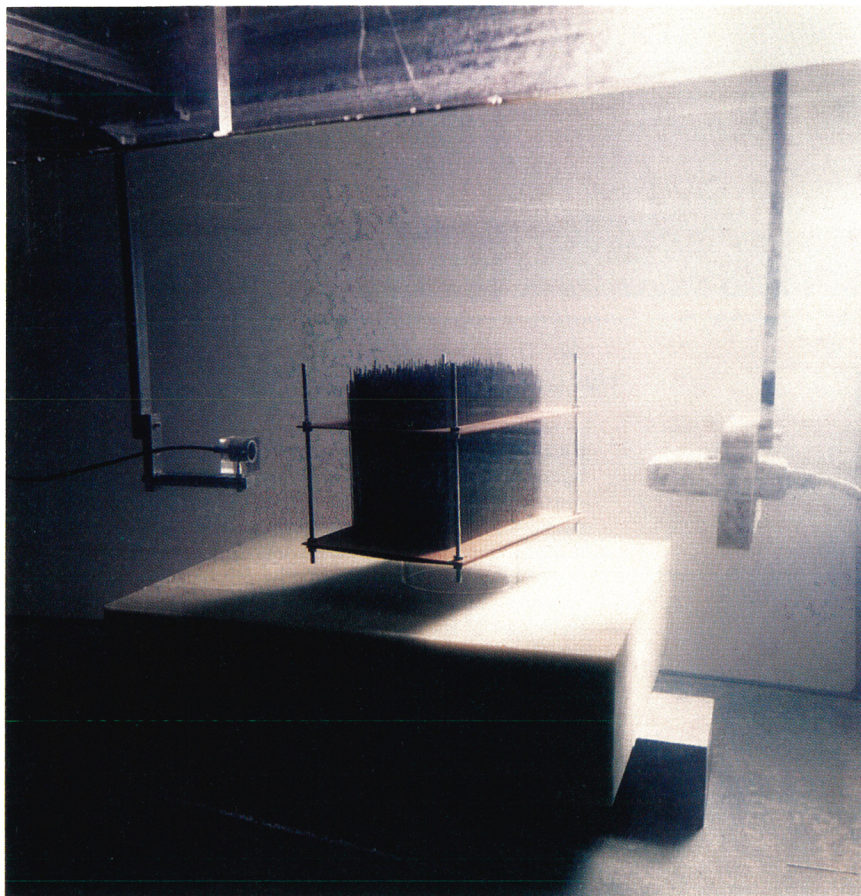


FIGURE 1. MULTIPLE SCATTERING of an ultrasonic pulse from the pointlike transducer (left) by a forest of steel rods (center) does not prevent the 96-element mirror array (right) from sending a time-reversed wave back through the forest to focus narrowly on the source. The experiment⁵ was done in a water tank in our Paris laboratory.

satisfied as long as the spatial part of the wave operator is self-adjoint.

If the source is pointlike, we know how to generate a wave that propagates through any inhomogeneous medium and focuses back on the source. But details of a source smaller than the shortest wavelength are lost and one comes up against the classical diffraction limit. Evanescent waves containing information on details smaller than the wavelengths involved cannot be sensed by the time-reversing acoustical cavity. If a wideband pulse is emitted by an ideal point source, the returning field refocuses on it with a spot whose dimensions are on the order of the smallest wavelength.

For the same reasons, the transducers covering the cavity surface need not be uniformly distributed over the whole surface. Because the smallest details are filtered out by diffraction, the surface can be adequately sampled by a finite number of transducers distributed on a two-dimensional array with spacing equal to half the smallest wavelength. That brings in enough information to reconstruct the source.

In practice, a time-reversing cavity is difficult to realize. The time-reversal operation is usually performed on a limited angular area, called a time-reversal mirror. Each transducer has its own electronics: detection amplifier, analog-to-digital converter, digital memory and a programmable generator capable of synthesizing the temporally inverted signal stored in the memory.²

The basic principle of time-reversed acoustics is similar to that of phase-conjugated optics, which has been extensively studied in recent years.³ Time reversal of $p(\mathbf{r}, t)$ is equivalent, for each of the spectral components $P(\mathbf{r}, \omega)$, to complex conjugation. Here $P(\mathbf{r}, \omega)$ is the tem-

poral Fourier transform of $p(\mathbf{r}, t)$. For a single-frequency signal, time reversal is equivalent to complex conjugation of the amplitude.

