Time-Reversed Acoustics

Matt Hurliman
PHYS 536

BE BOUNDLESS

Motivations

A few general motivating pursuits –

- Communicate quickly & efficiently
- Locate objects
- Apply forces

Motivations

Conventional methods –

- Throw physical objects
- Direct acoustic waves
- Shoot photon beam
- Powerful electromagnets

All dangerous in their own right!

Inspiration - Waves

Imagine a pebble dropped into water

Inspiration - Waves

Now consider its time-reversal

Inspiration - Waves

Can we replicate this time reversal?

- Time symmetry of system
- Entropy precludes T-symmetry at macroscopic scales
- Adiabatic processes = low entropy

Acoustic waves are approximately adiabatic!

- Below $\sim 1\ GHz$ – easy upper-bound to work within

Motivation

Demonstration of elastic wave *Time-Reversed Acoustics*

BYU Acoustics Research Group 2017 [5]

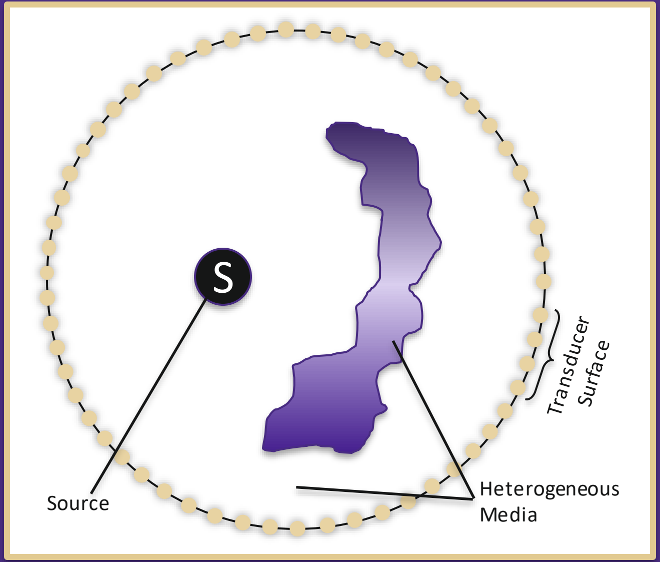
Ideal TR Configuration

Medium (heterogeneous)

Acoustic source

Enveloping transducer surface

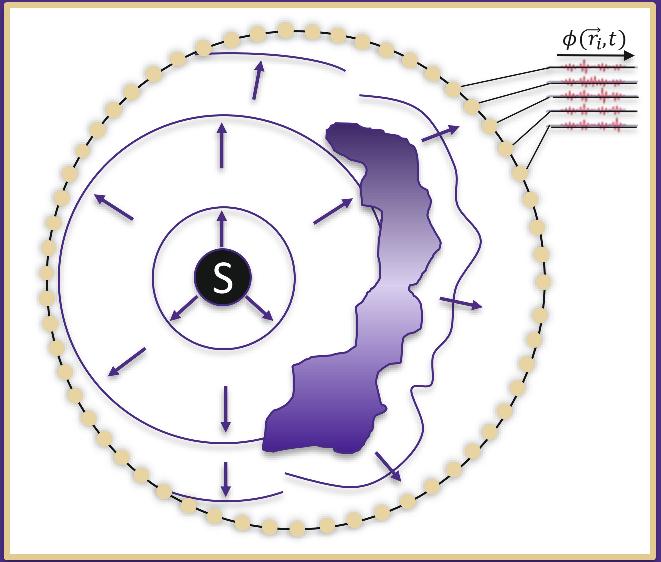
- Called the *Time Reversal Mirror (TRM)*



