IEEE Distinguished Lecture

Hofstra University

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REVERSING TIME:

A WAY TO UNRAVEL DISTORTED

COMMUNICATIONS?

Dr. JAMES V. CANDY

Lawrence Livermore National Laboratory & University of California, Santa Barbara

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ORGANIZATION

- *INTRODUCTION*
- *BACKGROUND*
- *WHAT IS TIME-REVERSAL?*
- *T/R PROCESSING FOR COMMUNICATIONS*
- *PROOF-OF-PRINCIPLE EXPERIMENTS*
- *NARROW-BAND P2P?*
- *NARROW-BAND A2P?*
- *WIDE-BAND A2P?*
- *SUMMARY*

INTRODUCTION

Signal Processing

is based on developing a processor to extract the useful information from noisy uncertain data while rejecting the extraneous

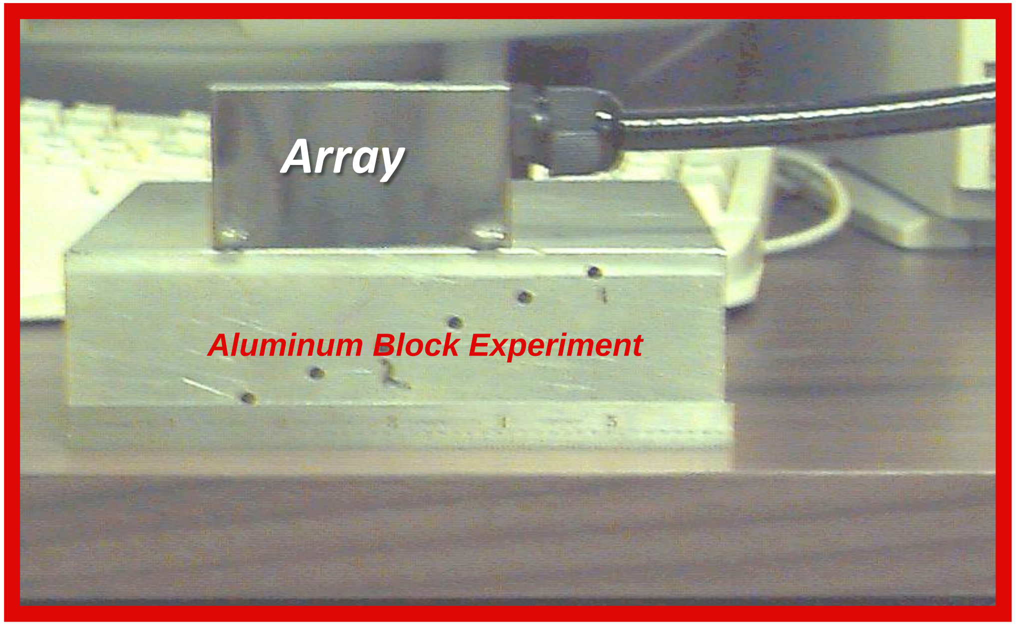
In acoustics, the signal can be a sound, a digitized measurement, an image, a noisy measurement … or even a "wave"