For a broadband waveform, however, optical phase conjugated mirrors cannot produce true time reversal. They are limited by the time responses of optical detectors, which are very long compared to the period of optical waves. An optical phase conjugated mirror must exploit nonlinear effects to conjugate monochromatic signals. For narrow-band waveforms, these nonlinear processes are used to conjugate the complex envelope of the waveform. That is not equivalent to a true time reversal, except in the limit of zero bandwidth.

Optical phase conjugated mirrors exhibit retro-reflectance: Light from a localized source is directed back to the source. In microwave radar, "retrodirective arrays," also based on nonlinear mixing, exhibit similar behavior.⁴ But for large bandwidth waveforms, these devices cannot reconstruct the exact time-reversed history of short pulses.

Multiple scattering

Three years ago, my students Arnaud Derode, Phillipe Roux and I carried out the first experimental demonstration of the reversal of a multiply scattered acoustic wave by means of a time-reversal mirror.⁵ The experiment was carried out in a water tank. The wave, starting as a pulse of 3 MHz ultrasound from a small source, propagated through a scattering obstacle of about two thousand thin steel scattering rods to a linear array of 96 piezoelectric transducers. (See figure 1.) Each transducer recorded its part of the incident wave front and then time-reversed and retransmitted the signal, thus creating a wave that propagated back through the scatterers to the source.