Procedure

Step 1: Forward Propagation

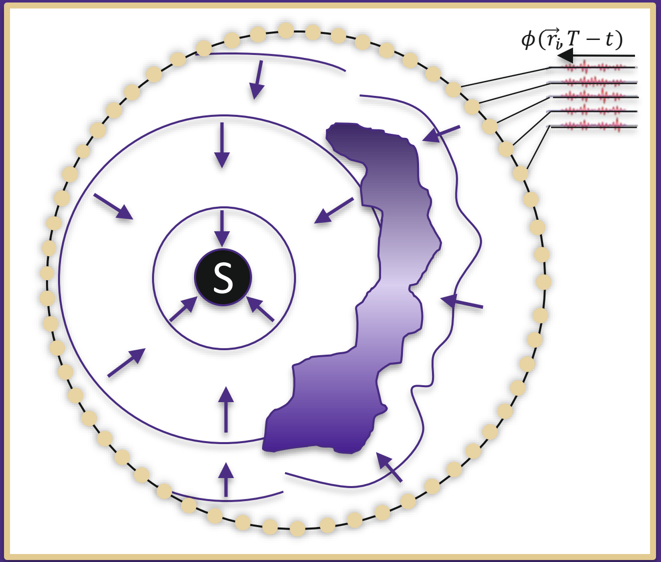
- Point source emits acoustic pulse
- Pulse propagates radially
- Wavefront distorted by heterogeneities
- Each transducer records signal, $\phi(\vec{r_i}, t)$



Procedure

Step 2: Time-Reversal

- Each transducer time-reverses signal
- Re-emits reversed signal, $\phi(\vec{r_i}, T - t)$
- Wavefront is distorted inversely
- Disparate wavefronts meet at source



TR in Free Field

Experiment in water tank

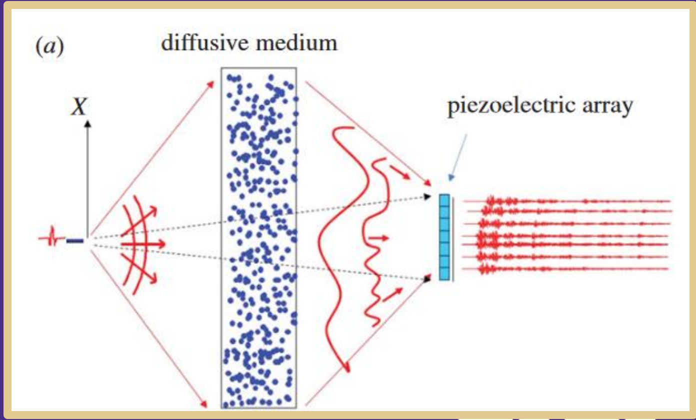
2000 metal rods diffusive medium

Acoustic source transducer

- Hydrophonic microphone as well

Linear array of 96 PE transducers

- Note: Only subtends small angle of source



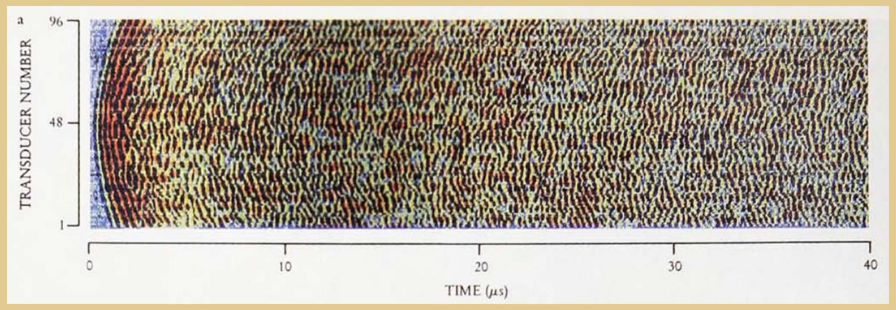
[2]

TR in Free Field

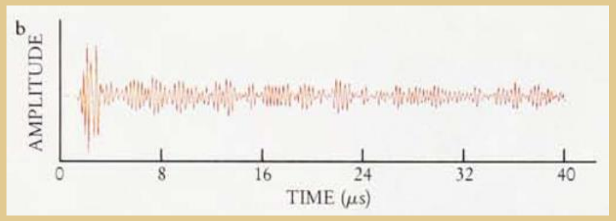
Forward propagation:

1. Source impulse $1\ \mu s\ @\ 3\ MHz$
2. Received signal $> 200\ \mu s$
3. Ballistic wavefront hits first
4. Rod-scattered waves cause chaotic ripples thereafter

