EMC+SIPI 2018
July 30 - August 3, 2018 Long Beach, CA

2018 IEEE SYMPOSIUM ON ELECTROMAGNETIC COMPATIBILITY, SIGNAL AND POWER INTEGRITY
YOUR PORT FOR EMC+SIPI COMPLIANCE

Unique Applications of Time-Reversed Electromagnetic Waves

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Physics and ECE Departments, University of Maryland

EMC + SIPI
Long Beach, CA
30 July, 2018

U.S. NAVAL RESEARCH LABORATORY

Outline

Time-Reversal Invariance of the Wave Equation

in a domain
without source →

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

Time-Reversal Invariance of the Wave Equation

in a domain
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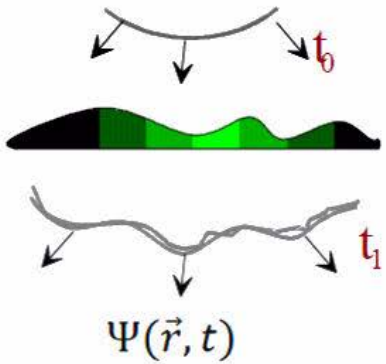
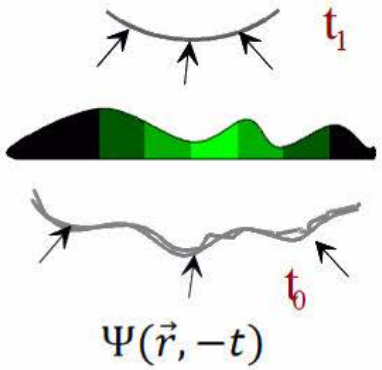
This equation contains $\frac{\partial^2\Psi}{\partial t^2}$

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

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

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





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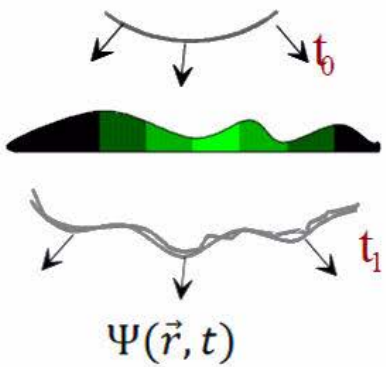

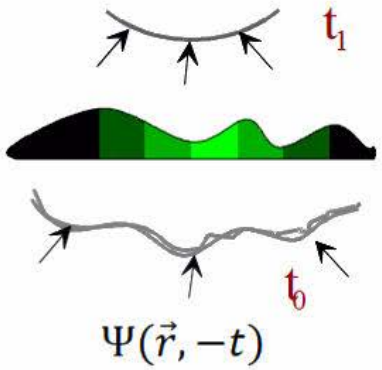

Classical (macroscopic) wave equations usually include dissipation, destroying TRI

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

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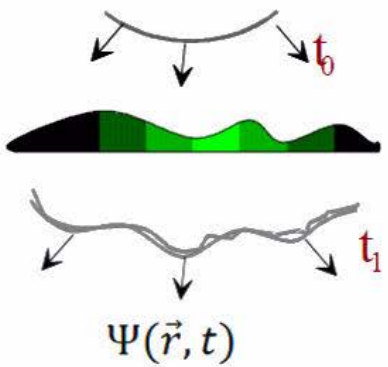
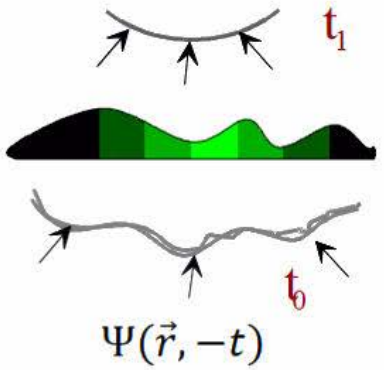




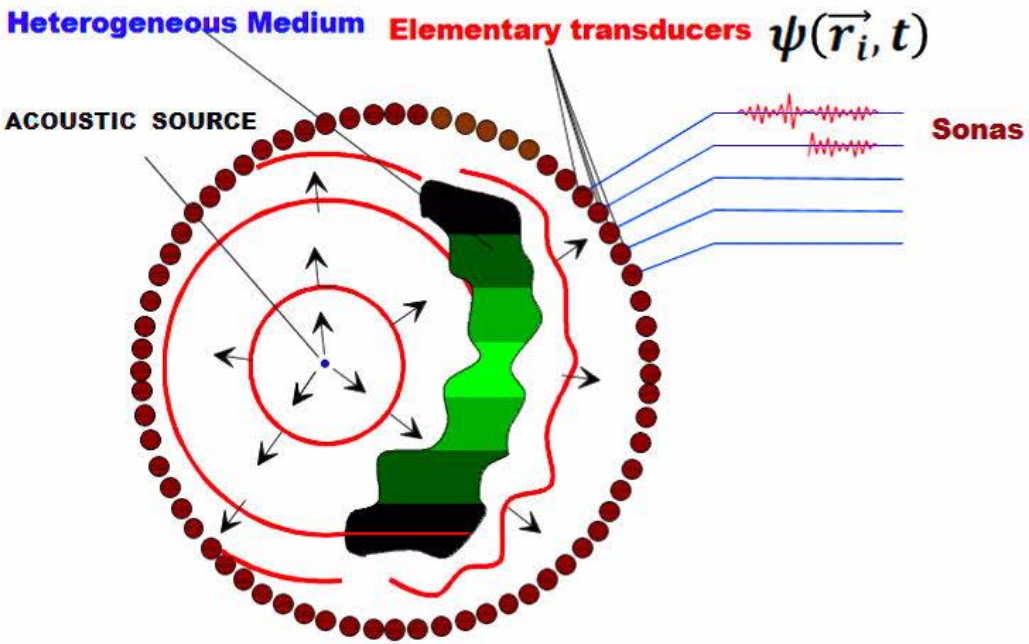
Classical (macroscopic) wave equations usually include dissipation, destroying TRI

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

But lossy classical waves still display coherent behavior …

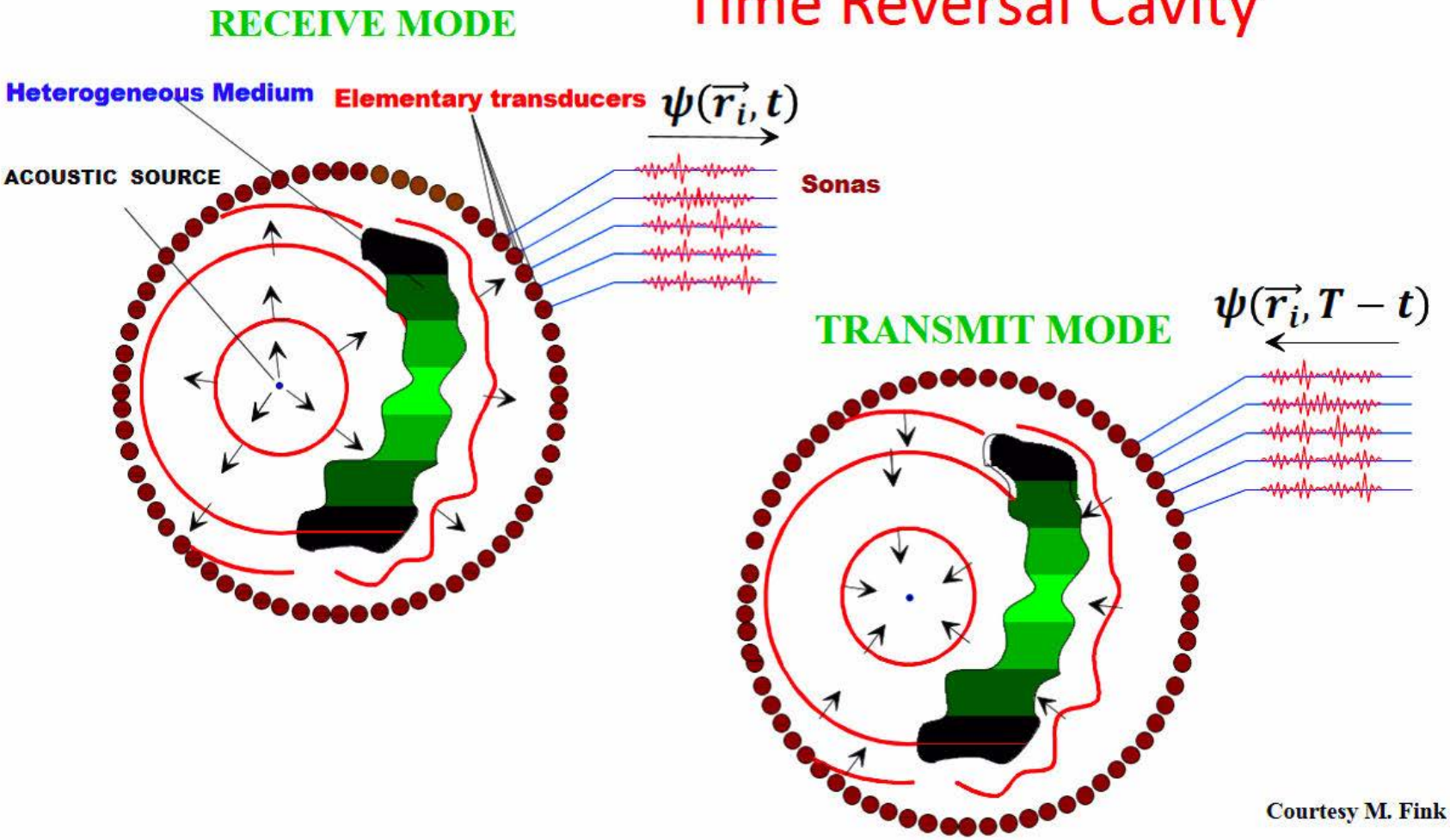
Time Reversal Cavity

RECEIVE MODE



Courtesy M. Fink

Time Reversal Cavity



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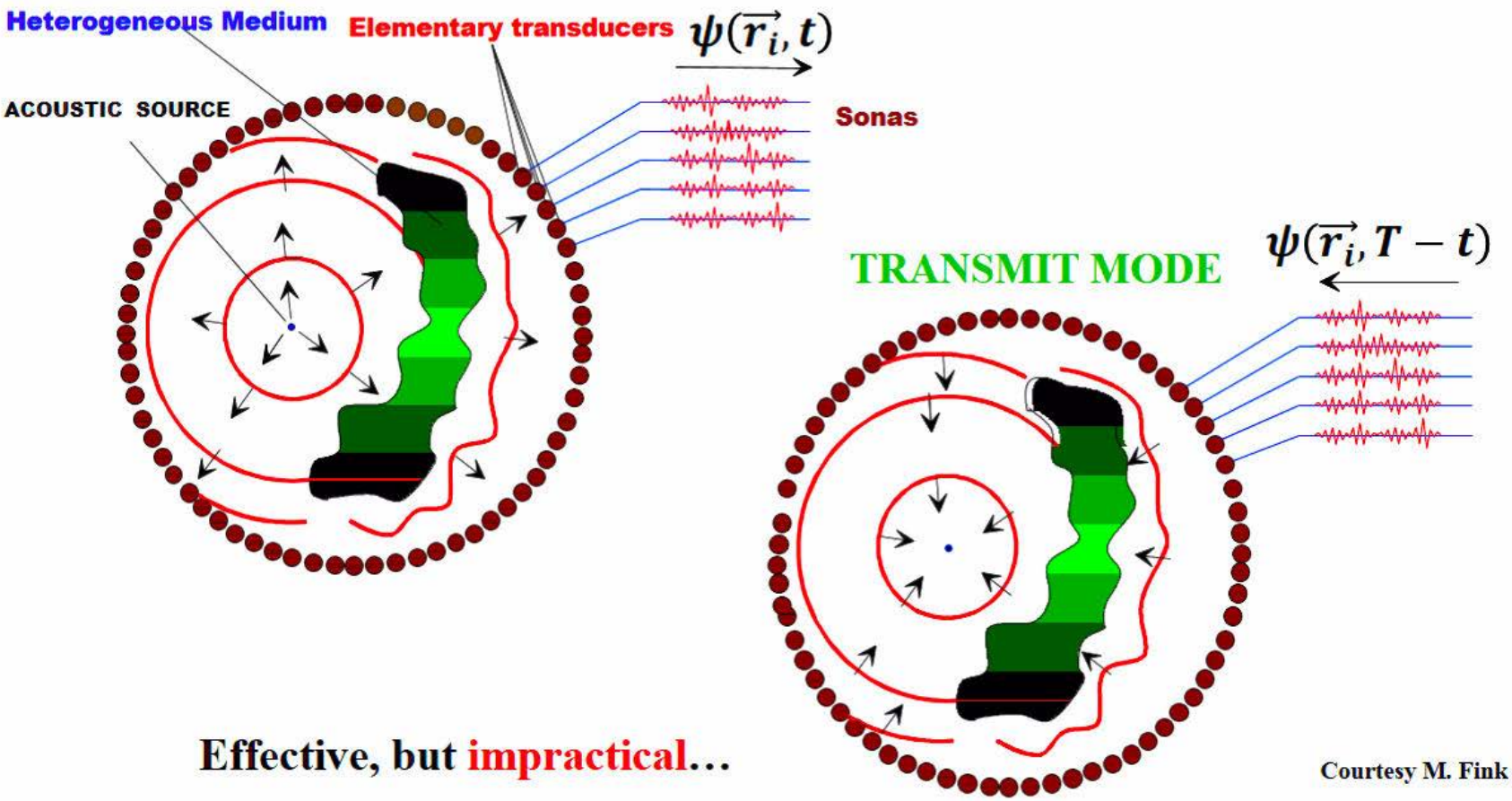


Effective, but impractical…

Courtesy M. Fink

There have to be 'smarter' ways to exploit time-reversal invariance…

Outline

Introduction

Time-Reversal Mirrors

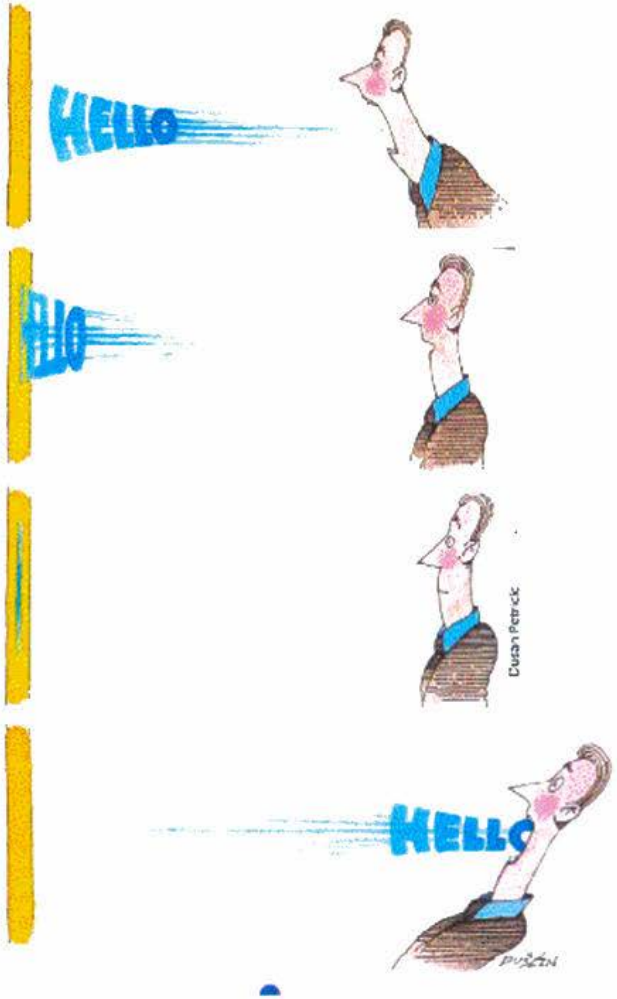
- **The Ordinary Time-Reversal Mirror**
  - **The Chaotic Time-Reversal Sensor (CTRS)**
- **Nonlinear Time-Reversal Mirror**
- **Applications of Time-Reversal Mirrors**
  - **Synthetic Sonas for Reconstruction at an Arbitrary Location**
  - **Wireless Power Transfer**

Future Plans

Time-Reversal and EMC

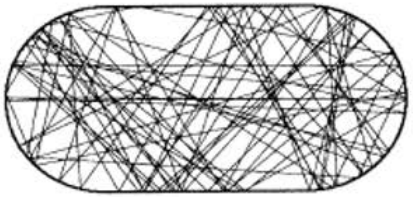
Conclusions

Concept of a Time-Reversal Mirror



Consider Wave Propagation in Ray-Chaotic Enclosures

Propagation of a Gaussian Wave Packet



The two-dimensional Stadium Billiard
shows Ray Chaos

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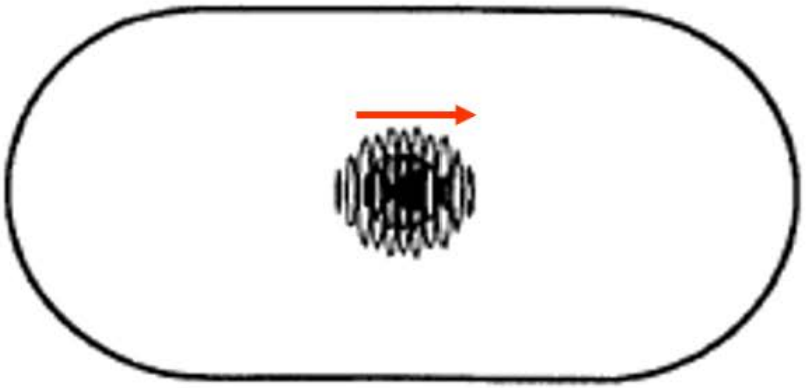

t/T = 0, 0.5, 1, 2, 6

T = time to propagate along horiz. axis

Tomsovic+Heller PRE 47, 282 (1993)

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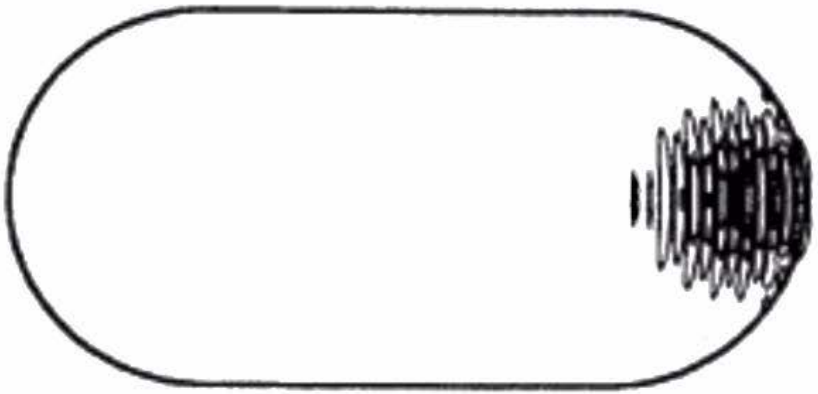

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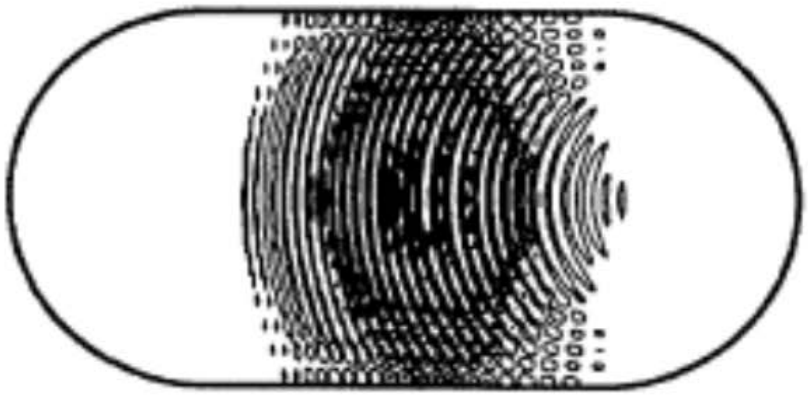

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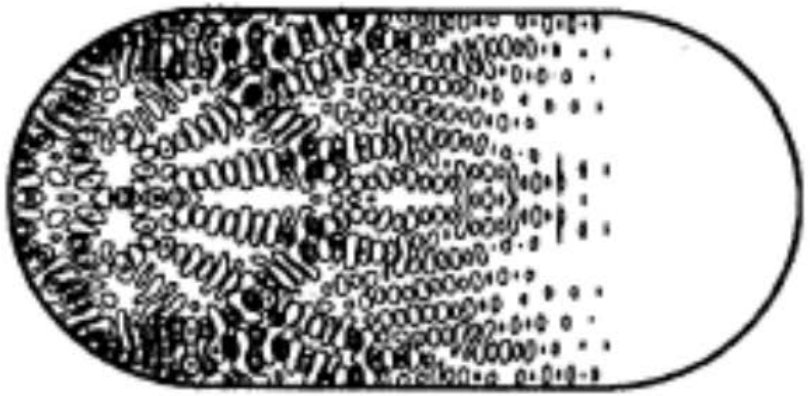

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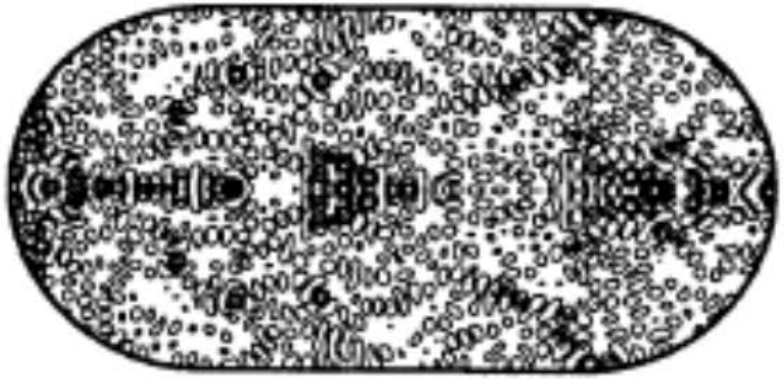

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Ray-Chaos-Enabled Time Reversal Mirror

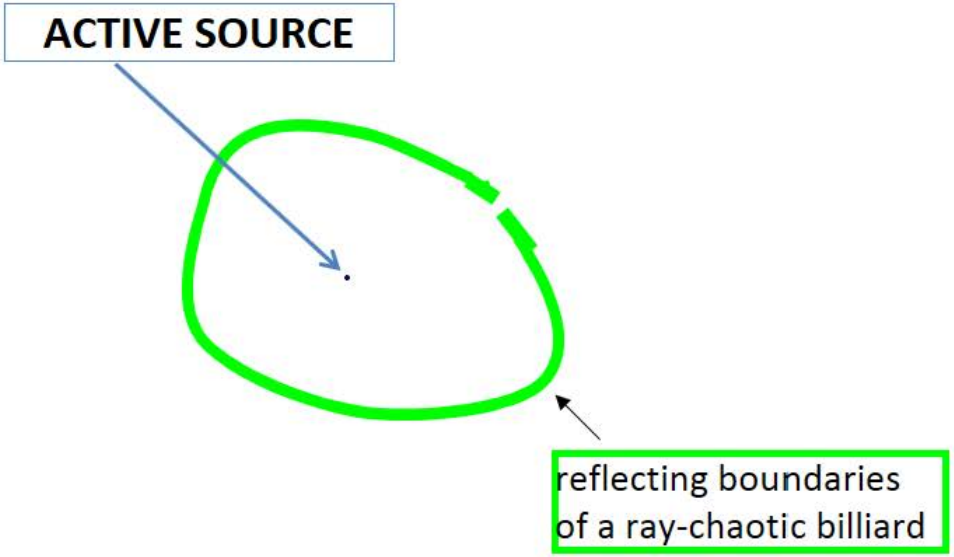
A simple 'time reversal mirror'

Ray-Chaos-Enabled Time Reversal Mirror

A simple 'time reversal mirror'

Ray-Chaos-enabled Single-Channel Time Reversal Mirror

Draeger and Fink PRL 1997



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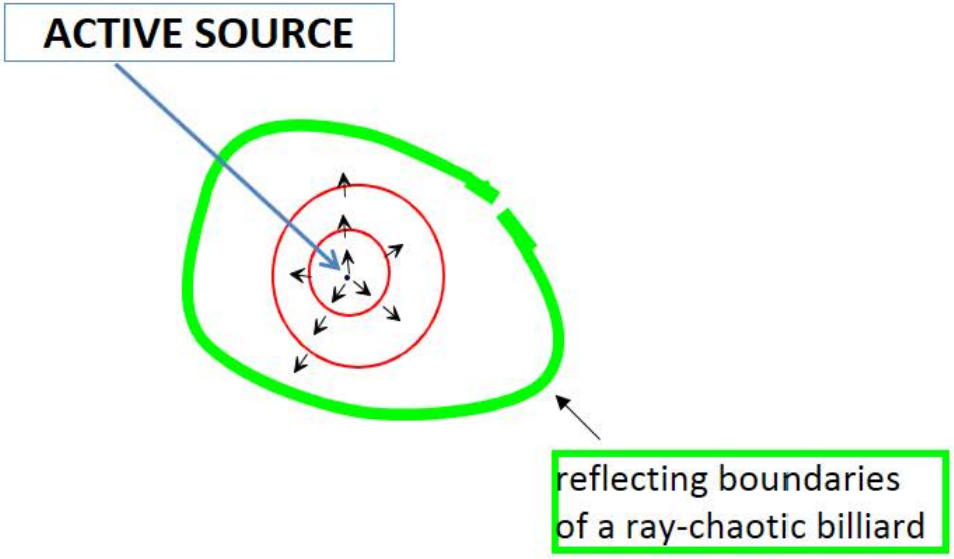

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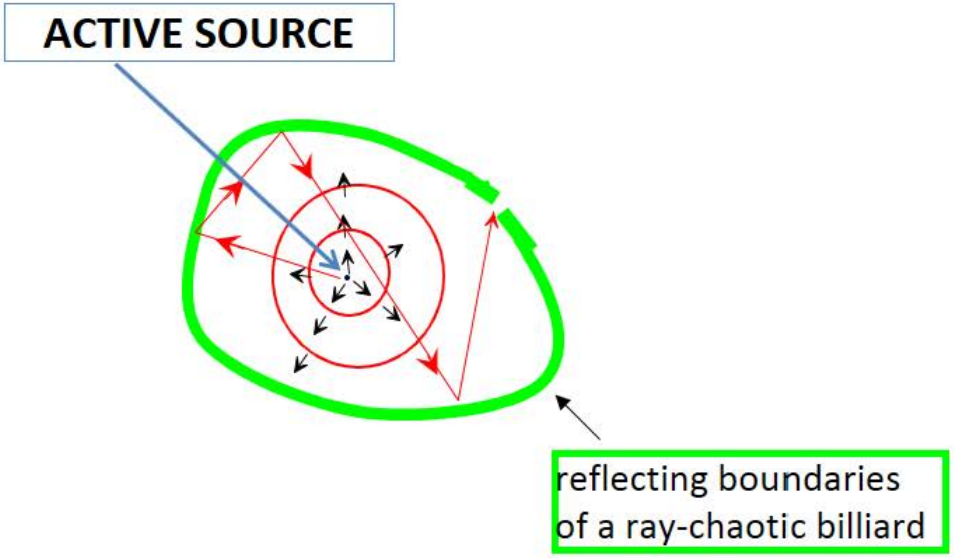

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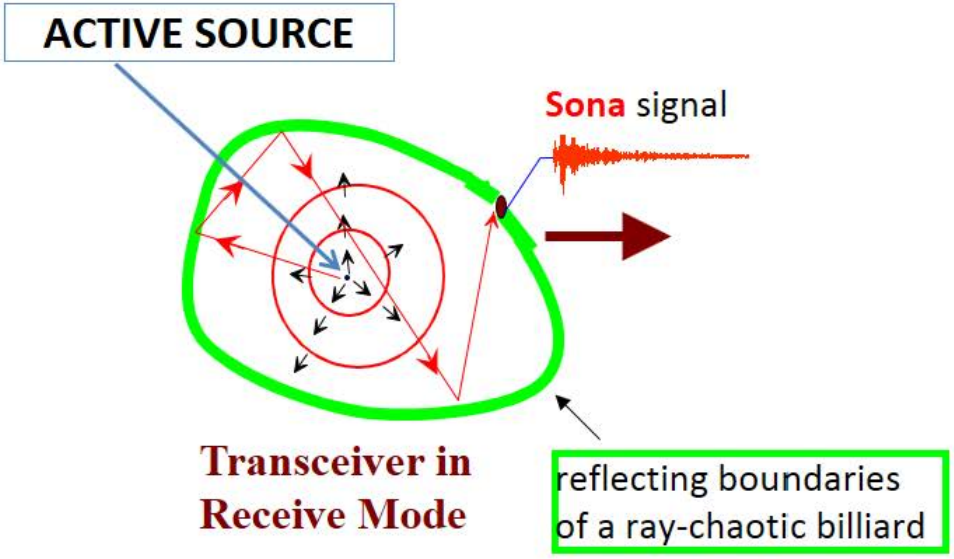

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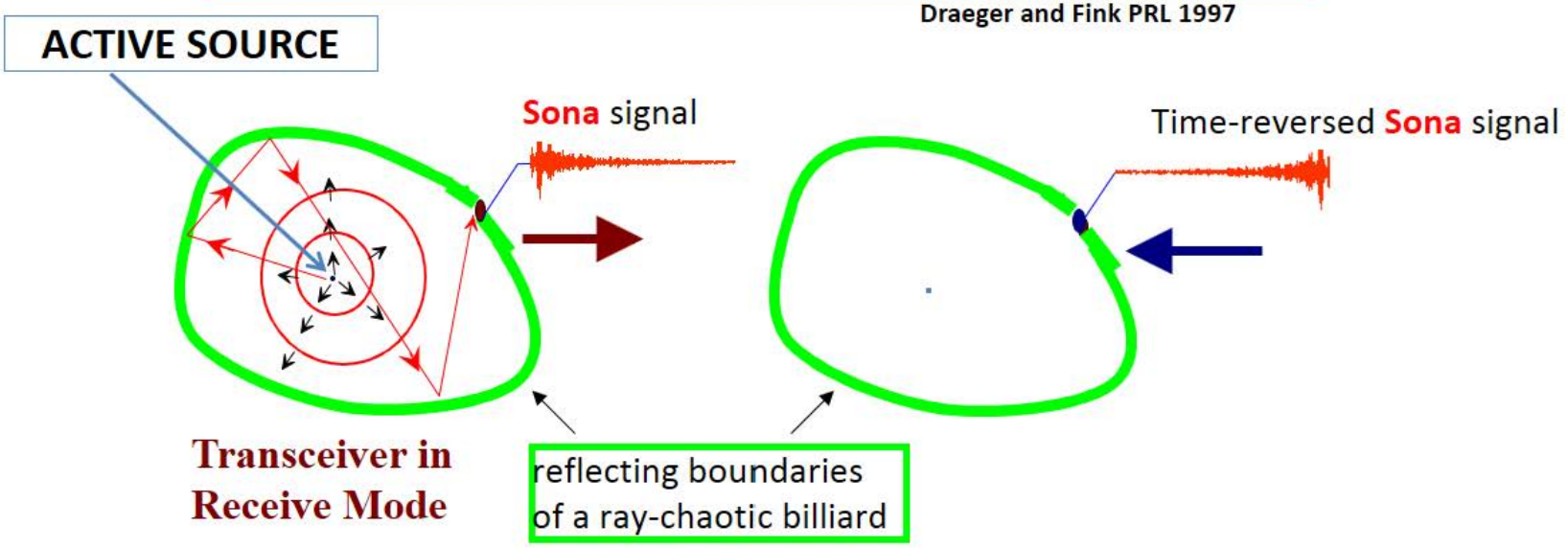

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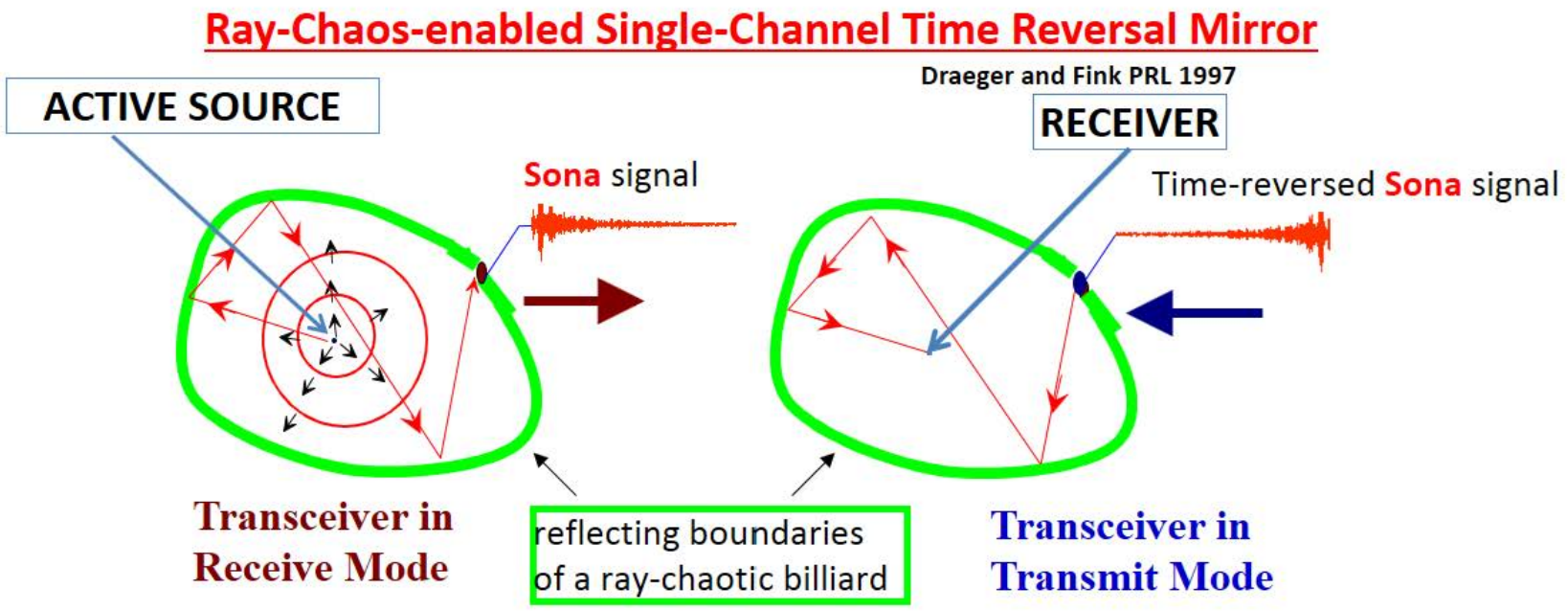

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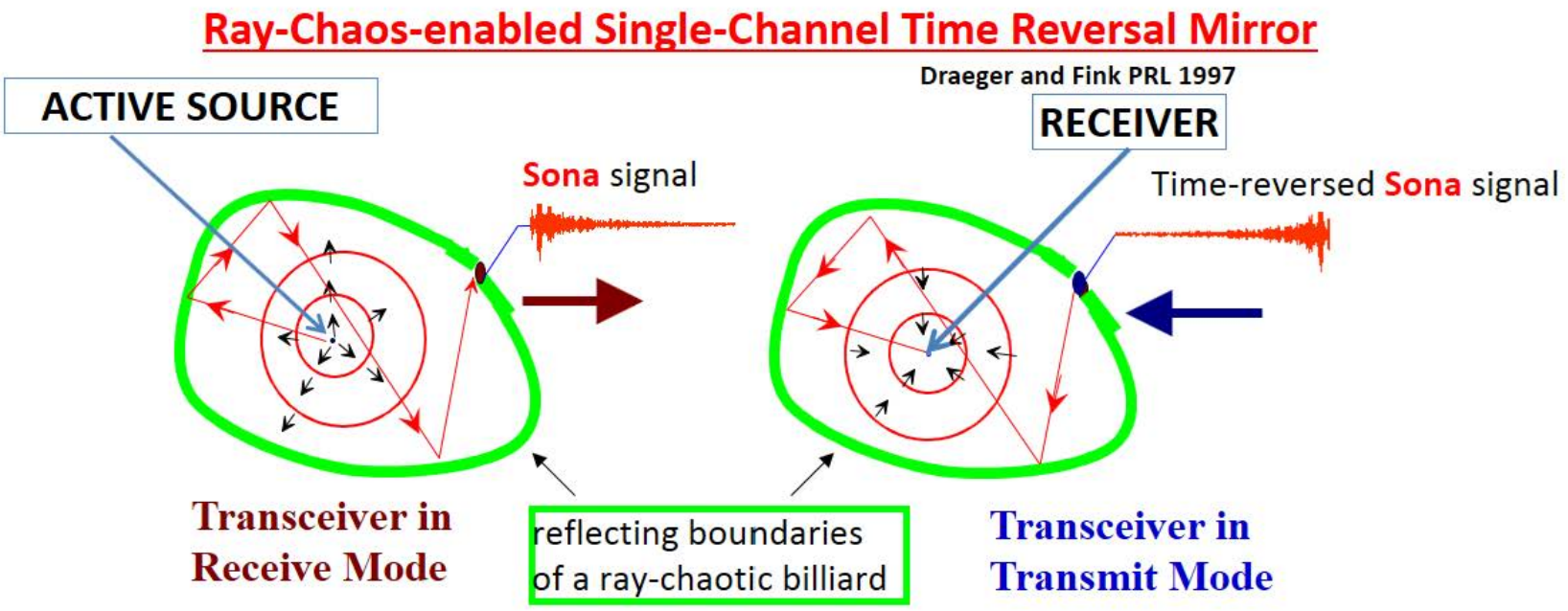