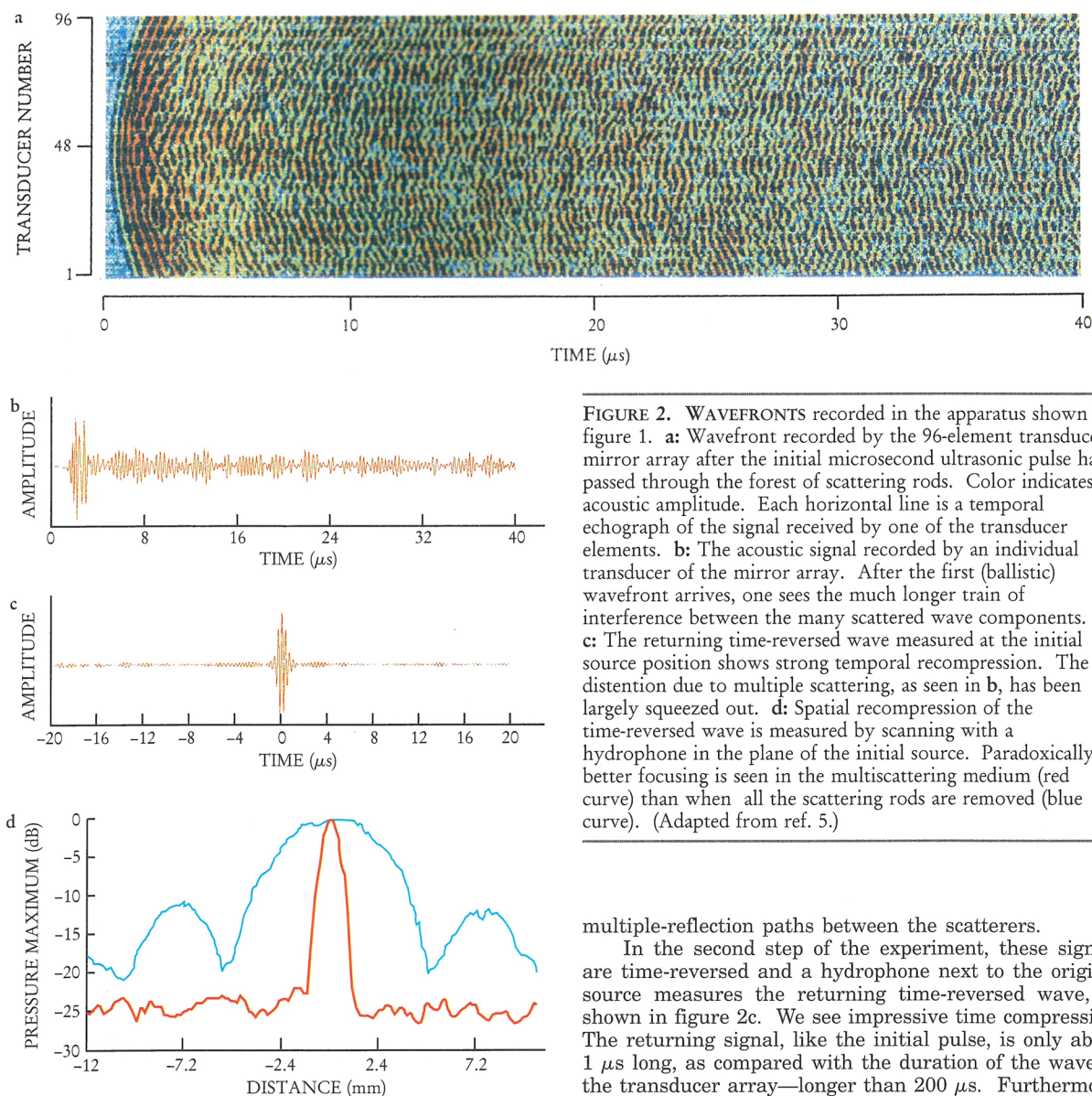


FIGURE 2. WAVEFRONTS recorded in the apparatus shown in figure 1. **a:** Wavefront recorded by the 96-element transducer mirror array after the initial microsecond ultrasonic pulse has passed through the forest of scattering rods. Color indicates acoustic amplitude. Each horizontal line is a temporal echograph of the signal received by one of the transducer elements. **b:** The acoustic signal recorded by an individual transducer of the mirror array. After the first (ballistic) wavefront arrives, one sees the much longer train of interference between the many scattered wave components. **c:** The returning time-reversed wave measured at the initial source position shows strong temporal recompression. The distortion due to multiple scattering, as seen in **b**, has been largely squeezed out. **d:** Spatial recompression of the time-reversed wave is measured by scanning with a hydrophone in the plane of the initial source. Paradoxically, better focusing is seen in the multiscattering medium (red curve) than when all the scattering rods are removed (blue curve). (Adapted from ref. 5.)

At 3 Mhz the acoustic wavelength in water is 0.5 mm, and the microsecond duration of the initial pulse corresponds to only three oscillations. Each transducer element was 0.35 mm across. The two thousand 0.8 mm diameter scattering rods were randomly arrayed, parallel to each other and perpendicular to the acoustic path, with a mean spacing of 2 mm. They scattered the initially coherent wavefront from the source as it passed through them.

Figures 2a and 2b show the multiply scattered waveforms recorded by the transducer array after the wave had traversed the forest of rods. After the arrival of a first wavefront (the ballistic wave), the trace in figure 2b shows a very long incoherent wave, which can continue for several hundred microseconds. This extended aftermath comes, of course, from the multiple scattering of the acoustic wave off the many rods between the source and the receiver. It sums contributions from all the possible

multiple-reflection paths between the scatterers.

In the second step of the experiment, these signals are time-reversed and a hydrophone next to the original source measures the returning time-reversed wave, as shown in figure 2c. We see impressive time compression: The returning signal, like the initial pulse, is only about 1 μ s long, as compared with the duration of the wave at the transducer array—longer than 200 μ s. Furthermore, the time-reversed beam is focused on the source as a spot six times thinner than what one observes in a similar experiment without the scattering rods. (See figure 2d.)

This somewhat paradoxical result, that multiple-scattering media are better at refocusing than are homogeneous media, warrants some explanation. In a homogeneous medium, the resolution depends on the angular aperture of the transducer array as seen from the focal point. But as seen through a medium full of scattering obstacles, the effective focusing aperture is widened by the longer multiple-scattering path lengths. After the time-reversal operation, the whole multiple-scattering medium behaves, in effect, as a coherent focusing source whose large angular aperture enhances the resolution at the final focus.

This experiment demonstrated extraordinary *insensitivity* to initial conditions. The recorded signals were sampled with 8-bit analog-to-digital converters with a sampling rate of 20 MHz. That was enough information to ensure excellent back-propagation through several thousand random scatterers. Contrast this result with classical particle mechanics, where it's practically impossible to achieve reasonable time-reversal with only a few hundred