Field amplitude ϕ (color) measured by each of 96 transducers



Field amplitude ϕ measured by single transducer

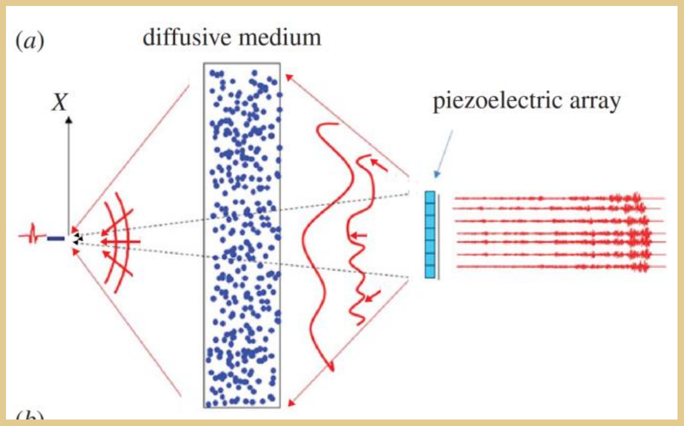


[1]

TR in Free Field

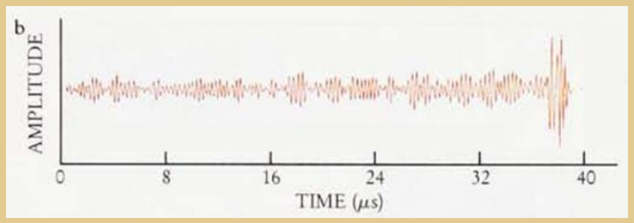
TR propagation:

- Transducer signal is reversed & emitted
- Emission over long time period - 40 μs
- Time-delayed waves scatter ~ inversely
- Convergence at acoustic source - 1 μs

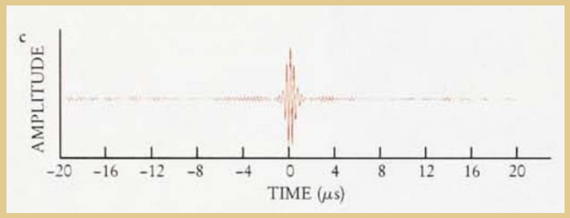


[2]

Time-reversed signal of single transducer



Hydrophone at acoustic source - 1 μs spike!



[1]

TR in Free Field

This is an amazing result!

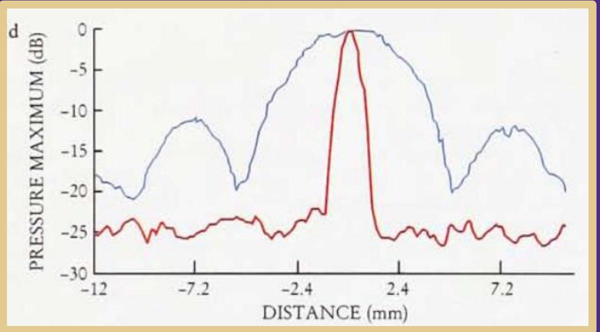
- 1 μs impulse response w/o explicit medium knowledge
- Spatial resolution of ~5 mm (limited to $\frac{\lambda}{2}$)

No rods → 6x *worse* resolution

- Resolution depends on subtended angle
- For most purposes subtended angle $\ll 4\pi\ sr$

Scattering is *necessary* for effective TRA

- Acts as magnifier for TR propagation



Spatial spread of acoustic impulse of TR signal at original source with (red) and without (blue) diffusive media [1]

TR in Ergodic Cavity

Finite, solid elastic medium

- Glass, plastic, metal, etc.

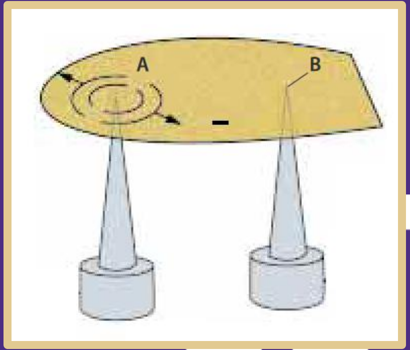
Acoustic source transducer

TRM is implemented by a *single* transducer

- Laser doppler vibrometer (LDV) – measures surface displacement by detecting phase variations in laser light

BYU LEGO experiment demonstrating the precision of TR impulse within an ergodic cavity [6]