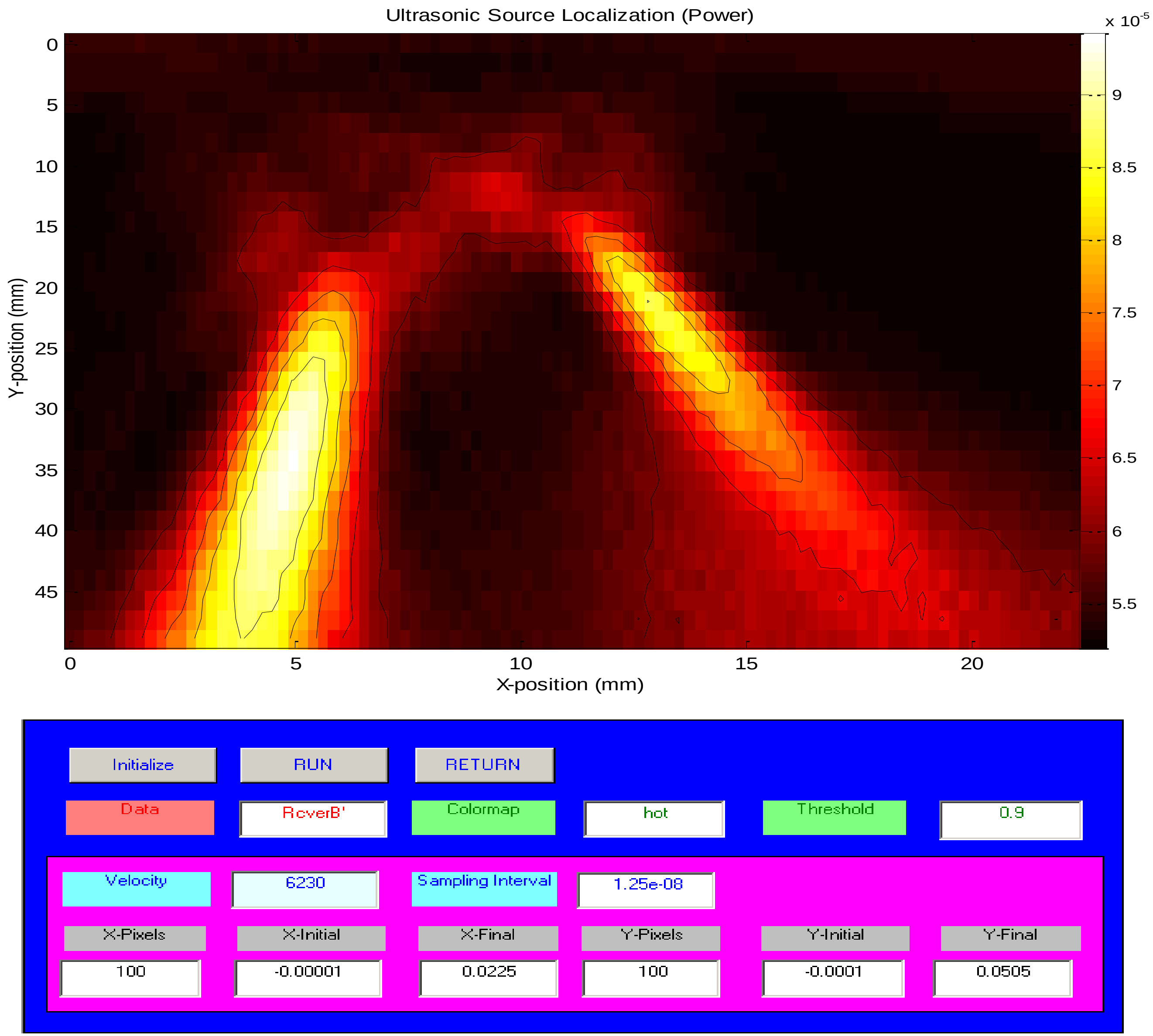
A wave is a special signal based on *space* and *time* (e.g. pebble dropped into a puddle)

Flaw detection and imaging can be achieved using acoustic transmitters in an ultrasonic array