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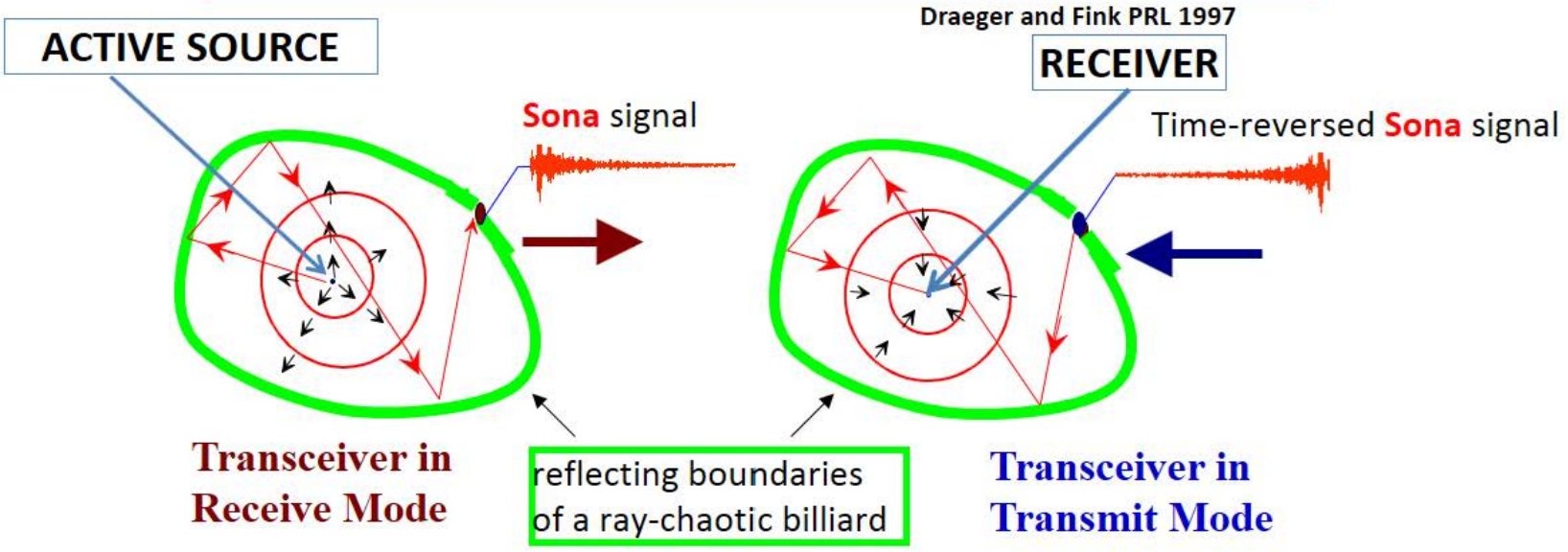
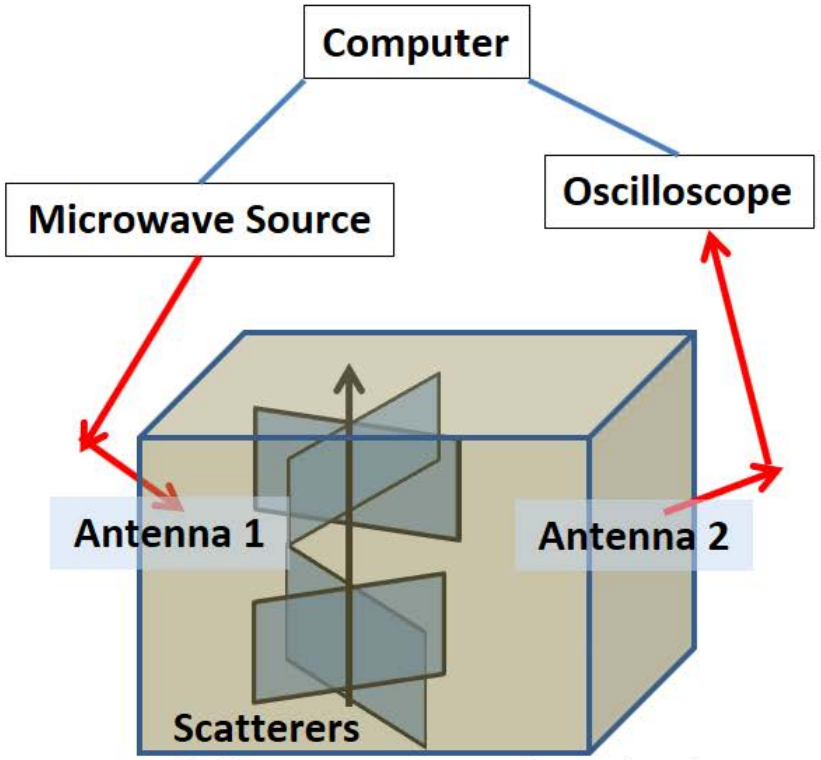


Even though only a small fraction of energy is actually measured, the reconstruction can be very good …

Image courtesy of M. Fink

Electromagnetic Time-Reversal Mirror Experimental Setup

Ordinary Time-Reversal Mirror



$1m^3$ aluminum cavity (Gigabox)

$\lambda \sim 4$ cm

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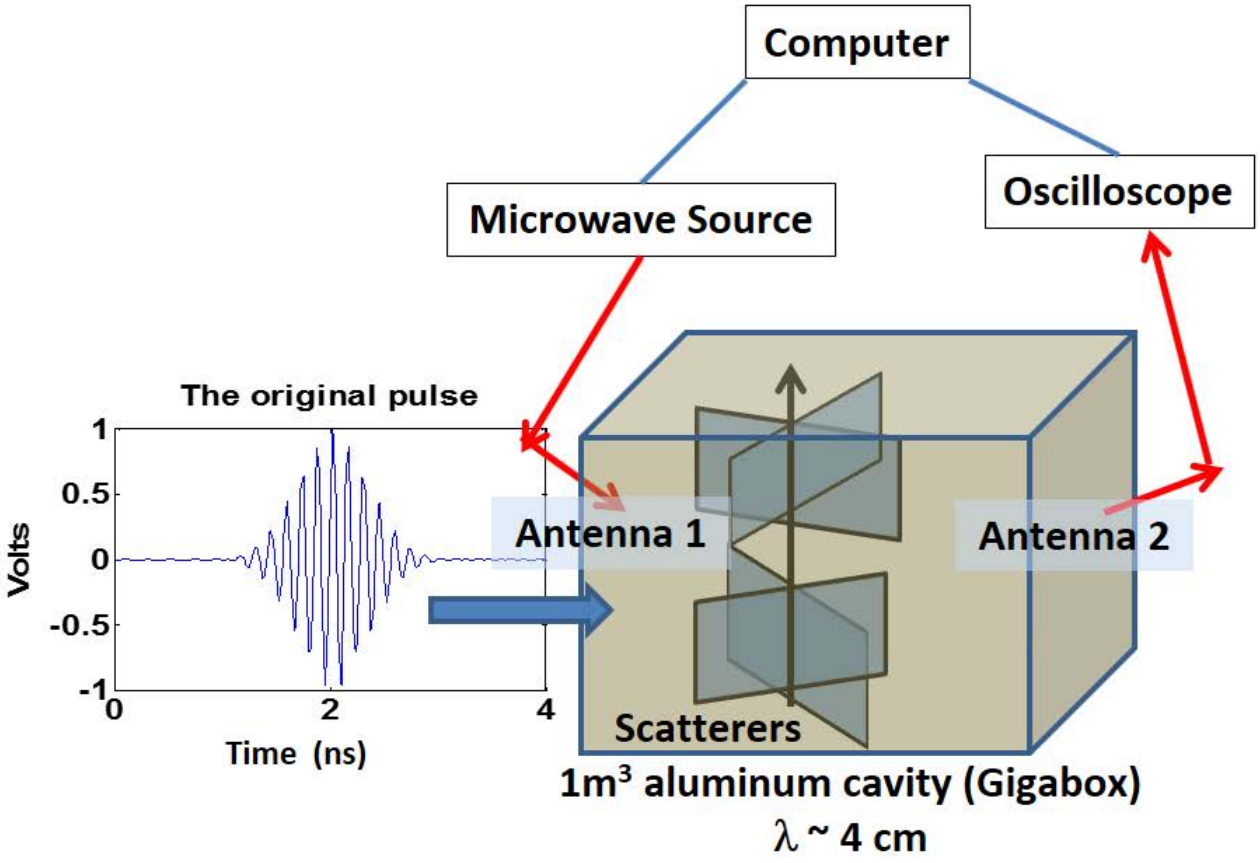

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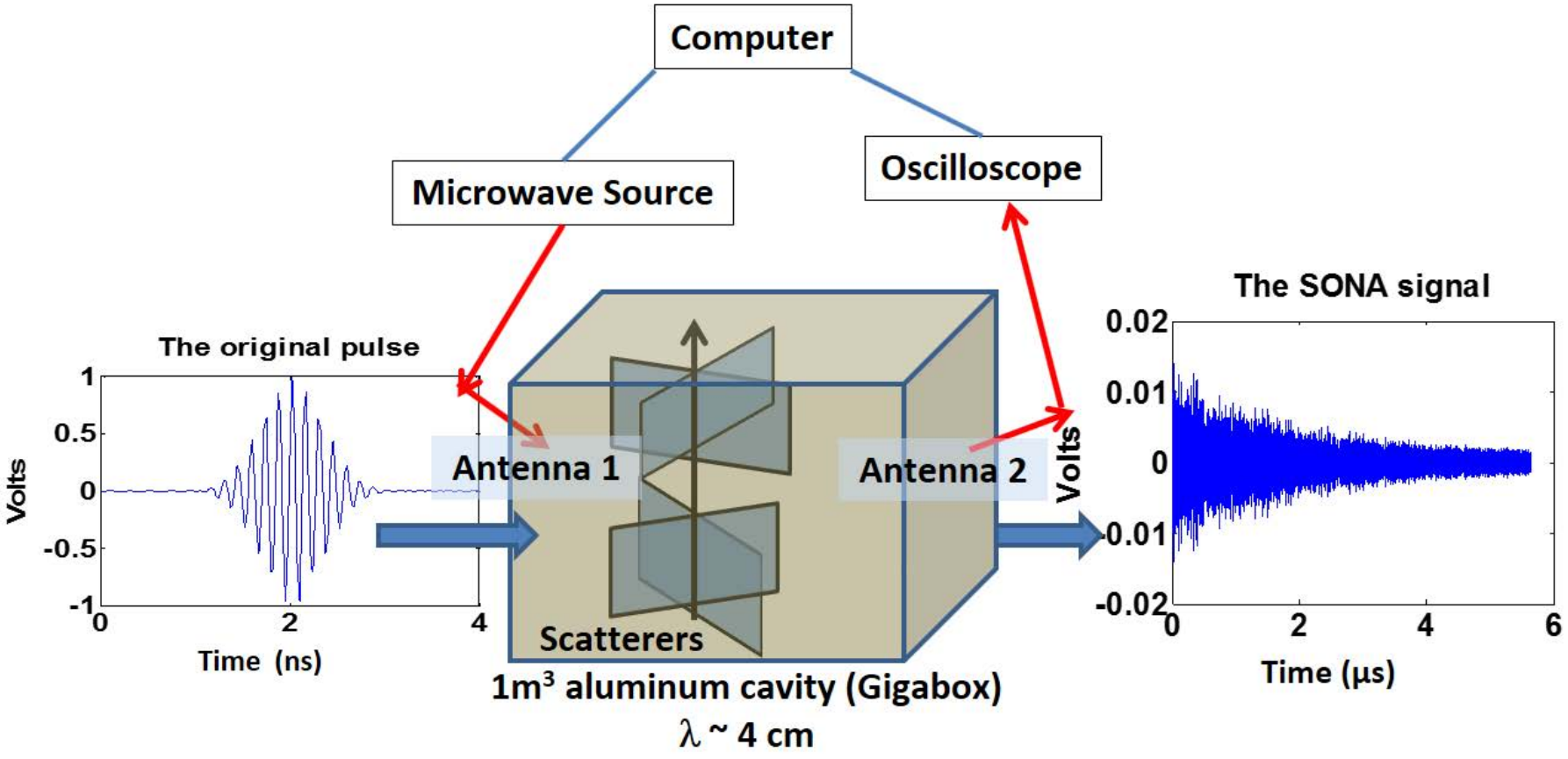

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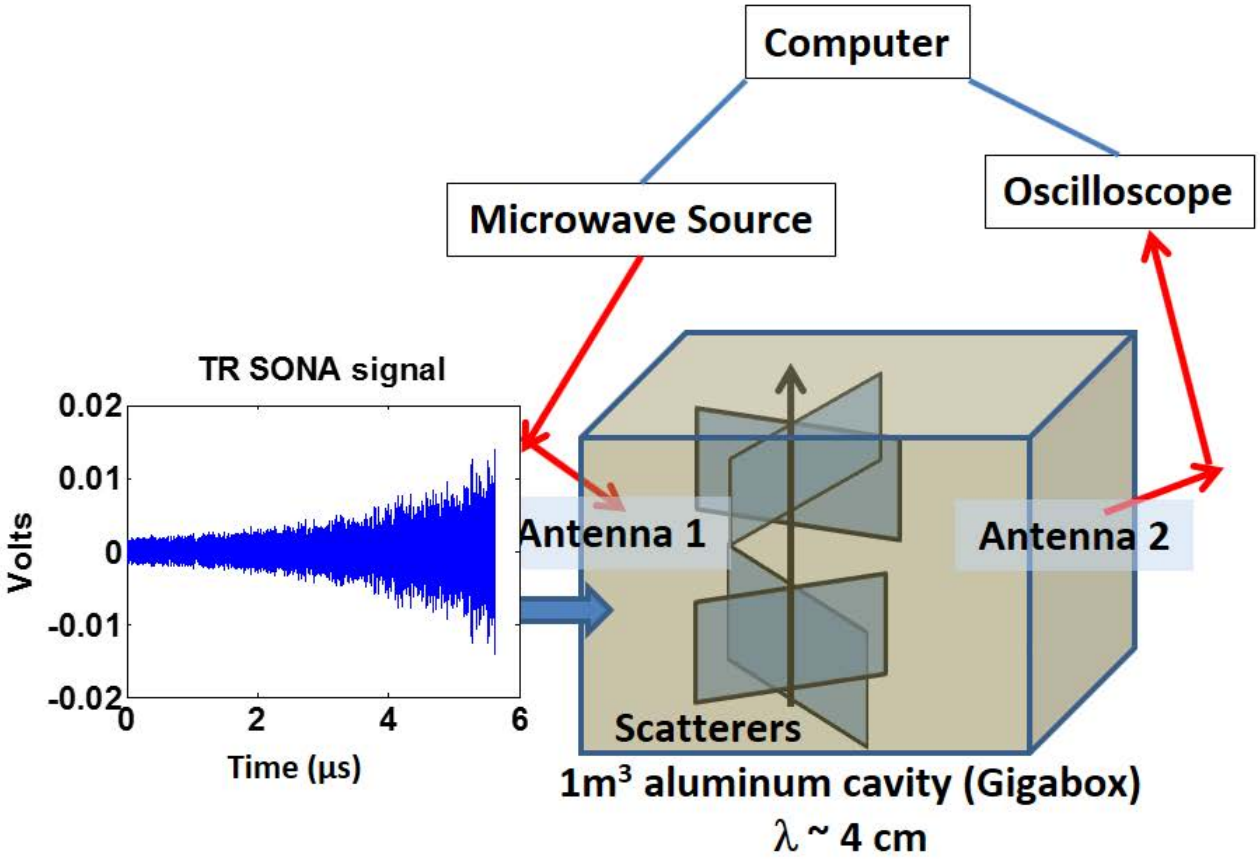
Ordinary Time-Reversal Mirror

Spatial Reciprocity of the wave equation is used to simplify the experiment



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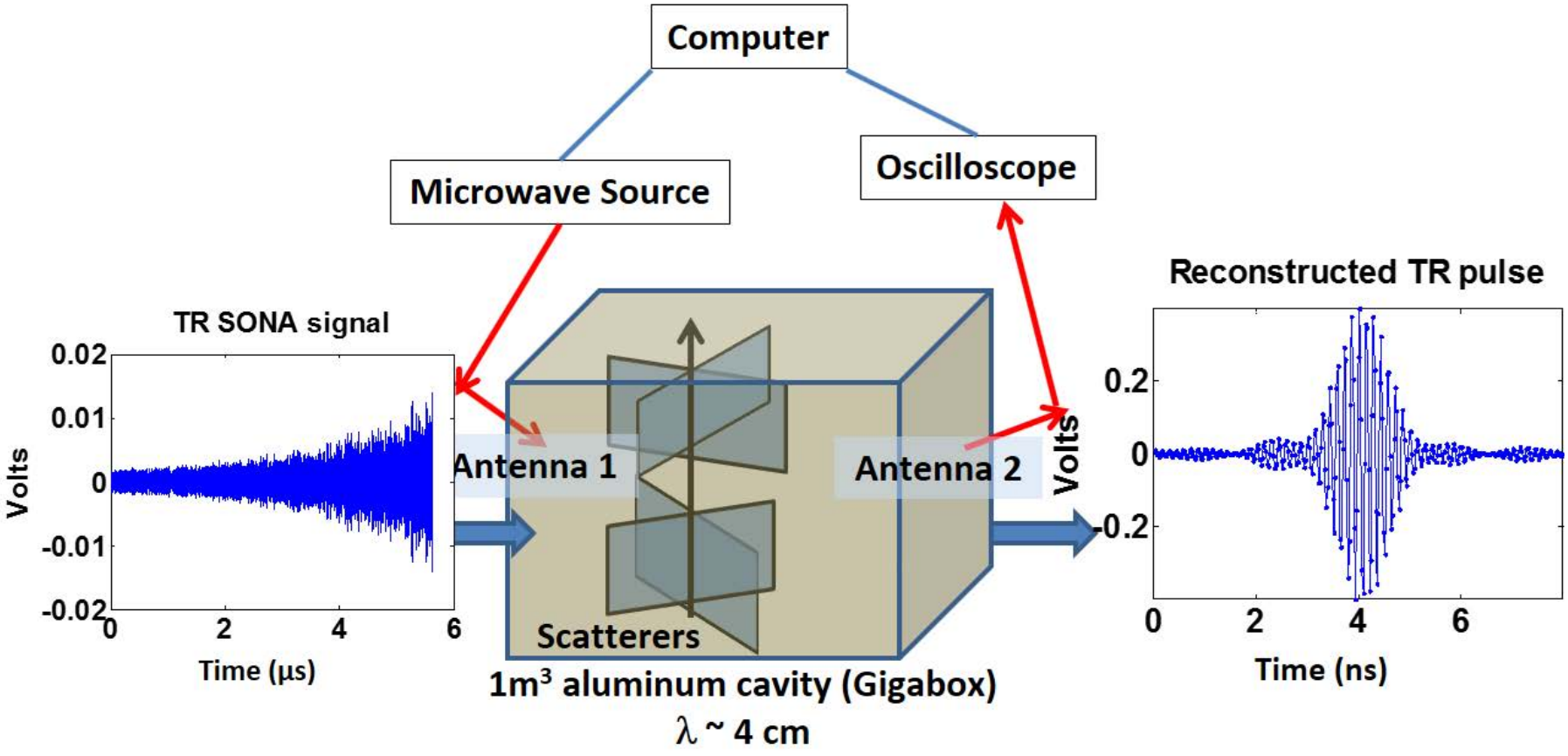

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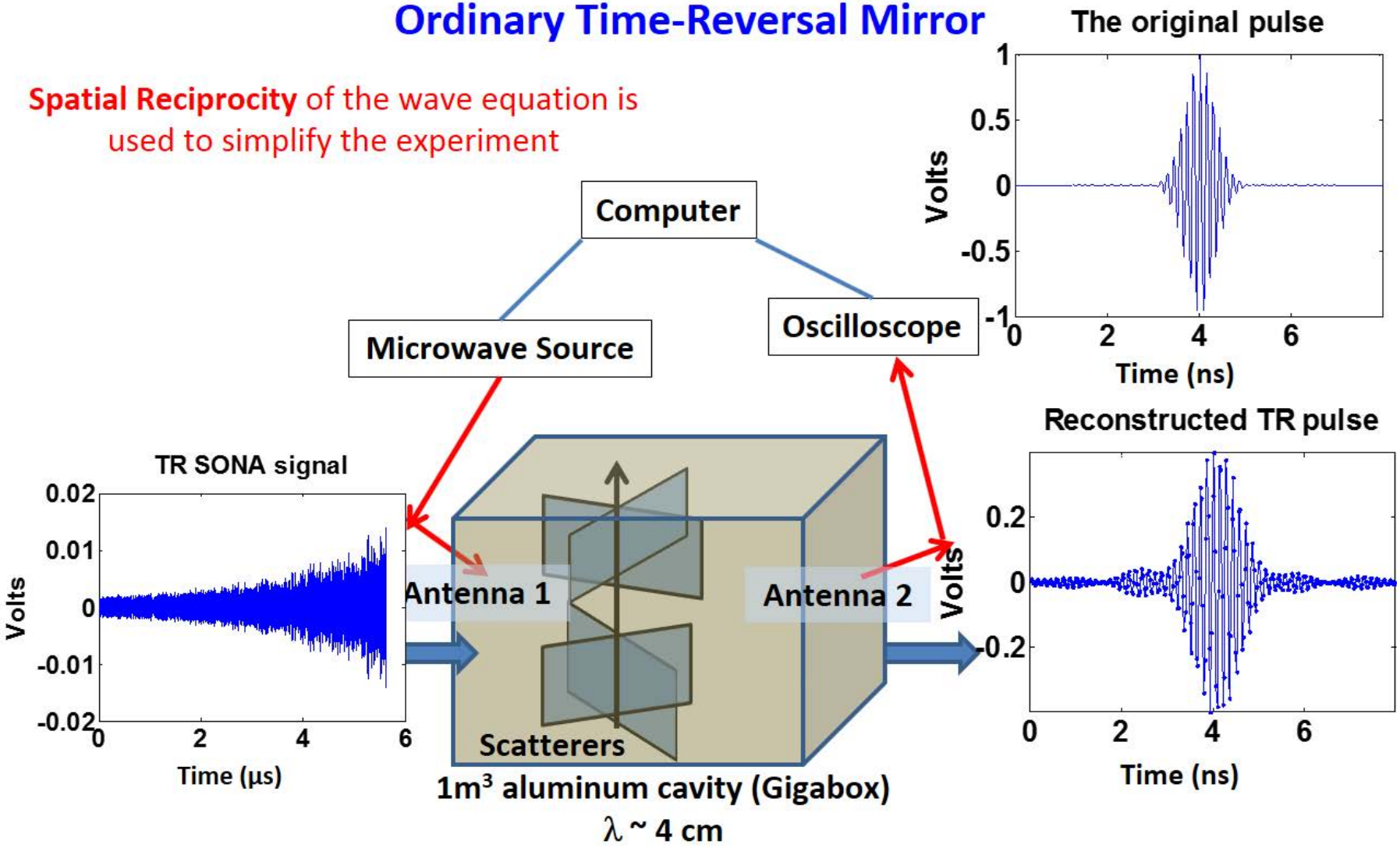
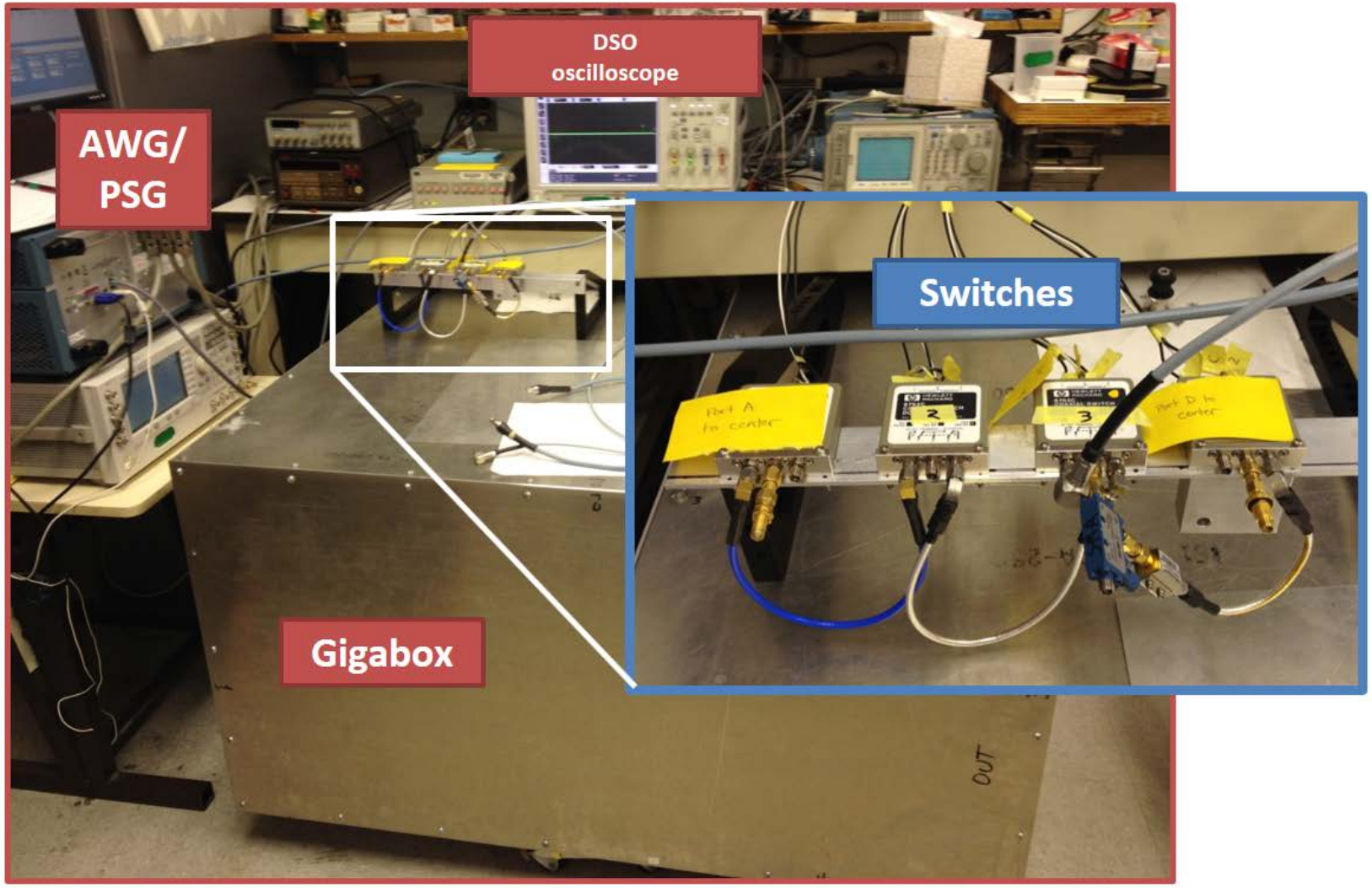
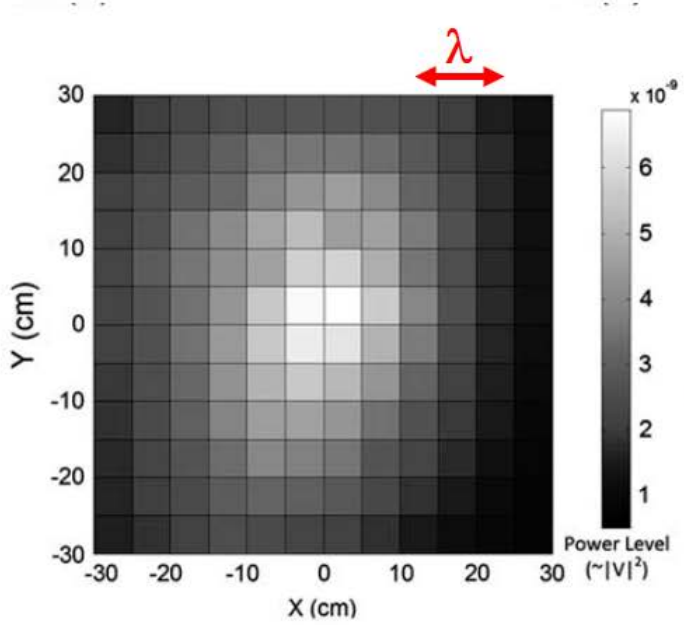


Automated Time-Reversal Experiment



The Reconstruction is Also Localized in Space



Field Strength of Reconstruction

J. of Electromagnetic Waves and Applications **27**, 1262 (2013)

Focusing an arbitrary RF pulse at a distance using time-reversal techniques

Sun K. Hong[a]*, Biniyam T. Taddese[b], Zachary B. Drikas[a], Steven M. Anlage[b] and Tim D. Andreadis[a]

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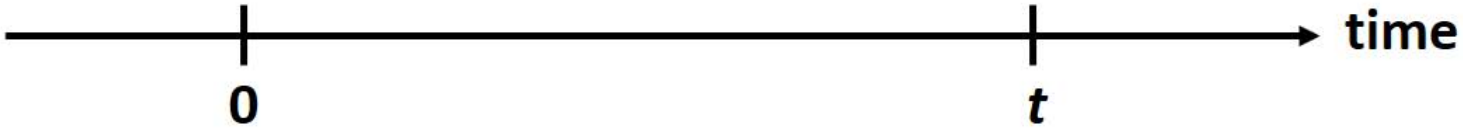
Time-Reversal and EMC

Conclusions

Wave Chaos in the Time-Domain

Extension of Quantum Fidelity to Classical Waves

Loschmidt Echo:



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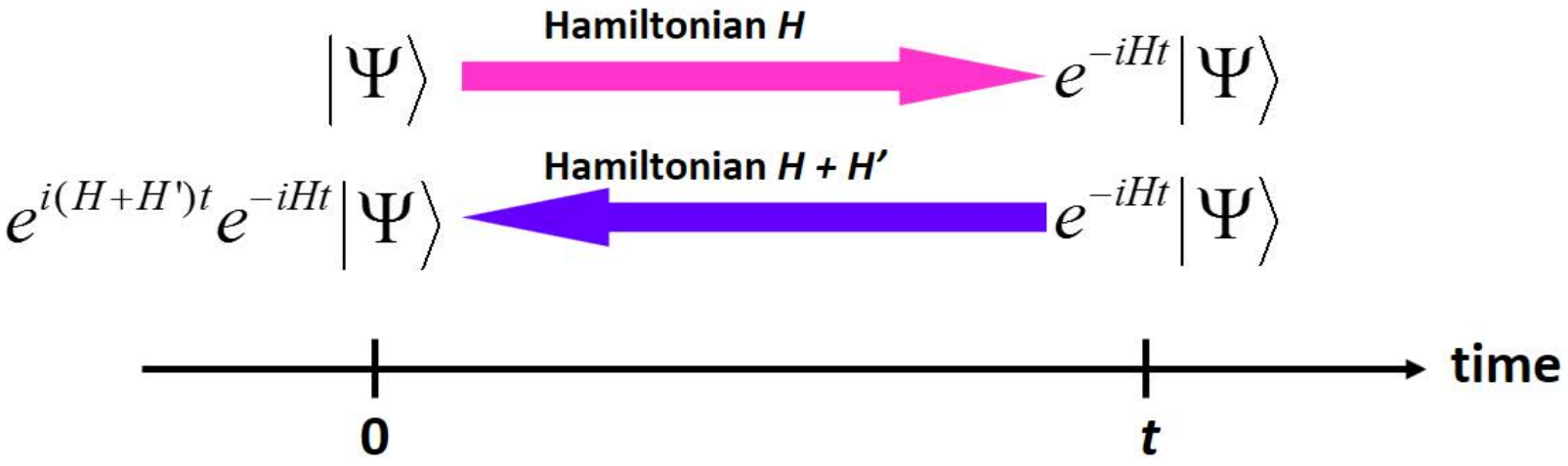

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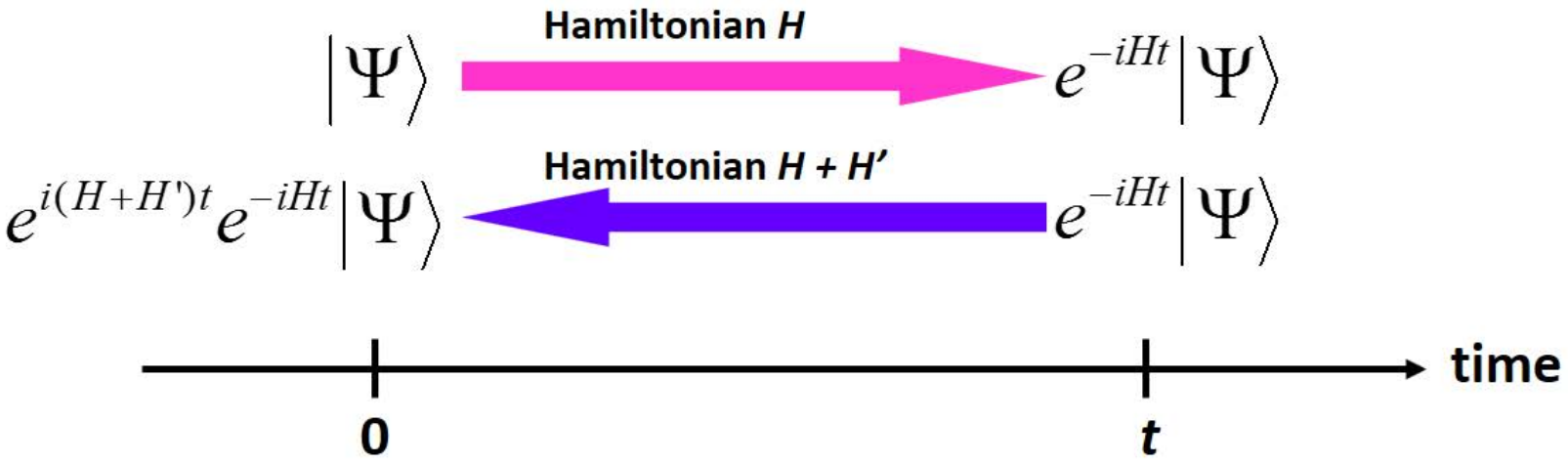