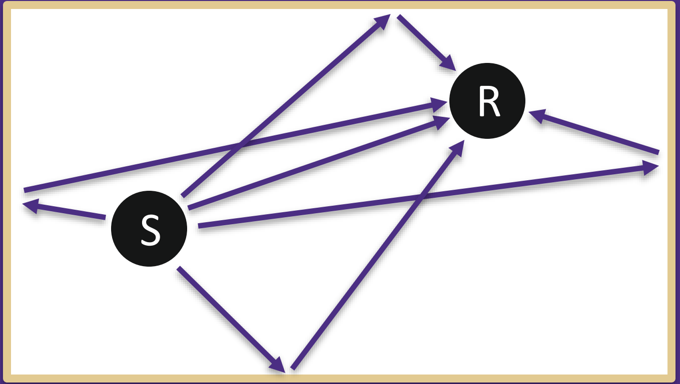
Simplified diagram of TR within ergodic cavity [2]



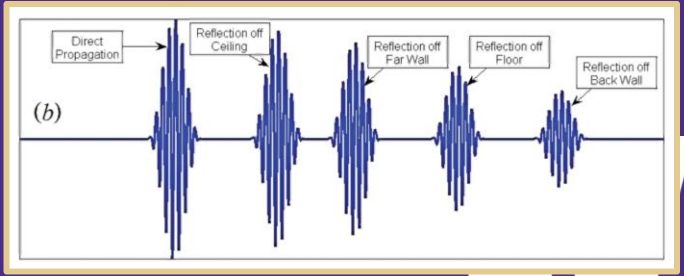
TR in Ergodic Cavity

Forward Propagation

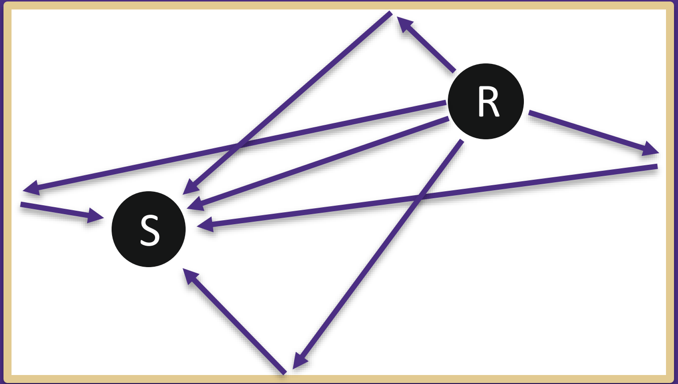
- Source emits pulse
- Direct wave reaches receiver
- Indirect waves reflect off cavity walls
- Indirect waves reach receiver at times in accordance with total distance



Simplified signal received at source – considering only small number of ray paths [4]



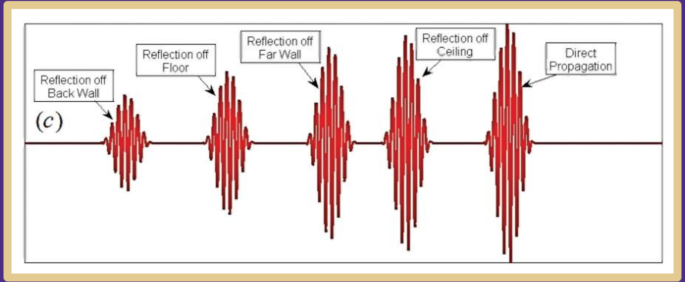
TR in Ergodic Cavity



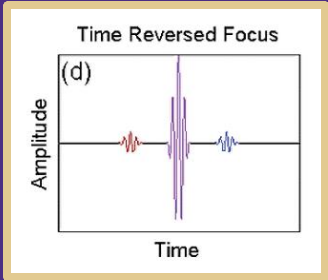
Reverse Propagation

- Choose cut-off point, time-reverse signal
- Emit TR signal over 10's of μs
- Pulses reflect off cavity surfaces
- Direct + reflected waves converge at focal point