T/R Prototype Unit

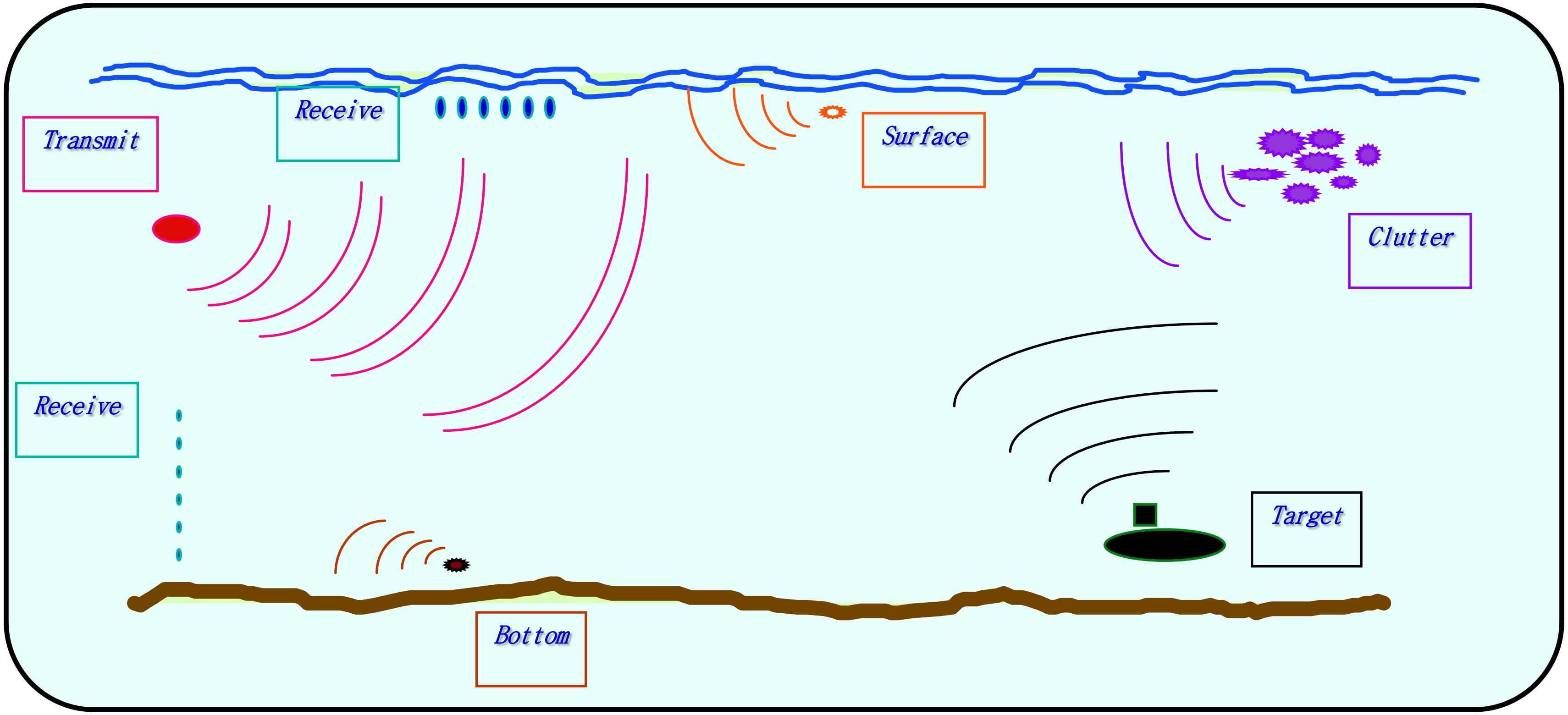
Control Computer/Display



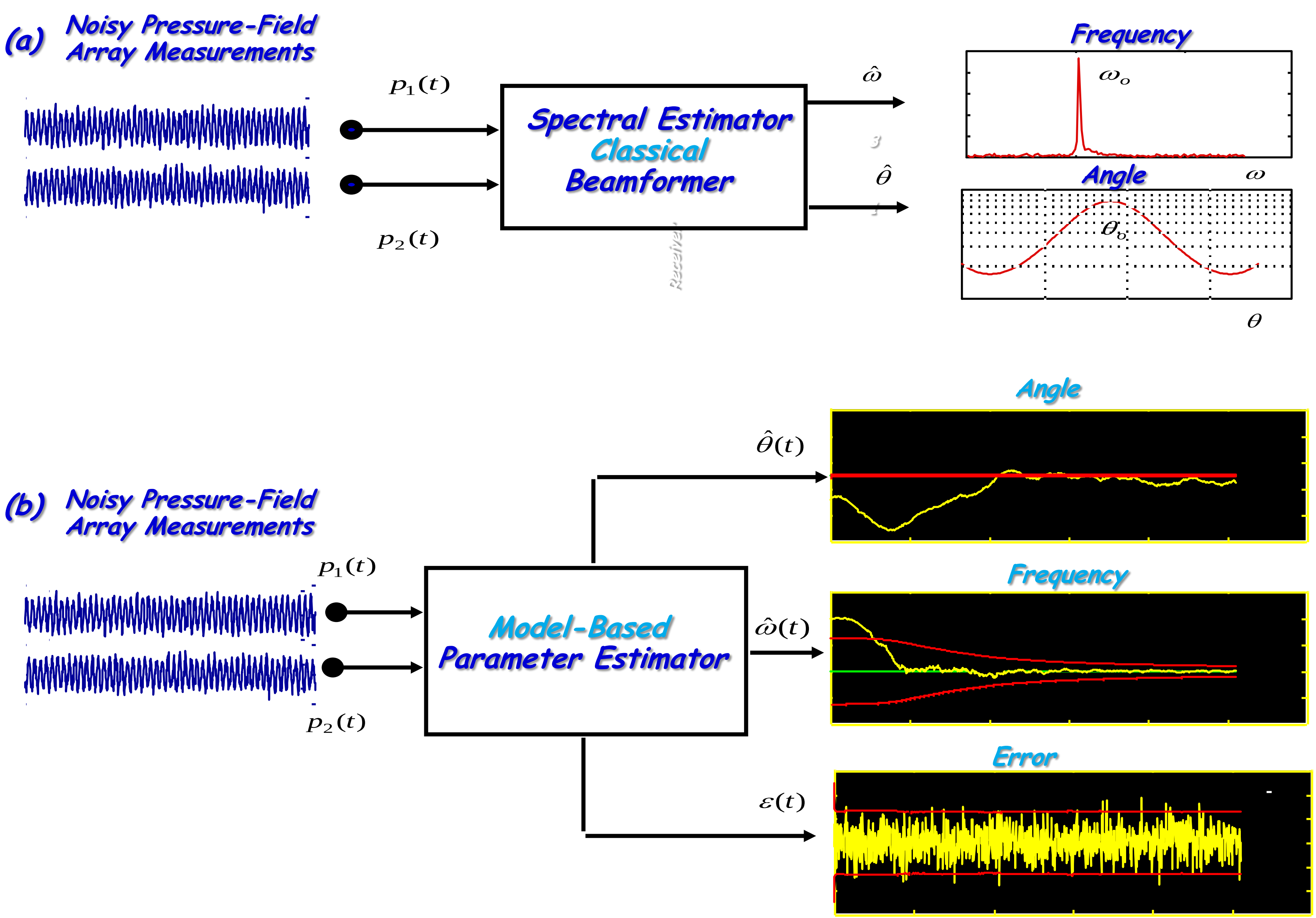


Ultrasonic Source Localization (Power)
x 10^-5
9
8.5
8
7.5
7
6.5
6
5.5
0
5
10
15
20
25
30
35
40
45
Y-position (mm)
0
5
10
15
20
X-position (mm)
Initialize
RUN
RETURN
Data
RcverB'
Colormap
hot
Threshold
0.9
Velocity
6230
Sampling Interval
1.25e-08
X-Pixels
100
X-Initial
-0.00001
X-Final
0.0225
Y-Pixels
100
Y-Initial
-0.0001
Y-Final
0.0505

