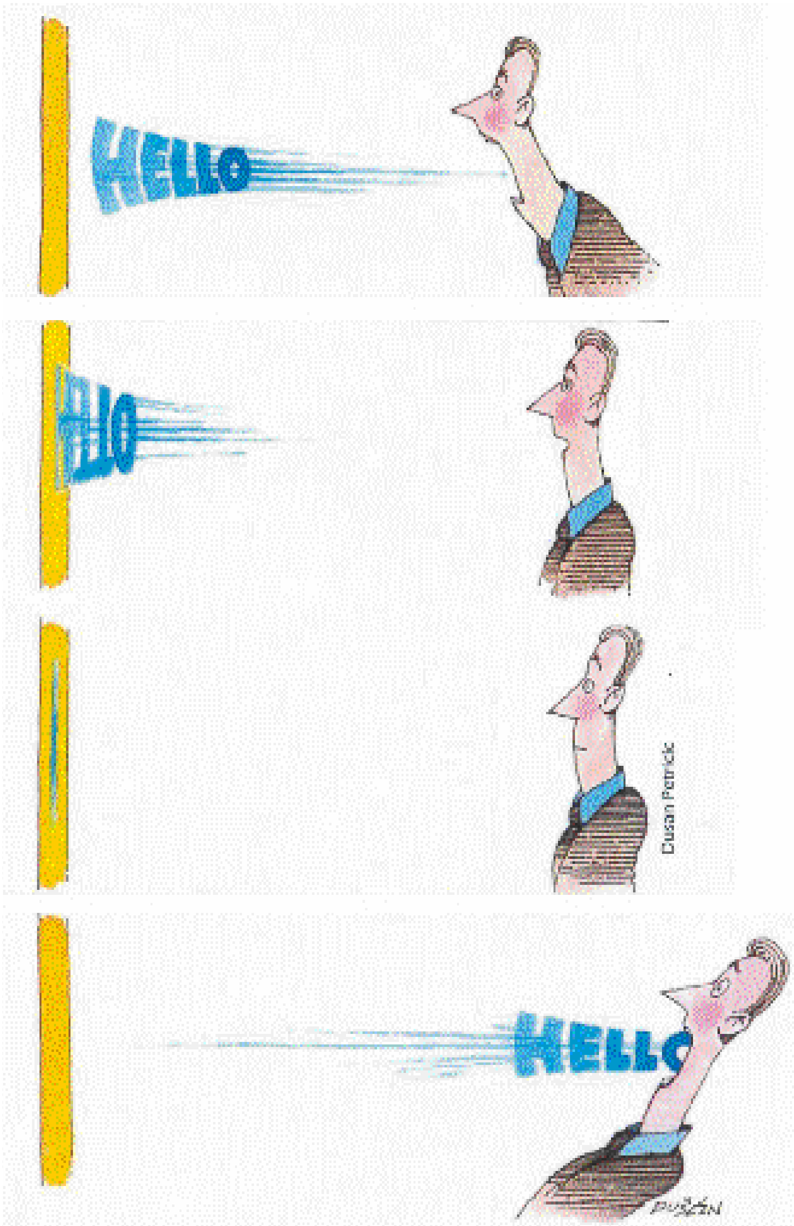
The Chaotic Time-Reversal Sensor



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Office of Naval Research
Revolutionary Research . . . Relevant Results

Overview

Classically chaotic systems display extreme sensitivity to initial conditions
… which suggests good sensor applications

Sensors often utilize waves (acoustic, electromagnetic, seismic, etc.) for detection

Wave Chaotic systems show extreme sensitivity to **perturbations**

Time Reversal and *Spatial Reciprocity* are two 'hidden' symmetries of the wave equation that can be exploited to simplify the wave chaotic sensor

We have developed a novel sensor paradigm that combines the extreme sensitivity of wave chaotic systems with the simplicity of time-reversed and spatially reciprocal waves to create:

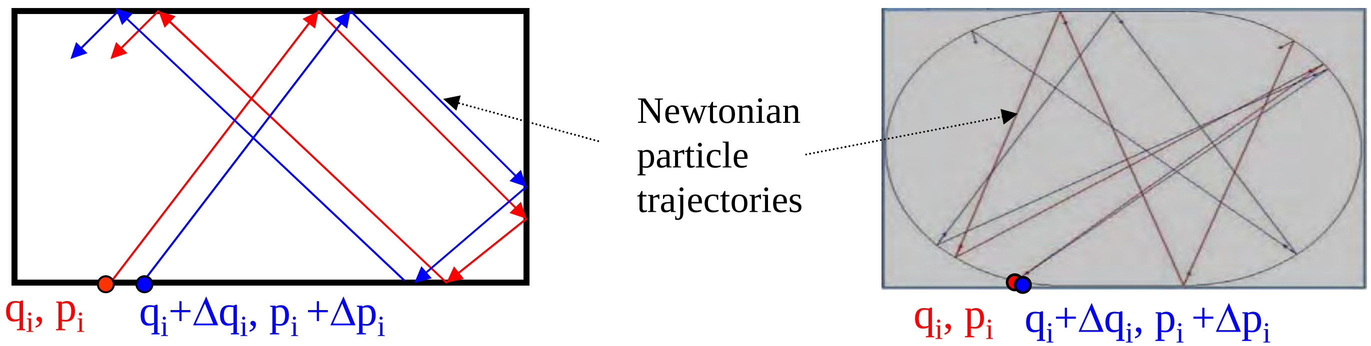
The **CHAOTIC TIME-REVERSAL SENSOR**

Wave Chaos?

1) Classical chaotic systems have diverging trajectories

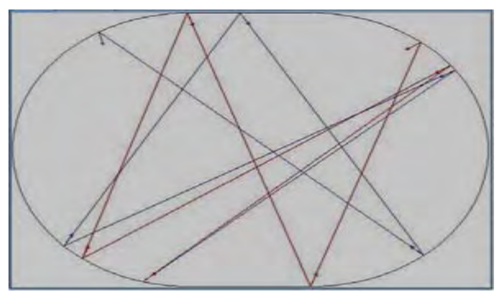
2-Dimensional "billiard" tables with hard wall boundaries