Fidelity Amplitude

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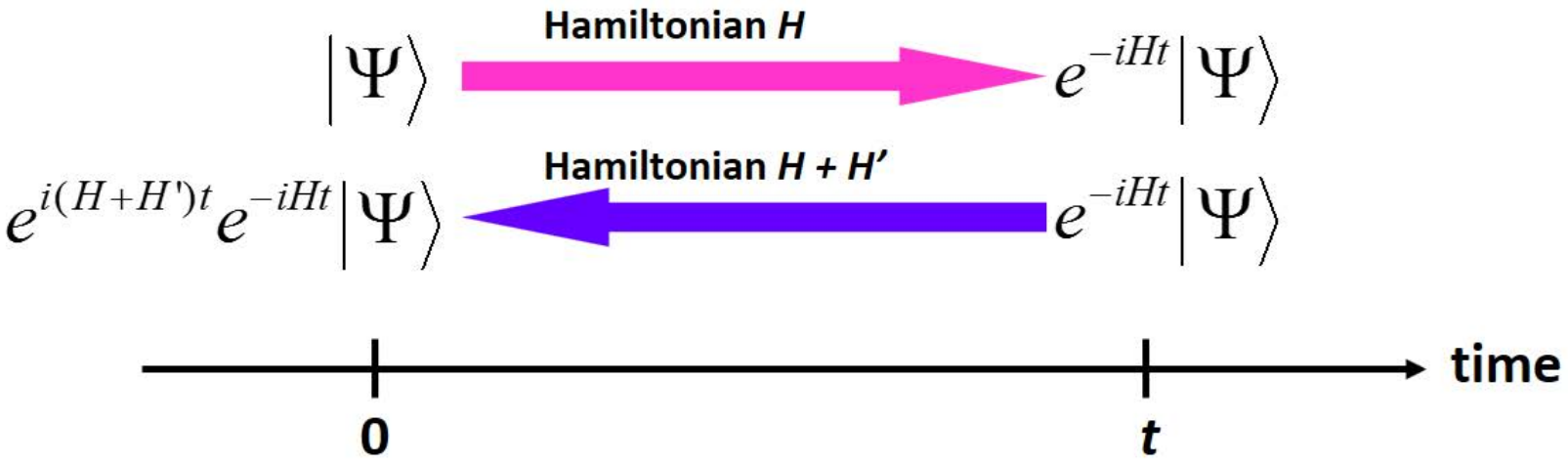
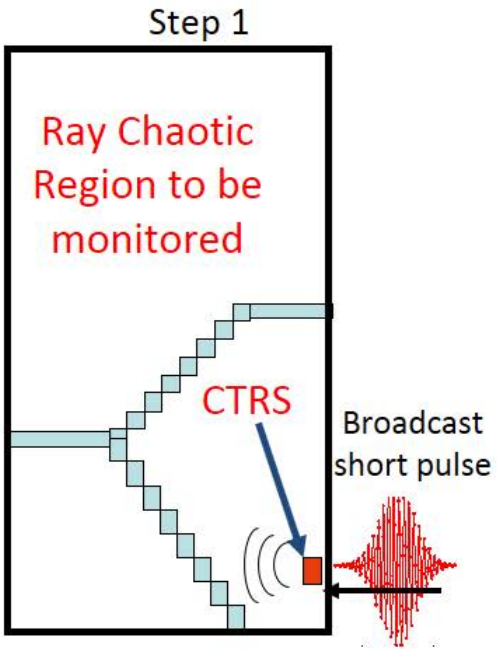


Fidelity Amplitude

$$f_{H'}(t) = \langle \Psi | e^{i(H+H')t} e^{-iHt} | \Psi \rangle$$

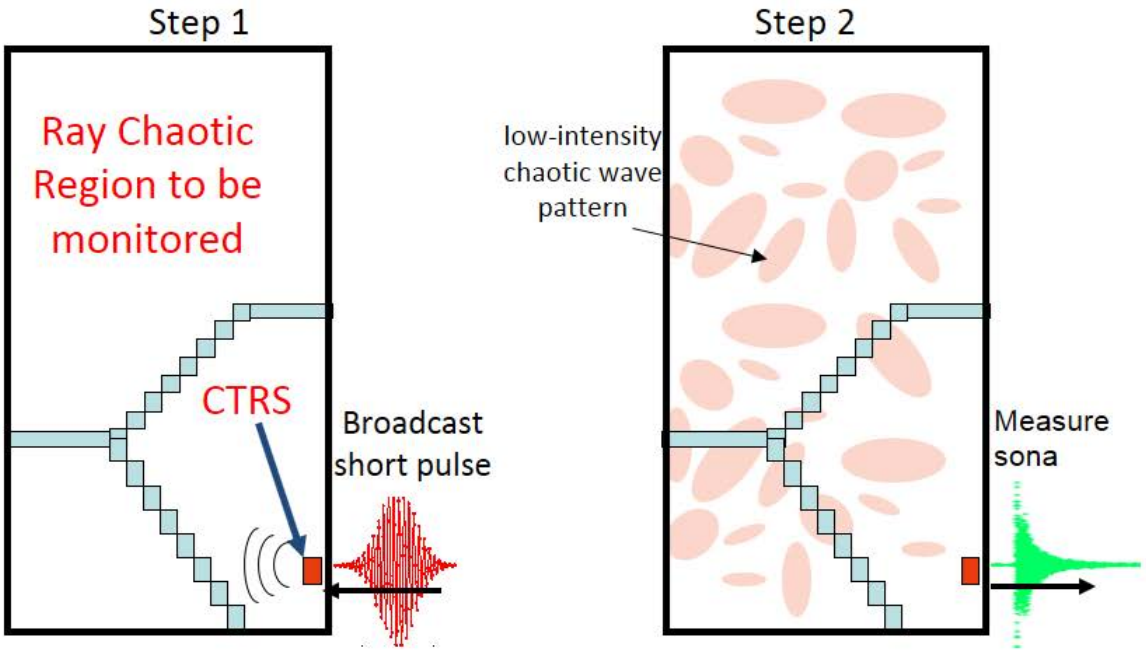
Fidelity decays rapidly (~exponentially in time), particularly for classically chaotic systems

Apply this concept to classical waves:
"Chaotic Time-Reversal Sensor"



Operation of an Acoustic version of the Chaotic Time-Reversal Sensor

US Patent 9424665



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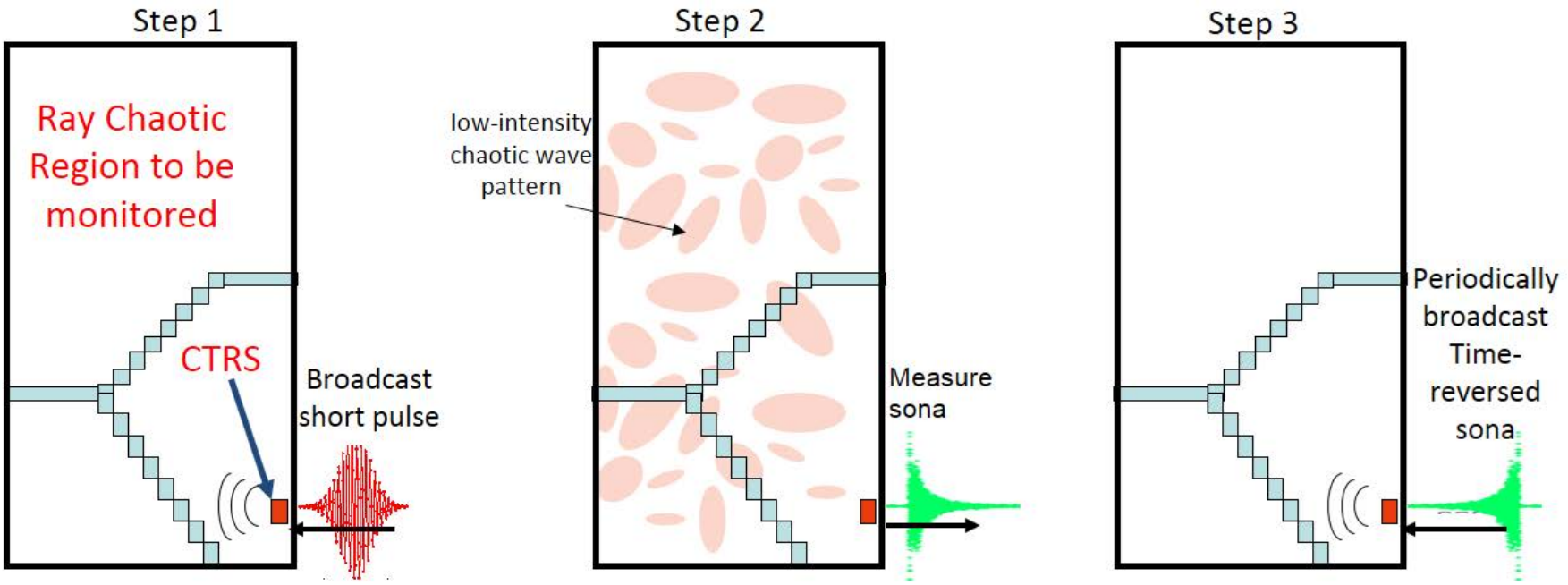

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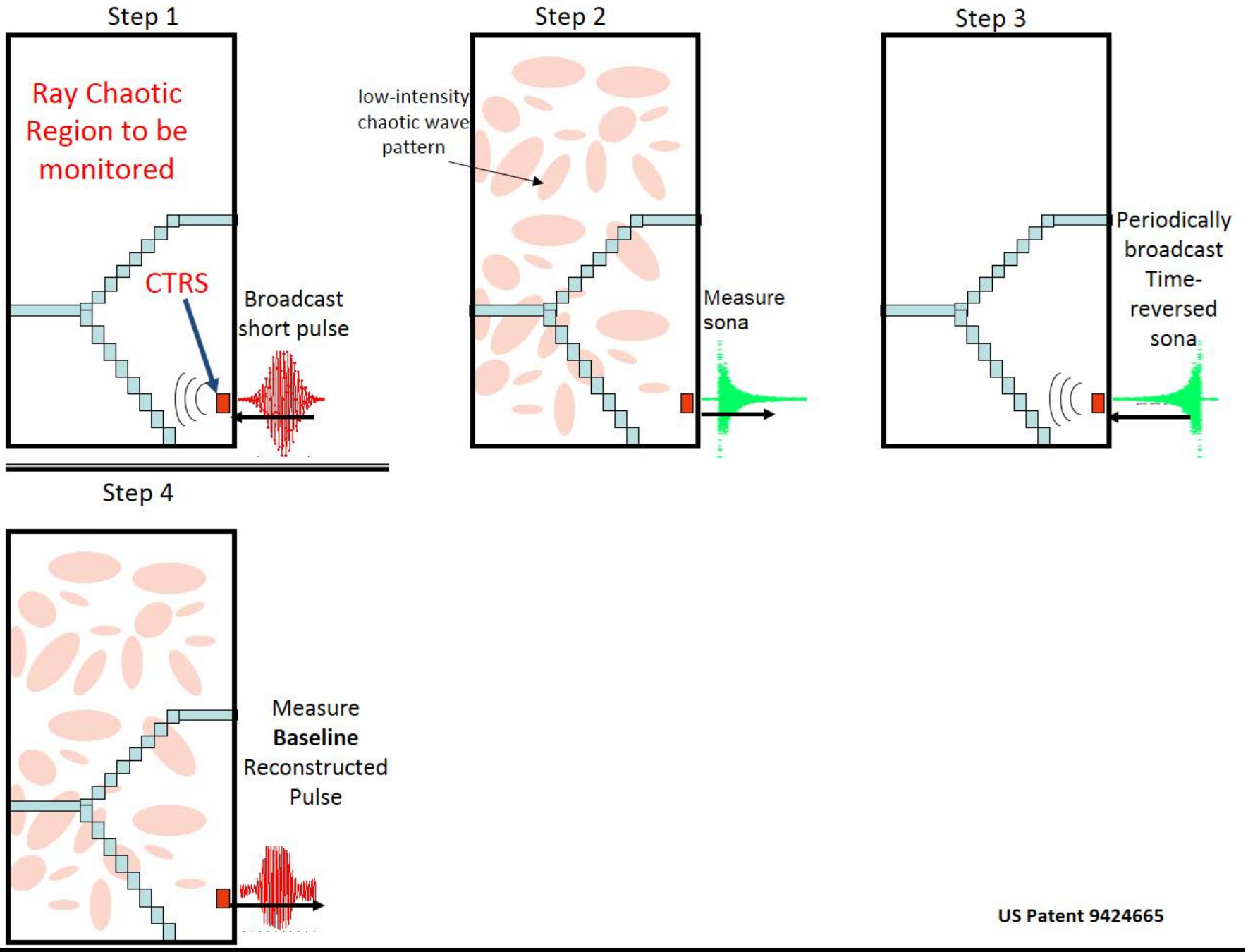

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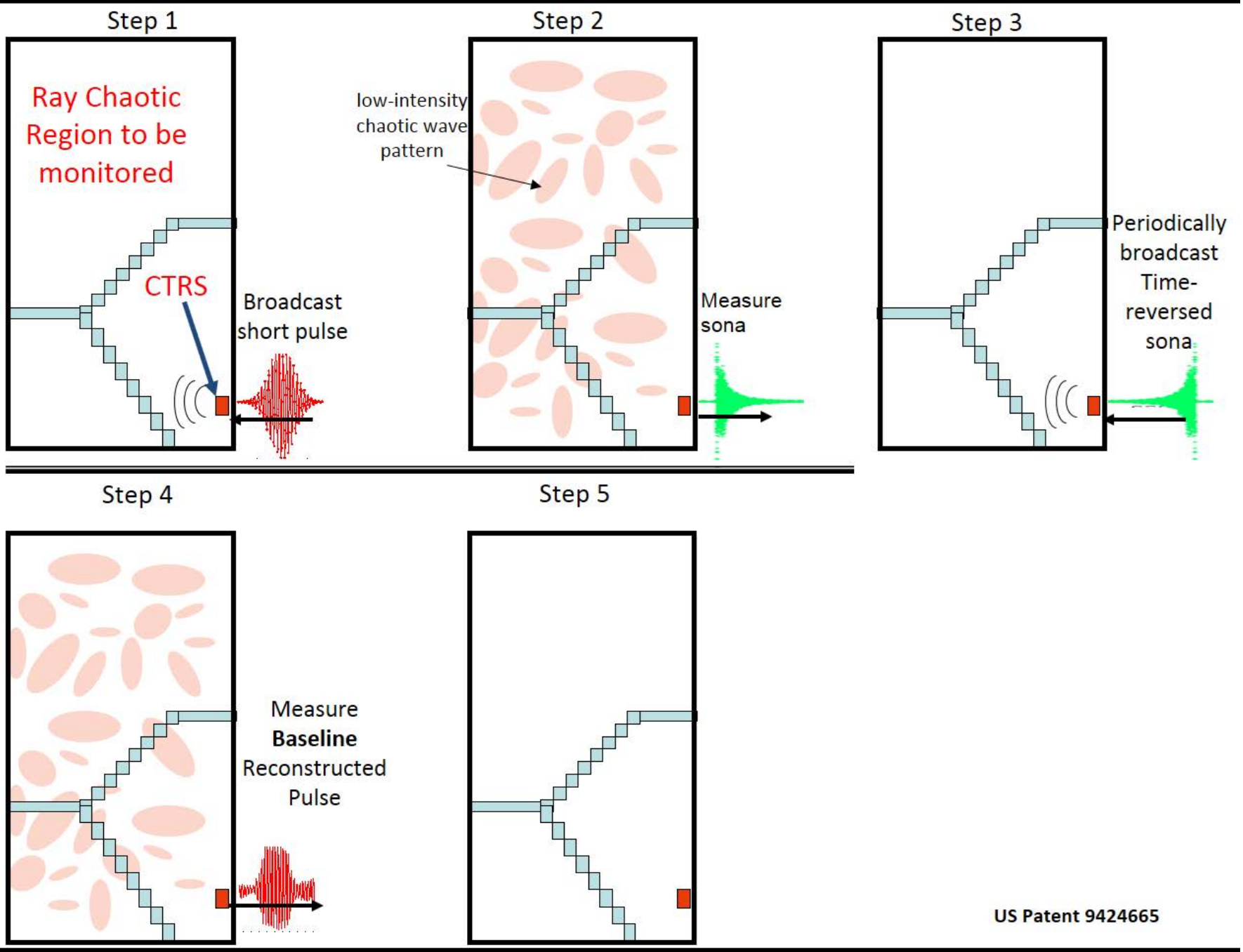

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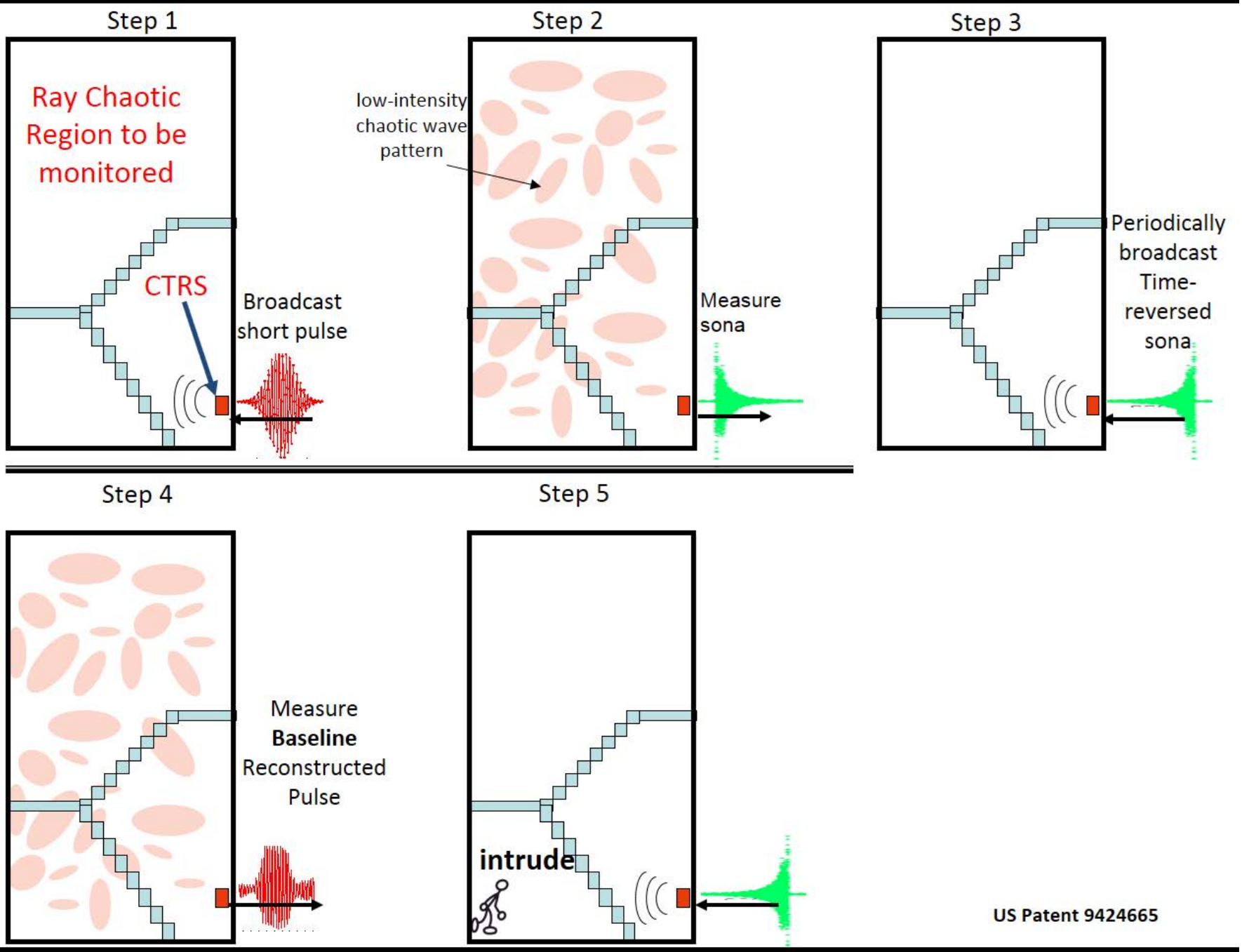
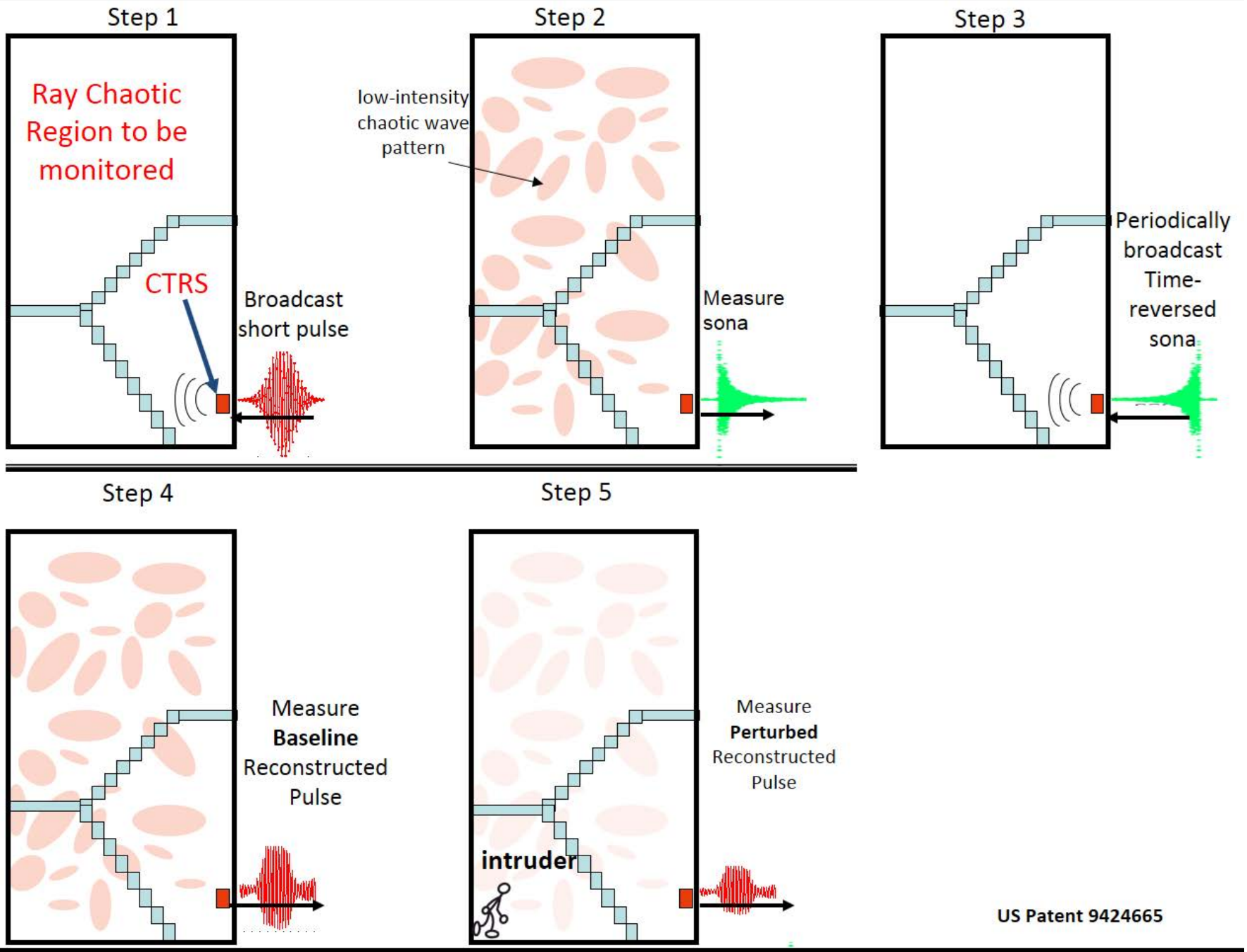

Step 1
Ray Chaotic Region to be monitored
CTRS
Broadcast short pulse
Step 2
low-intensity chaotic wave pattern
Measure sona
Step 3
Periodically broadcast Time-reversed sona
Step 4
Measure Baseline Reconstructed Pulse
Step 5
intrude
US Patent 9424665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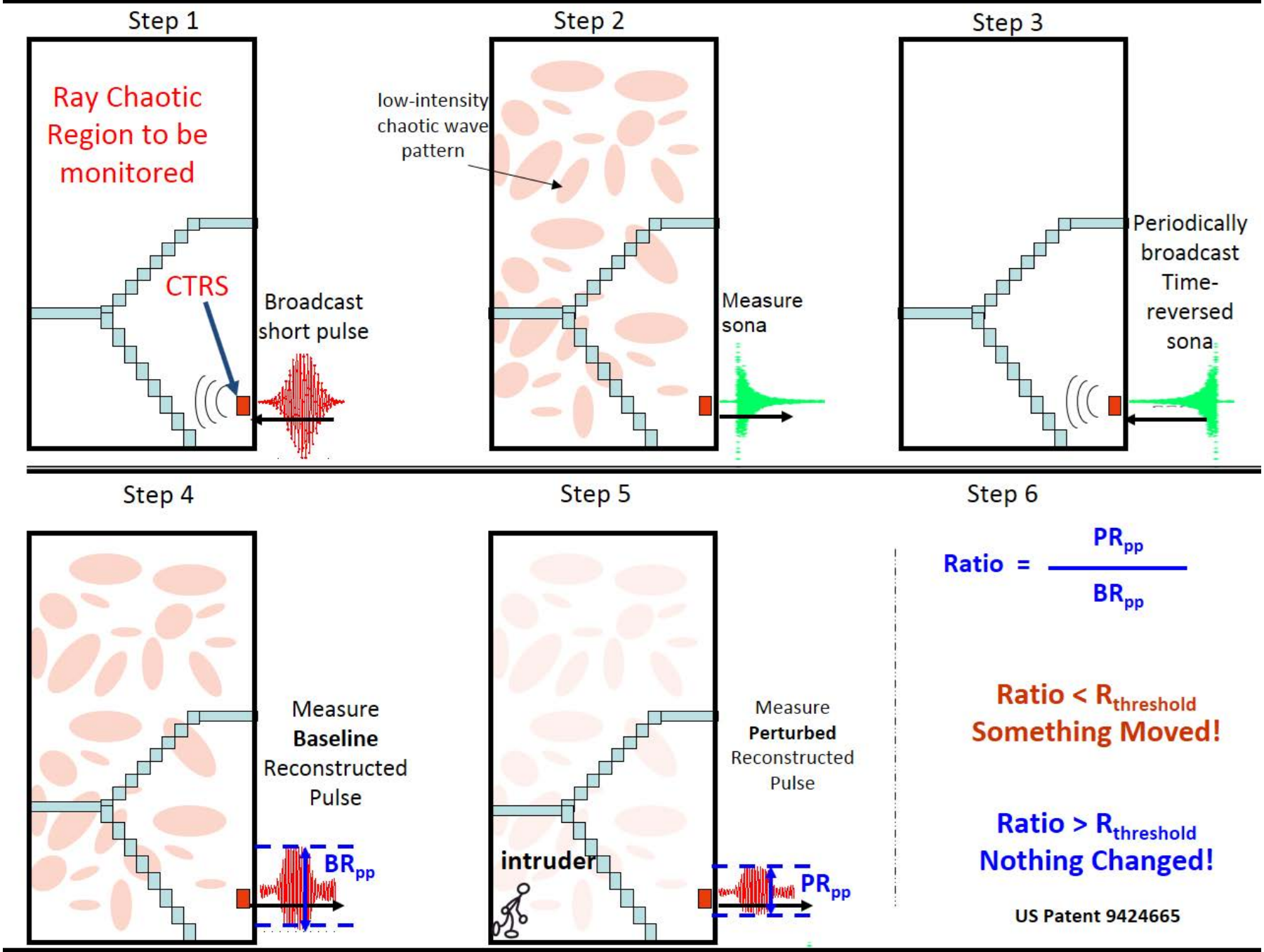
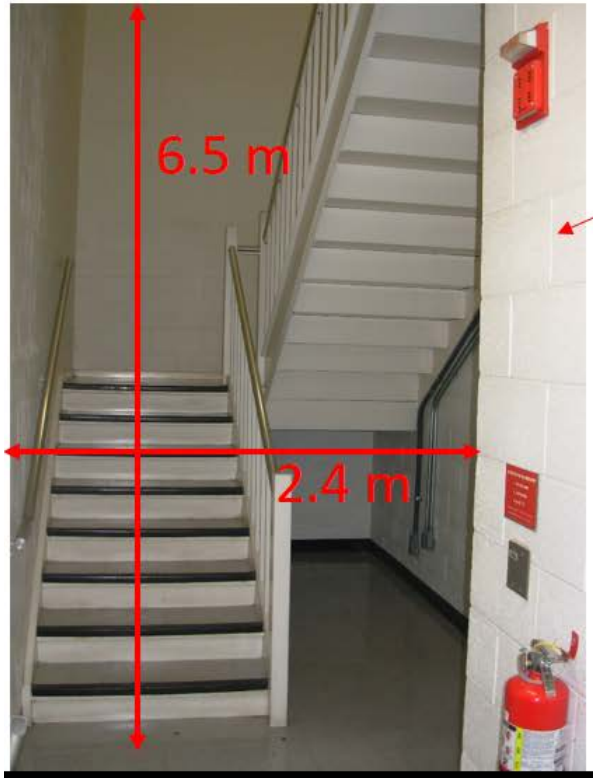
Periodically broadcast Time-reversed sona
Step 4
Measure Baseline Reconstructed Pulse
Step 5
intruder
Measure Perturbed Reconstructed Pulse
US Patent 9424665

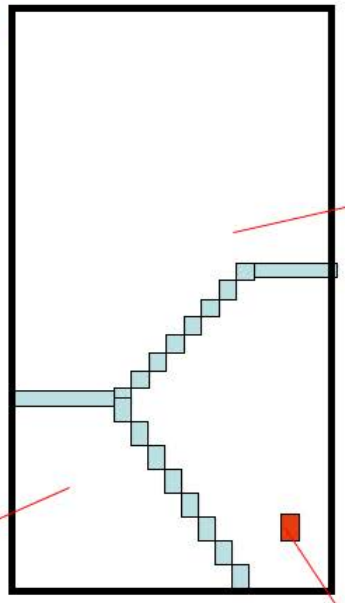

Step 1
Ray Chaotic Region to be monitored
CTRS
Broadcast short pulse
Step 2
low-intensity chaotic wave pattern
Measure sona
Step 3
Periodically broadcast Time-reversed sona
Step 4
Measure Baseline Reconstructed Pulse
BRpp
Step 5
intruder
Measure Perturbed Reconstructed Pulse
PRpp
Step 6
Ratio = PRpp / BRpp
Ratio < Rthreshold
Something Moved!
Ratio > Rthreshold
Nothing Changed!
US Patent 9424665

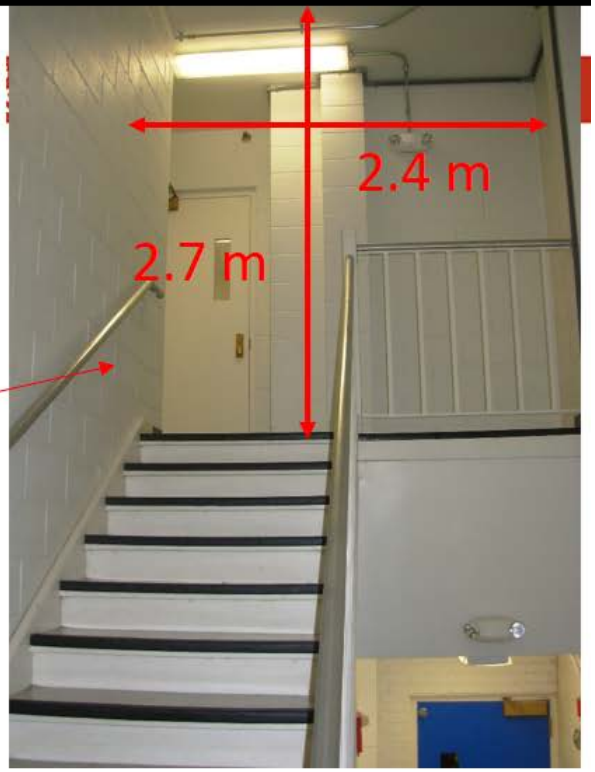
Appl. Phys. Lett. **95** , 114103 (2009)
New J. Phys. **15**, 023025 (2013)

Demonstration of an Acoustic CTRS in a Stairwell

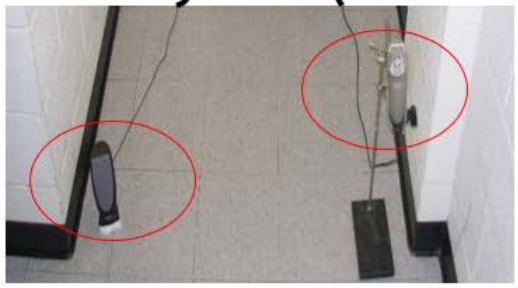
Ray chaos permits use of a single-channel time-reversal mirror







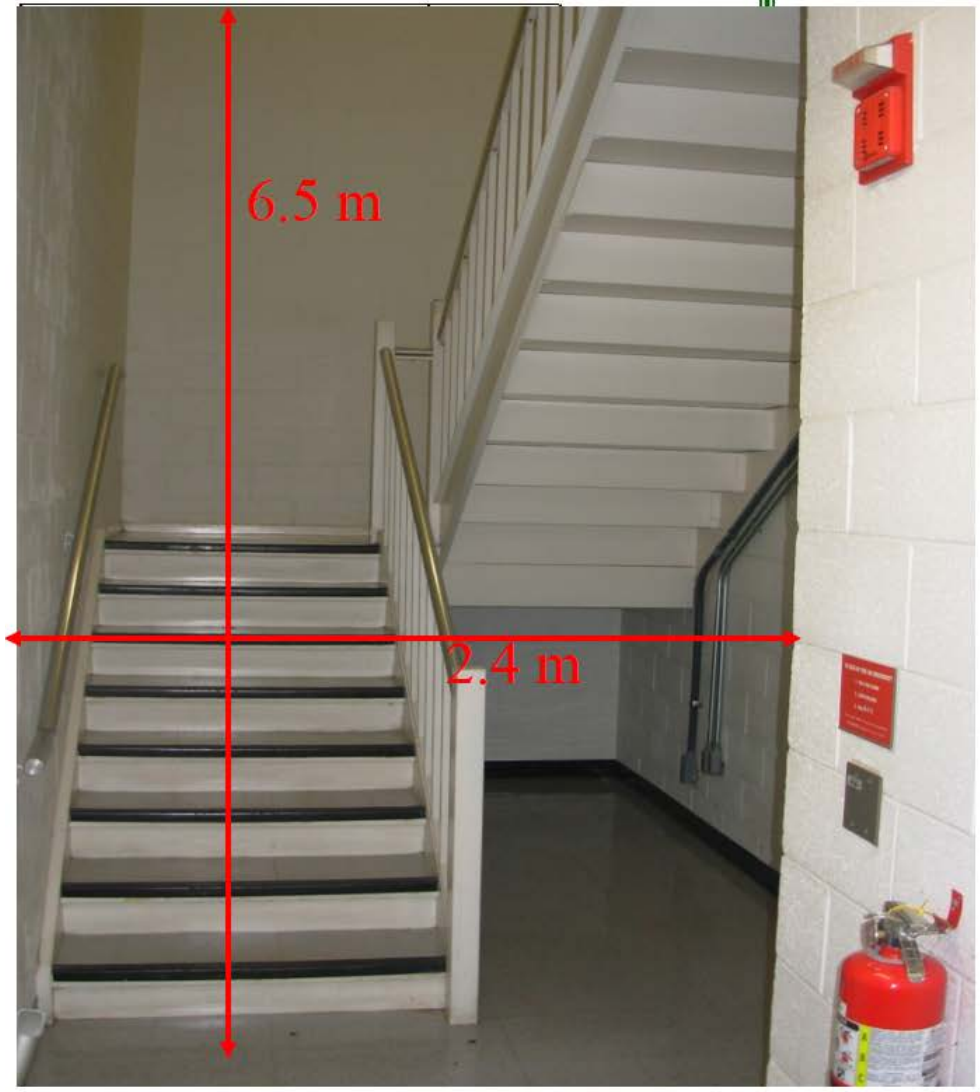
Laptop Computer



Spatial Reciprocity used here

Experiment to test the sensing techniques

Schematic of the stairwell used as a resonant cavity.