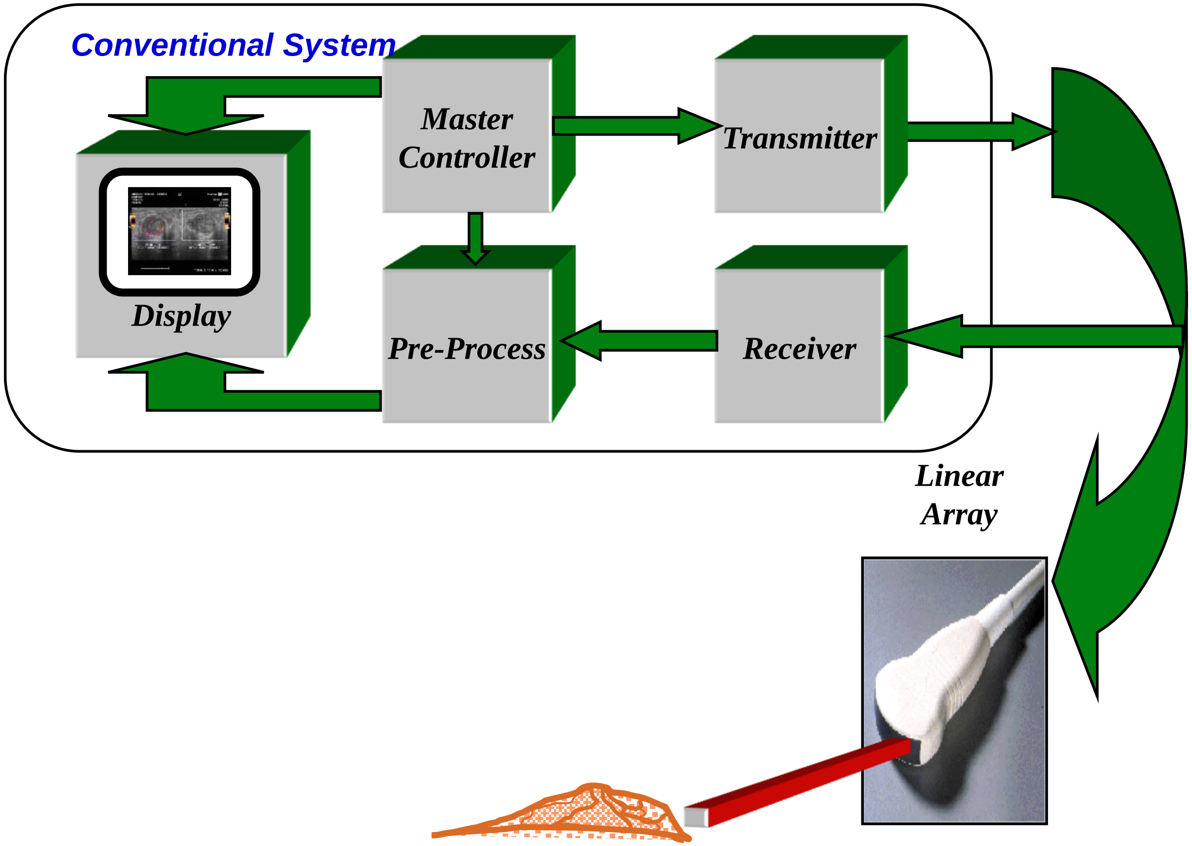
The ocean is a complex noisy, dynamic environment