Time-reversed signal of receiving transducer

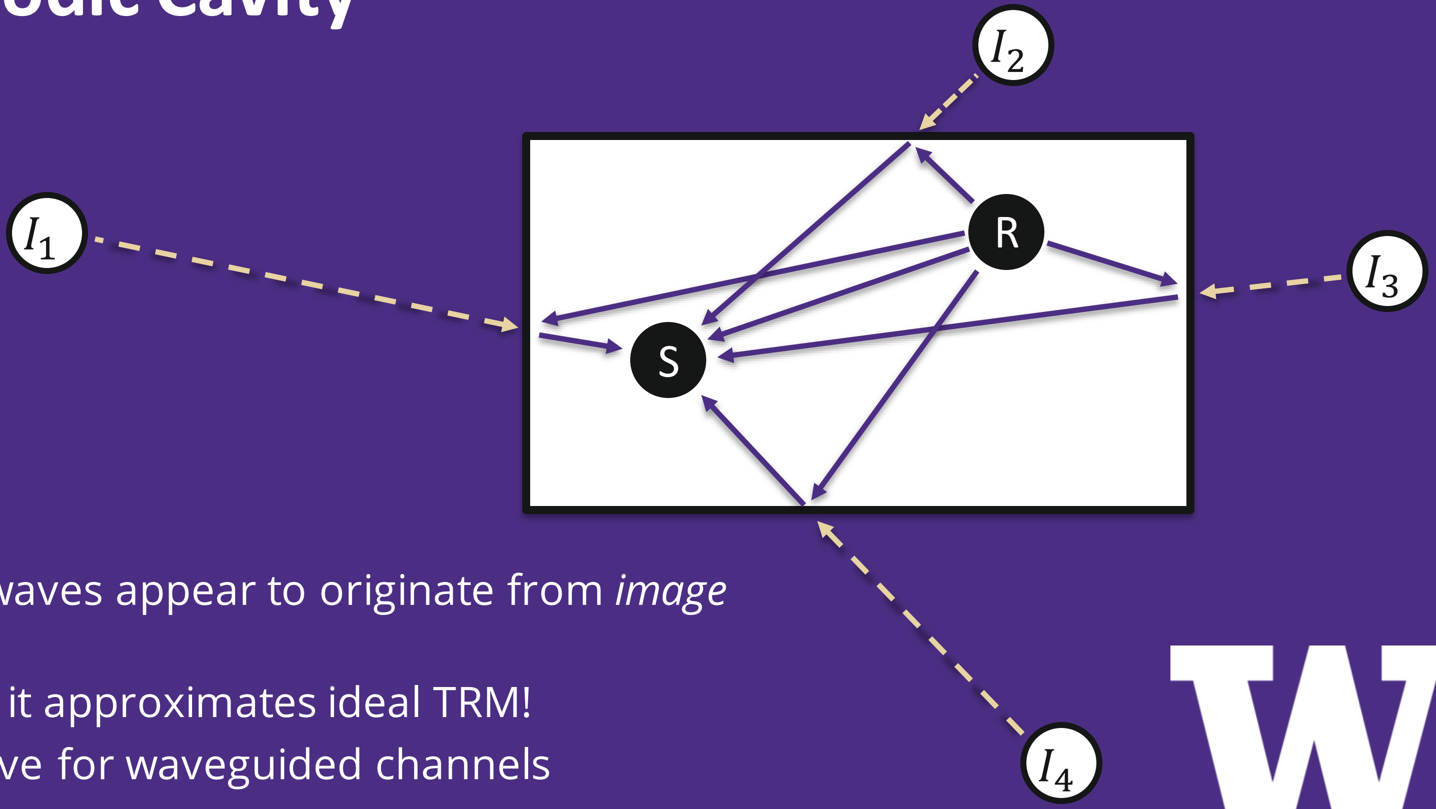


Impulse response at source



[4]

TR in Ergodic Cavity



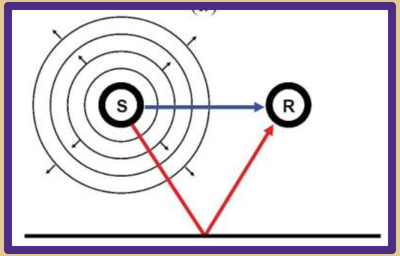
- Scattered waves appear to originate from *image* sources
- In the limit it approximates ideal TRM!
- Also effective for waveguided channels

Reciprocal TR

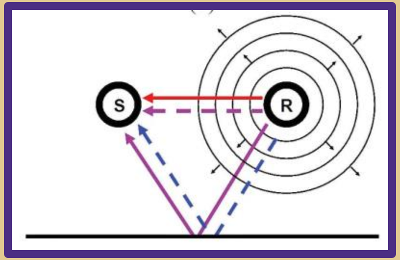
Spatial reciprocity facilitates additional mode of propagation