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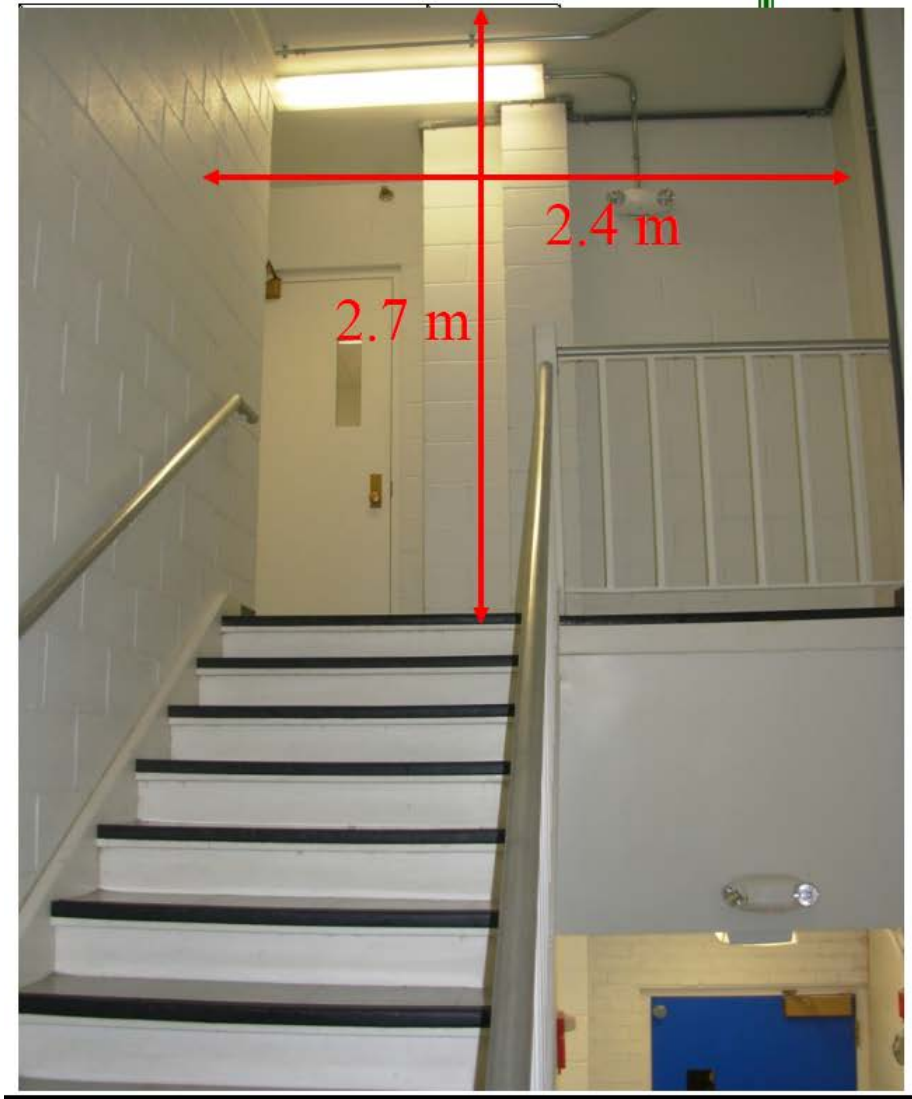

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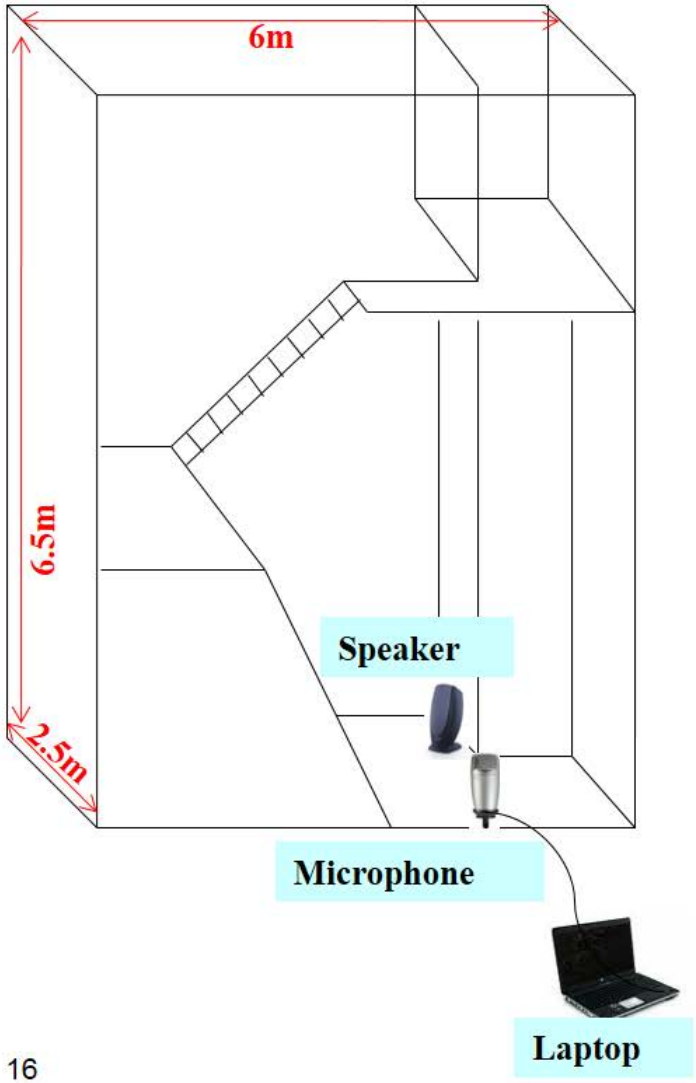

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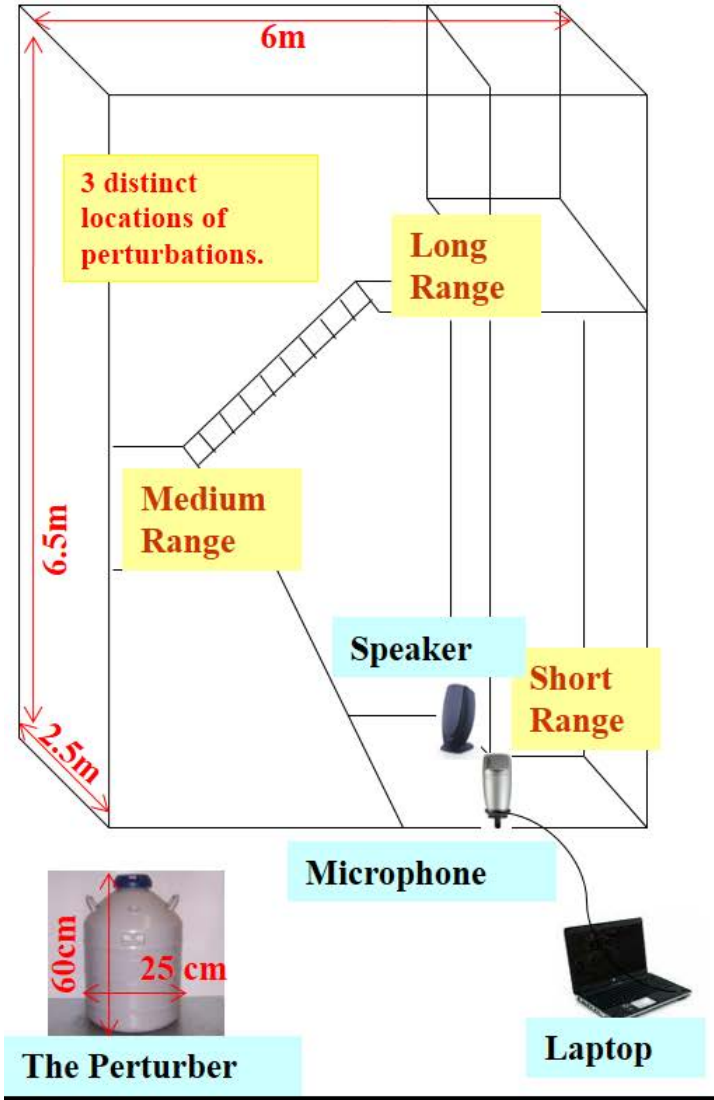

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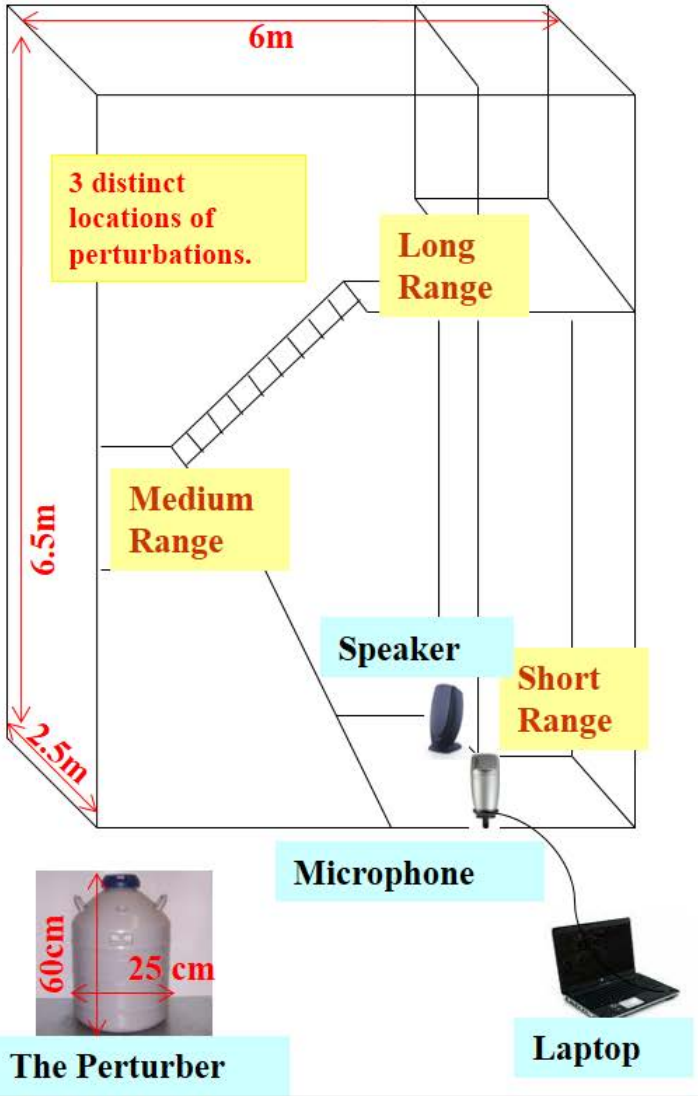

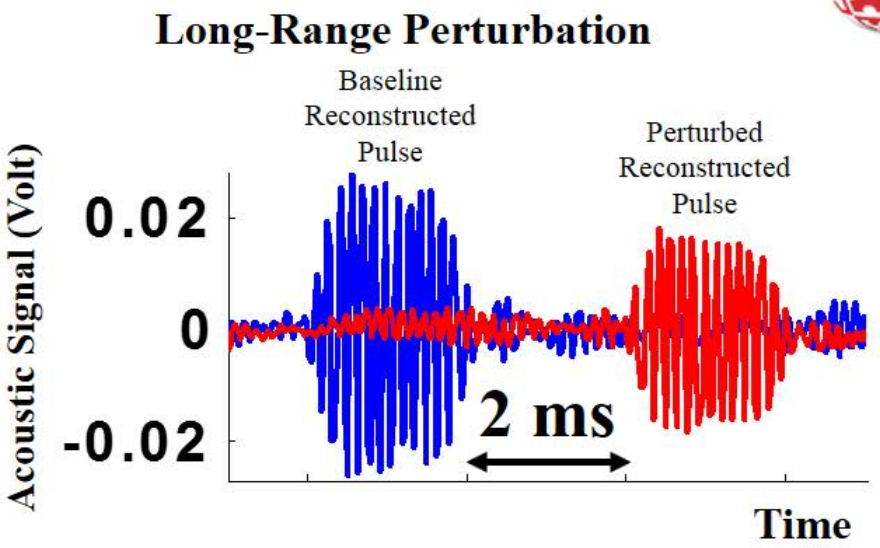

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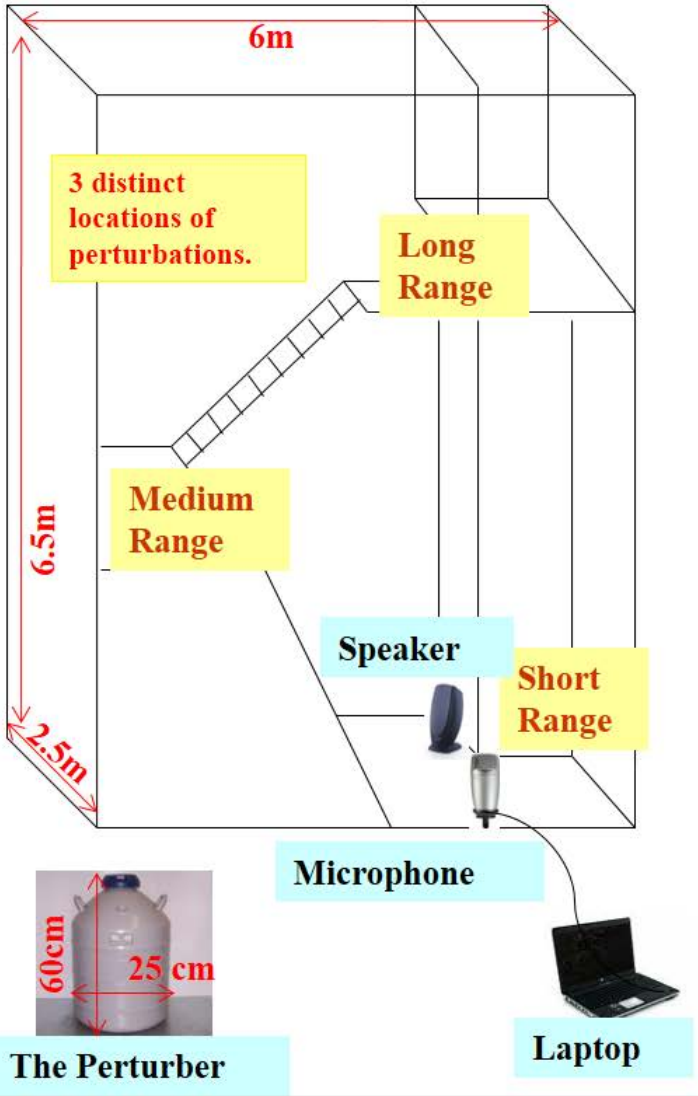

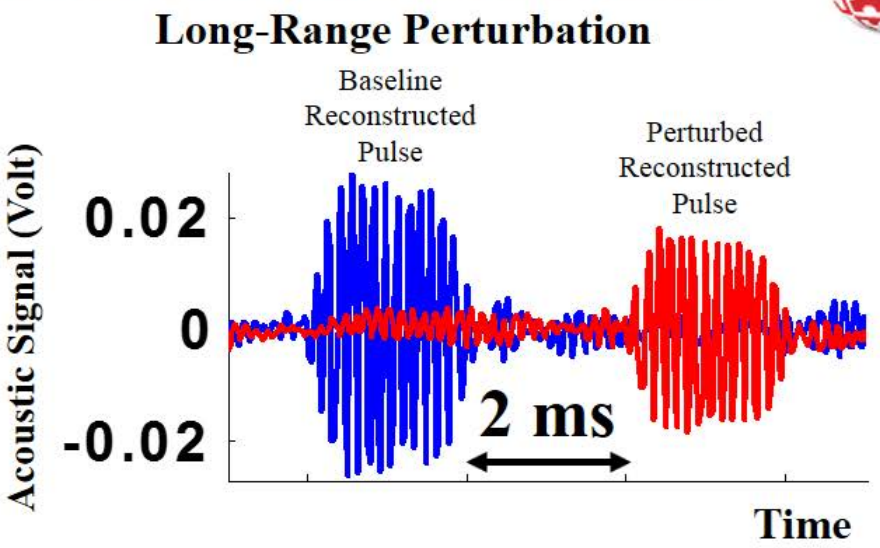

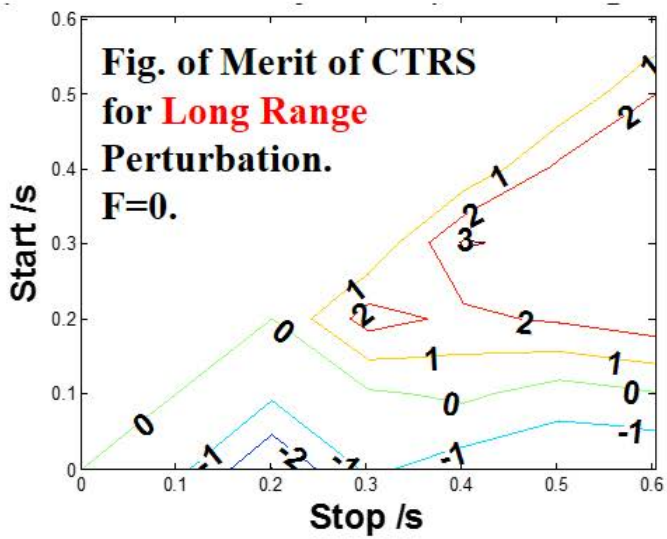

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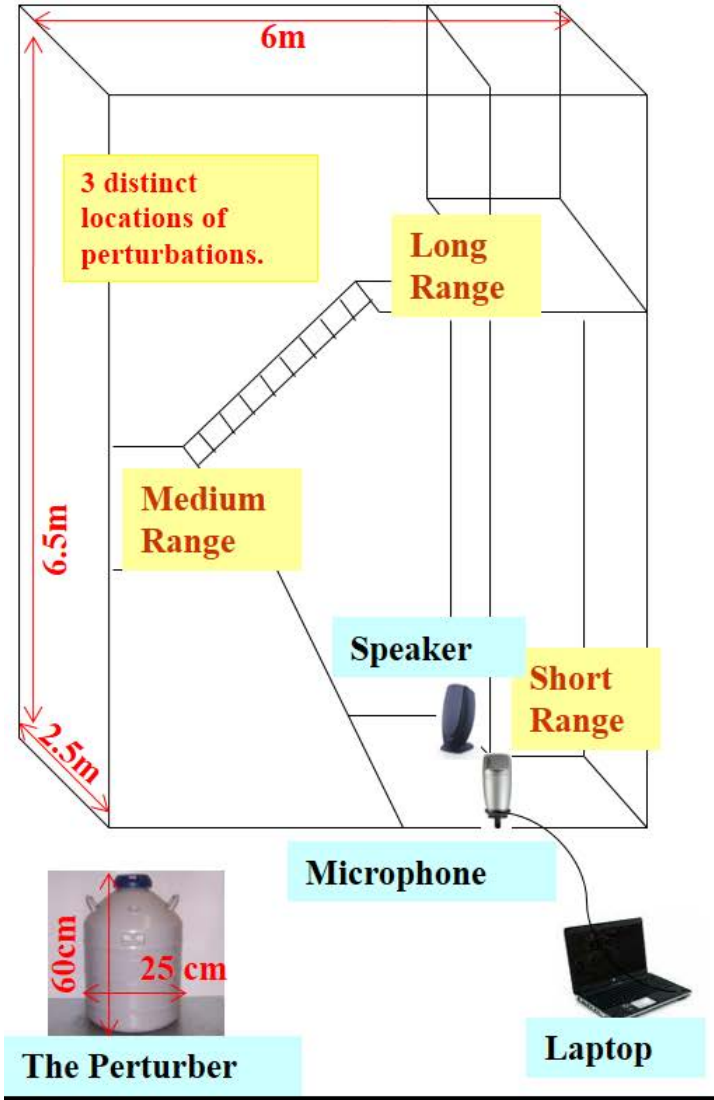

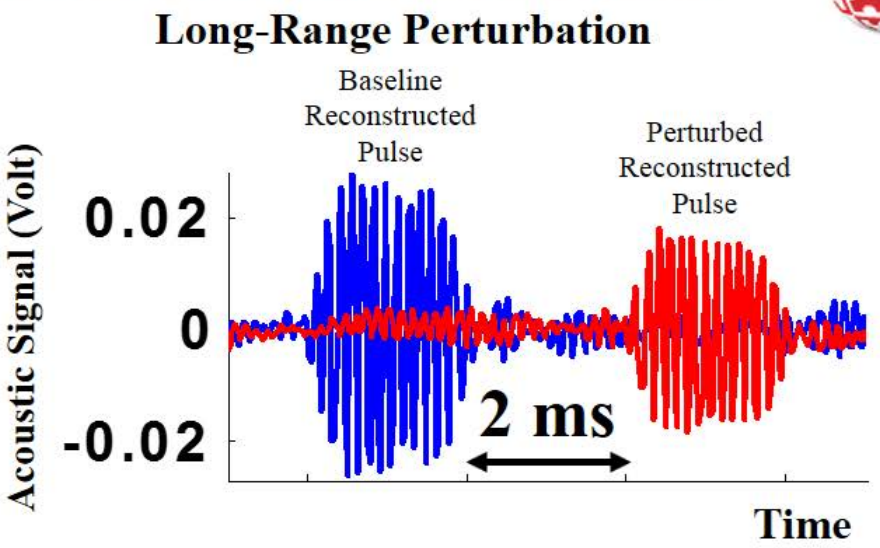

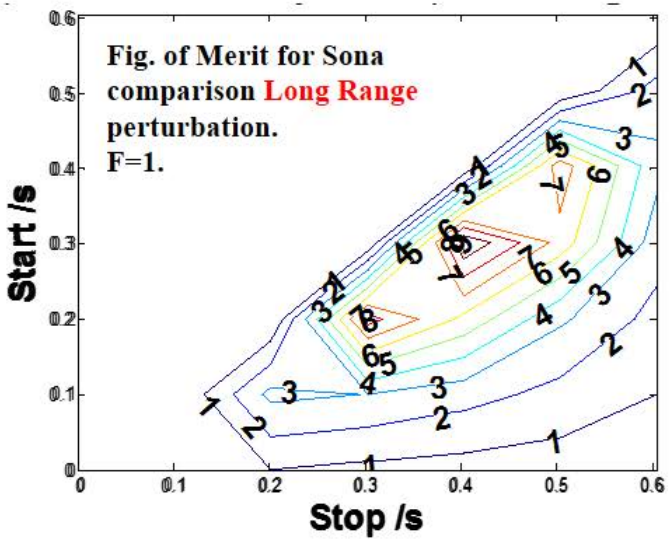

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Ray-Chaos-enabled Single-Channel Time Reversal Mirror

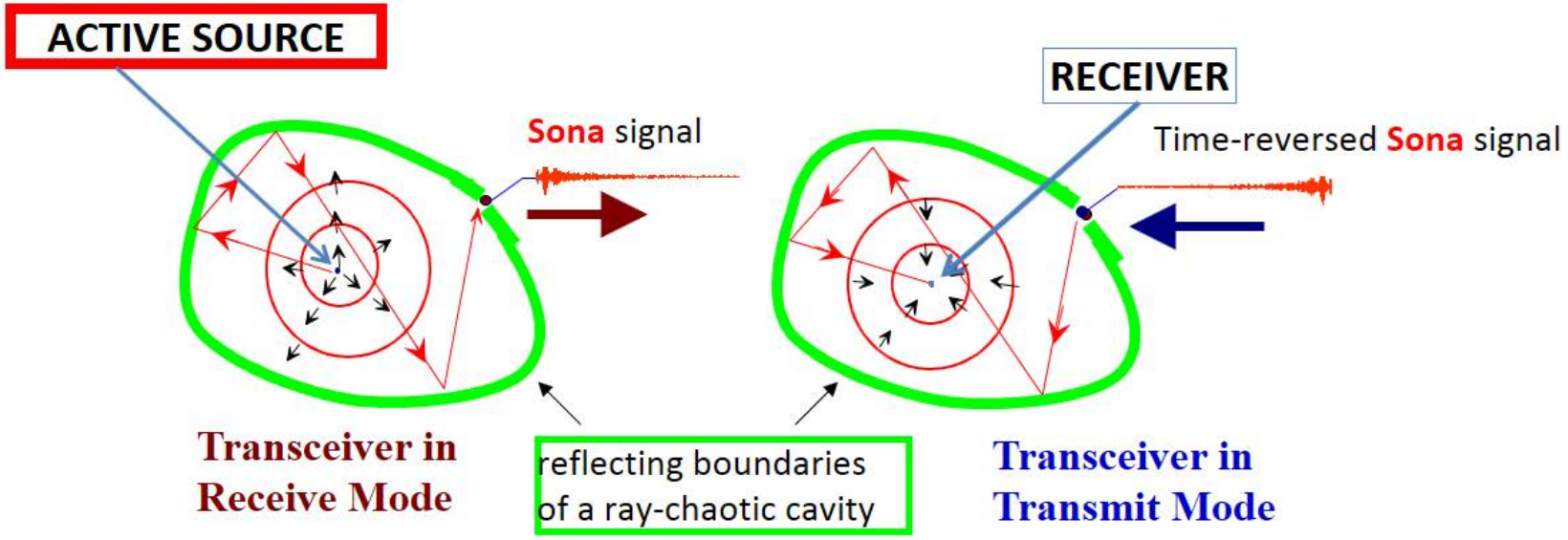

Image courtesy of M. Fink

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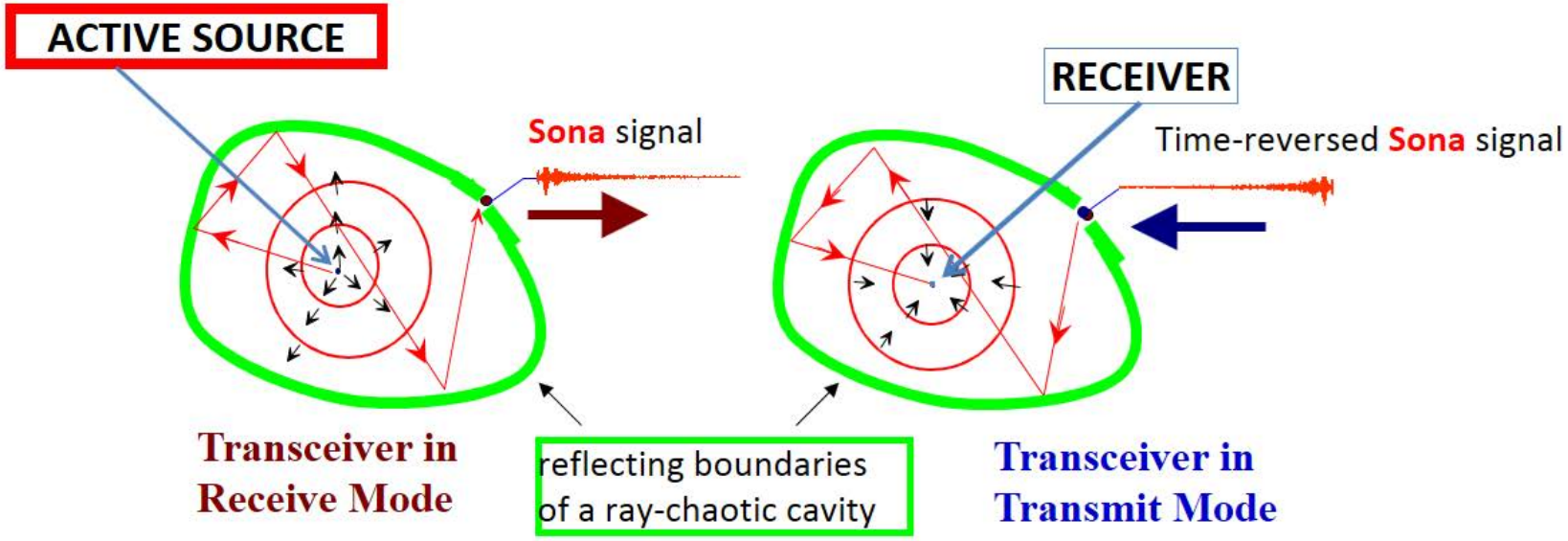
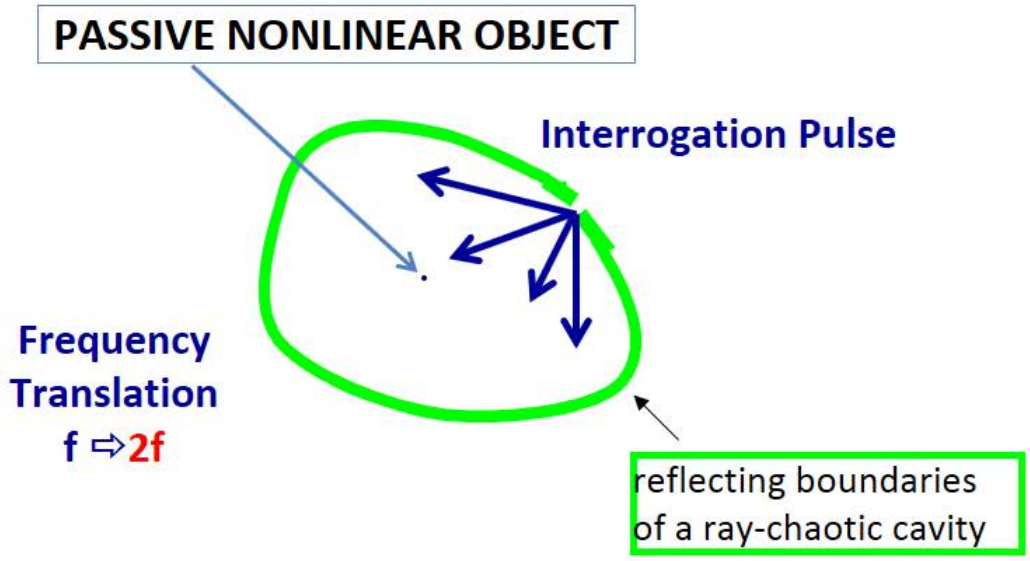


Can We Achieve Energy Focusing Without the ACTIVE SOURCE Step?

Image courtesy of M. Fink

NONLINEAR TIME REVERSAL MIRROR



Based on similar ideas in nonlinear acoustics
T. J. Ulrich, *et al.*, JASA (2006)

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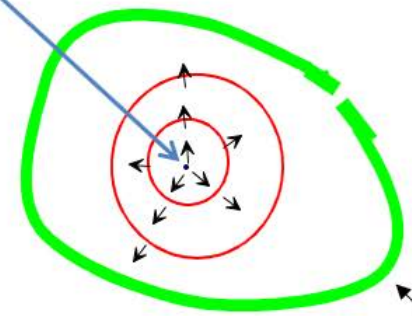
NONLINEAR TIME REVERSAL MIRROR

PASSIVE NONLINEAR OBJECT



Frequency Translation
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reflecting boundaries
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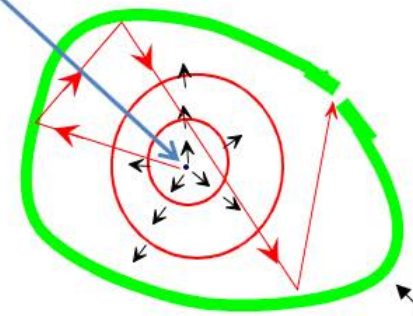

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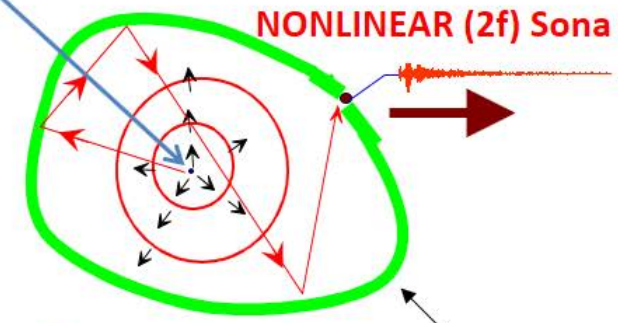

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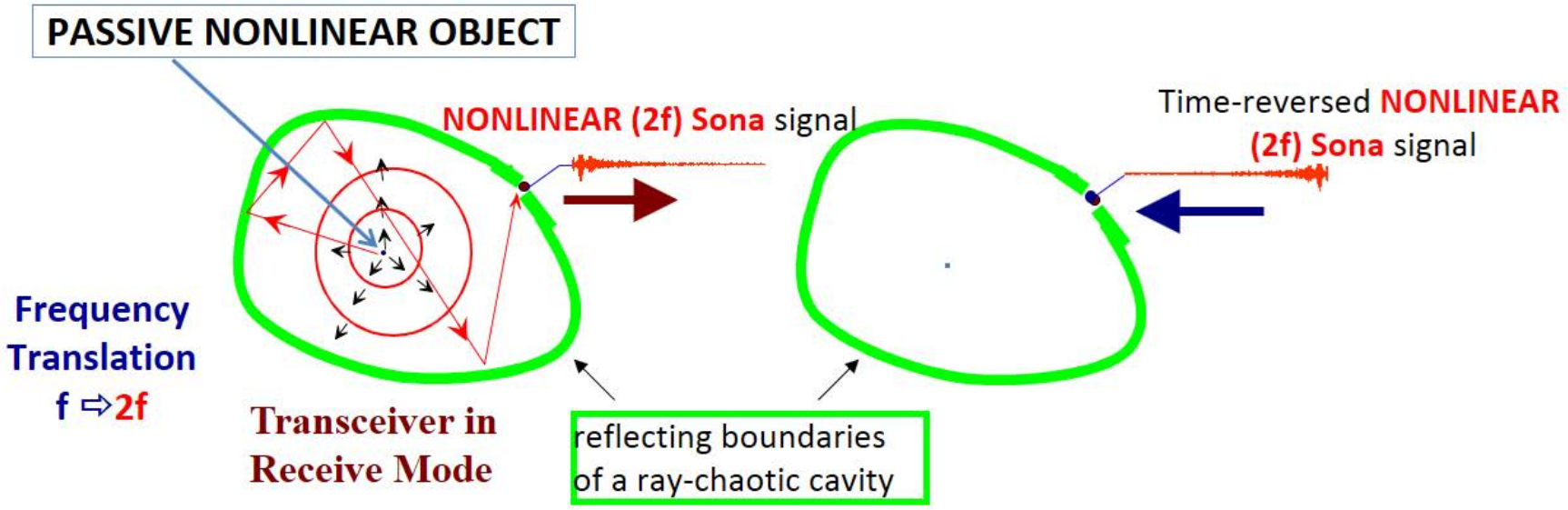

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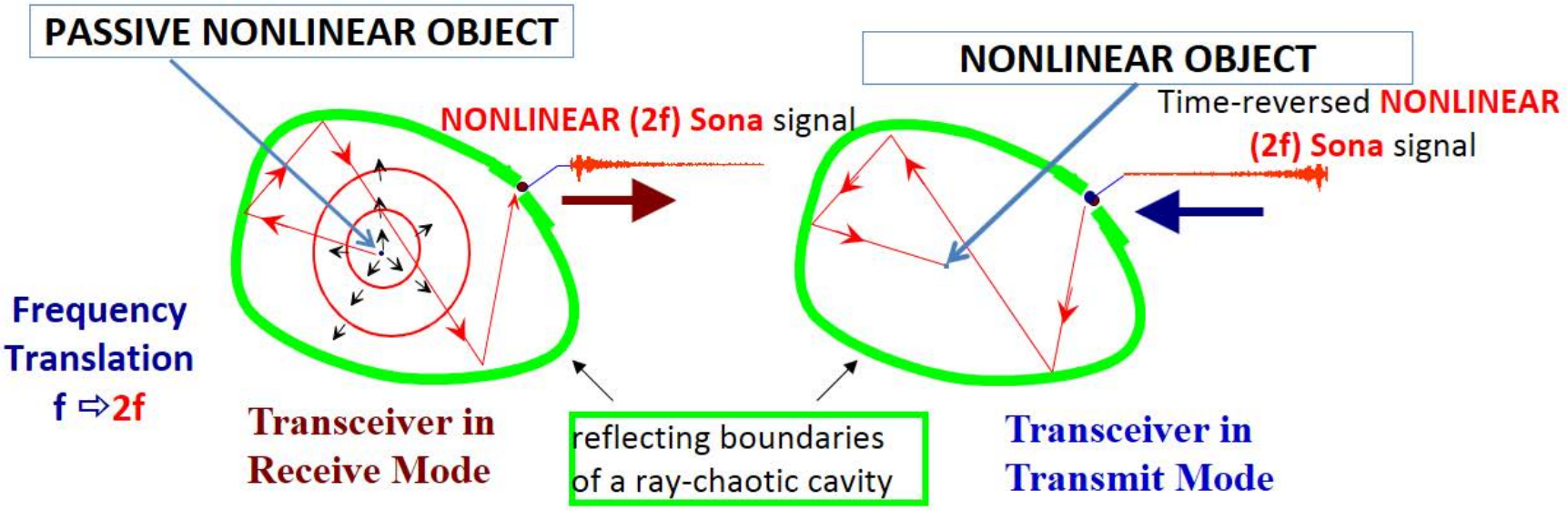