Regular system | Chaotic system



2) Linear wave systems can't be chaotic

In the ray-limit it is possible to define chaos



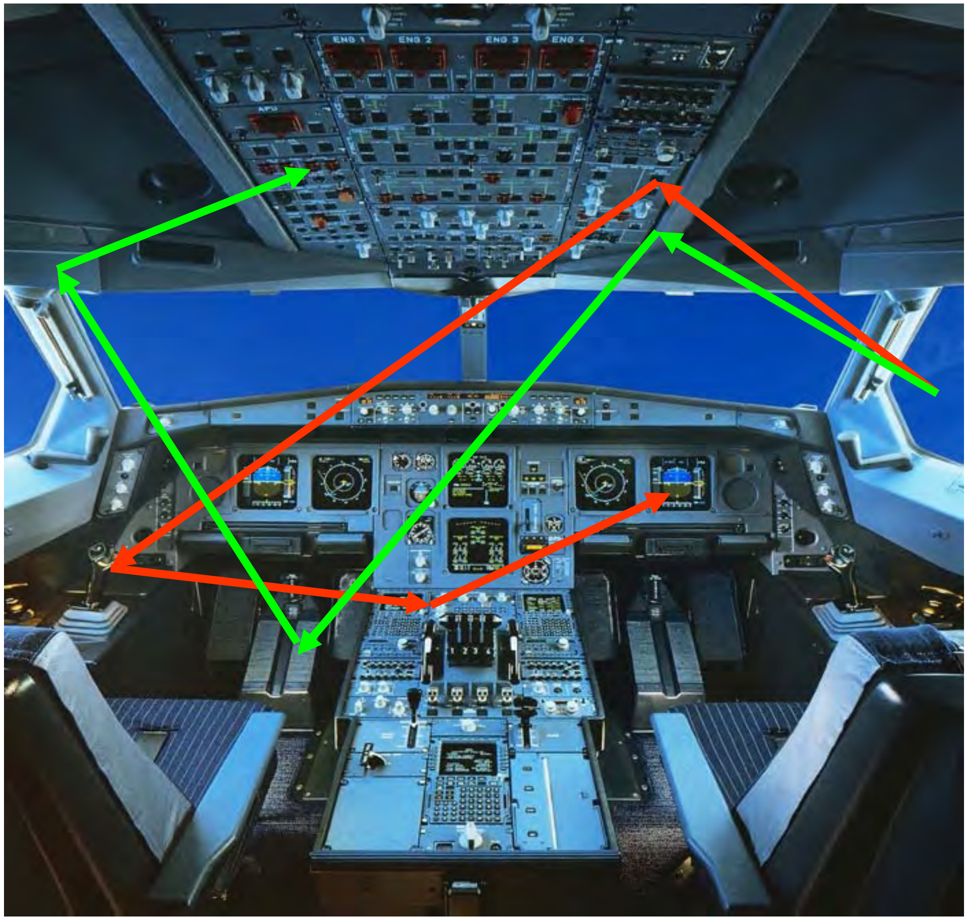
"ray chaos"

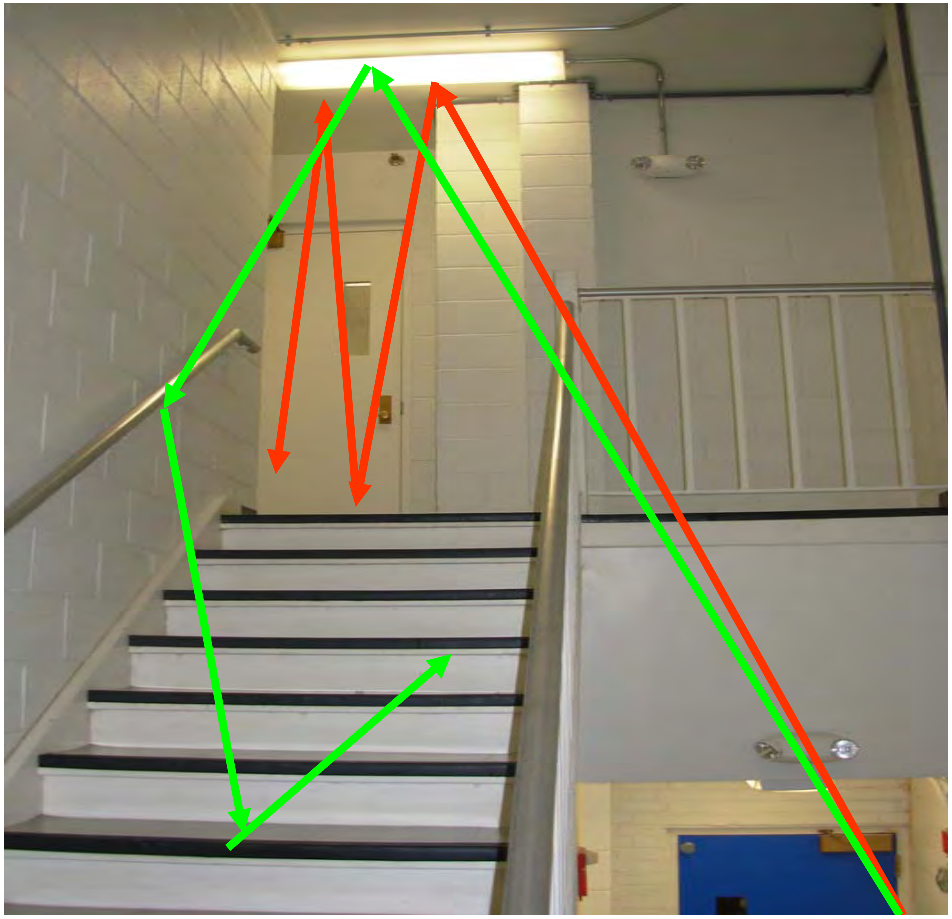
3) However in the semiclassical limit, you can think about <u>rays</u>

Wave Chaos concerns solutions of wave equations which, in the semiclassical limit, can be described by ray trajectories

Ray Chaos

Many enclosed three-dimensional spaces display ray chaos





Now Consider Wave Propagation in Ray-Chaotic Enclosures

Propagation of a Gaussian Wave Packet

The two-dimensional Stadium Billiard shows Ray Chaos

The waves eventually propagate to all parts of the billiard

Solve the wave equation (Electromagnetic, Acoustic, Schrödinger equation, etc.) in a ray-chaotic enclosure

Examine the solutions in the semiclassical regime: $0 < \lambda << \text{System Size}$

t/T = 0, 0.5, 1, 2, 6

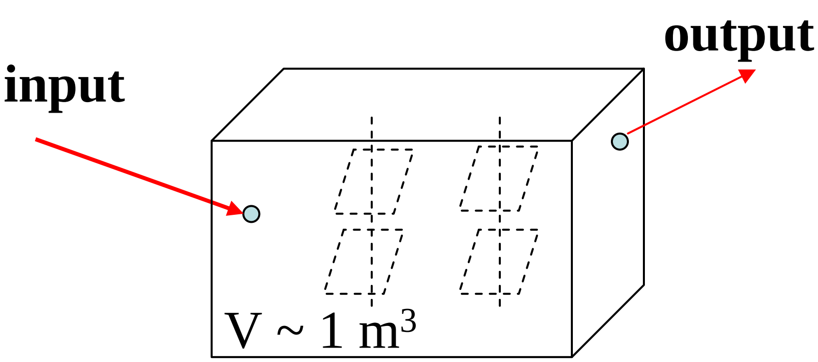
T = time to propagate along horiz. axis

Tomsovic+Heller PRE 47, 282 (1993)