1. Perform forward propagation
2. Record signal at R
3. Emit TR signal from S *(instead of R)*
4. Targeted impulse at R *(instead of S)*

Forward Propagation

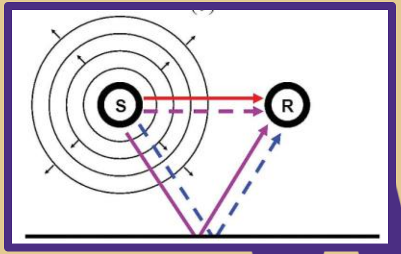


TR Propagation



[4]

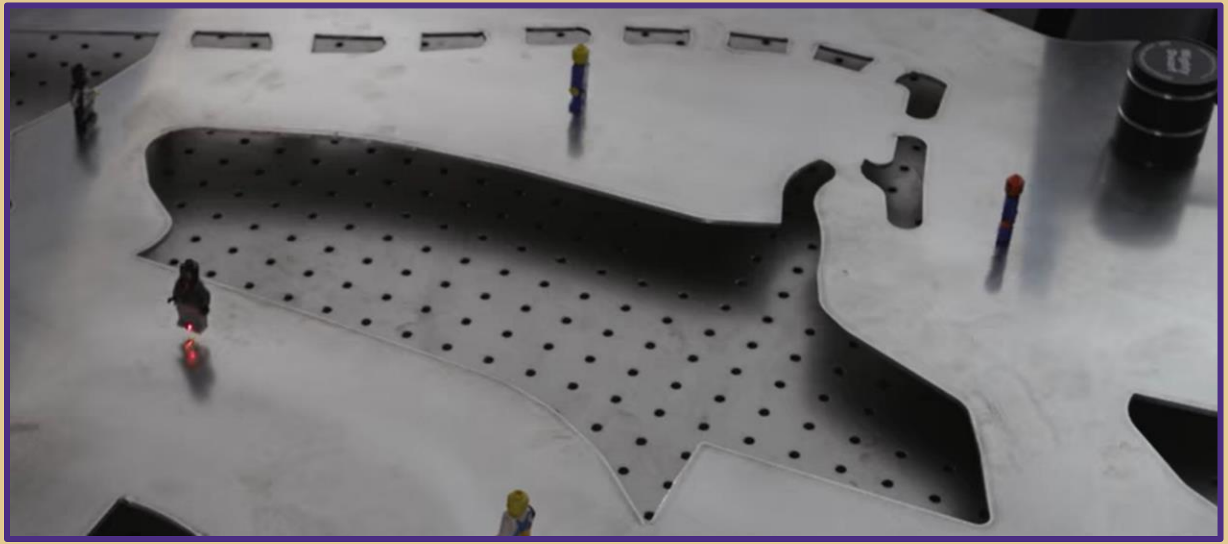
Reciprocal TR Propagation



Reciprocal TR

Lego Demo

BYU LEGO demo – chirp speaker in top-right, LDV in bottom-left next to LEGO man experiencing constructive interference of propagating reciprocal TR acoustic waves [6]



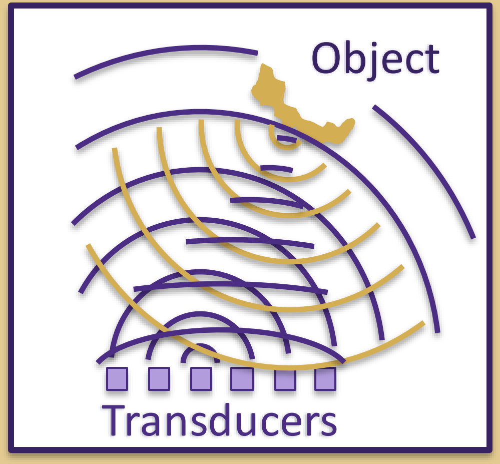
- Elastic ergodic cavity medium
- Speaker induces calibration acoustic wave
- Laser Doppler Vibrometer measures $\phi(\vec{r}, t)$
- Reciprocal TR – speaker emits TR signal, $\phi(\vec{r}, T - t)$
- Disparate elastic wavefronts converge constructively at location

Pulse-Echo Detection

Focus on unknown objects in medium

- Transducer emits pulse
- Wavefront bounces off object
- Reflected wave arrives at transducer array

Voila, TR signal is a broadcast to focus pulse at object!