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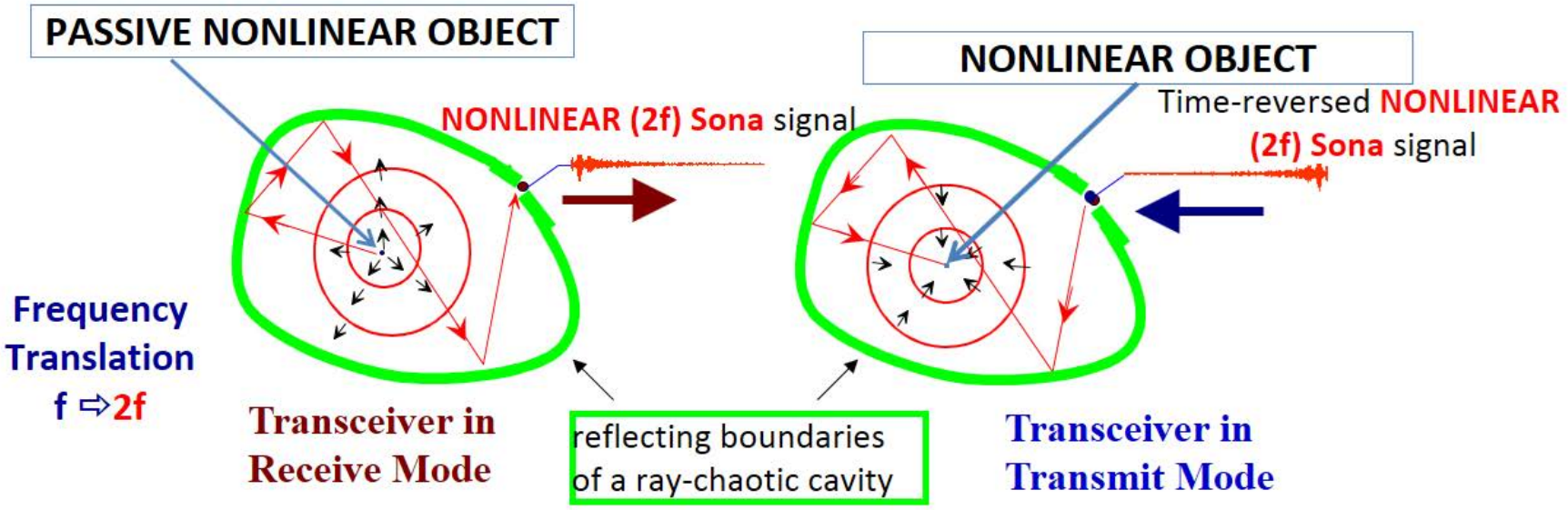

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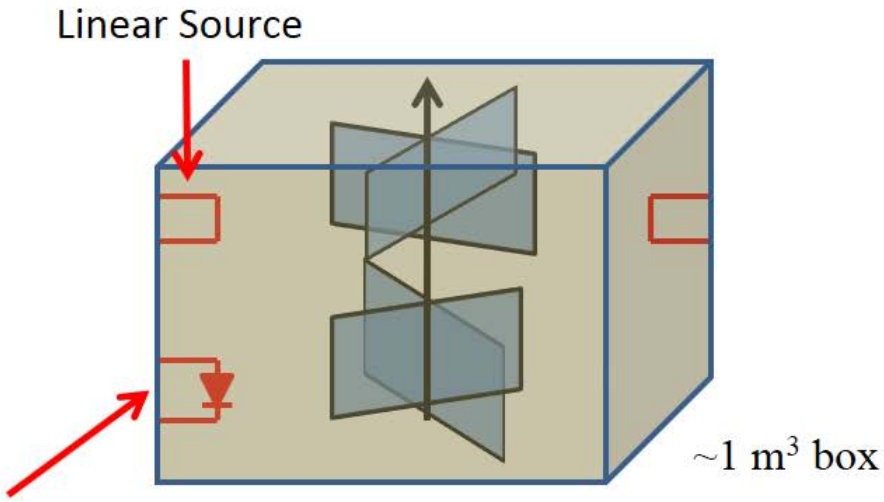
Extension: Adding Nonlinearity to The Electromagnetic Time-Reversal Mirror



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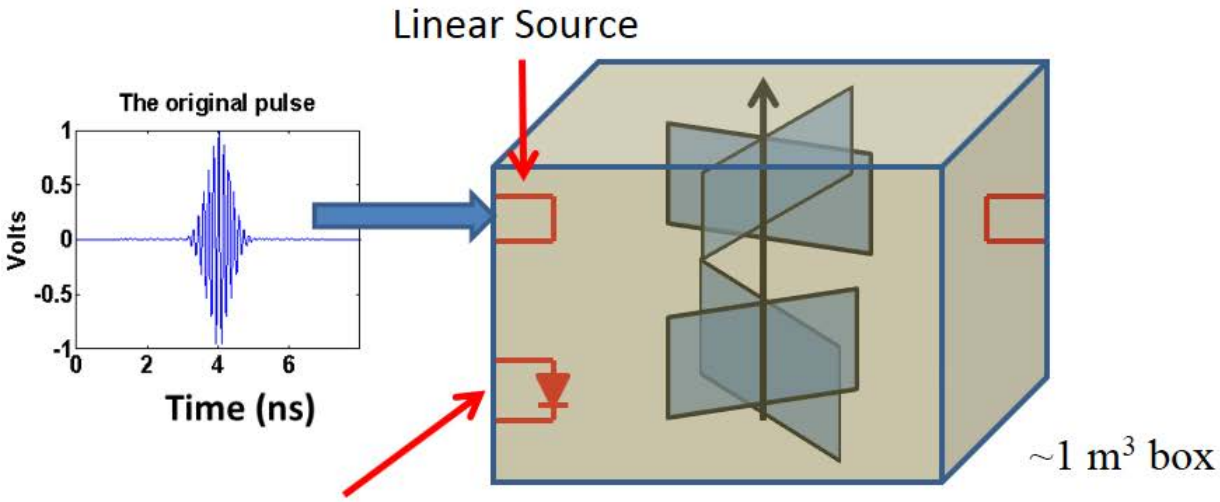

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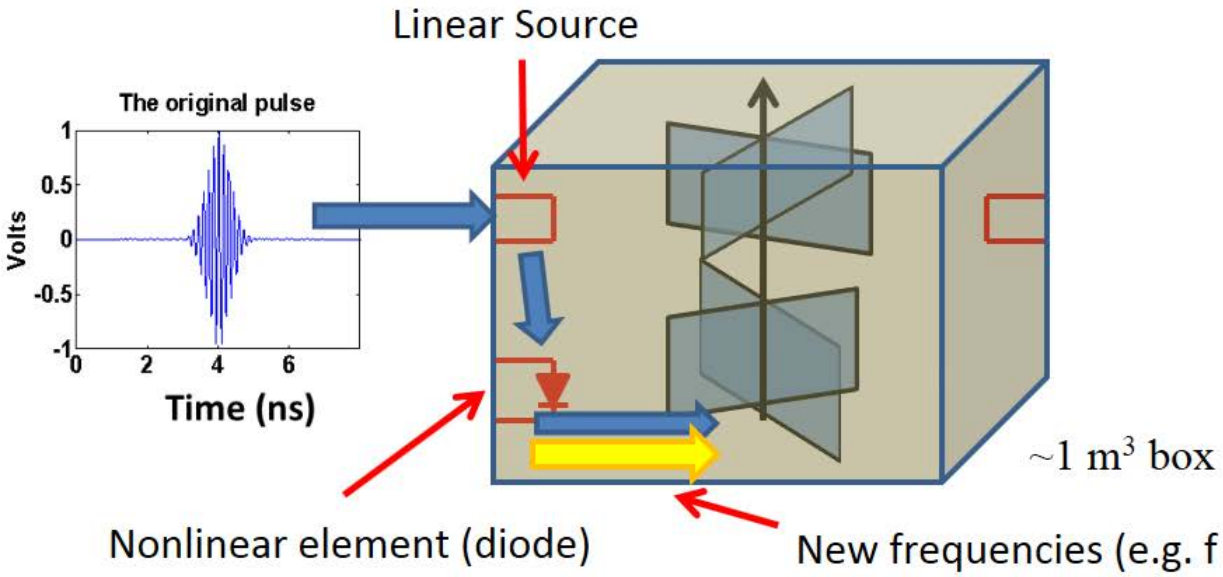

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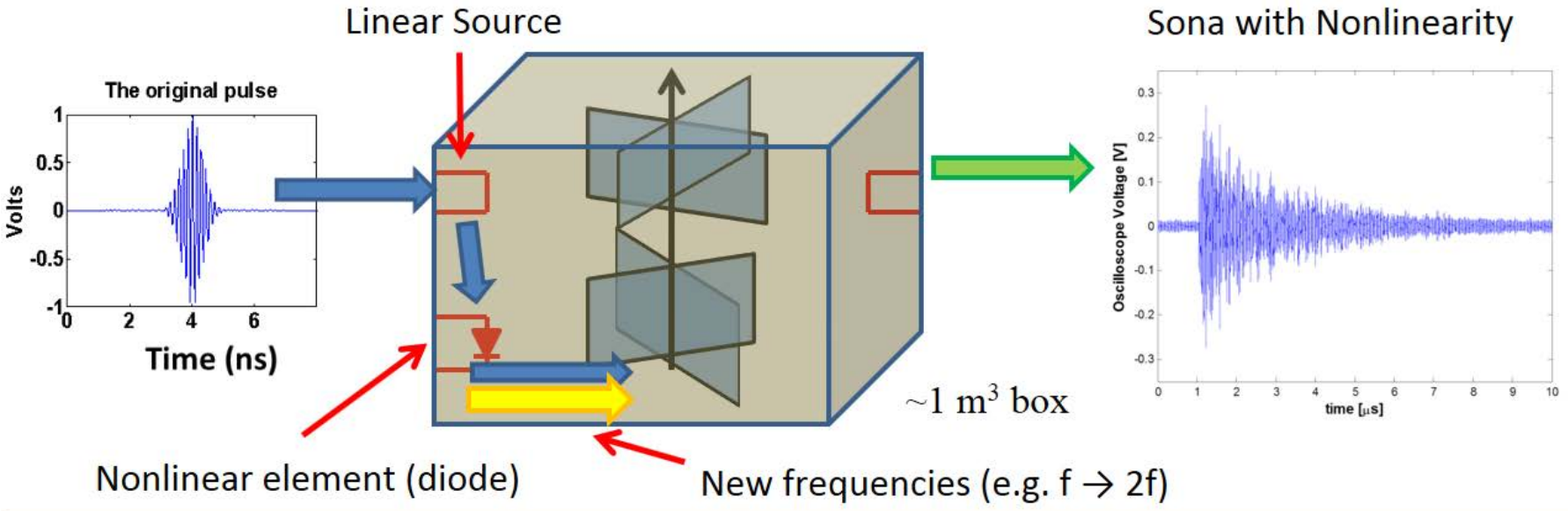

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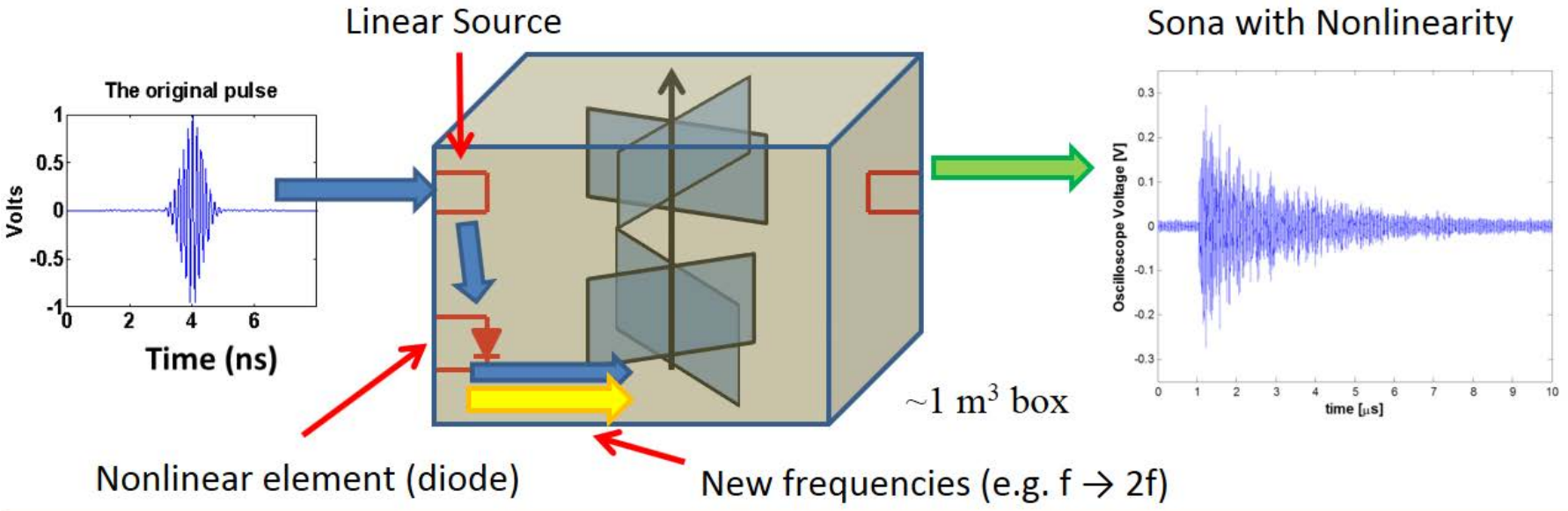

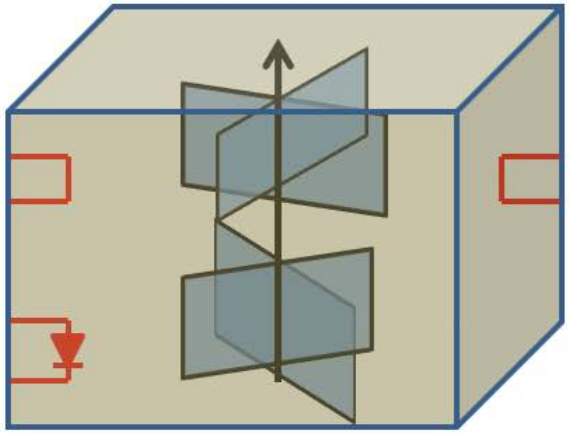

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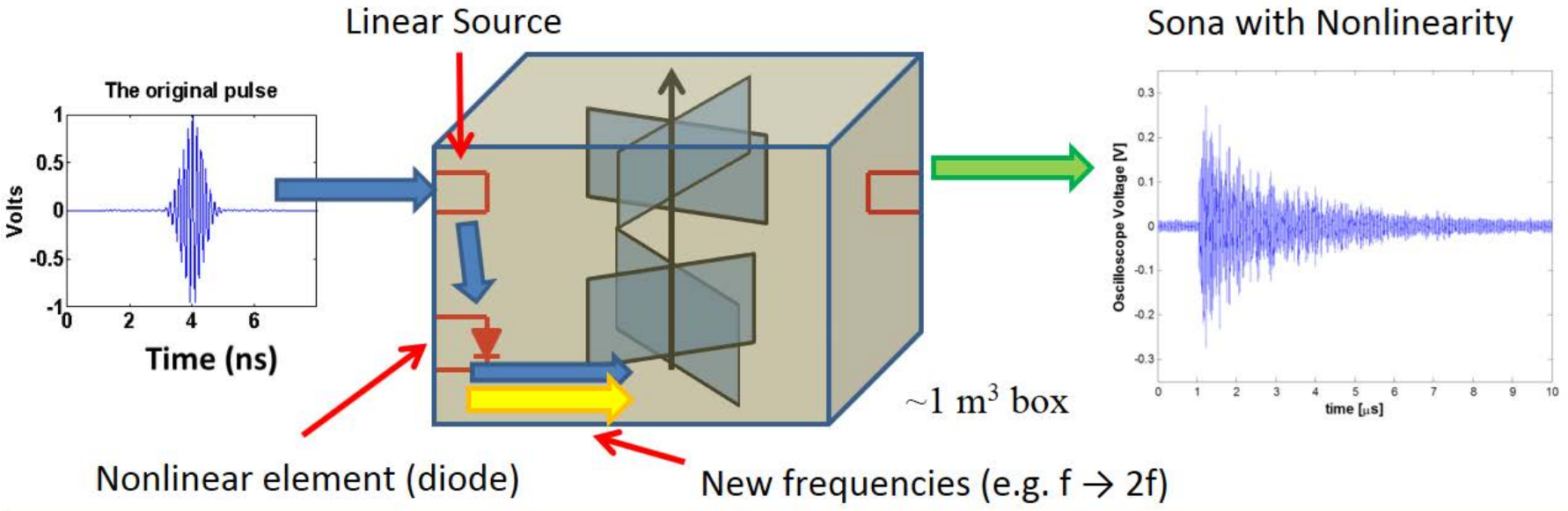

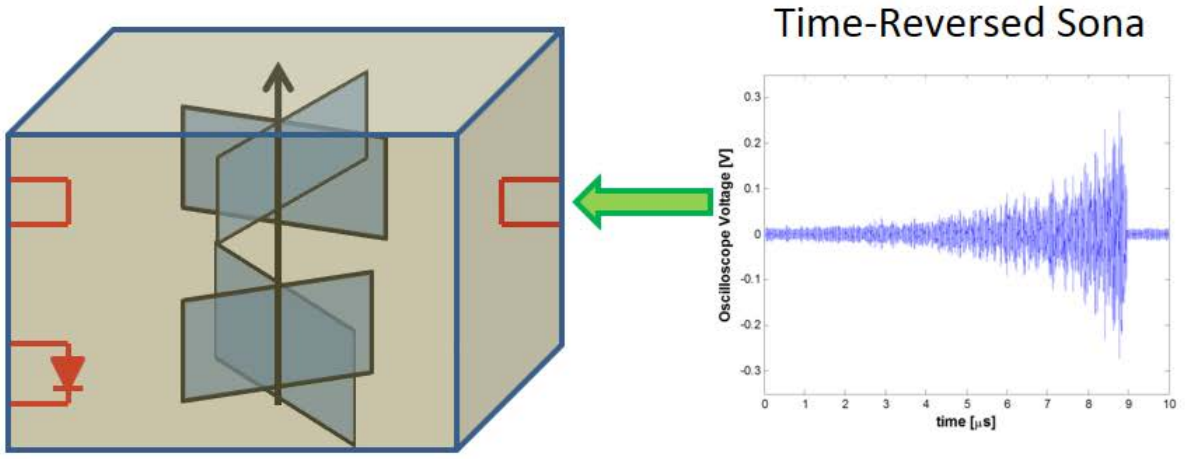

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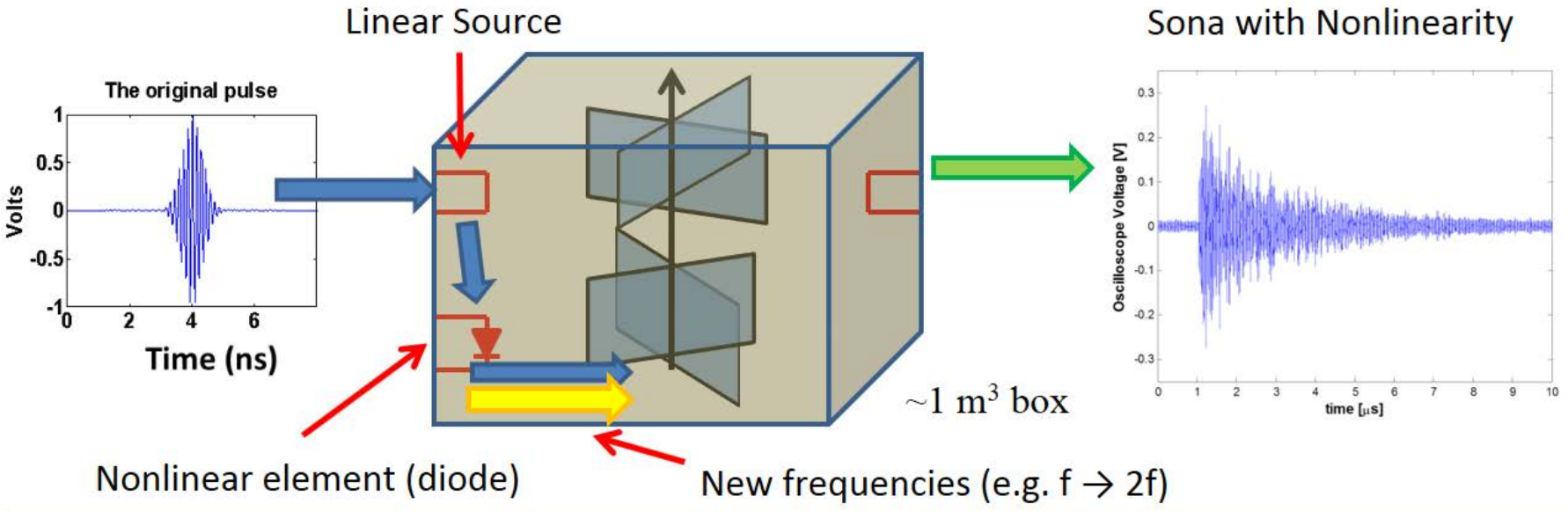

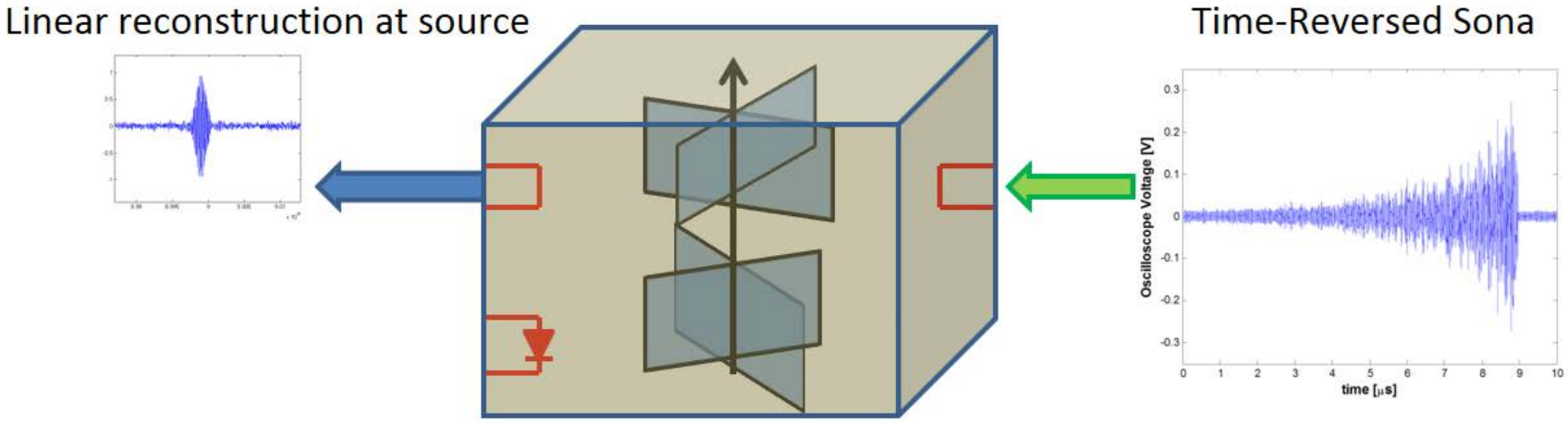

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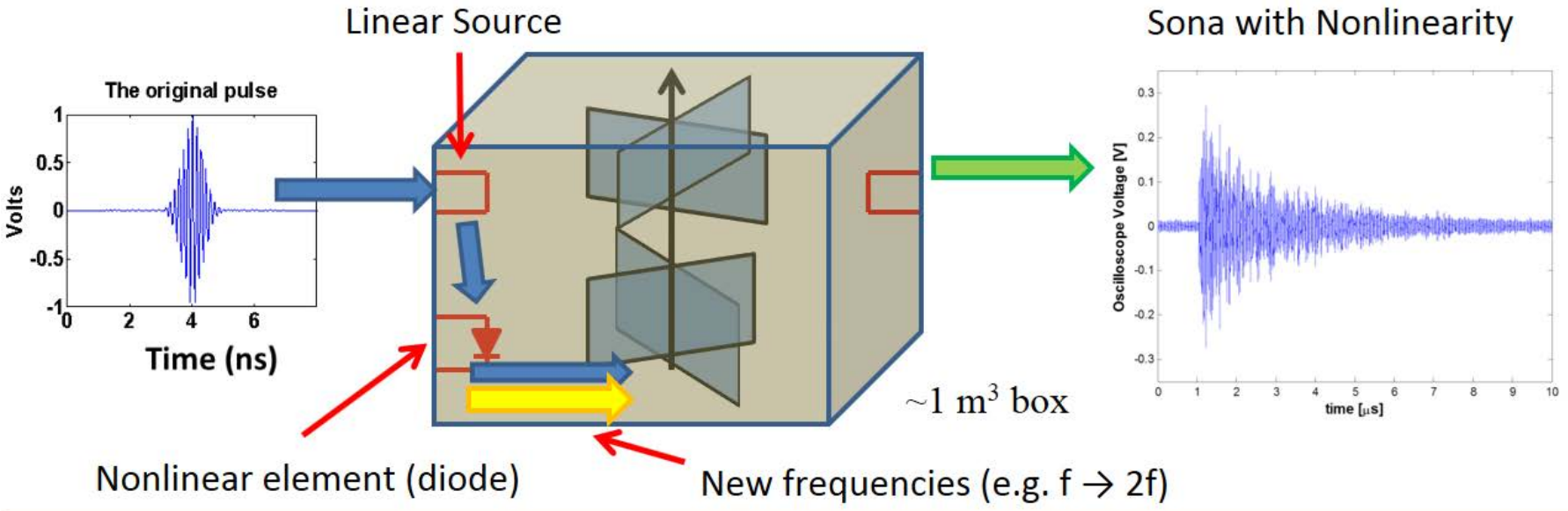

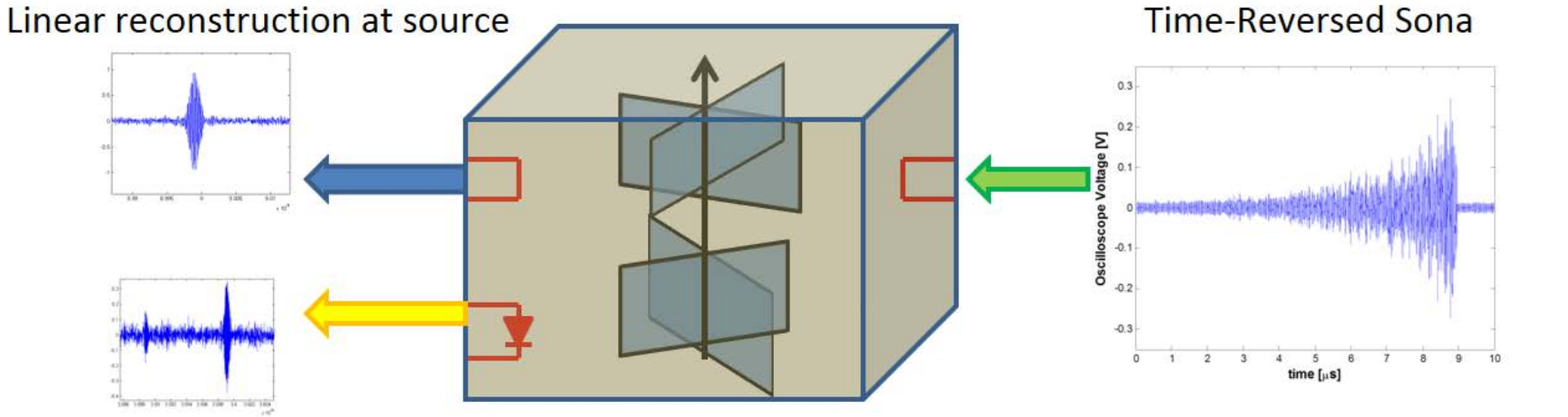

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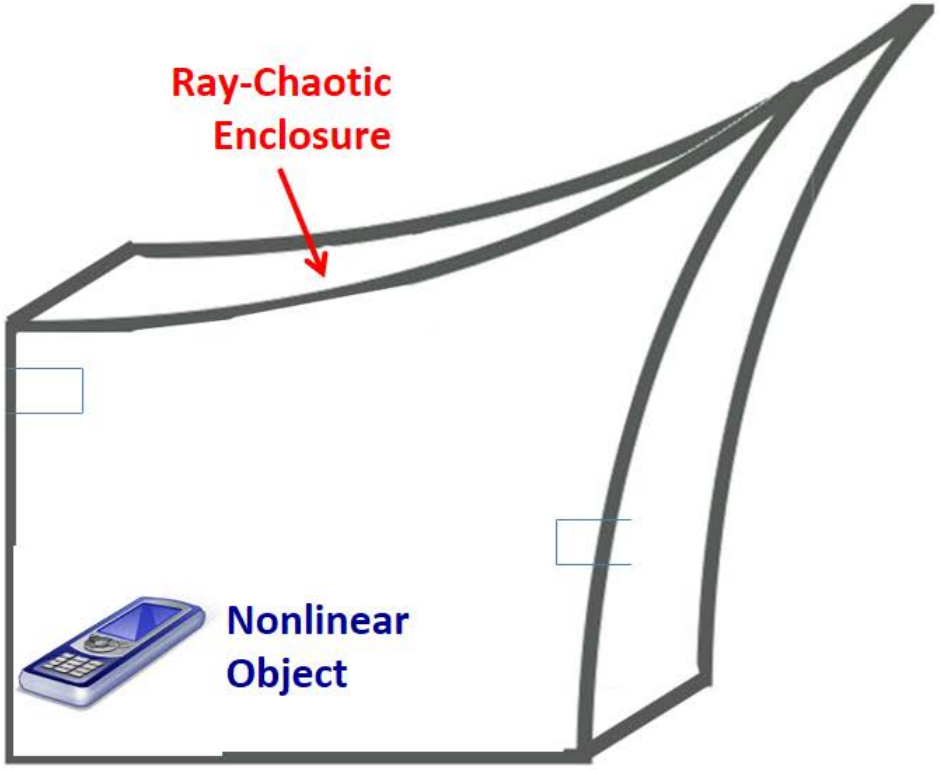
Directed communication channel with a nonlinear element at an arbitrary, unknown, location



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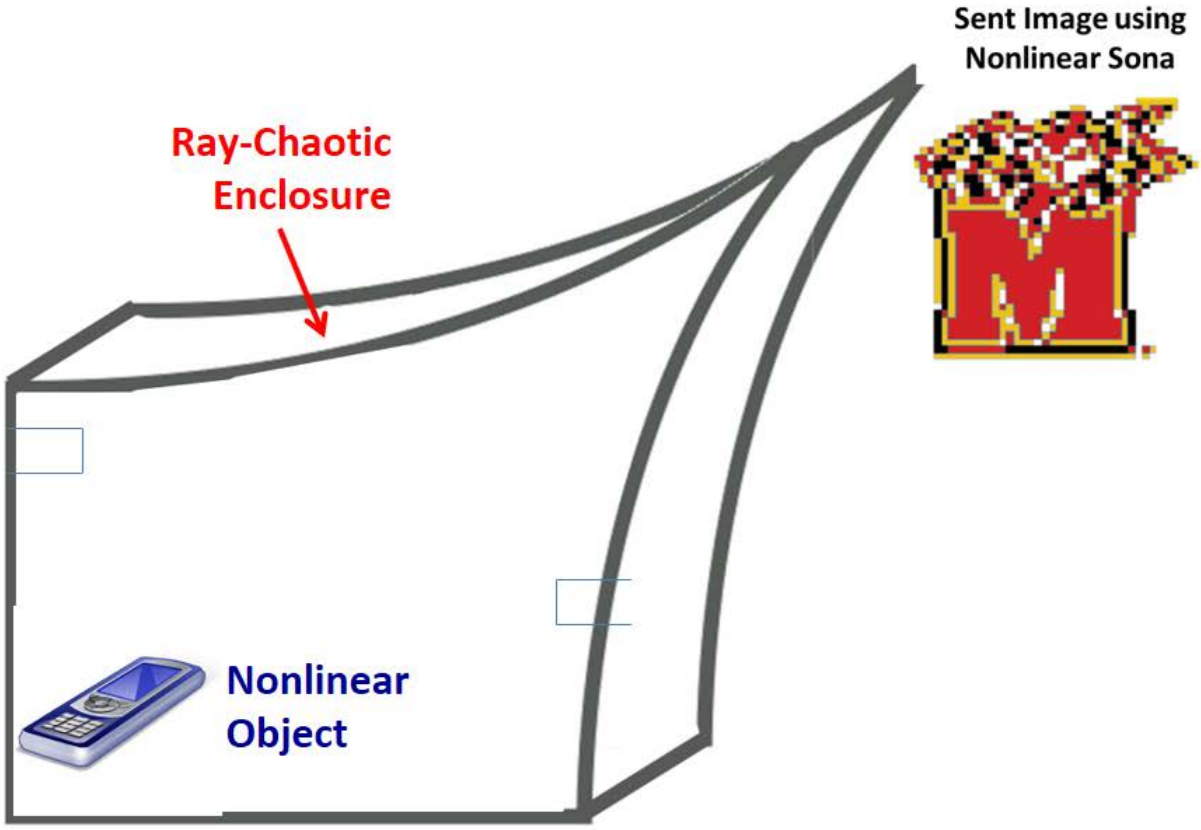

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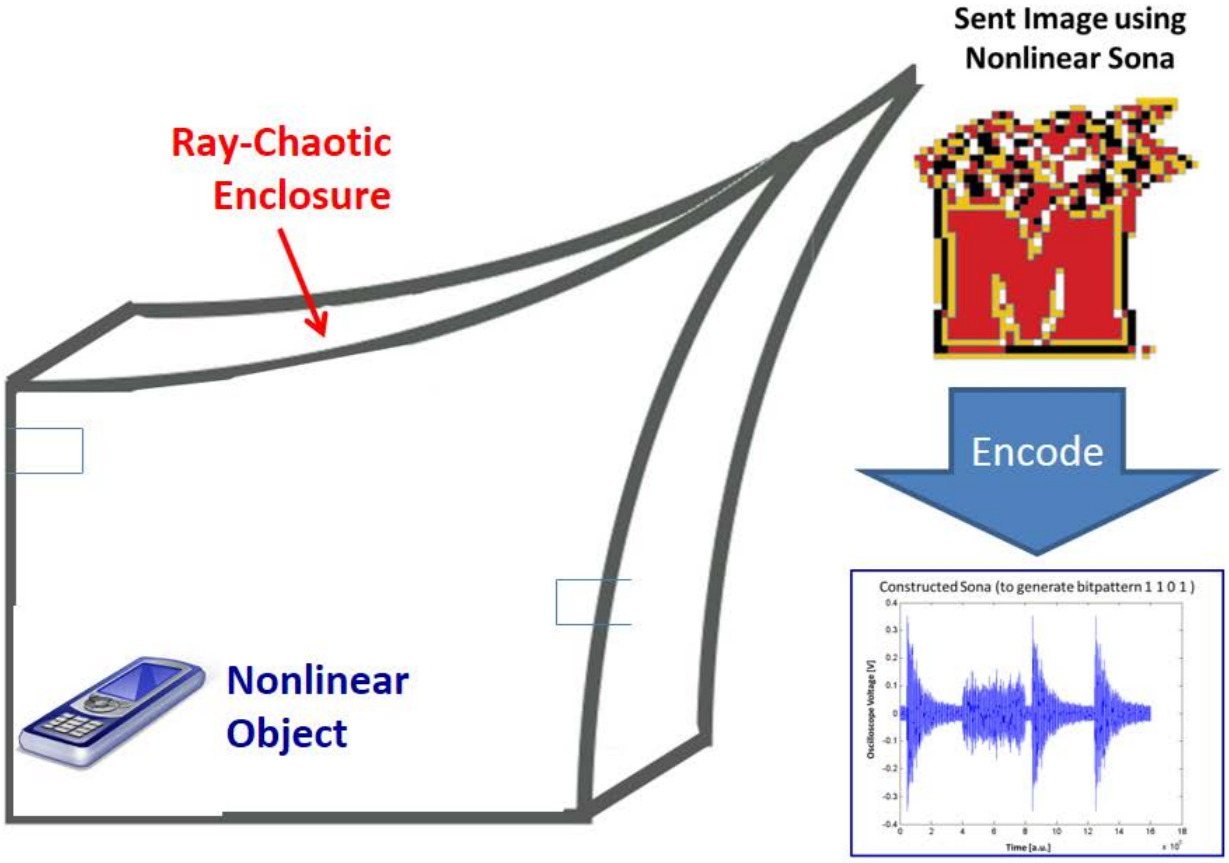