Experimental Test of the extreme sensitivity to perturbations

Create a ray-chaotic microwave ($\lambda \sim 5$ cm) box

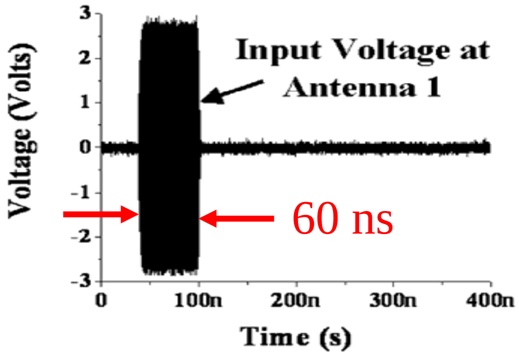
Mode-stirred chamber with 4 paddles on 2 spindles (GigaBox)

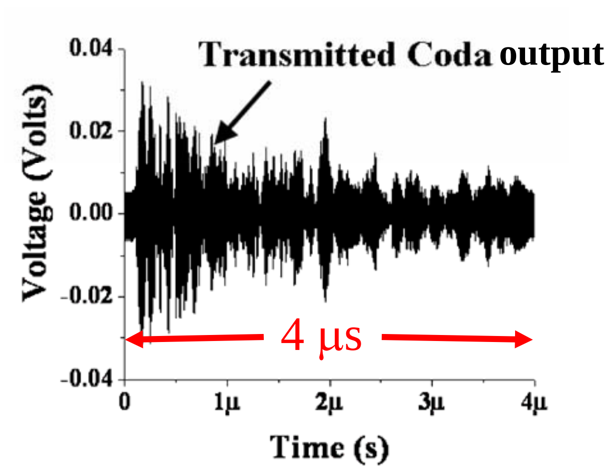


V = 1.27 x 1.27 x 0.66 $m^3 \sim 1$ m^3

Movie of Sensitivity of Coda Signal to Small Perturbations of the GigaBox

60-ns-long pulse of 7 GHz radiation injected into the GigaBox at Port 1

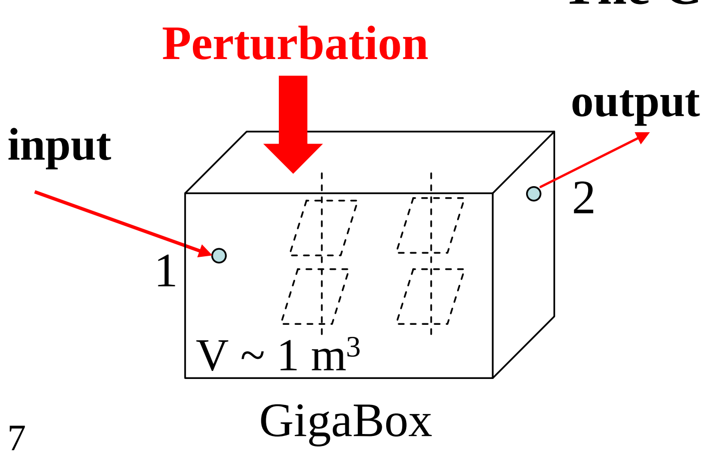




A long coda signal is measured at port 2

One wall of the GigaBox is perturbed

The Coda signal is very sensitive to perturbation



GigaBox Coda Sensitivity Movie

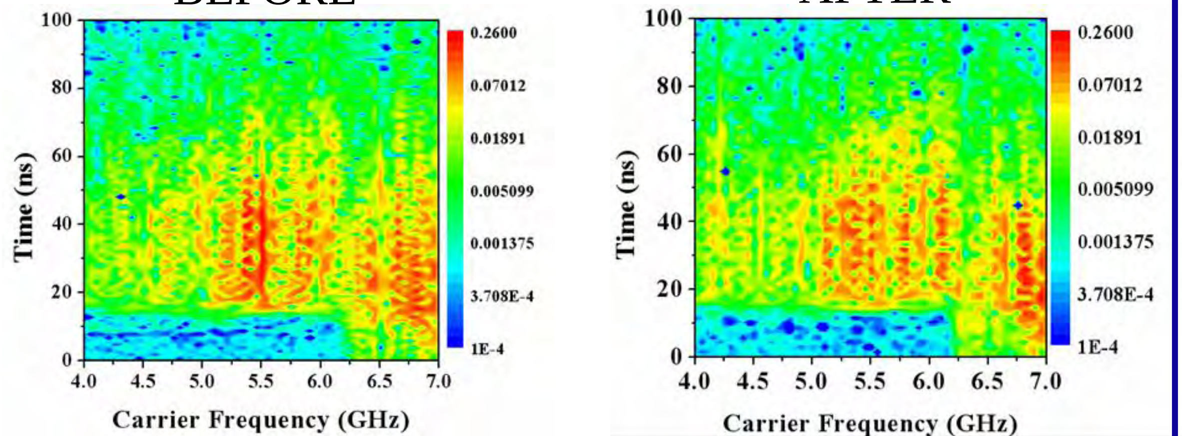
DSCN7700 Coda Take 4

Coda Signals are Difficult to Handle and Manipulate

Coda signals are noisy, awkwardly large, and hard to compare to each other

"Electromagnetic Fingerprints" of a computer box

BEFORE AFTER



US Provisional Patent Application 60/885,265

There's Got To Be a Better Way!

We exploit Time-Reversal Invariance (using a time-reversal mirror) and Spatial Reciprocity to simplify the detection step and make the CTRS less susceptible to noise

The CTRS essentially checks for time-reversal symmetry and spatial reciprocity for waves propagating inside the ray-chaotic enclosure

Wave propagation in a non dissipative heterogeneous medium

$\Psi(r,t)$ acoustic pressure field (scalar), or electric field (vector)

$c(r)$ is the wave speed in a heterogeneous medium

in a domain
<u>without source</u> $\rightarrow$

$$\nabla^2\Psi - \frac{1}{c^2}\frac{\partial^2\Psi}{\partial t^2} = 0$$

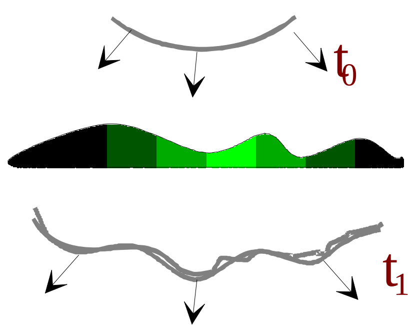
Spatial Reciprocity — Time Reversal Invariance