Waves largely incoherent until focal point

Pulse-Echo Detection

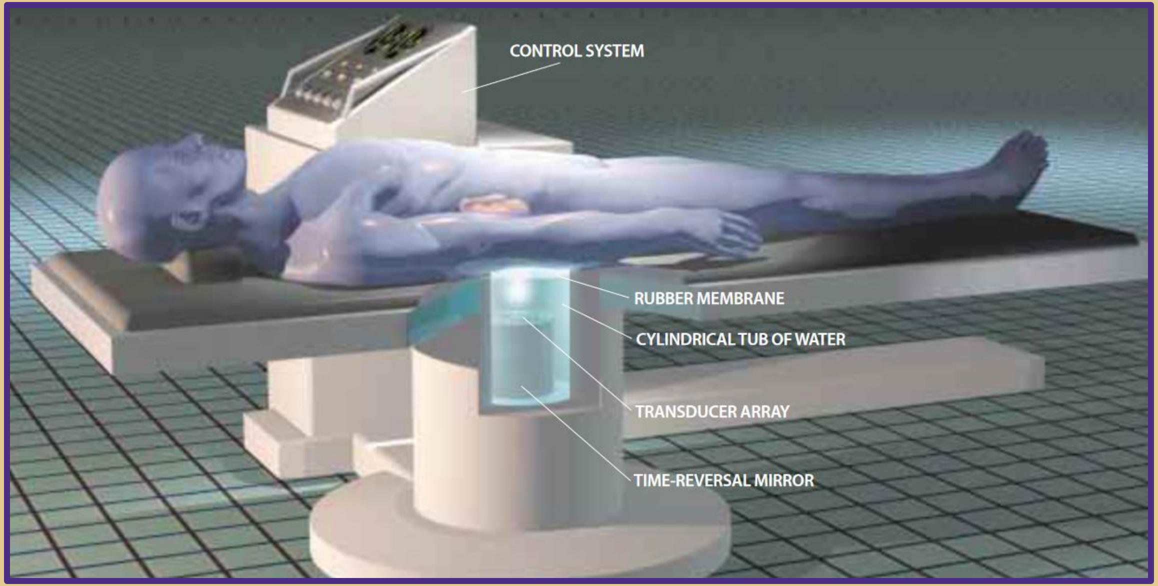
Procedure is self-focusing, stabilizes over time

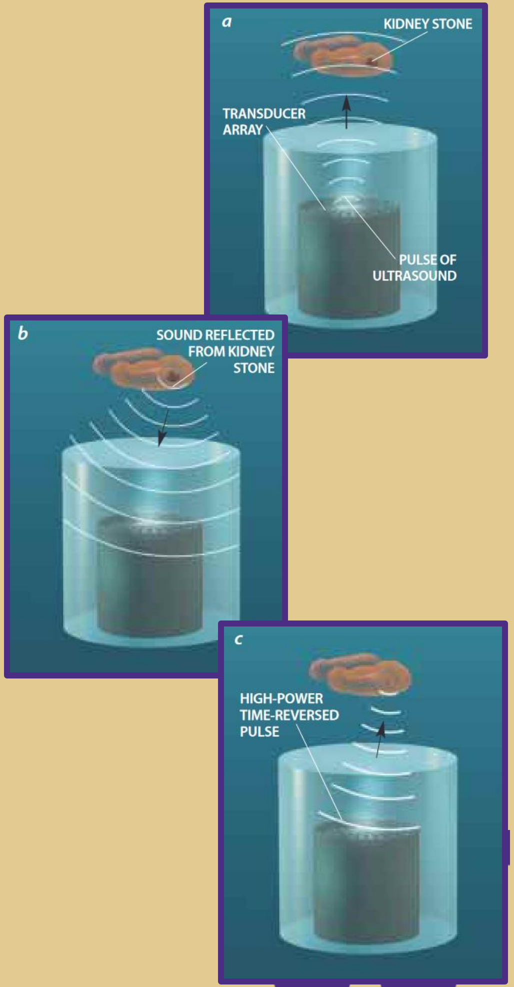
- Array continuously updates TR signal
- Focal reflections emit stronger response
- Stronger response → more focused signal