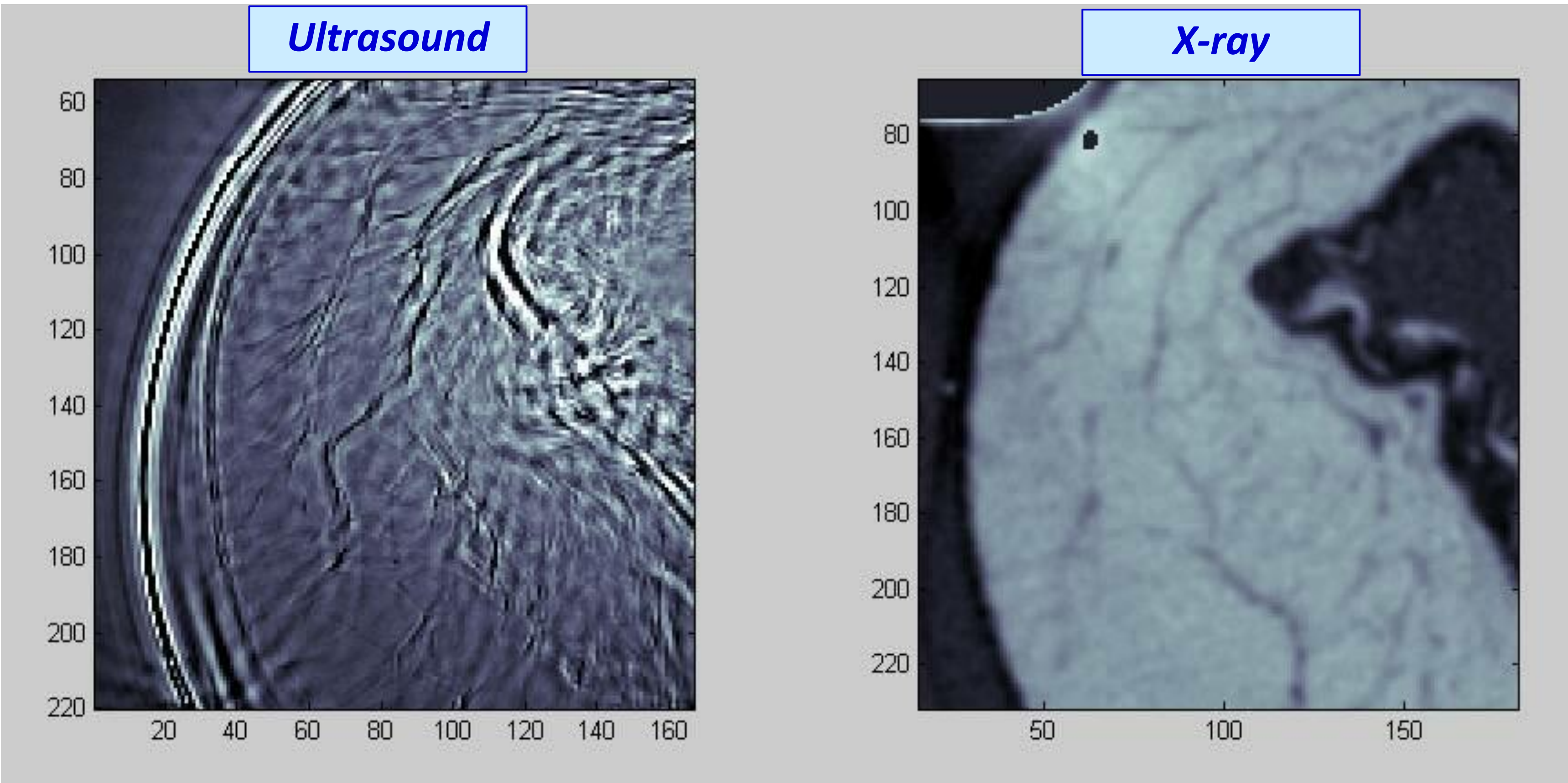
Finding a target is a difficult problem !!!