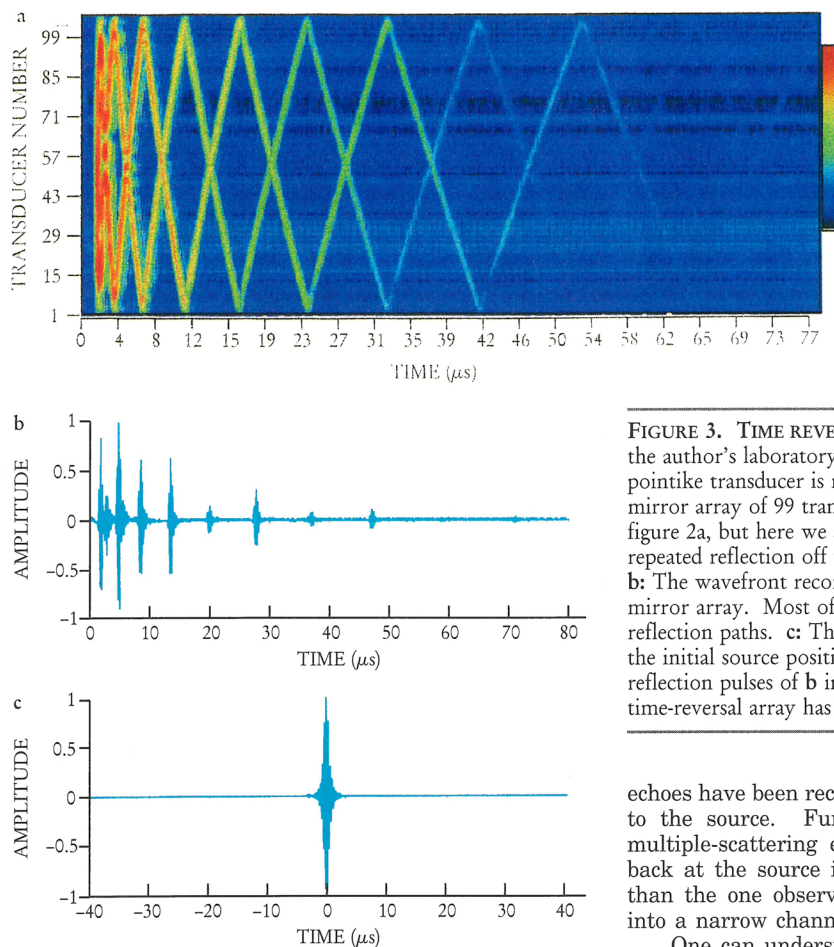


FIGURE 3. TIME REVERSAL IN A WAVEGUIDE CHANNEL in the author's laboratory. **a:** The wavefront transmitted by a pointlike transducer is recorded 80 cm downstream by a mirror array of 99 transducers. The format is the same as in figure 2a, but here we see a set of ten wavefronts due to repeated reflection off the channel's interface boundaries. **b:** The wavefront recorded by an individual transducer of the mirror array. Most of the wave energy is in the multiple-reflection paths. **c:** The time-reversed wave measured back at the initial source position. The compression of the multiple reflection pulses of **b** into a single pulse shows that the time-reversal array has compensated for the multipath effects.

particles, even in a computer simulations. For these purposes, wave physics is much more robust.

Waveguides

Another application of time reversal in acoustics involves compensation for multipath propagation in waveguides or cavities. For example, time-reversal mirrors can compensate for the multipath propagation that limits the capacity of underwater acoustic communication in the ocean. The problem arises because acoustic transmissions in shallow water bounce off the ocean surface and floor, so that a transmitted pulse gives rise to multiple copies arriving at the receiver.

A simple experiment carried out in an ultrasonic waveguide by Phillippe Roux demonstrates the effectiveness of the time-reversal processing in dealing with this problem. He put a pointlike source in a water channel bounded by two parallel interfaces—one with a steel plate, the other with the air. Eighty centimeters downstream of the source, he placed a 99-element time-reversal array in the waveguide. Figures 3a and 3b show the transmitted field recorded by the array after the propagation of a pulse through the channel. After the arrival of the first wavefront, corresponding to the direct path, we see a set of later signals due to multiple reflections of the incident wave off the two interfaces.

Figure 3c shows the wave field measured back at the source after time reversal of the first 100 μsec of the signal received by the downstream array. Once again, the time recompression is impressive: The first ten multipath

echoes have been recombined into a single pulse returning to the source. Furthermore, as was the case in the multiple-scattering experiment, the time-reversed beam back at the source is focused onto a much smaller spot than the one observed in water that is not constrained into a narrow channel.

One can understand this better focusing in terms of the theory of images in a medium bounded by two mirrors. For an observer at the source point, the 40 mm high time-reversal mirror appears to be accompanied by an infinite set of virtual images related to multipath propagation. For the first ten arrivals, therefore, the effective aperture of the mirror array is ten times larger than the real aperture. William Kuperman and colleagues at the University of California, San Diego, have recently done an acoustics experiment in a channel extending 120 m below the surface of the ocean. At a sound frequency of 500 Hz (roughly musical B above middle C) they used a 24-element time-reversal mirror to accomplish focusing and multipath compensation at a distance of 7 km. Antares Parvulescu performed similar experiments in the sea more than 30 years ago, with only one transducer working in a time-reversed mode.⁶ His apparatus had no computer and, in any case, a one-element time-reversal mirror is not efficient. Parvulescu did see time compression, but the side lobes were high and focusing was rather poor.