This equation contains $\dfrac{\partial^2\Psi}{\partial t^2}$

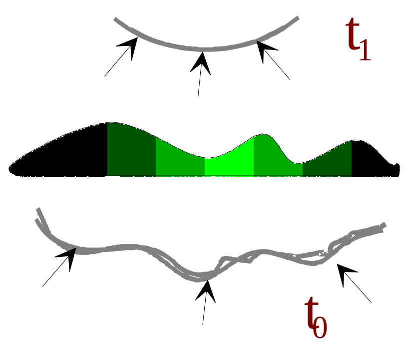
Then if $\Psi(r,t)$ is a solution

$\Psi(r,-t)$ is also a solution

because $\dfrac{\partial^2\Psi(r,-t)}{\partial t^2} = \dfrac{\partial^2\Psi(r,t)}{\partial t^2}$

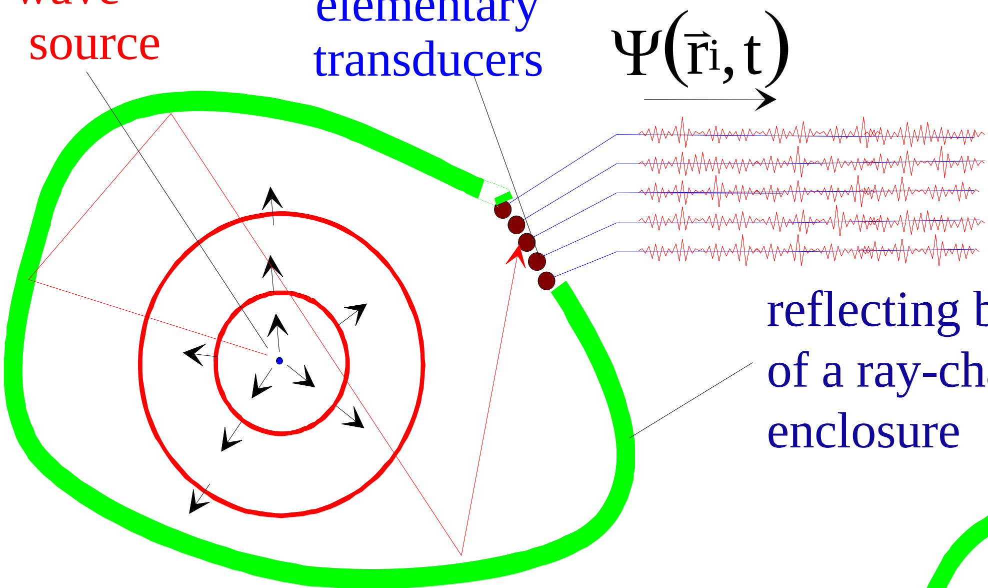


$\Psi(r,t)$



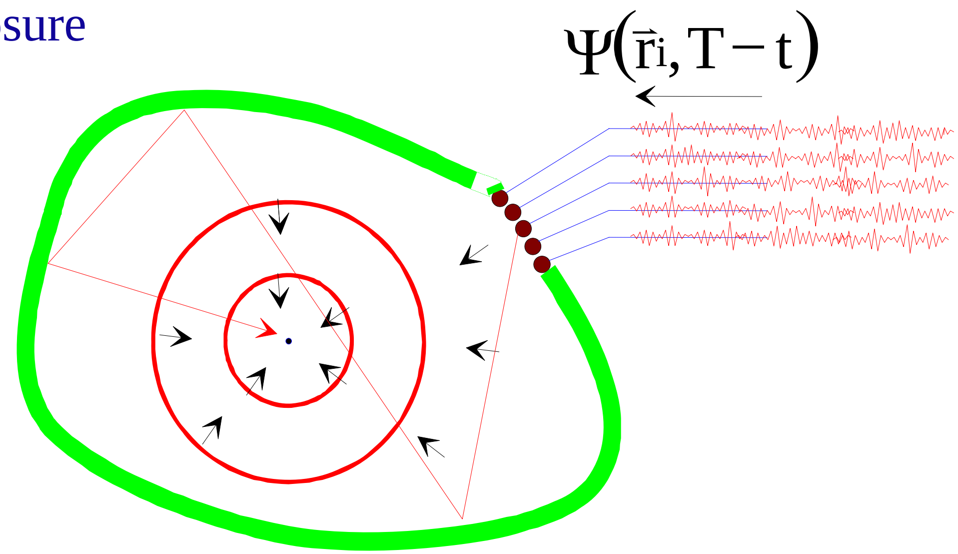
$\Psi(r,-t)$

The effect of boundaries on Time Reversal Mirror



Receive mode

Rays moving in the "wrong" direction eventually bounce around and find the time-reversal mirror

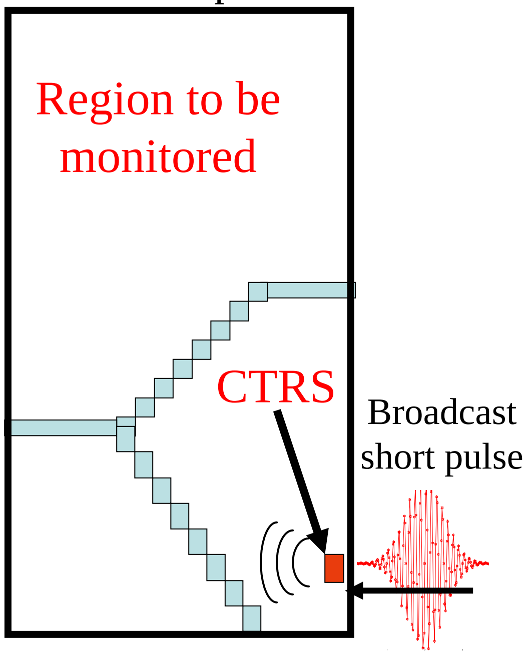


Transmit mode

Ray-chaotic scattering greatly assists the re-production of the wave excitation at the source