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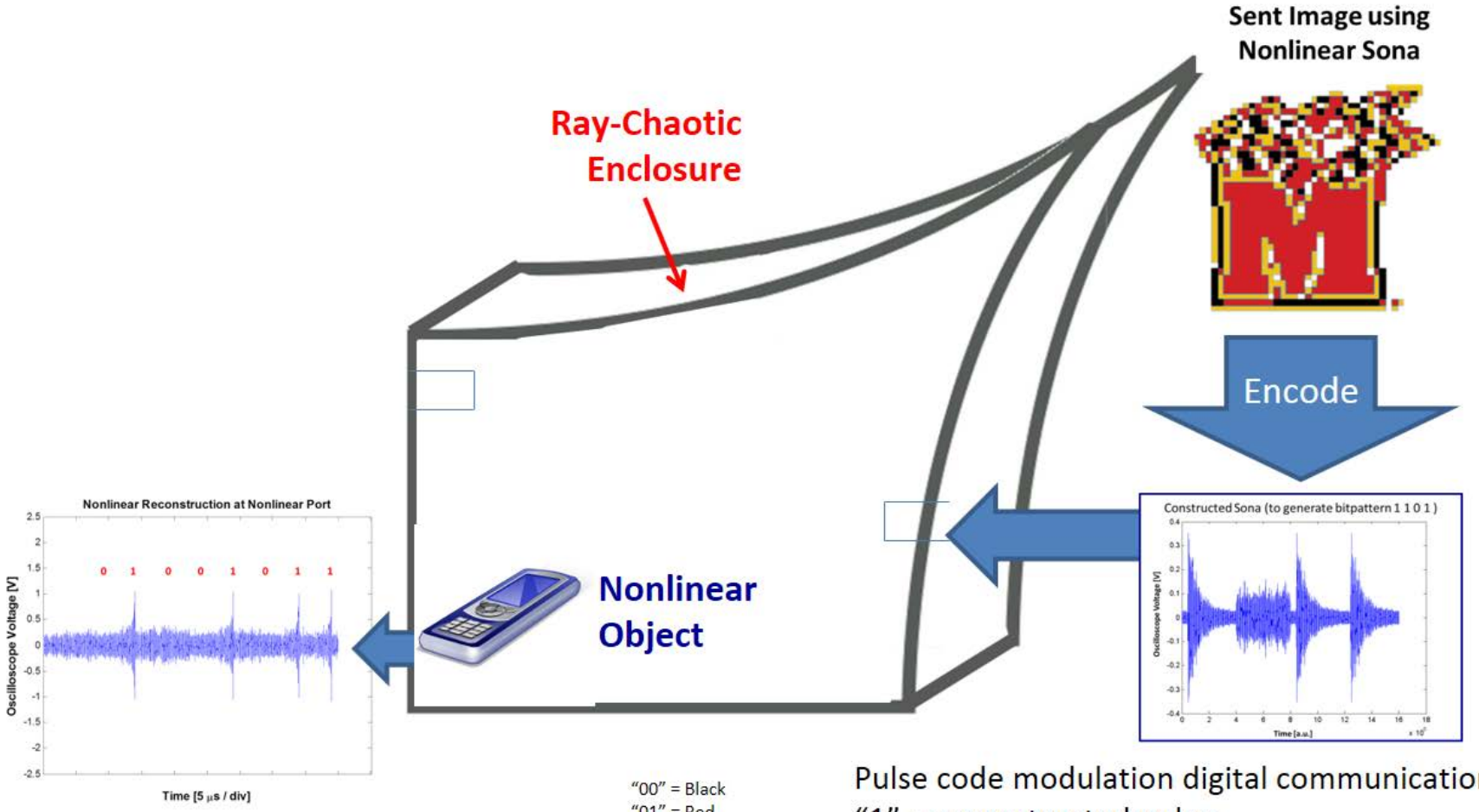

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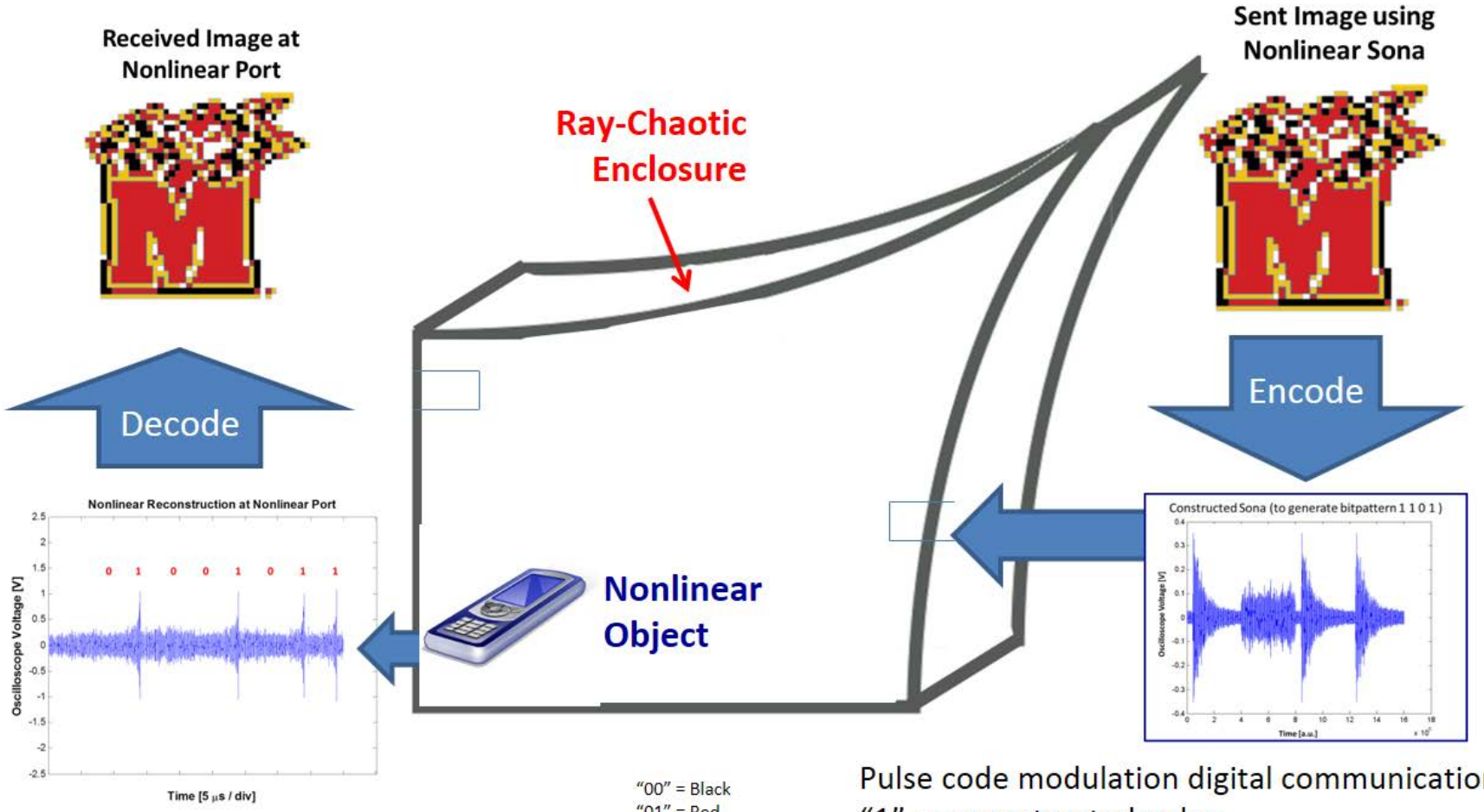

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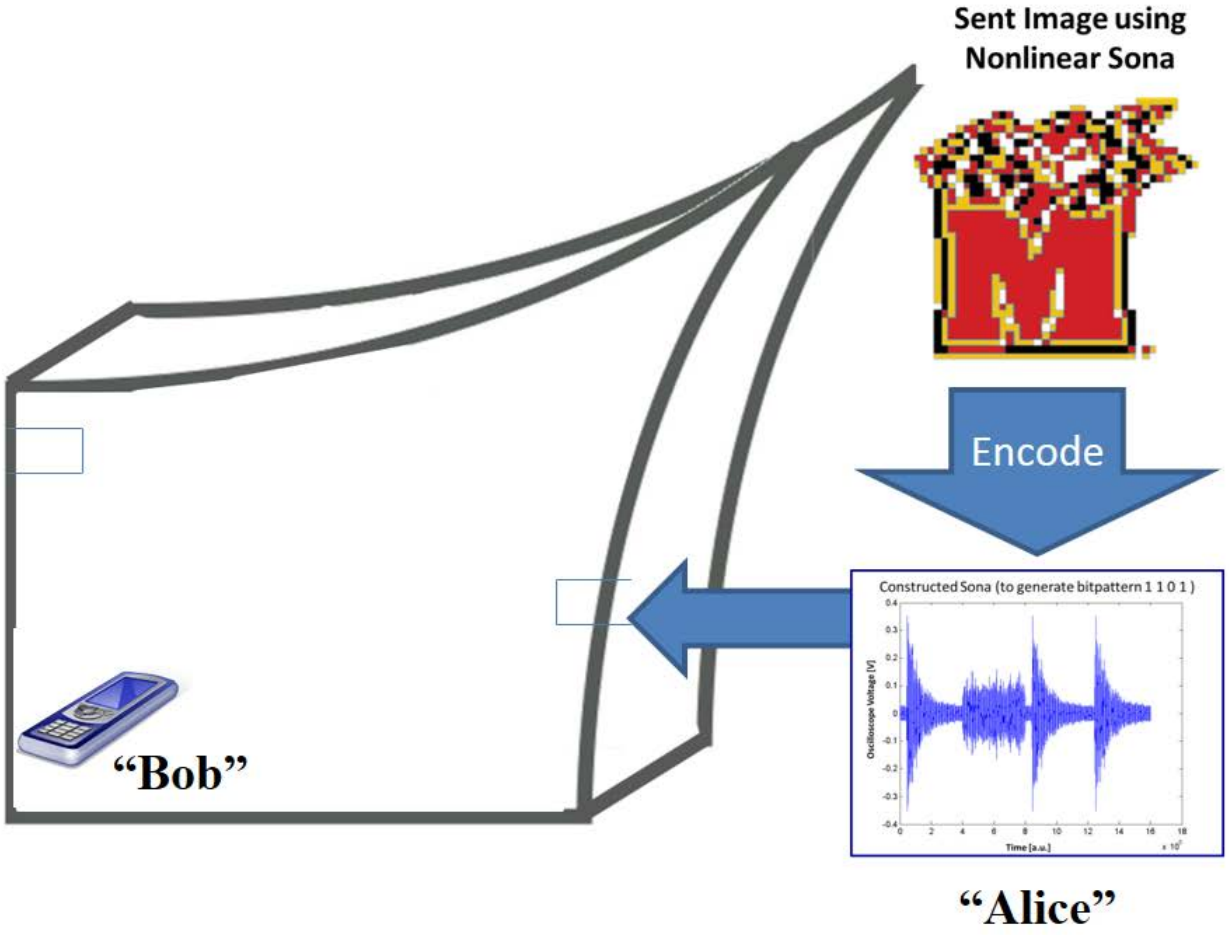

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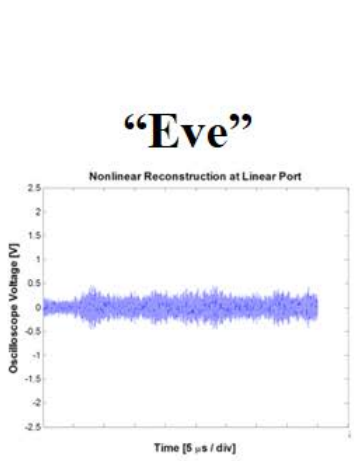

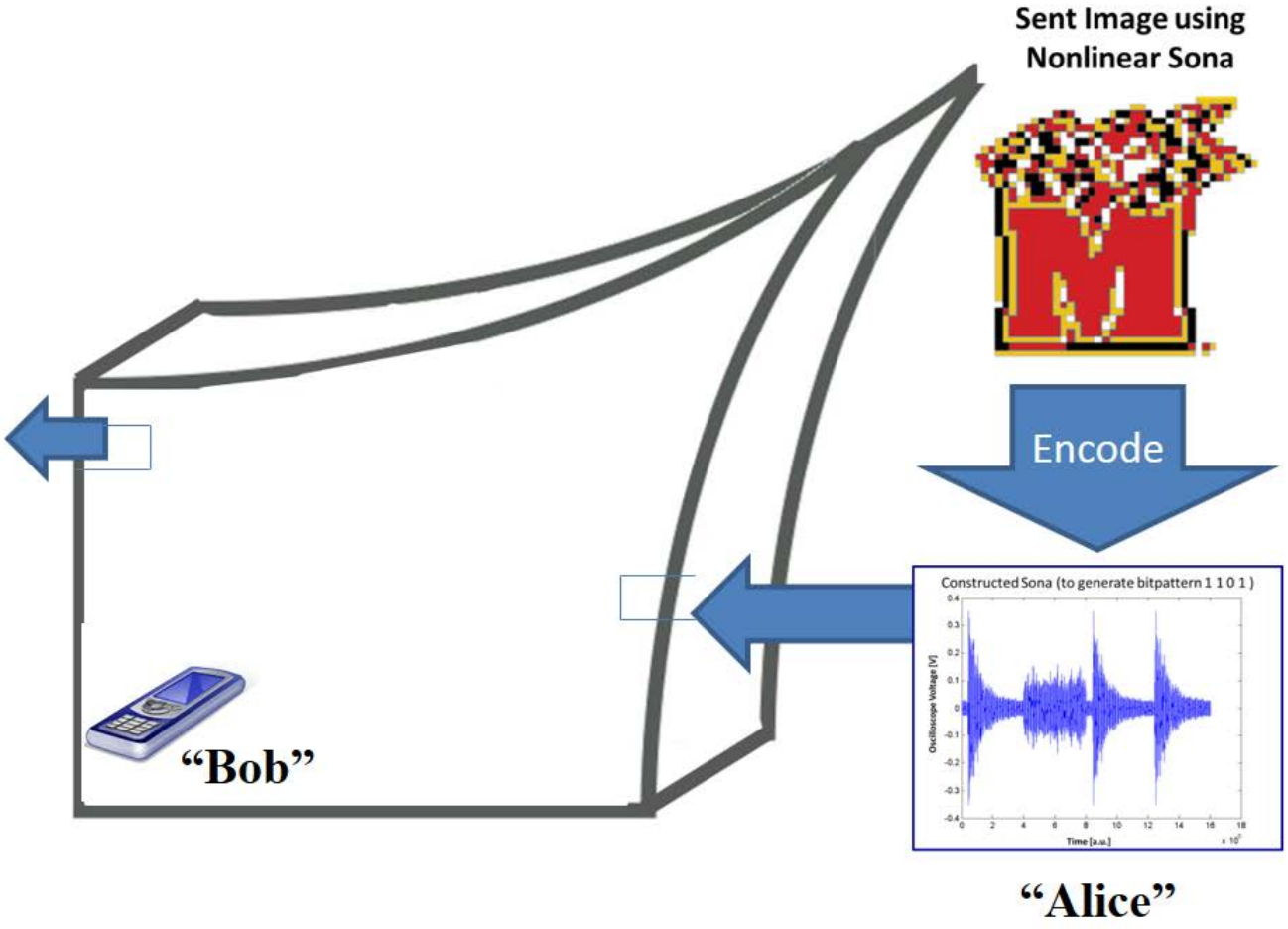

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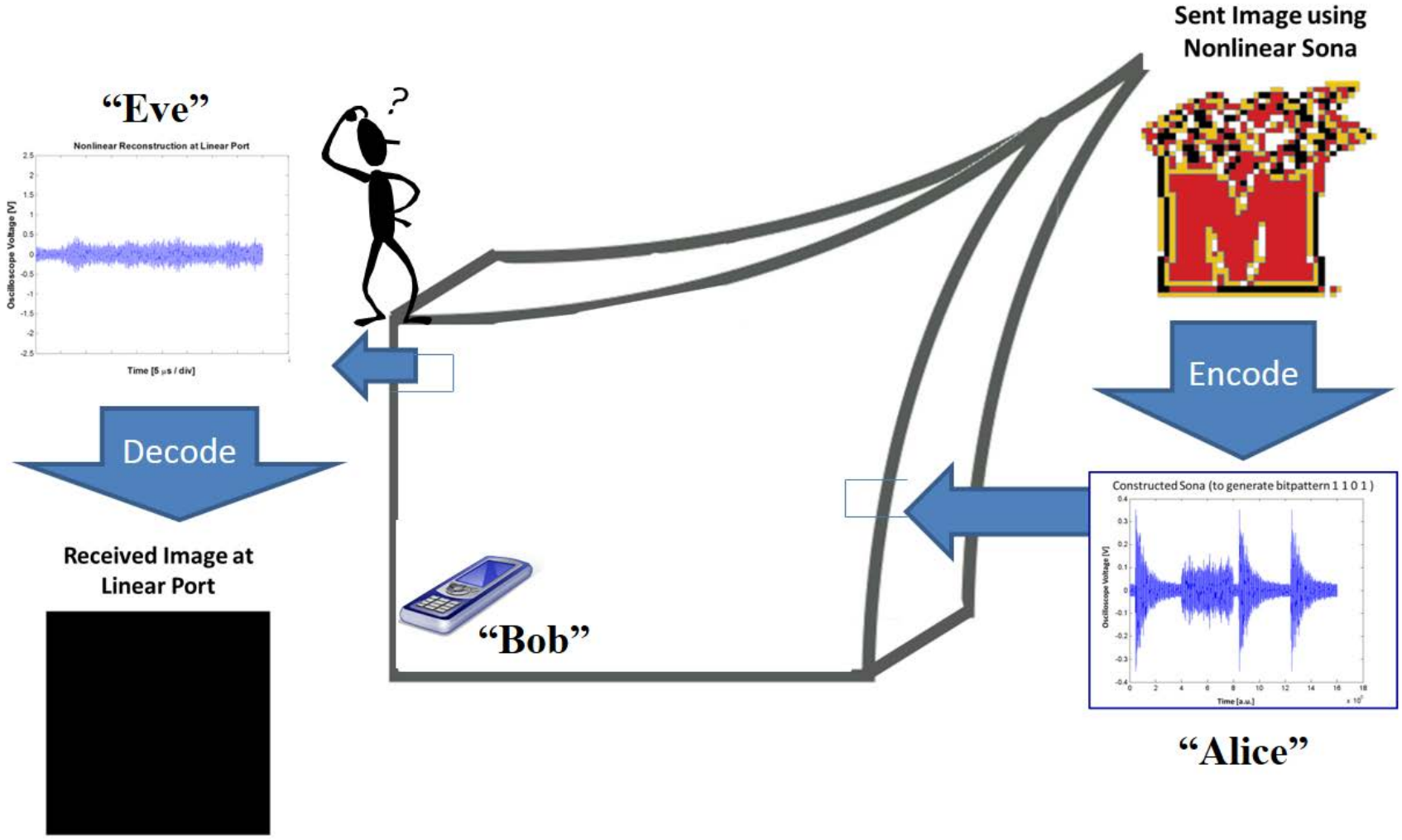
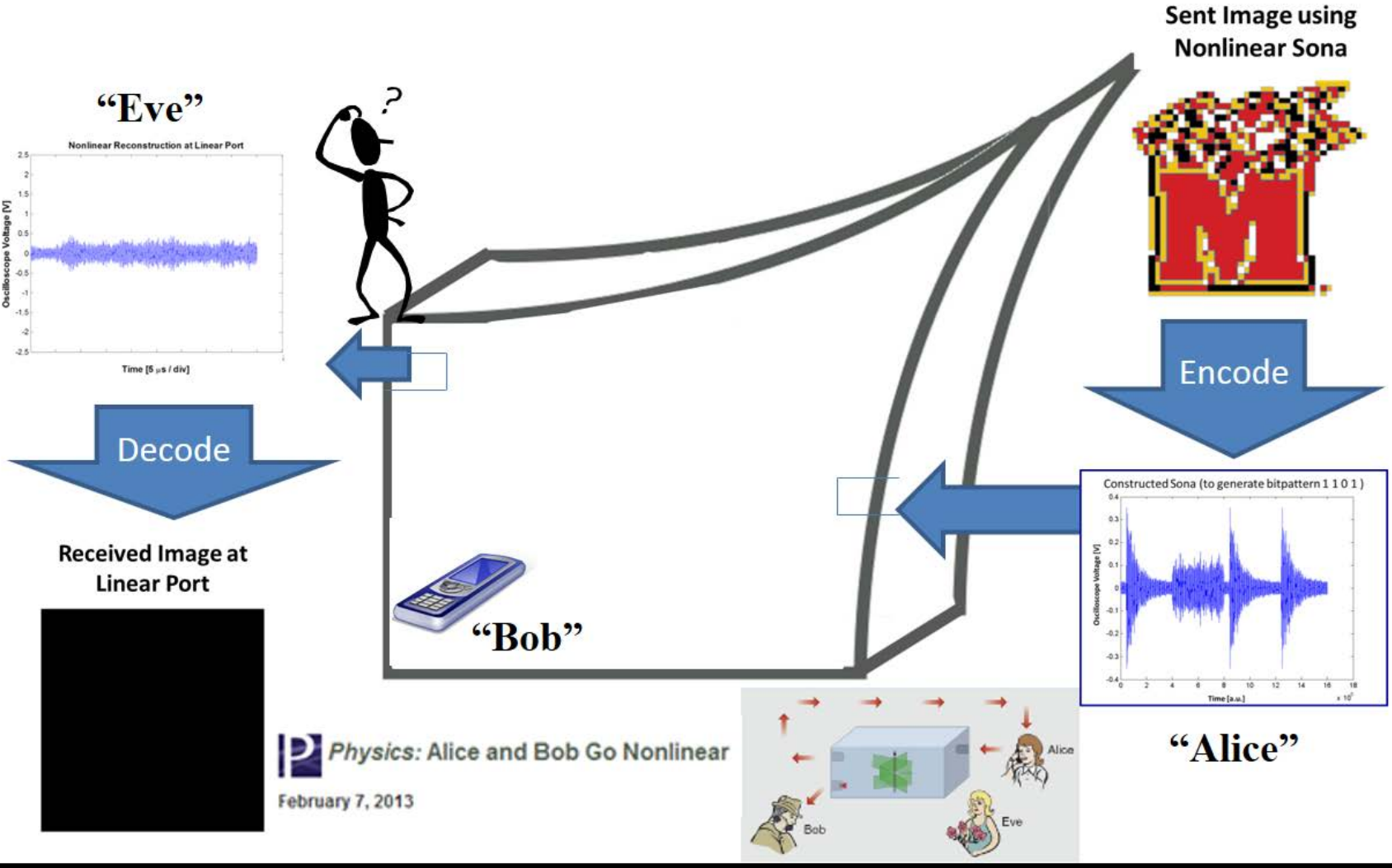


Application (1)

Directed communication channel with a nonlinear element at an arbitrary, unknown, location



Nonlinear Electromagnetic Time Reversal in an Open Semireverberant System

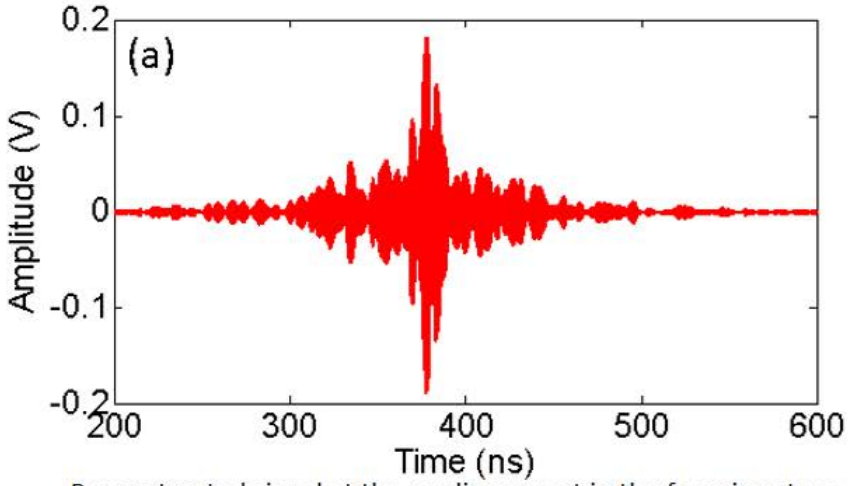
Sun K. Hong,[1*] Victor M. Mendez,[1] Trystan Koch,[2,3] Walter S. Wall,[1] and Steven M. Anlage[2]

PHYSICAL REVIEW APPLIED 2, 044013 (2014)

U.S. NAVAL RESEARCH LABORATORY

Demonstration of the 'Pulse Inversion Method' to efficiently measure the nonlinear sona

FIG. 1. Metallic enclosure used for the nonlinear time-reversal experiment in an anechoic chamber. The nonlinear element is placed inside the enclosure while transmit and receive (TRM) antennas are placed outside the enclosure.



Reconstructed signal at the nonlinear port in the focusing stage

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- The Ordinary Time-Reversal Mirror
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Future Plans

Time-Reversal and EMC

Conclusions

Time-Reversed Collapse at an Arbitrary Location

Bo Xiao, *et al.*, Phys. Rev. E 93, 052205 (2016)

No need for an active source or a passive nonlinear object at the intended focusing location!

Time-Reversed Collapse at an Arbitrary Location

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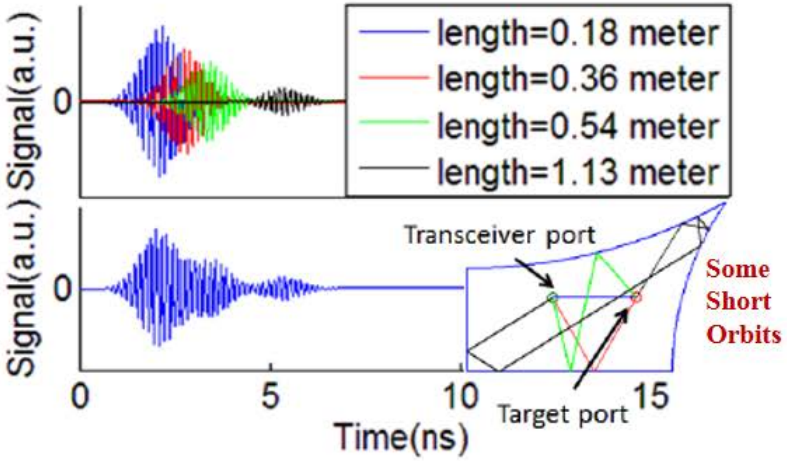

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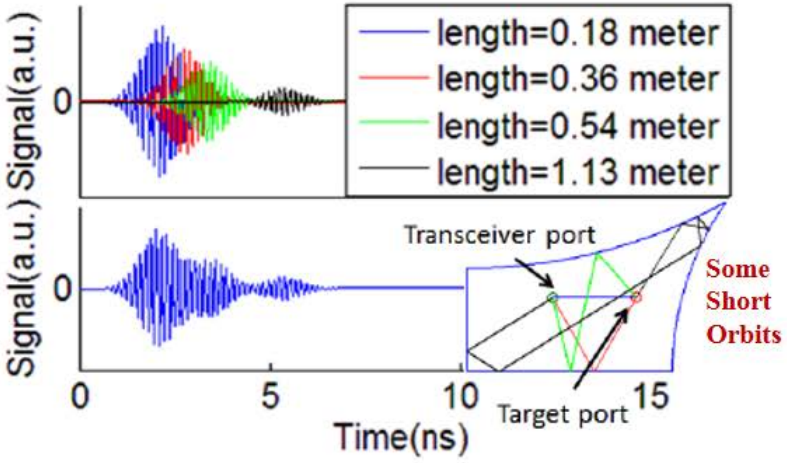

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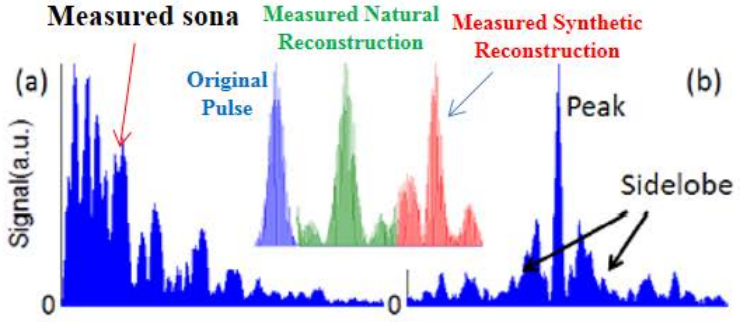

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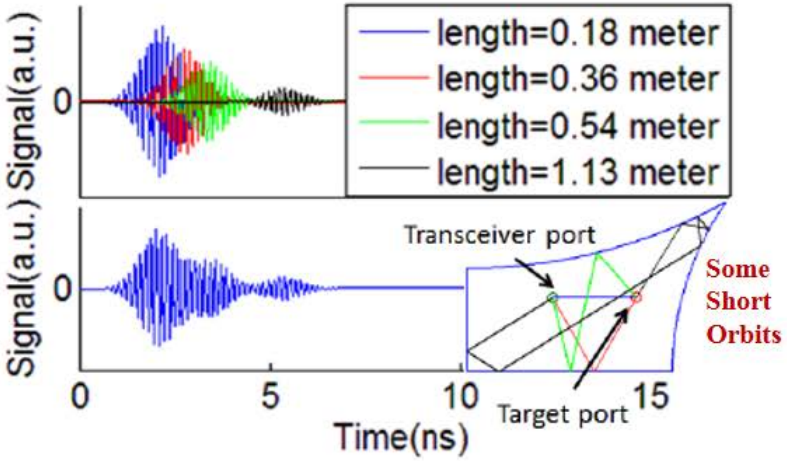

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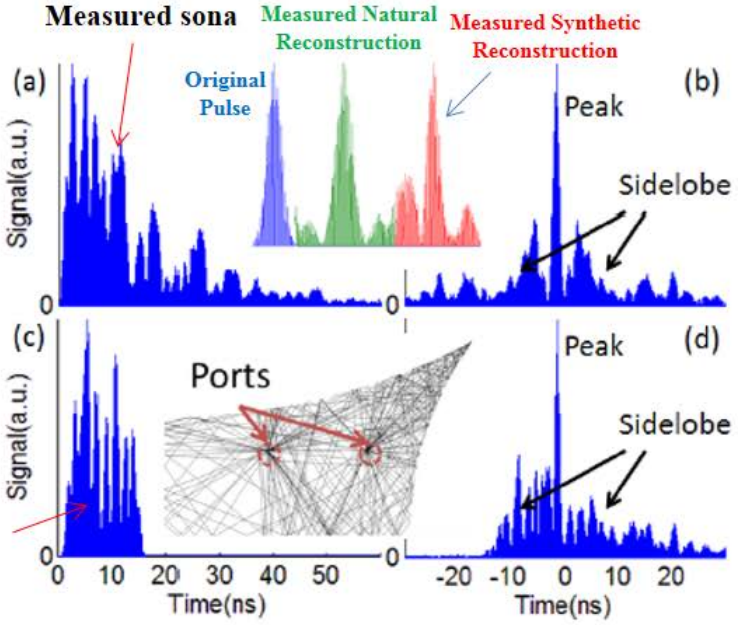

NEW Time-Reversal using synthetic sona

Synthetic sona

Time-Reversed Collapse at an Arbitrary Location

Bo Xiao, *et al.*, Phys. Rev. E 93, 052205 (2016)

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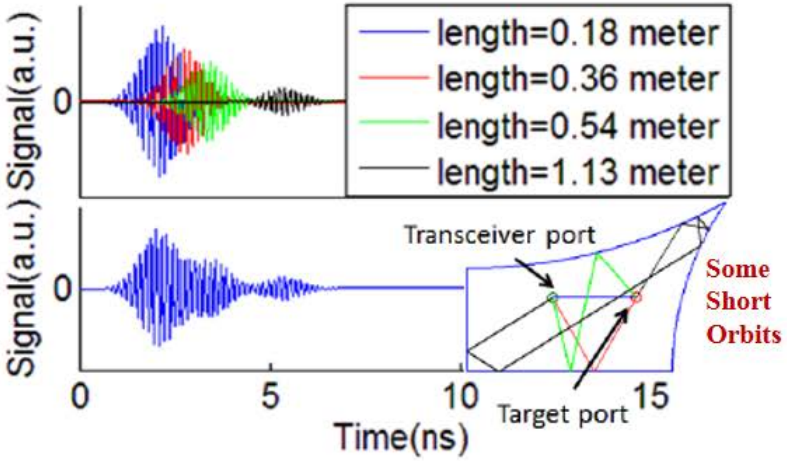

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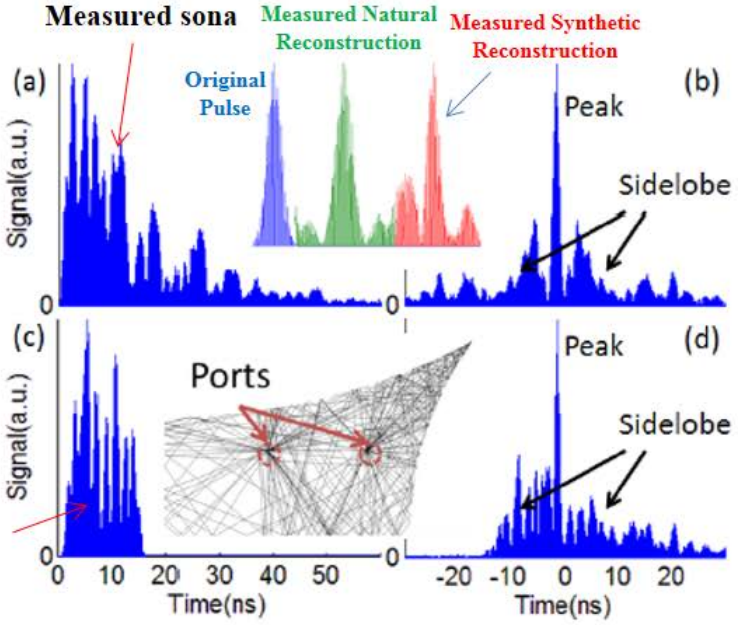


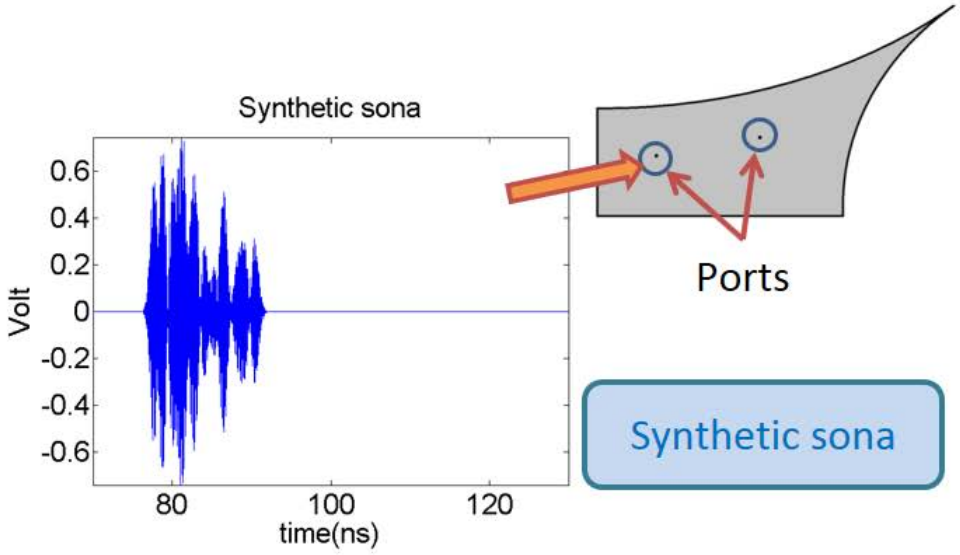
Also:

1) **Showed that quality of synthetic sona reconstruction depends on $\langle |S_{12}|^2 \rangle$**

2) **Best results when the synthetic sona duration is on the order of the 1/e decay time of the billiard**

Synthetic sona

Synthetic Sona Reconstruction



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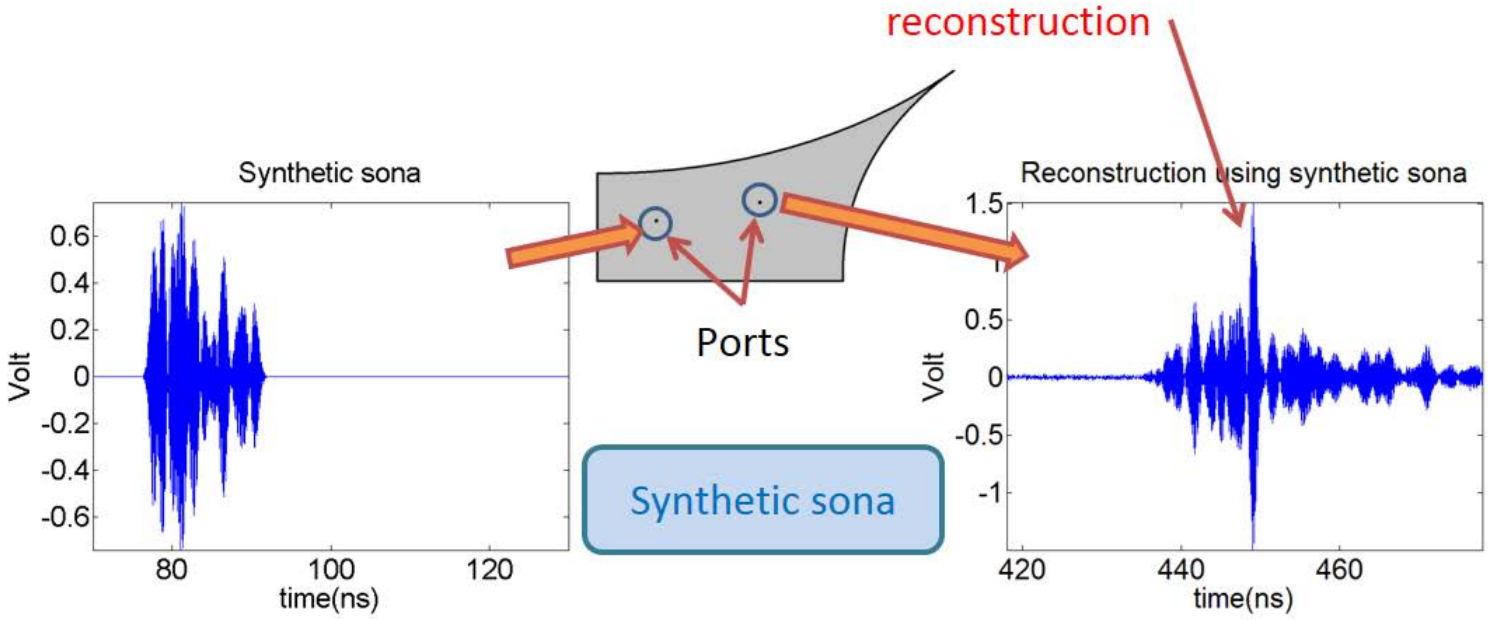