Concluding our discussion of time reversal with waveguides, I point out that both temporal and spatial compression of the time-reversed wave field can be used to create very high-power acoustic pulses at the source location from low-power excitations. Our group is now developing shock-wave generators that exploit this kind of compression.

Another exciting domain of applications is called acoustic room dereverberation. My colleague Bruno Sallé, among others,⁷ has obtained promising results in this area. Sallé's recent work at our university employed a set of 64 loudspeakers and microphones in a strongly reverberating room. To produce a clear acoustic message $s(t)$ at one

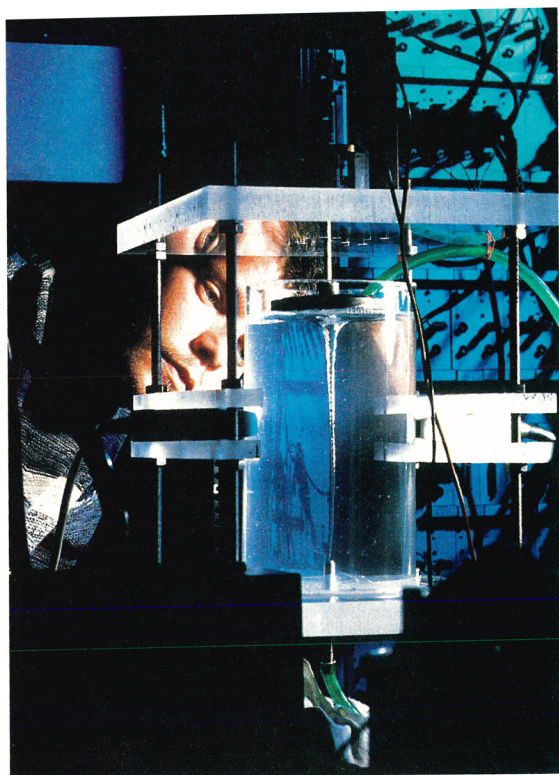


FIGURE 4. VORTICITY induced by the rapid rotation of a disk atop a water-filled Plexiglas cylinder in the author's laboratory is measured by two linear, horizontal arrays of acoustic time-reversal mirror elements, seen here abutting the left and right sides of the cylinder. The long, thin vortex of spinning liquid, visible along the cylinder axis, is anchored by a drain in the bottom center.

location $\mathbf{r}_s$ in the room, he first measured the Green's function $G(\mathbf{r}_i, \mathbf{r}_s, t)$ that connects a source signal at $\mathbf{r}_s$ in this room to the signal perceived by each of the 64 sensors located at the positions $\mathbf{r}_i$. Because the wave equation is linear, each loudspeaker i is driven by an electrical signal $s_i(t) \otimes G(\mathbf{r}_i, \mathbf{r}_s, -t)$, where $\otimes$ indicates a convolution product.

Alternatively, one could send different messages simultaneously from the same loudspeaker to different locations in the room. Having measured the Green's function throughout the room, one could broadcast, from each loudspeaker i , the superposition

$$\sum_j s_j(t) \otimes G(\mathbf{r}_i, \mathbf{r}_{sj}, -t)$$

so that a listener at $\mathbf{r}_{sj}$ would hear only the message $s_j(t)$.

Vortices

All of these experiments show the focusing capability of time-reversal mirrors in a static medium. But one can also make use of time-reversal mirrors in hydrodynamics.⁸ However, for our purposes, time-reversal invariance is only valid in an approximately Galilean reference frame. In other frames, inertial effects such as a strong Coriolis force would break the symmetry and complicate the issues. To achieve time reversal in a frame rotating with a significant angular velocity Ω would require reversing the angular velocity of the reference frame. Otherwise the time-reversed beam would be laterally shifted from its original source by a distance of order $2\Omega L^2/c$, where L

and c are the propagation distance and velocity. Although the shift is usually negligible compared to the wavelength, it can be measured in rapidly rotating frames.⁸

Roux and I have developed a device to measure various kinds of vortices in fluids. Because acoustic waves are carried along by the rotating fluid particles, the acoustic equation contains source terms that are no longer time-reversal invariant. To measure the effect of small-diameter vortices, we have built a double time-reversal mirror that works as a vortex amplifier. The idea is to play a kind of time-reversal ping-pong between two time-reversal mirrors: Two mirrors are placed facing each other across the diameter of a Plexiglas cylinder full of liquid rotating about its axis, as shown in figure 4. Time reversal is done sequentially, 1000 times per second, between the two arrays. When one array emits an acoustic pulse, the other receives, time-reverses and reemits the wave.