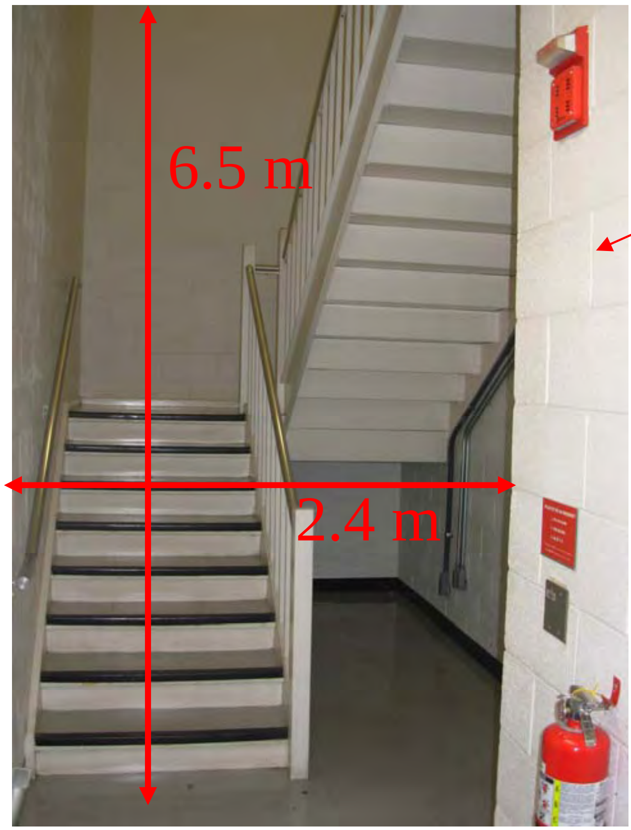
A <u>single channel</u> works very well!