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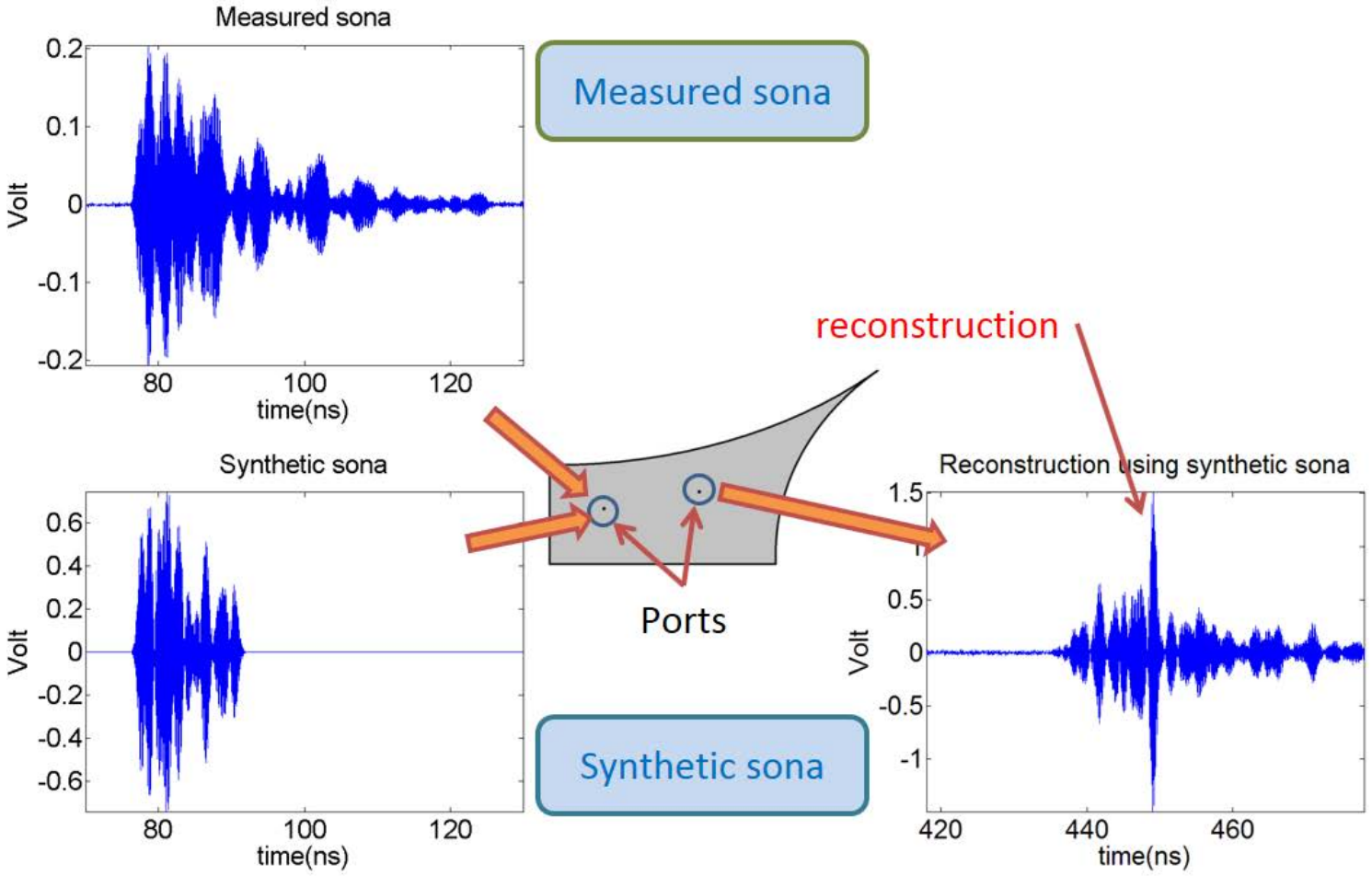

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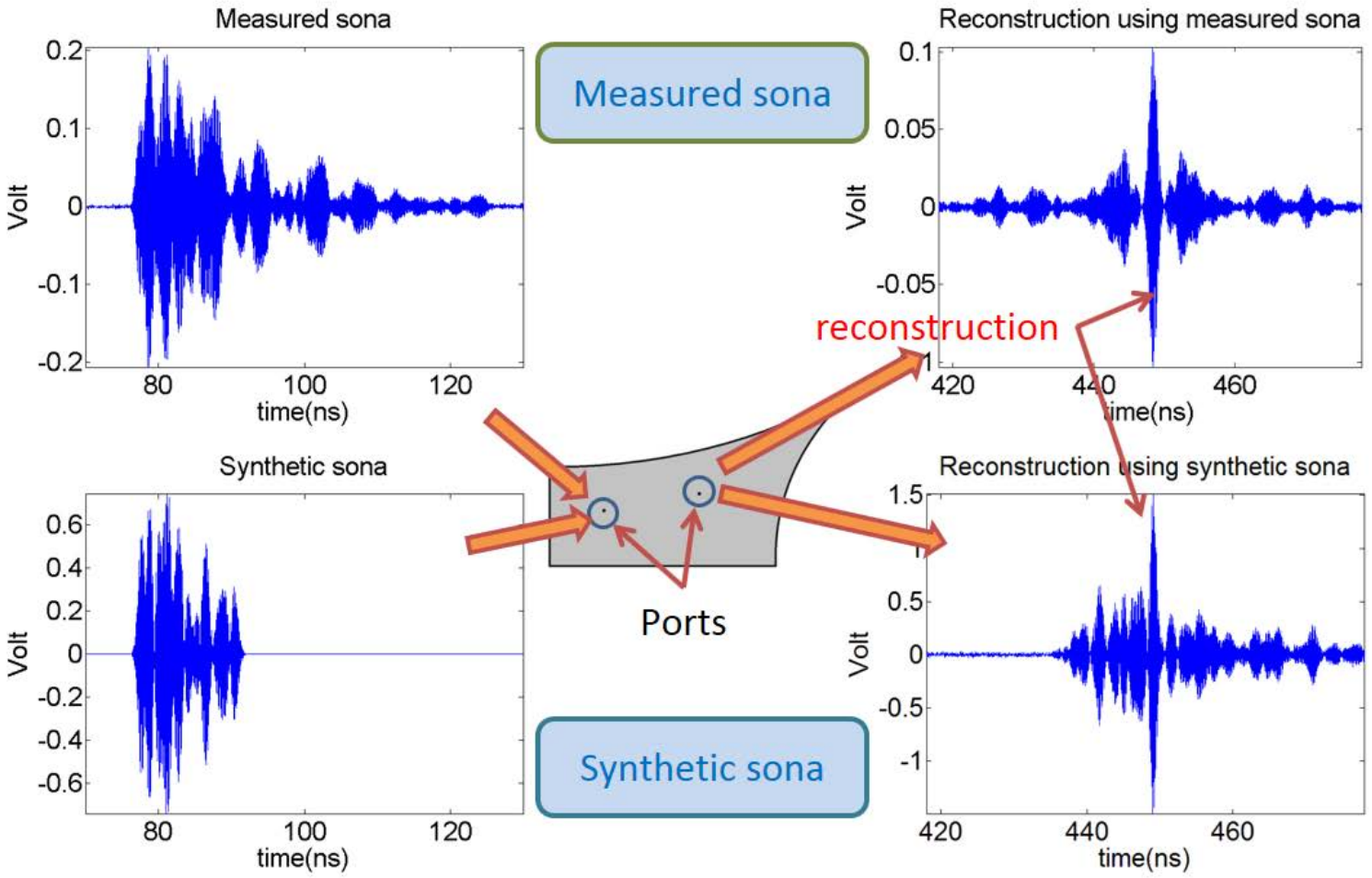

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Time Reversal for WPT

Requires…

1. Spatial reciprocity of the wave equation
2. Reflective surfaces
3. Ray-chaotic environment

Time Reversal for WPT

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1. Spatial reciprocity of the wave equation
2. Reflective surfaces
3. Ray-chaotic environment

Provides…

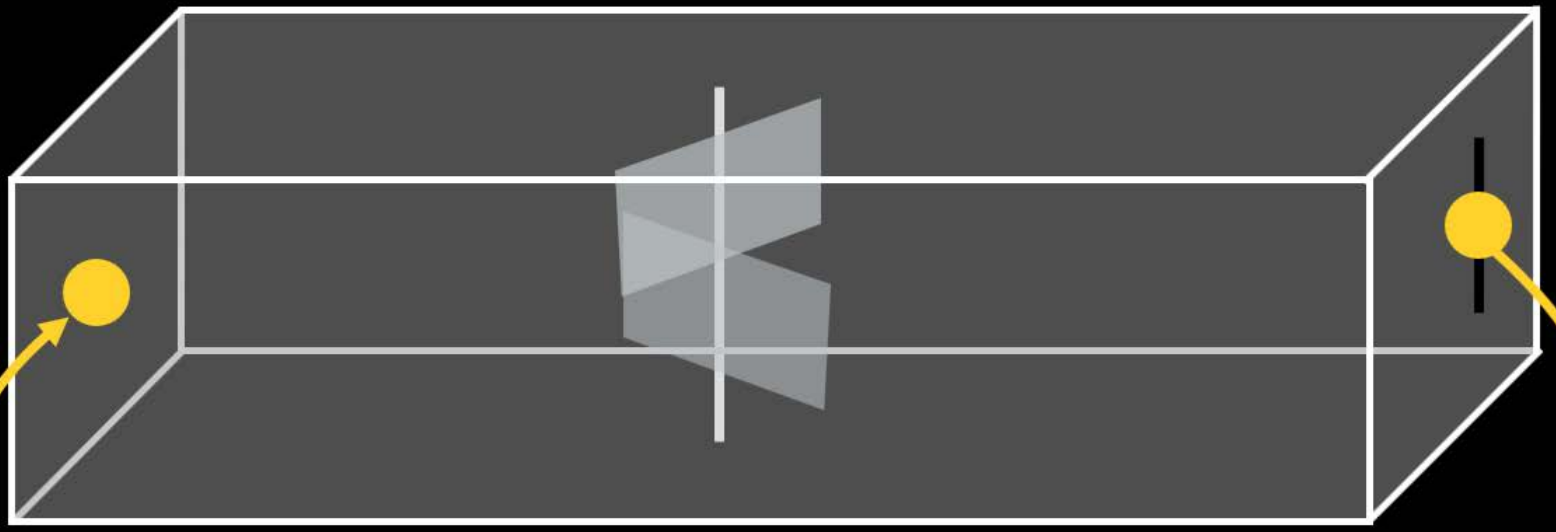
1. Range (not limited to free space drop-off)
2. Resilience to obstructions
3. Power concentrated at any given location

Experimental Setup

Power Source

Scattering panels ensure **ray chaos**

Client Device (on MikroMove)



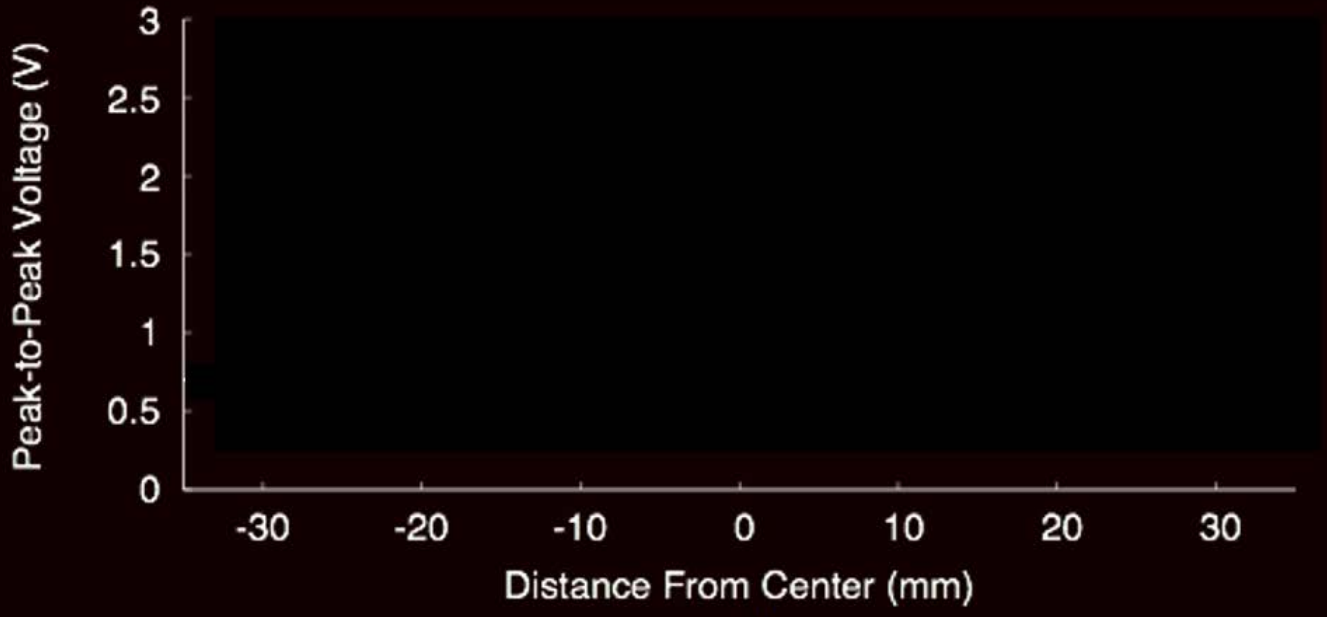
Wave Generation (TX)

PSG ← AWG

Wave Analysis (RX)

MATLAB ← Oscilloscope

Spatial Profiling of Reconstruction



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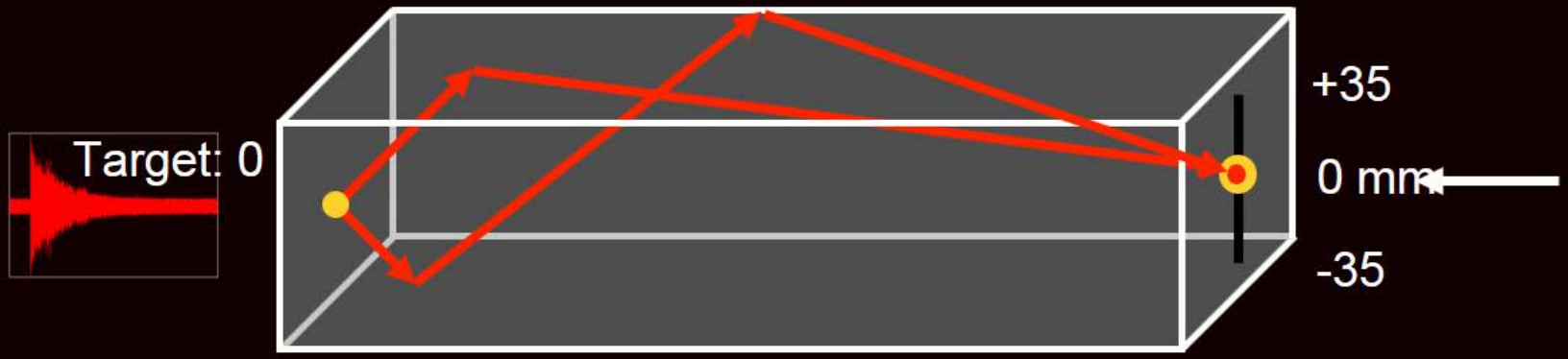

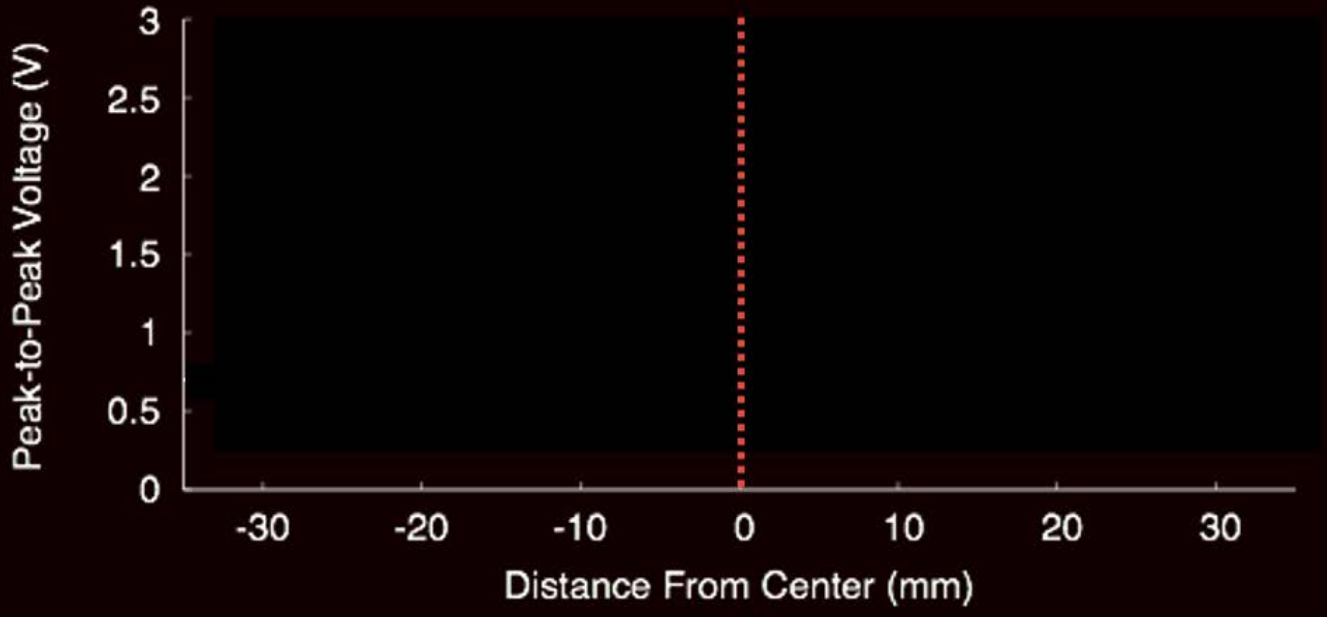

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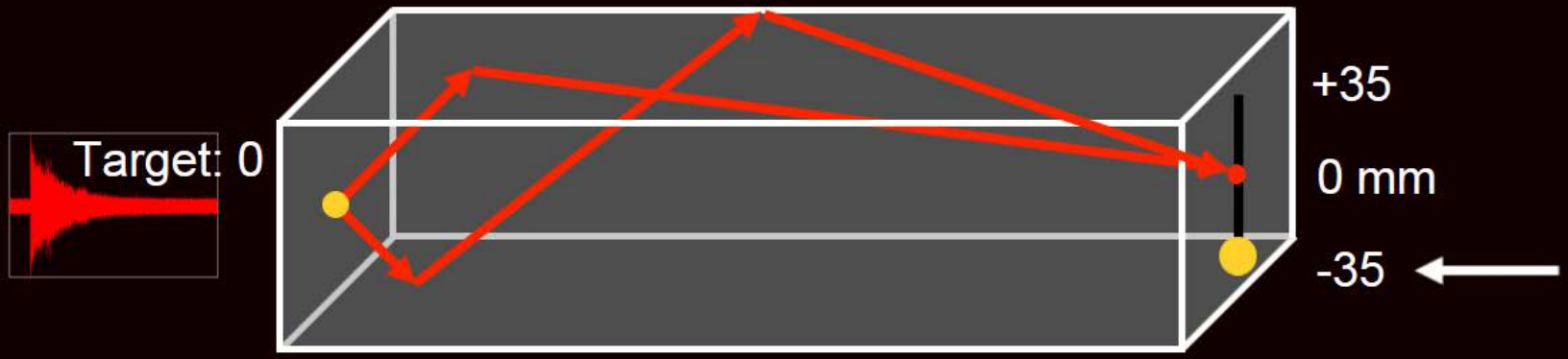

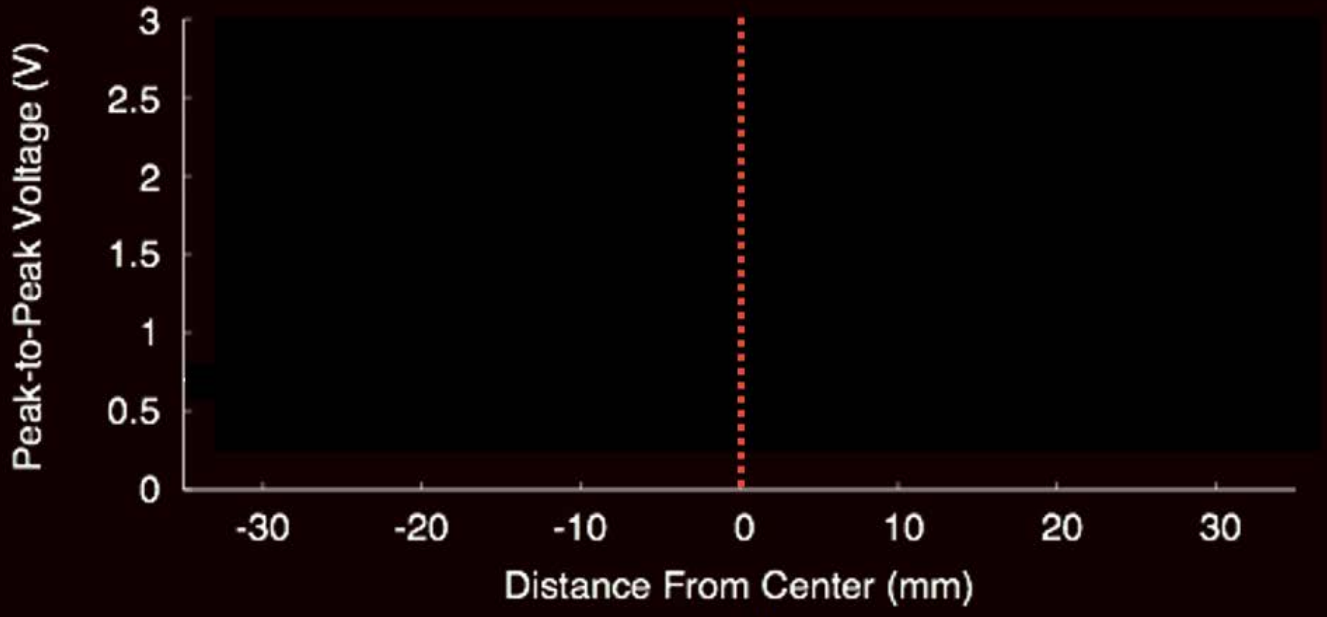

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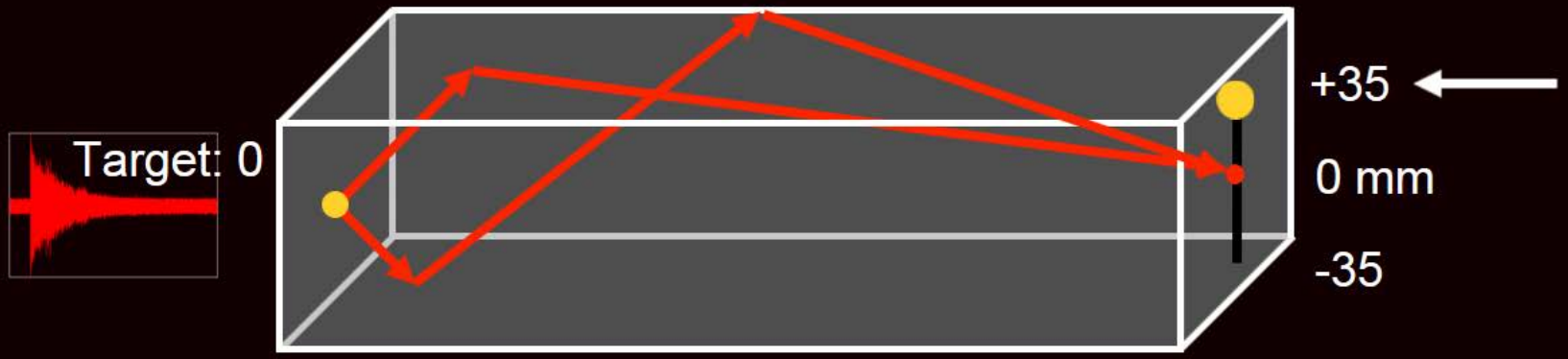
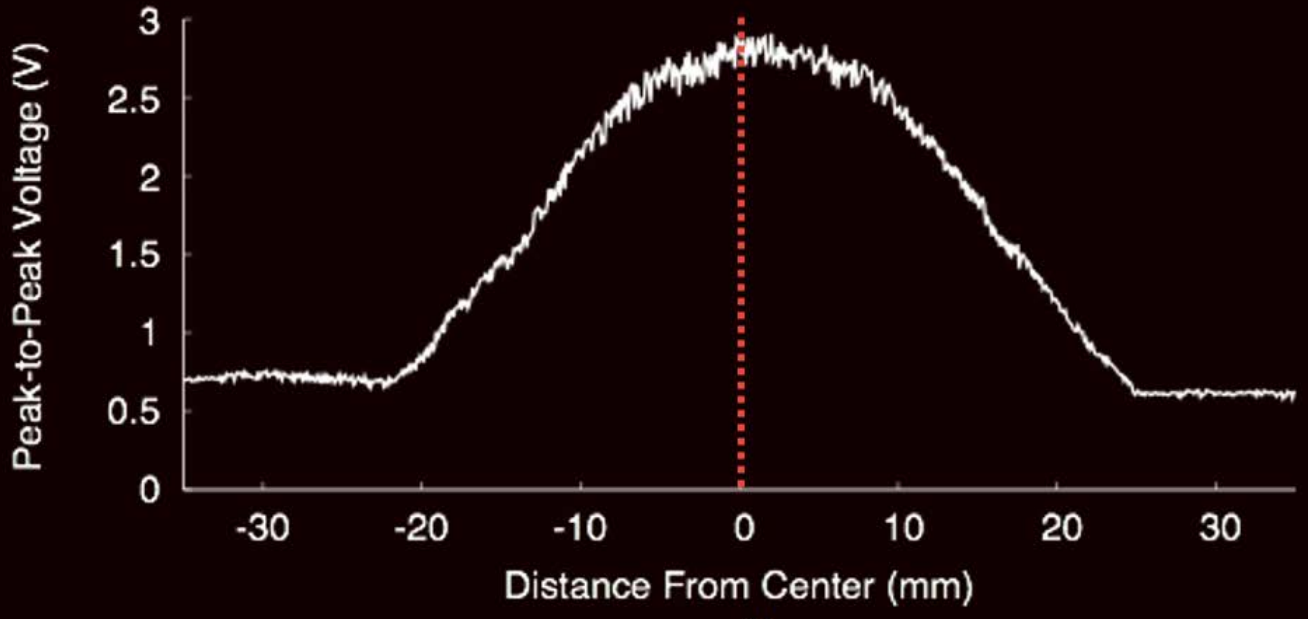
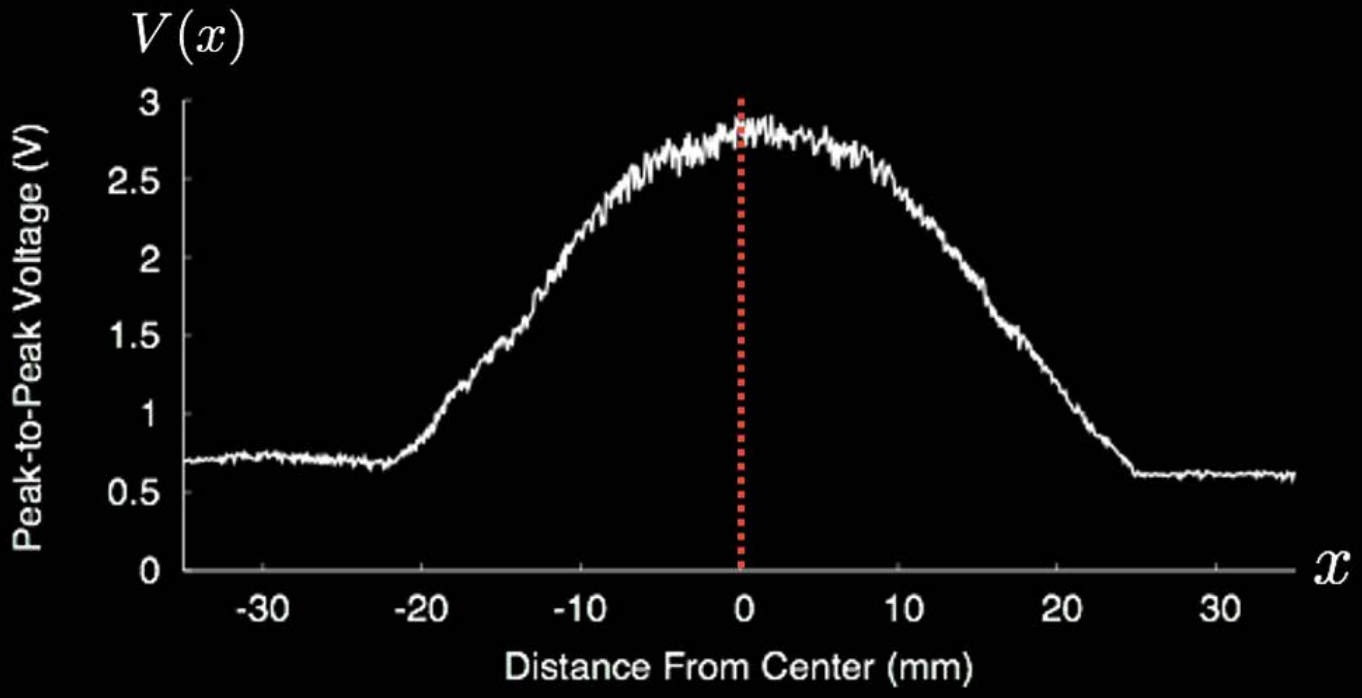




Spatial Profiling of Reconstruction

$$V(x) = a \cdot \left| sinc\left(\frac{x+c}{b}\right) \right| + d$$



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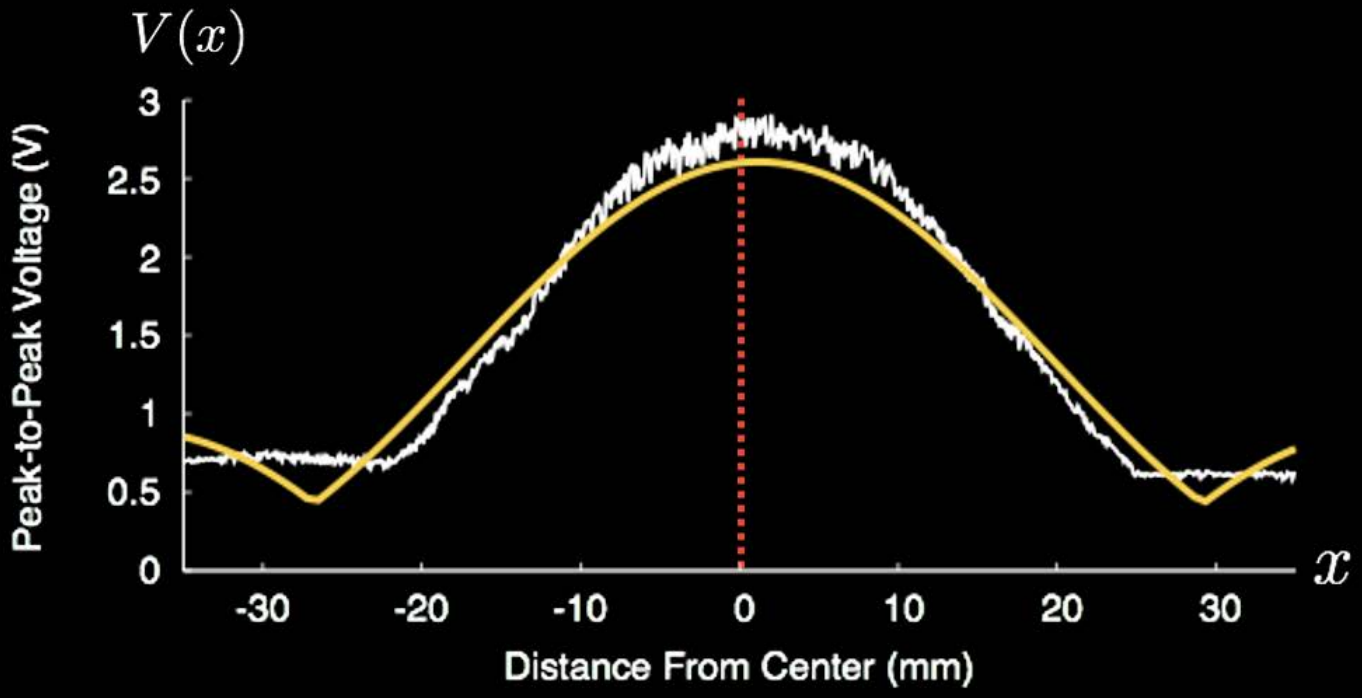

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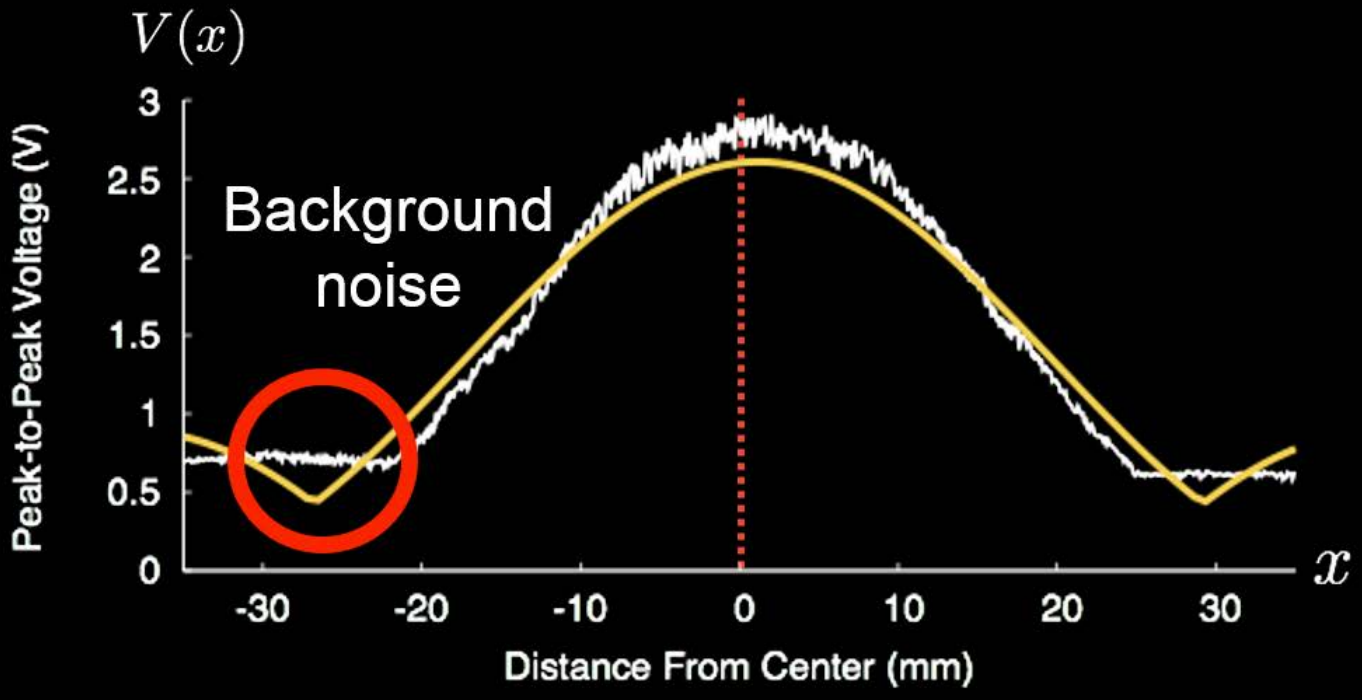