In the absence of rotational flow, time-reversal invariance ensures that many consecutive back-and-forth propagations between the two arrays do not modify the emitted plane-wave front. (See figure 5a). But when the cylinder is rotated rapidly about its axis, the acoustic wavefront is modified at each propagation through the resulting fluid flow. To amplify this wavefront distortion, we send the acoustic wave repeatedly back and forth through the flow. A steady-state flow produces enough amplification of the effect of the vorticity to let us measure very small vortices.

We have tested various types and sizes of vortices. Figure 5b, for example, shows the result we got in the presence of the very thin vortex filament visible in figure 4. The vorticity ω (the curl of the velocity field) in that case is concentrated in a thin core about 1 mm across, comparable to the acoustic wavelength. Outside the vortex, the fluid is irrotational; the curl of the velocity field vanishes. But even in this irrotational region, any line integral of the circulating velocity around the core has a nonzero value Φ , the so-called vortex flux. After repeated back-and-forth reversal, the ultrasonic wave is no longer a plane wave. It has acquired a discernible dislocation at the vortex line, as one can see in figure 5b.

This result can be thought of as a classical acoustic analog of the well-known Aharonov-Bohm effect observed in quantum mechanics,⁹ where one sees a phase shift between charged-particle trajectories that pass on opposite sides of a long, thin magnetic solenoid without actually entering the region of field. Our analog of the magnetic field is ω , and our velocity field is the analog of the electromagnetic vector potential. The Aharonov-Bohm phase shift depends only on the magnetic flux trapped in the solenoid, which is the analog of Φ , our vortex flux. The analogous dislocation of the quantum wavefront by the solenoid was predicted in 1980 by Michael Berry and coworkers.⁹ In our experiment, the measurement of the ultrasonic phase dislocation allows us to determine, within about 5%, the velocity circulation induced by the vortex. Such rotating-fluid experiments show promise for applications in meteorology and for the measurement of ocean flow. The effect of a tornado, for example, might in future be measured with low-frequency double time-reversal mirrors.

Pulse-echo detection

Perhaps the most promising area for the application of time-reversal mirrors is pulse-echo detection. There one is concerned with detecting, imaging and sometimes even destroying passive reflecting targets. The low velocities of ultrasonic waves make it possible to separate reflecting targets at different depths. A piezoelectric transducer first sends out a short pulse and then detects the echoes from the various targets.

Nondestructive evaluation is used to find cracks and

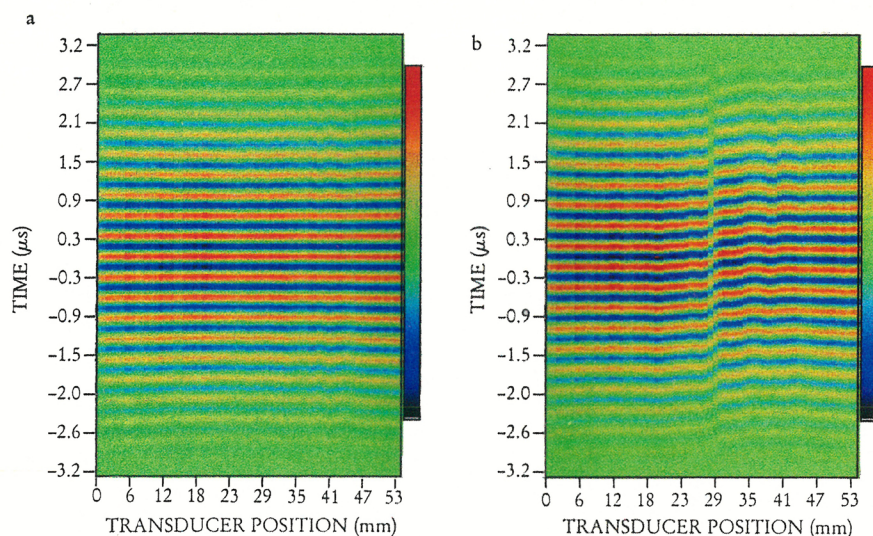


FIGURE 5. AFTER BOUNCING back and forth between the two mirror arrays on opposite sides on the cylinder of water shown in figure 4, the wavefront of a microsecond acoustic pulse is recorded by one of the arrays, (a) when the water is static, and (b) when it is rotating rapidly around the cylinder axis. Color indicates acoustic pressure. The abscissa marks the positions of the 64 transducers on the 53 mm long horizontal array. The wavefront dislocation evident in **b** provides a rather precise real-time measurement of the water's circulation.