Allows objects to be trivially tracked over time

Pulse-Echo Detection

Kidney Stone Pulverization



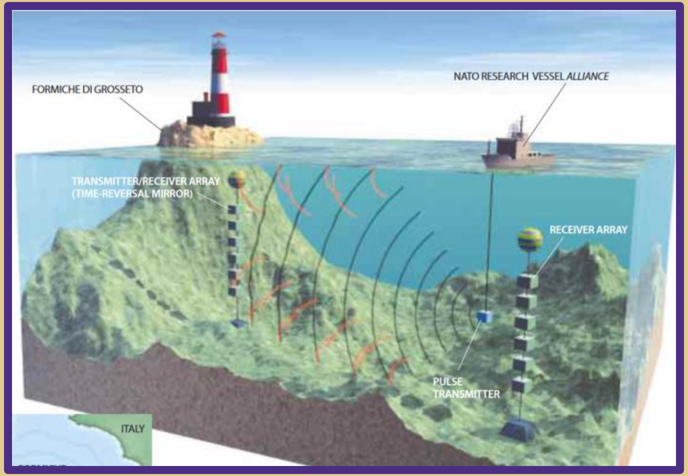


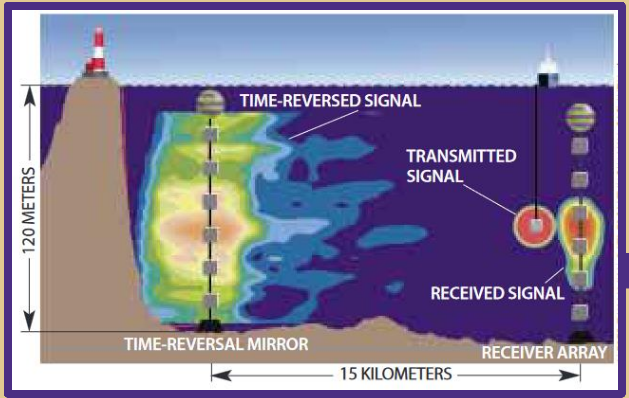
Visualization of mechanism and properties of kidney stone detection, tracking, and pulverization [2]

Underwater Communication

- Conventional UC w/ direct pressure waves
- Bounces off floor/surface degrade quality
- In TR bounces *enhance* quality by creating wider angle TRM
- Focused signal at range of 30 km
- Bonus: Waves are incoherent until focal point – physical encryption!

1996 experiment utilizing TRA to induce focused high-amplitude signals at distances of 30 km in the Mediterranean Sea [7]





References

1. Fink, M. (1997). TIME REVERSED ACOUSTICS. *Physics Today,* 50, 3, 34. https://doi.org/10.1063/1.881692
2. Fink, M. (1999). TIME-REVERSED ACOUSTICS. *Scientific American*, *281*(5), 91–97. http://www.jstor.org/stable/26058488
3. Anderson et al. (2008). TIME REVERSAL. *Acoustics Today*, 4(1), 3. http://www.jstor.org/stable/26058488
4. Fink, M. (2016). FROM LOSCHMIDT DAEMONS TO TIME-REVERSED WAVES. *The Royal Society*, 374(2069). https://doi.org/10.1098/rsta.2015.0156
5. Heaton et al. (2017). TIME REVERSAL FOCUSING OF ELASTIC WAVES IN PLATES FOR EDUCATIONAL DEMONSTRATION PURPOSES. *J. Acoust. Soc. Am.,* 141(2), 1084-1092. https://dx.doi.org/10.1121/1.4976070
6. Barnes et al. (2022). THE PHYSICS OF KNOCKING OVER LEGO MINIFIGURES WITH TIME REVERSAL FOCUSED VIBRATIONS. *J. Acoust. Soc. Am.,* 151(2), 738-751. https://doi.org/10.1121/10.0009364
7. Kuperman et al. (1998). PHASE CONJUGATION IN THE OCEAN: EXPERIMENTAL DEMONSTRATION OF AN ACOUSTIC TIME-REVERSAL MIRROR. *J. Acoust. Soc. Am.,* 103, 25. https://doi.org/10.1121/1.417477