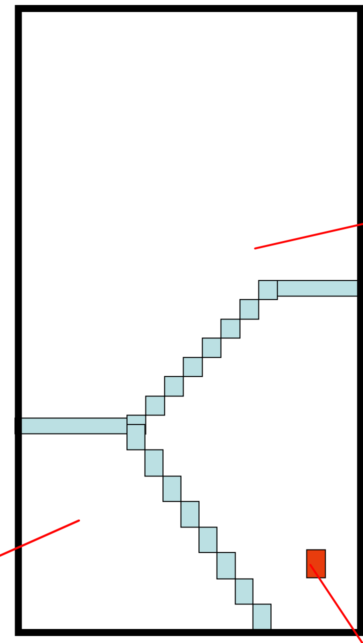
Step 1

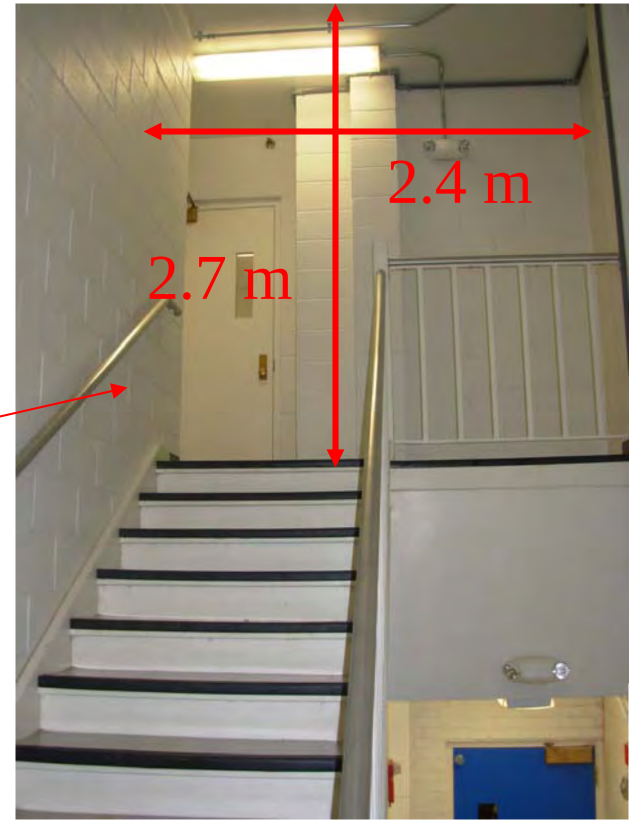


Operation of the Acoustic CTRS

Demonstration of the Acoustic CTRS in a Stairwell

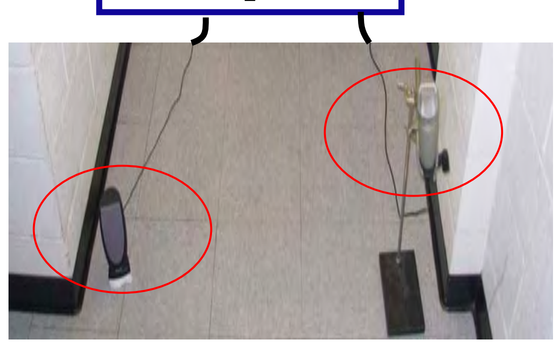






Laptop Computer

Small, Cheap Simple Sensor

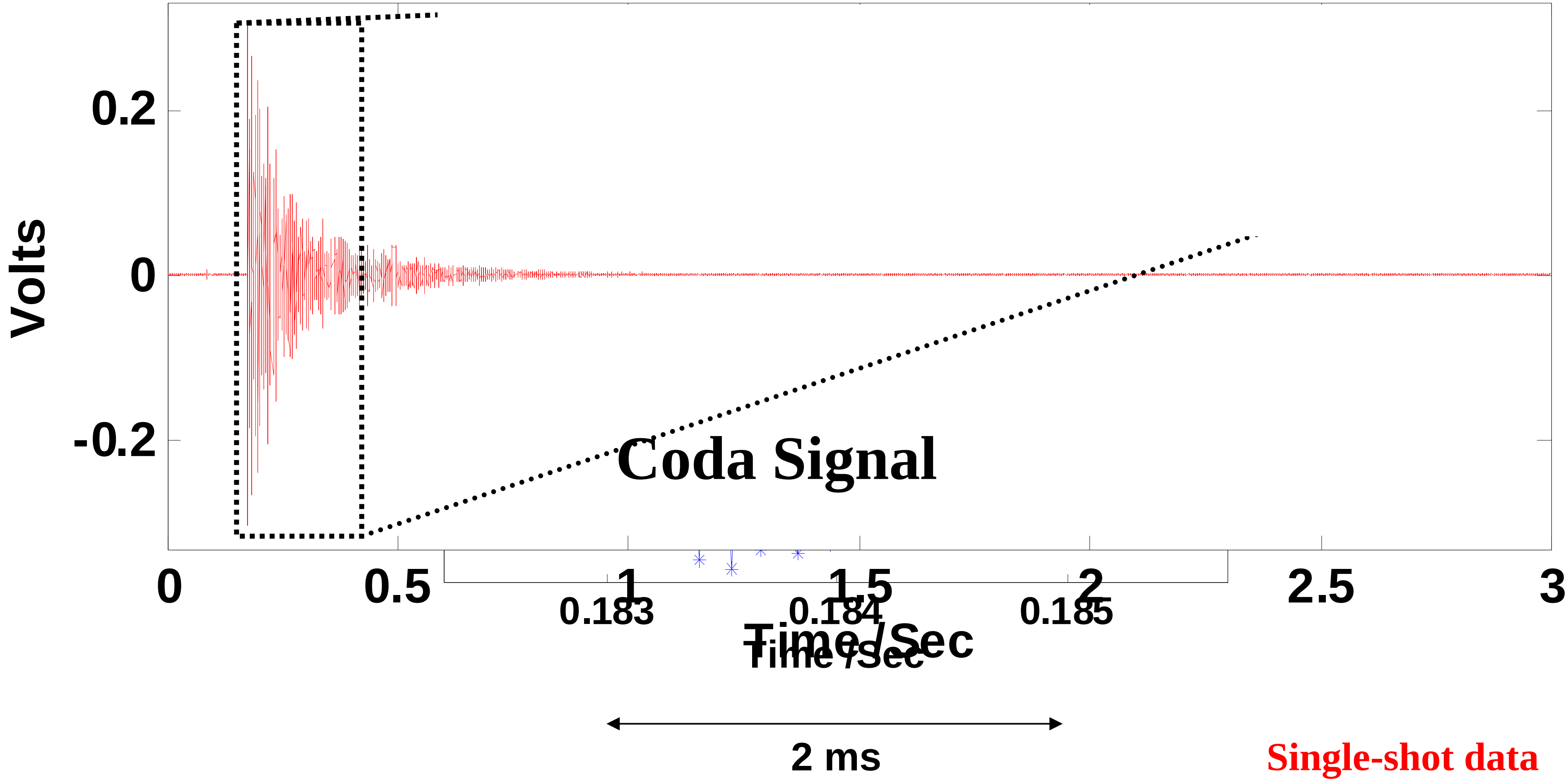


Spatial Reciprocity used here

Acoustic CTRS in Stairwell:- The incident pulse and Coda signal

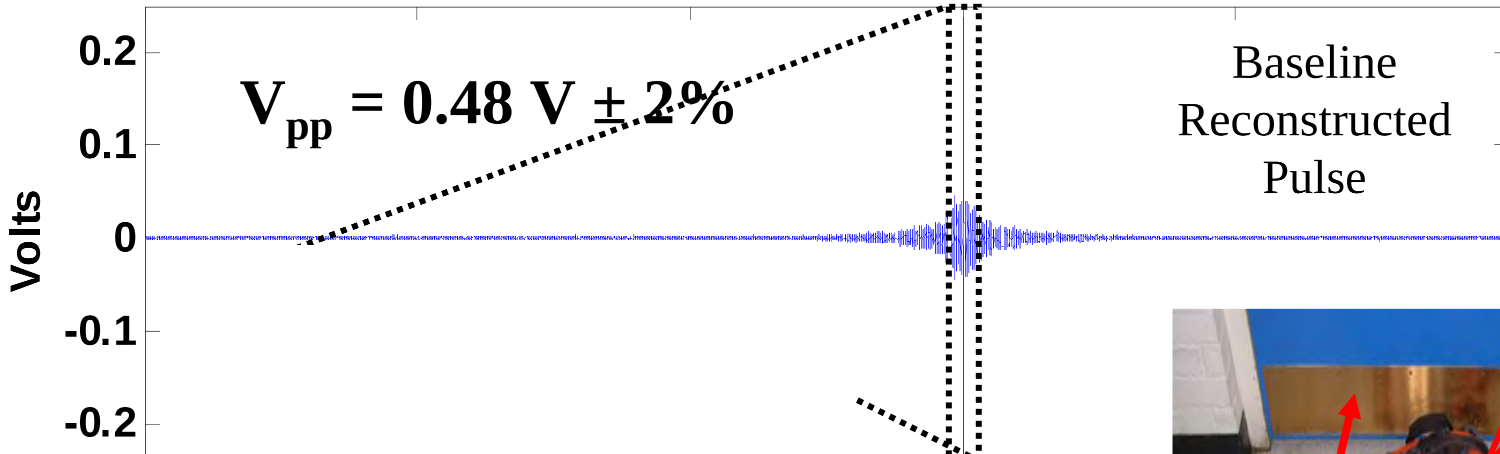
Acoustic pulse with a **7 kHz (λ~5 cm)** center frequency

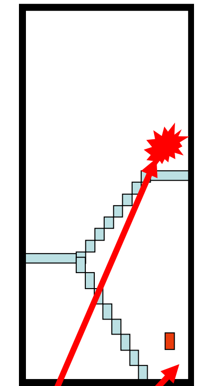
The wavelength controls the size of the intruder that can be detected.



Single-shot data

Acoustic CTRS: Effects of Perturbation

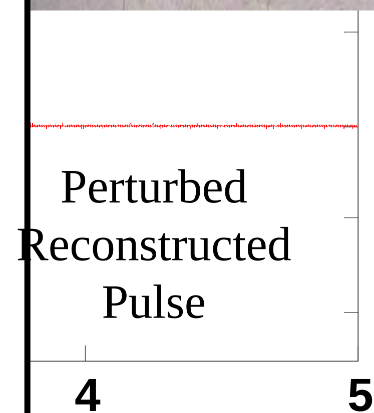




However, a far-away Perturbation is NOT detected by the simple CTRS!

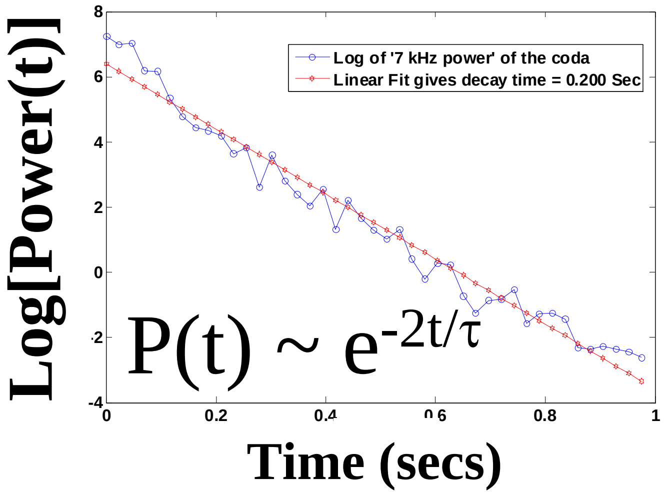
Acoustic waves suffer dissipation, breaking time-reversal invariance

An improvement is needed



Problem: Dissipation of Acoustic Waves inside the Stairwell

* Time-Reversal Invariance is lost *



1/e Decay Time τ = 0.2 sec
Consistent with Sabine's Formula:

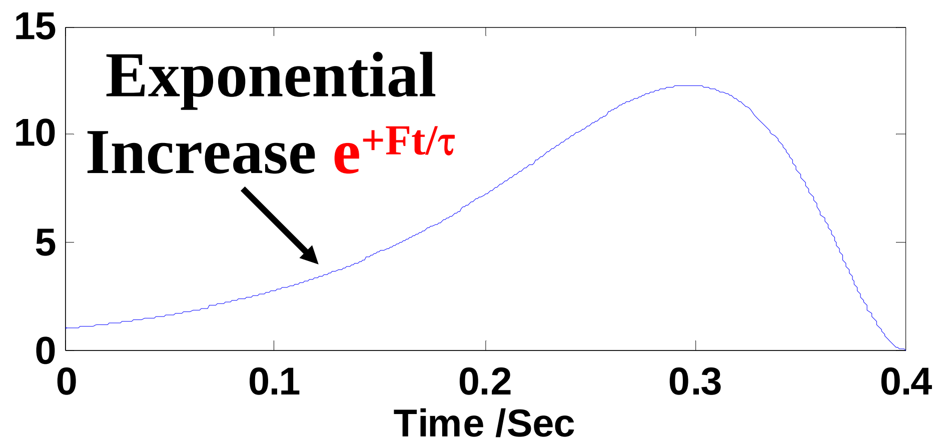
$$T_{reverberation} = 1.3\,\text{sec}$$

(60 dB decay time)

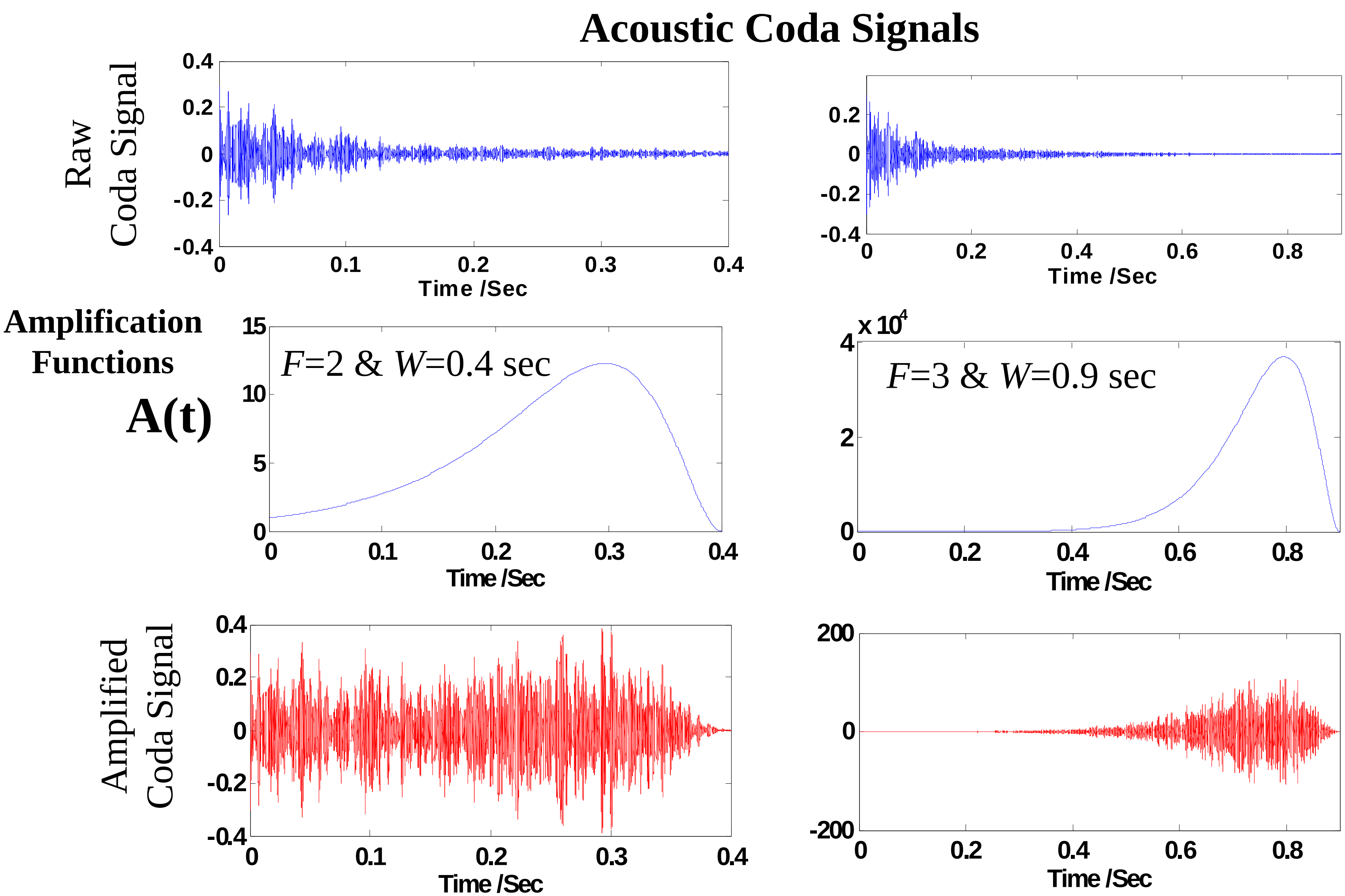
Solution: Exponential Amplification to overcome dissipation

Multiply the coda signal by an exponential $e^{+Ft/\tau}$ that is smoothly terminated after time *W*

$$A(t) = [1 - 4\left(\frac{t}{W}\right)^6 + 3\left(\frac{t}{W}\right)^8] * \exp\left(\frac{F*t}{\tau}\right)$$



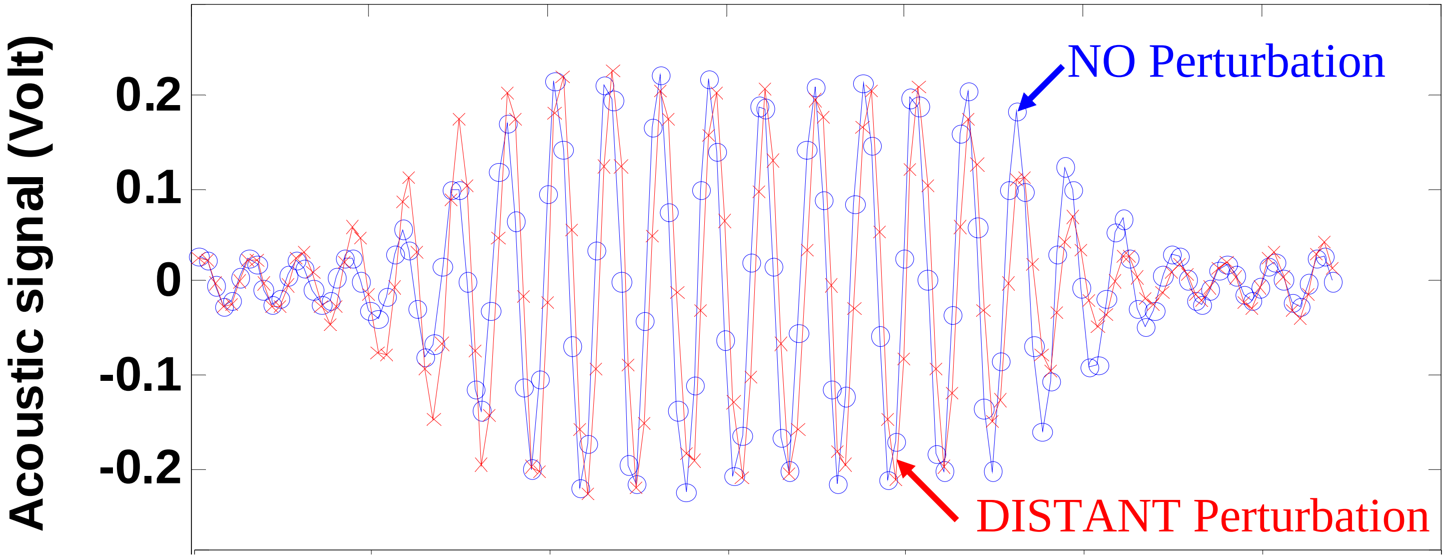
Solution: Exponential Amplification to overcome loss