defects within materials. In medical imaging, one looks for organ walls, calcification, tumors, gallstones or kidney stones. In underwater acoustics, one hunts for submarines, mines or objects buried under sediments. In all of these cases, the detection quality depends on the availability of the sharpest possible ultrasonic beams. The presence of a distorting medium between the targets and the transducers can drastically change the beam profiles. In medical imaging, for example, intervening fat, bone or muscle can seriously degrade focusing.

In the human body, ultrasonic velocity variations—from 1440 m/s in fat to 1675 m/s in collagen—defocus and deflect acoustic beams. In the nondestructive evaluation of materials, where the sample is usually immersed in a tank of liquid, the shape of the interface between the sample and the coupling liquid limits the detectability of small defects. In undersea acoustics, refraction due to oceanic structure on scales ranging from centimeters to tens of kilometers is an important source of distortion.

For all of these applications, a time-reversal mirror array might follow a three-step sequence.¹⁰ One part of the array generates a brief pulse to illuminate the region of interest through the distorting medium. If the region contains a point reflector, the reflected wavefront is selected by means of a time window and then the acquired information is time-reversed and reemitted. The reemitted wavefront refocuses on the target through the medium. It compensates also for any unknown deformation of the mirror array. In the language of signal theory, this time-reversal processing is a realization of a spatiotemporally matched filter to the propagation transfer function between the array and the target.¹¹

Although this self-focusing technique is highly effective, it requires the presence of a reflecting target in the medium. When the medium contains several targets, the problem is more complicated. But one can select a particular target by iteration of the time-reversal operation. If, for example, the medium contains two targets of different reflectivity, time reversal of the echoes from these targets generates two wavefronts focused on each target. The mirror produces the real acoustic images of the two targets on themselves. The higher-amplitude wavefront illuminates the most reflective target, while the weaker wavefront illuminates the second target. In this case, the time-reversal process can be iterated. After the first time-reversed illumination, the weaker target is illuminated more weakly and reflects a fainter wavefront than

that coming from the stronger target. After several iterations, the process converges and produces a wavefront focused on the more reflective target. It will converge if the separation between targets is sufficient to avoid the illumination of one target by the real acoustic image of the other one.

My colleague Claire Prada¹² has examined theoretically the convergence of time-reversal iteration in a multi-target medium and has derived the conditions for selecting the most reflective targets. But in some cases one might want to focus on the lesser reflectors. The theoretical analysis of the iterative time-reversal process has led to a very elegant solution to this problem. The method is called DORT, a French acronym for the diagonalization of the time-reversal operator.

In yet another interesting application of the pulse-echo time-reversal mirror, one puts an elastic target in resonance. If, for example, one illuminates an extended solid target with a short pulse, the backscattered field has several components: A first reflected wave, called the specular echo, is determined by the target geometry. That is followed by a series of waves—the so-called resonant echo—due to the propagation of surface and volume waves around and inside the scatterer. These waves, generated at particular points on the target, propagate at the surface or in the solid and then radiate into the fluid from different mode-conversion points on the scatterer that act as secondary sources.

Jean Louis Thomas of our group¹³ has studied the case of a hollow target off which the elastic part of the acoustic scattering is mainly due to circumferential waves: the so-called first symmetrical and antisymmetrical dispersive Lamb waves. Because these two waves have different velocities, they can be separated experimentally by time windows. They are generated at different points on the target. When we select each wavefront and time-reverse it separately, the energy of the reversed wave concentrates only at its own generation point. This process enhances the generation of each specific Lamb wave compared to the other reflected waves. By iterating this process, we can build a waveform that is spatially and temporally matched to each of the target's vibration modes. Prada has extended the DORT method¹³ to this type of target.