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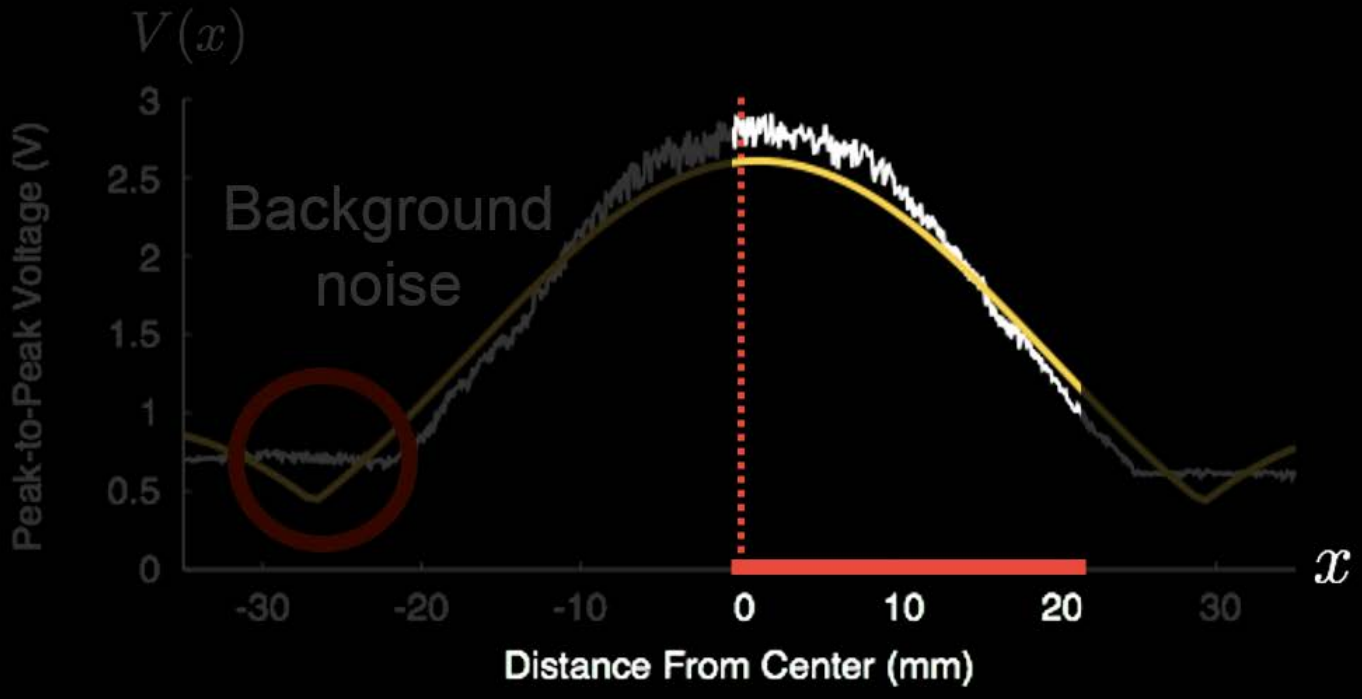
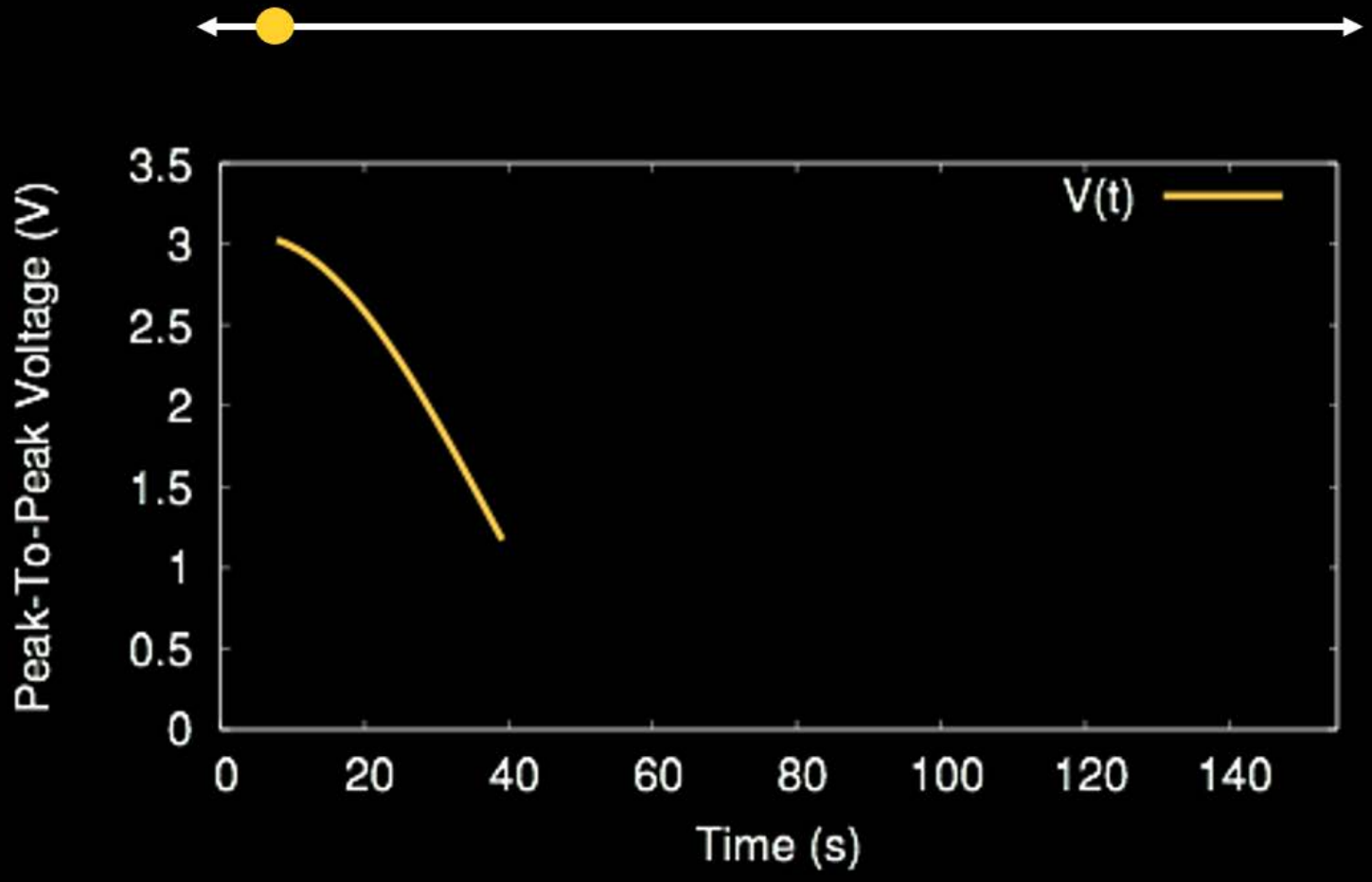


Targeting a Moving Receiver

"**Refresh**" the sona before it gets stale



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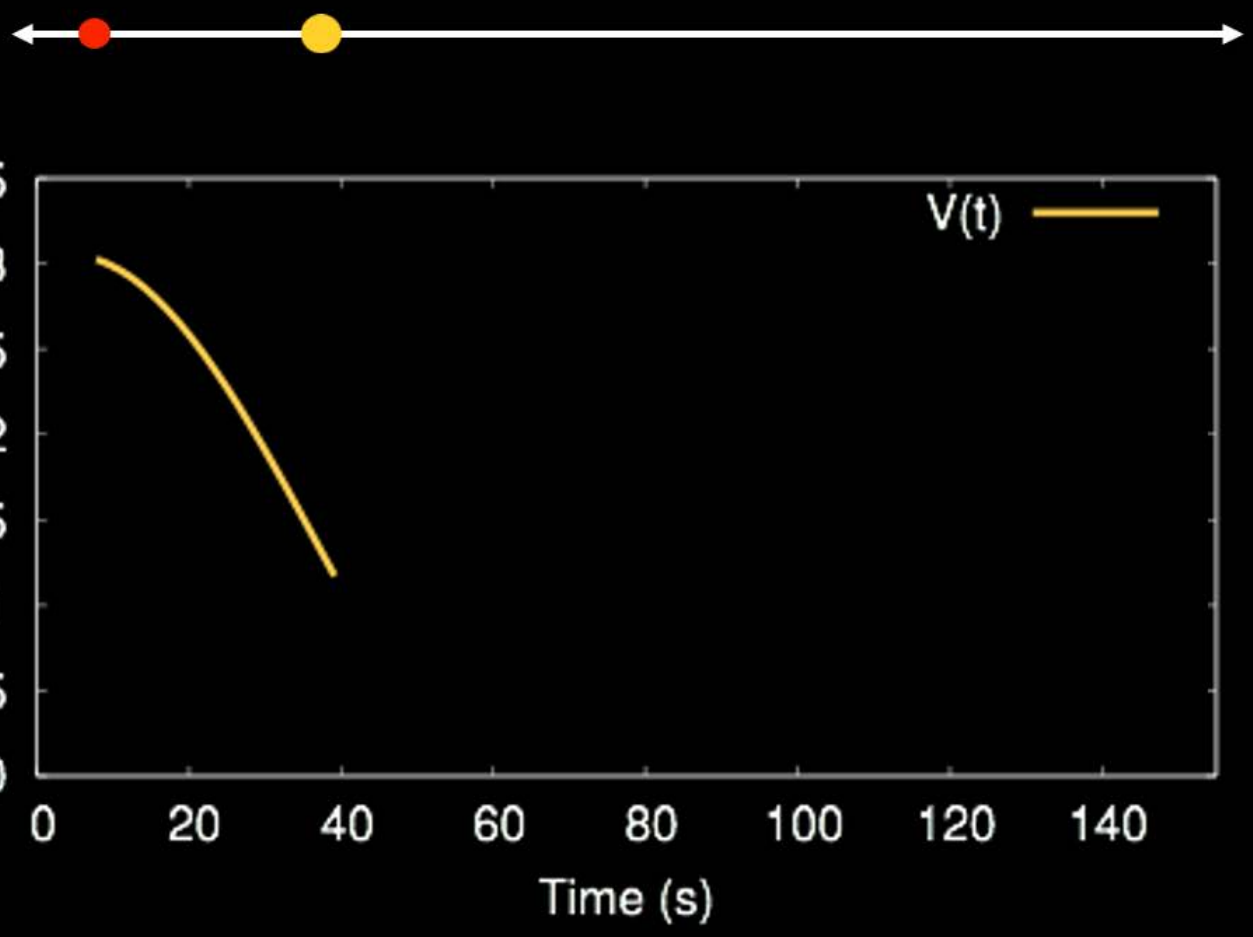

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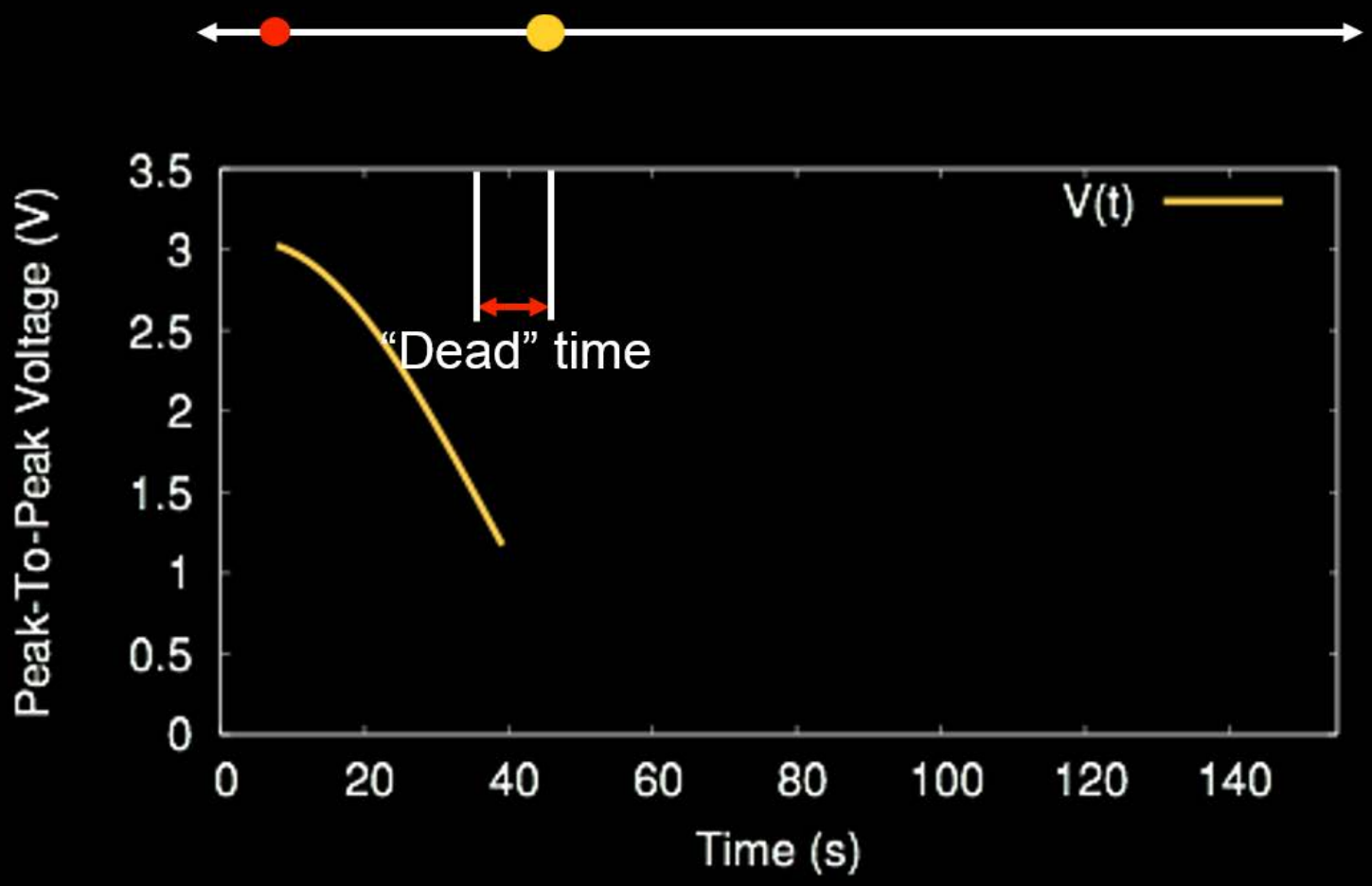

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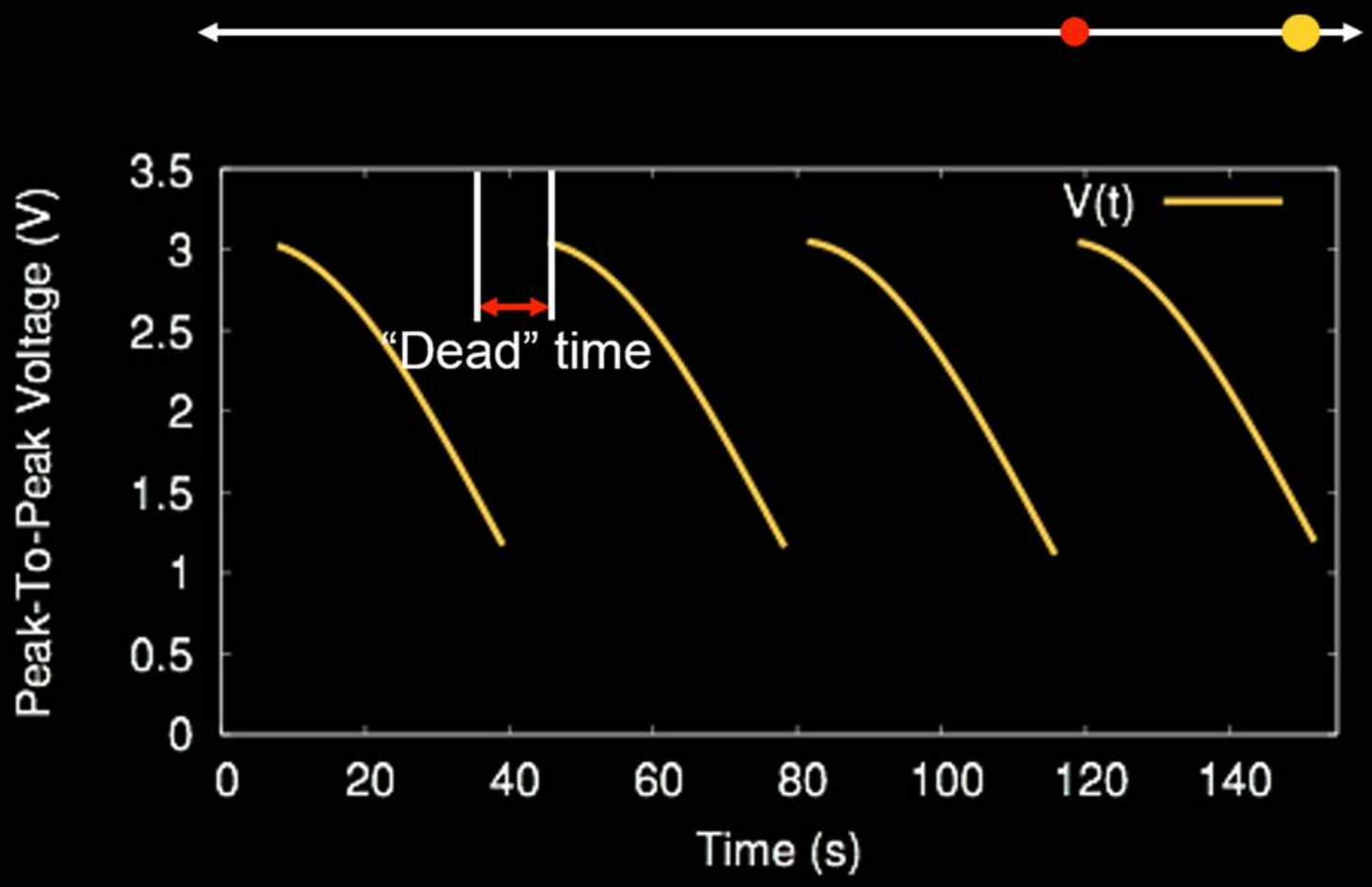

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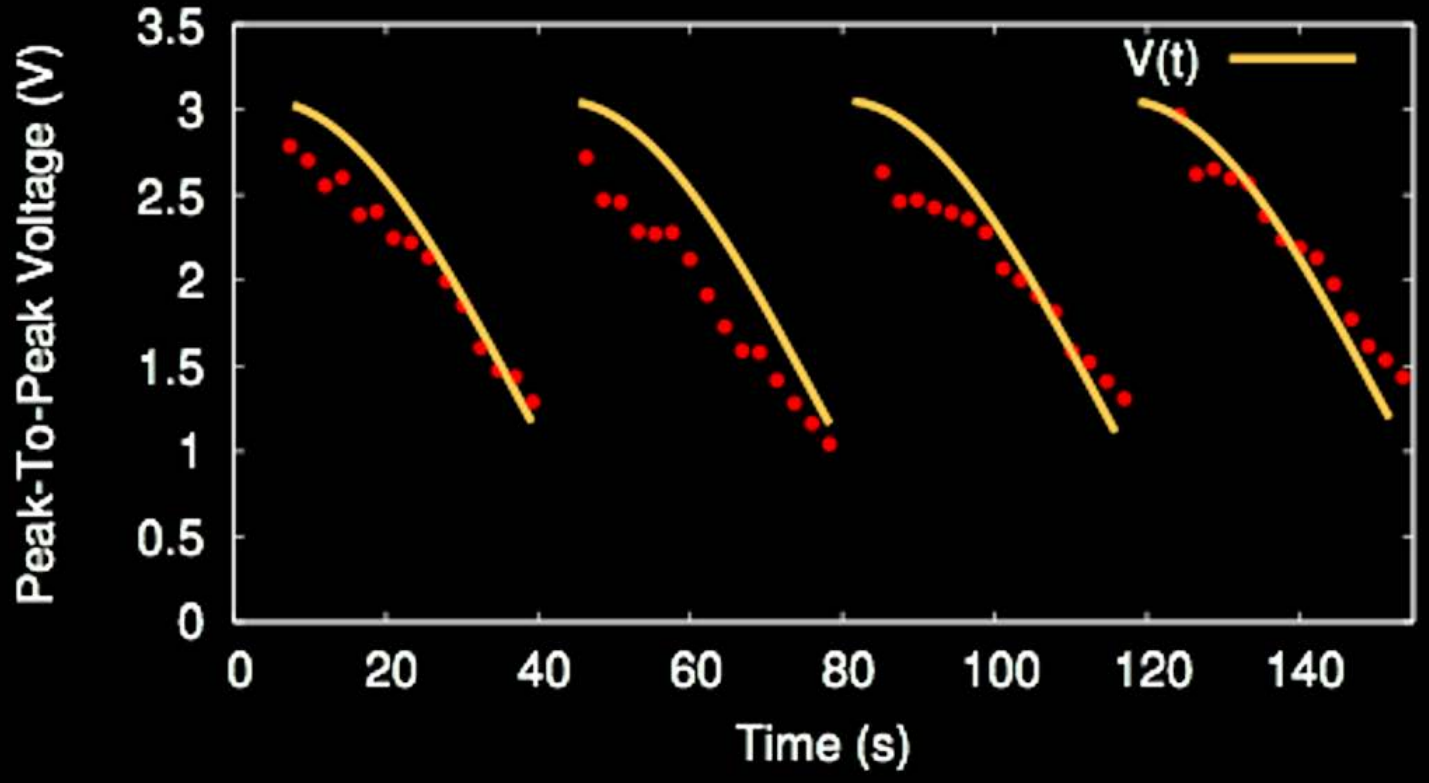
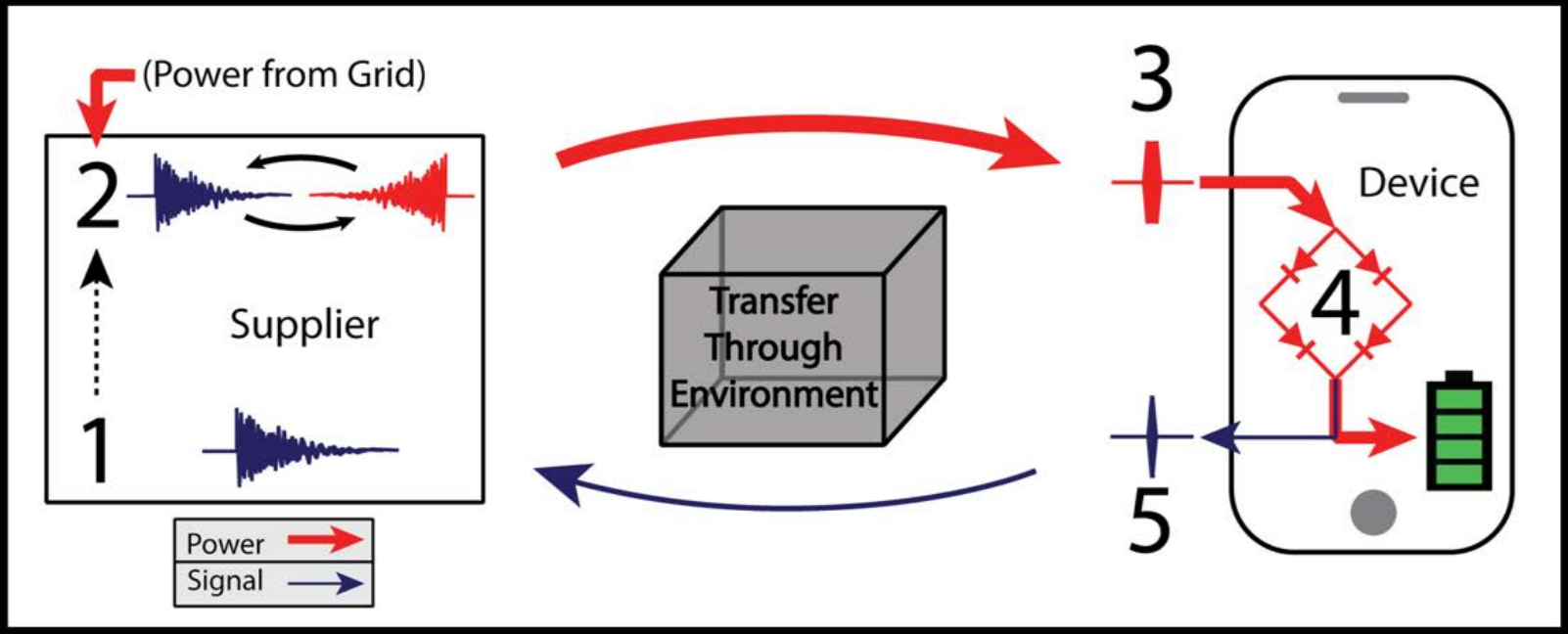
Experimental Results



Potential WPT System

Initialization — Supplier searches for participating devices (which may or may not have charge)

Steady State — Small fraction of power reflected by device, allowing supplier to find new location



Some Time-Reversed Electromagnetic Wave Publications from UMD / NRL

http://anlage.umd.edu/AnlageTR.htm

Biniyam Taddese, *et al.*, "**Sensor Based on Extending the Concept of Fidelity to Classical Waves**," Appl. Phys. Lett. **95** , 114103 (2009).

Biniyam Taddese, *et al.*, "**Sensing Small Changes in a Wave Chaotic Scattering System**," J. Appl. Phys. **108**, 114911 (2010).

Biniyam Taddese, *et al.*, "**Iterative Time Reversal with Tunable Convergence**," Electronics Letters **47**, 1165-1167 (2011).

Matthew Frazier, *et al.*, "**Nonlinear Time-Reversal in a Wave Chaotic System**," Phys. Rev. Lett. **110**, 063902 (2013).

Sun K. Hong, *et al.*, "**Focusing an arbitrary RF pulse at a distance using time-reversal techniques**," J. Electromag. Waves and Apps. **27**, 1262-1275 (2013).

Biniyam T. Taddese, *et al.*, "**Quantifying Volume Changing Perturbations in a Wave Chaotic System**," New J. Phys. **15**, 023025 (2013).

Matthew Frazier, *et al.*, "**Nonlinear Time-Reversal of Classical Waves: Experiment and Model**," Phys. Rev. E **88**, 062910 (2013).

Sun K. Hong, *et al.*, "**Nonlinear Electromagnetic Time Reversal in an Open Semireverberant System**," Phys. Rev. Applied **2**, 044013 (2014).

Bo Xiao, *et al.*, "**Focusing Waves at an Arbitrary Location in a Ray-Chaotic Enclosure Using Time-Reversed Synthetic Sonas**." Phys. Rev. E **93**, 052205 (2016).

Frank Cangialosi, *et al.*, "**Time Reversed Electromagnetic Wave Propagation as a Novel Method of Wireless Power Transfer**," 2016 IEEE Wireless Power Transfer Conference (WPTC) (2016).

Scott Roman, *et al.*, "**Selective Collapse of Nonlinear Time Reversed Electromagnetic Waves**," 2016 IEEE Wireless Power Transfer Conference (WPTC)(2016).

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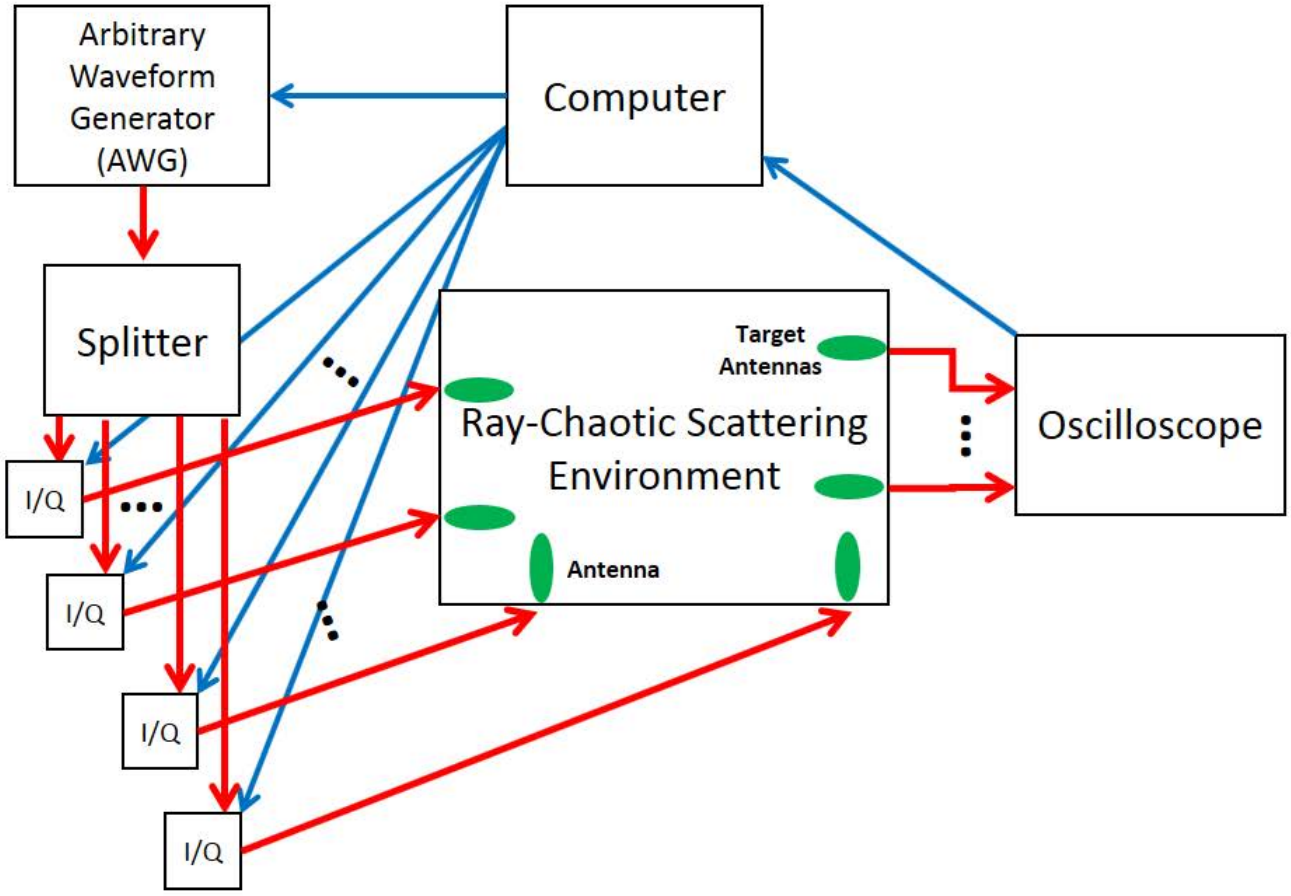
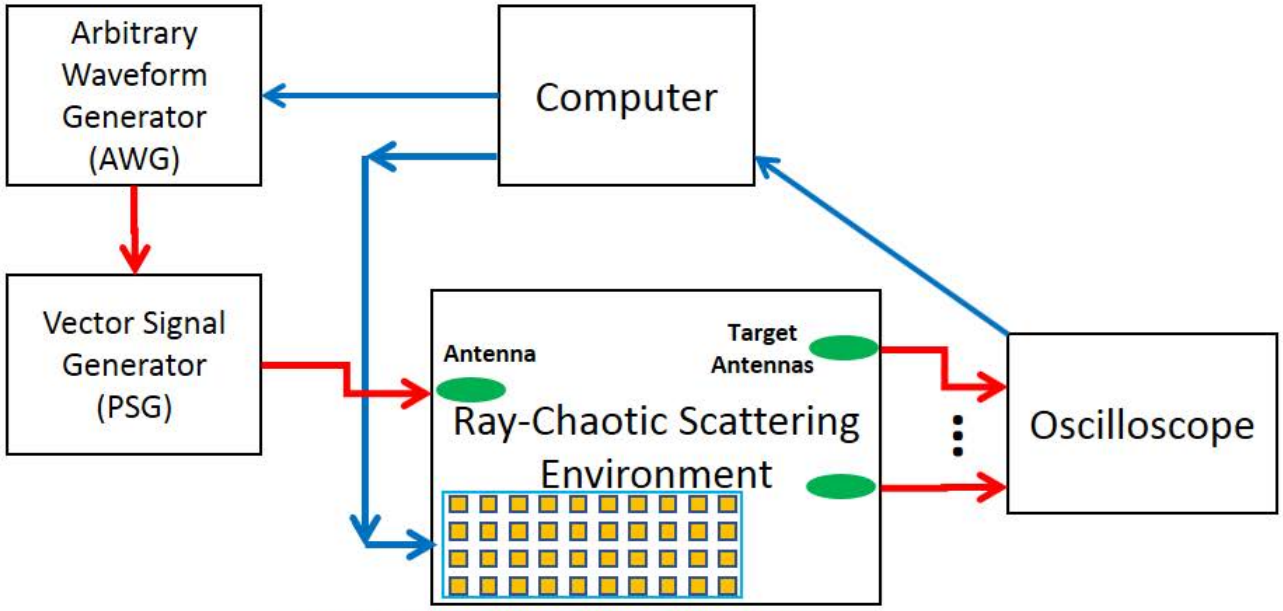
Future: Multi-Channel Time-Reversal Mirror



Future: Multi-Element Spatial Microwave Modulator



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How Could Time-Reversed Electromagnetic Waves Be Used for EMC?

Targeted EMC Testing

Direct an arbitrary time-domain waveform to an arbitrary location in a reverb chamber or other scattering environment

Nonlinear EMC Testing

Nonlinear response offers "back door" entry into systems
Could be used to inject un-wanted signals …

Time-Domain Random Coupling Model (RCM)

Generalize our RCM to time-dependent and nonlinear phenomena
Statistical theory of induced voltages in complex enclosures
See http://anlage.umd.edu/RCM/index.htm

Summary

- We have developed the first electromagnetic nonlinear time-reversal mirror
- T/R Waves have applications in Communications, Wireless Power Transfer and EMC
- Ray-Chaos is beneficial for Time-Reversal and Statistical modeling (RCM)
- Results with *synthetic sonas* show that impulses can be directed to arbitrary locations inside a ray-chaotic billiard, given knowledge of the scattering geometry

Related Publications:

B. Xiao, *et al.*, Phys. Rev. E 93, 052205 (2016)
M. Frazier, *et al.*, Phys. Rev. Lett. 110, 087002 (2013)
M. Frazier, *et al.* Phys. Rev. E 88, 062910 (2013)

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Mark Herrera
Heron Systems


Ming-Jer Lee
World Bank


Trystan Koch


Bisrat Addissie
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Post-Docs

Gabriele Gradoni

Mathew Frazier


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Tom Antonsen


Steve Anlage

NRL Collaborators: Tim Andreadis, Lou Pecora, Hai Tran, Sun Hong, Zach Drikas, Jesus Gil Gil

Funding: ONR, AFOSR, DURIP

2018 IEEE SYMPOSIUM ON ELECTROMAGNETIC COMPATIBILITY, SIGNAL AND POWER INTEGRITY

EMC+SIPI 2018

July 30 – August 3, 2018 *Long Beach, CA*

Your Port for EMC+SIPI Compliance

Why is the Reconstruction Less than Perfect?

Peak SNR = $20\log_{10}(V_{signal,peak} / V_{noise,peak})$

Incident pulse: 23 dB
Unperturbed case: 8.7 dB
Perturbed case: 4.7 dB

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For best reconstruction: Window size $T >> t_H$ (Heisenberg time, $\sim 1/\Delta f_{mean}$)
In this case, $T \sim t_H$ only

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Ideal case: zero losses, $T \rightarrow \infty$:

Perfect time reversal requires recording at both ports, not just one

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Frequency domain @ 7 GHz: $1-|S_{11}|^2 \approx -3$ dB, $|S_{21}|^2 \approx -25$ dB

i) Identical antennas: Little energy re-emerges after cavity excitation
ii) ½ energy promptly reflected, ½ enters cavity
iii) Despite very little energy emerging in port 2 we still get good reconstruction

Small fluctuations in Q: Each mode affected by loss in nearly the same way