Both of these amplified coda signals produce excellent detection for non-line-of-sight perturbations

Comparison of Reconstructed Acoustic Pulses with <u>Distant Perturbation</u>

Simple CTRS



Live Demonstration of the Acoustic CTRS

Step 0: Calibrate the CTRS for the particular enclosure and type of perturbation
- Already completed -

Step 1: Send 7 kHz, 2-ms-long pulse into room, record the resulting coda.
PLEASE KEEP QUIET!!! DON'T MOVE
Broadcast time-reversed coda into room and measure Baseline Reconstructed Pulse
Repeat (as a control experiment)

Step 2: **BACK ROW MOVE SLIGHTLY, BUT REMAIN QUIET (Perturbation 1)**
Broadcast time-reversed coda into room and measure Perturbed Reconstructed Pulse

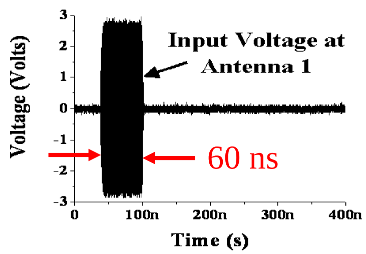
Step 3: **EVERYONE MOVE SLIGHTLY, BUT REMAIN QUIET (Perturbation 2)**
Broadcast time-reversed coda into room and measure Perturbed Reconstructed Pulse

Step 4: Compare the Baseline and Perturbed Reconstructed Pulses

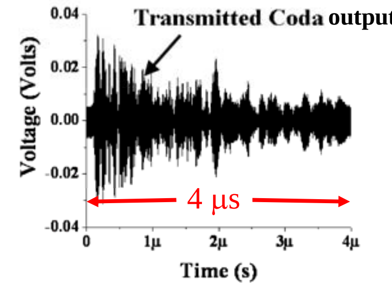
$$\frac{V_{p\text{-}p}\ \text{Perturbed Reconstructed Pulse}}{V_{p\text{-}p}\ \text{Baseline Reconstructed Pulse}}$$

Movie of Reconstructed Pulse Sensitivity to Perturbations in the Electromagnetic (GigaBox) Case

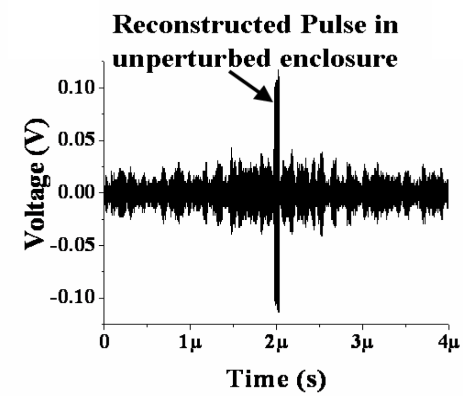
A 60-ns-long pulse of 7 GHz radiation has been sent into the GigaBox at Port 1



The coda signal is recorded at port 2

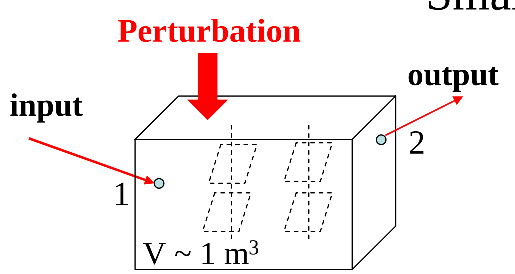


The time-reversed coda signal is played back at port 2



A reconstructed pulse is detected at Port 1

Small perturbations are made to one wall of the GigaBox



Reconstructed Pulse Movie, Take 2

Conclusions

A new sensor paradigm has been developed based on the extreme sensitivity of wave chaotic systems to small perturbations

The properties of Time-Reversal invariance and Spatial Reciprocity have been exploited to simplify the sensor

The sensor has been demonstrated with both acoustic and electromagnetic waves
The acoustic sensor can be made small and inexpensive

Exponential amplification can be used to dynamically change the range of sensitivity of the sensor

Some Background Publications:

S. Hemmady, *et al*., Phys. Rev. Lett. 94, 014102 (2005)
S. M. Anlage, *et al*., Acta Physica Polonica A 112, 569 (2007)

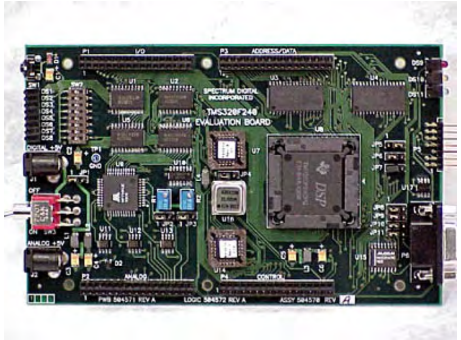
http://www.csr.umd.edu/anlage/AnlageQChaos.htm

Many thanks to: E. Bradshaw, R. Prange, S. Fishman, M. Fink, A. Richter, F. Schafer, S. Hemmady

Future Plans

Simplify the acoustic CTRS
- Integrate ultrasonic piezos and Digital Signal Processing card into a small package
- Repetitive averaging to improve signal/noise

Spectrum Digital
DSP Card



Multiple CTRS sensors connected in a network
- Localize the position and size of the perturbation

Wavelength Diversity
- Sense perturbations of different size
- More sophisticated waveforms to dynamically probe different length scales

Basic Research on quantifying perturbations
- How does scattering fidelity decay with different types of perturbations?