Clinical promise

One of the first medical application of the pulse-echo time-reversal mirror would be the destruction of stones in

kidneys and gallbladders. Although such stones can be accurately located by x-ray or ultrasonic imaging, it is difficult to focus the ultrasonic waves through inhomogeneous tissue tightly enough to destroy them. Furthermore, the movement of the stones during breathing cannot easily be tracked. Therefore, with clinical systems now in use, it takes several thousand ultrasonic shots to destroy a stone. With present-day piezoelectric devices, it is estimated, only 30% of the shots reach the targeted stone.

Ultrasonic time-reversal techniques can solve these problems. To locate a reflecting target such as a kidney stone in its environment of other stones and organ walls, one illuminates the zone of interest with a few elements of the transducer matrix. The reflected signals are then recorded by the whole matrix and time-reversed. When the process is iterated several times, the ultrasonic beam converges towards the most reflective area of a stone. The time-reversal iteration selects one of those spots. Once the spot has been reliably located, intermittent amplified pulses can be applied to shatter the stone. As breathing moves the stone, the process is repeated to track it in real time. Thomas, François Wu and I have developed a 64-channel time-reversal mirror 20 cm in diameter.¹⁴ It has already been tried successfully in two French hospitals, and clinical tests continue.

Another promising clinical application of self-focusing time-reversal mirrors is ultrasonic medical hyperthermia. In this technique, high-intensity ultrasound produces thermal effects as part of the acoustic energy is absorbed by tissue and converted to heat. If local temperature rises above 60 °C, tissue destruction can occur within seconds.

Focused ultrasound surgery was pioneered in the 1950s by William Fry at the University of Illinois, but only recently has it achieved general acceptance.¹⁵ Focal probes consisting of annular phased arrays are now marketed for the treatment of prostate cancer. These techniques are nowadays limited to the production of necrosis in static tissues that are not moving; applications to cardiac and thoracic surgery are limited by the tissue motion due to heartbeat and breathing.

At the University of Michigan, Emad Ebbini and coworkers are developing self-focusing arrays to solve this problem. Our group is working on clinical hyperthermic applications in the brain. Our challenge is to focus through the skull, which induces severe refraction and scattering of the ultrasonic beam. Thomas, Mickael Tanter and I have recently shown that the porosity of the skull produces strong dissipation, which breaks the time-reversal symmetry of the acoustic wave equation.¹⁶ In that case, time-reversal focusing is no longer an appropriate means of compensating for the skull. Therefore we have developed a new focusing technique that combines a correction of these dissipative effects with classical time-reversal focusing. It allows us to focus and steer an ultrasonic beam through the skull and focus it on a 1.5-mm spot, with very small side lobes.

Detecting flaws in solids

The detection of small defects in a solid is particularly problematic when the inspected object is made of heterogeneous or anisotropic material, or when the geometry of the sample is complicated. Usually, the sample and the ultrasonic transducers are immersed in water, and the transducers are moved to scan the zone of interest. But refraction at the water/solid interface can alter the ultrasonic beams. Furthermore, the longitudinally polarized ultrasound traveling in water can produce waves of different polarizations and velocities in the solid, which can support transverse and surface waves.

We have proposed and demonstrated the application

of self-focusing techniques involving time-reversal mirrors to the difficult task of focusing and steering an ultrasonic beam in a solid.¹⁷ Time-reversal mirrors automatically compensate for refraction, mode conversion and anisotropy. In a joint program with the (French) National Society for the Study and Construction of Aircraft Engines, we have developed a 128-element time-reversal mirror array to detect the presence of low-contrast defects within titanium alloys used in jet engines. This is a difficult problem, because titanium has a highly heterogeneous microstructure that produces much scattering noise, which can hide the echo from a defect.

Wu, Najet Chakroun, Véronique Miette and I have shown that the iterative pulse-echo mode allows us to autofocus and detect defects as small as 0.4 mm in 250-mm titanium billets.¹⁷ This technique, quite generally, offers better signal-to-noise ratios than alternative methods, and it can detect smaller defects in the billet core, where ultrasonic beams are severely distorted. Various such applications of time-reversal mirrors are now under investigation—for example, the detection of cracks in nuclear reactor components made of anisotropic, large-grain austenitic steel.

Because modern electronics now makes acoustic time-reversal technology easily accessible, I expect that applications will expand rapidly in a variety of areas. The most promising early applications have been in medicine and materials testing. Underwater telecommunication and detection are also important fields of interest. Beyond their promise for solving practical problems, time-reversal mirrors are also unique research tools for better understanding of wave propagation in complex static or dynamic media.

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