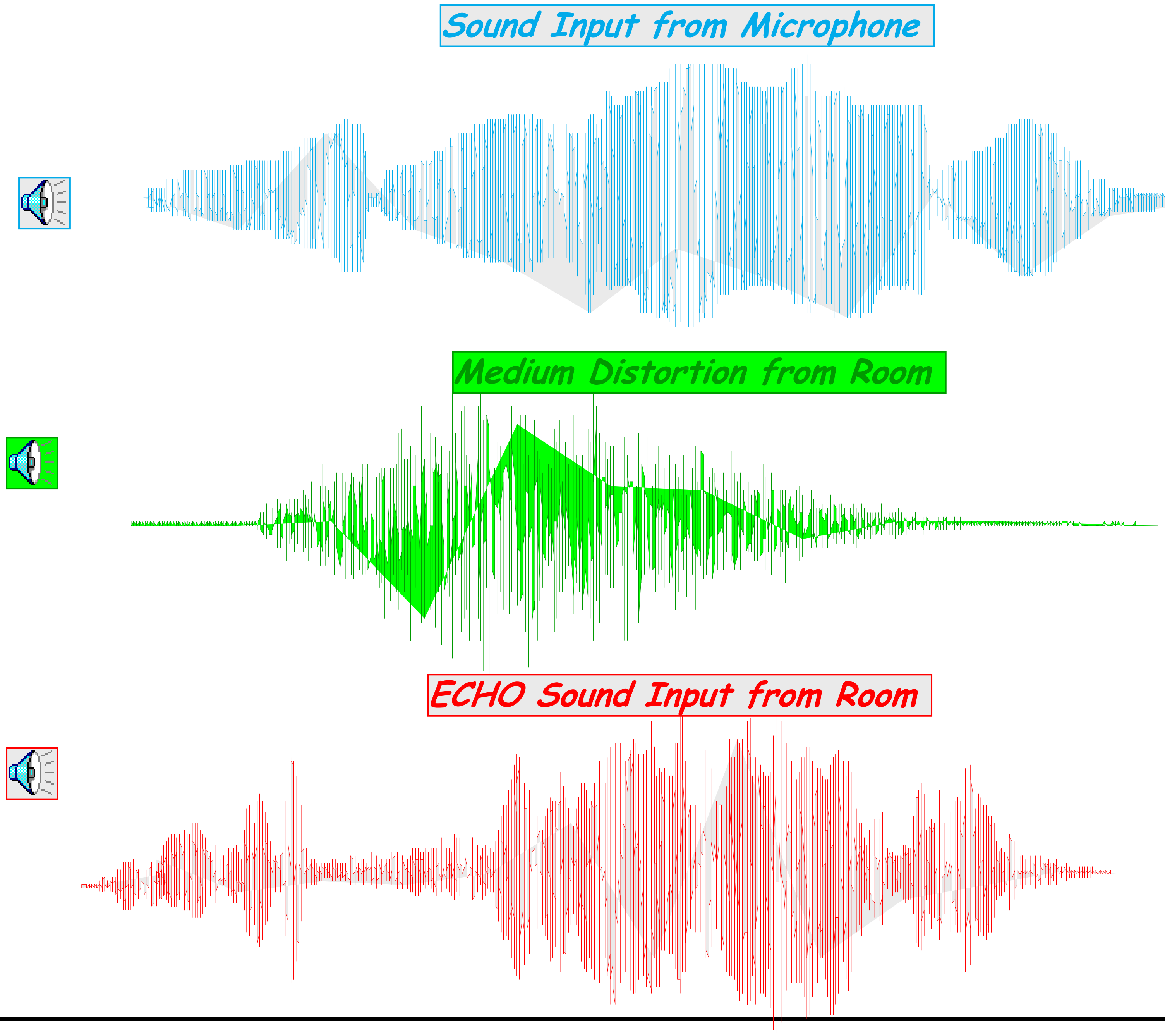

(a) Noisy Pressure-Field Array Measurements
$p_1(t)$
$p_2(t)$
Spectral Estimator
Classical
Beamformer
$\hat{\omega}$
$\hat{\theta}$
Frequency
ω_o
ω
Angle
θ_o
θ
(b) Noisy Pressure-Field Array Measurements
$p_1(t)$
$p_2(t)$
Model-Based
Parameter Estimator
$\hat{\theta}(t)$
Angle
$\hat{\omega}(t)$
Frequency
$\varepsilon(t)$
Error

APPLICATION: Medical Ultrasonic Scanner



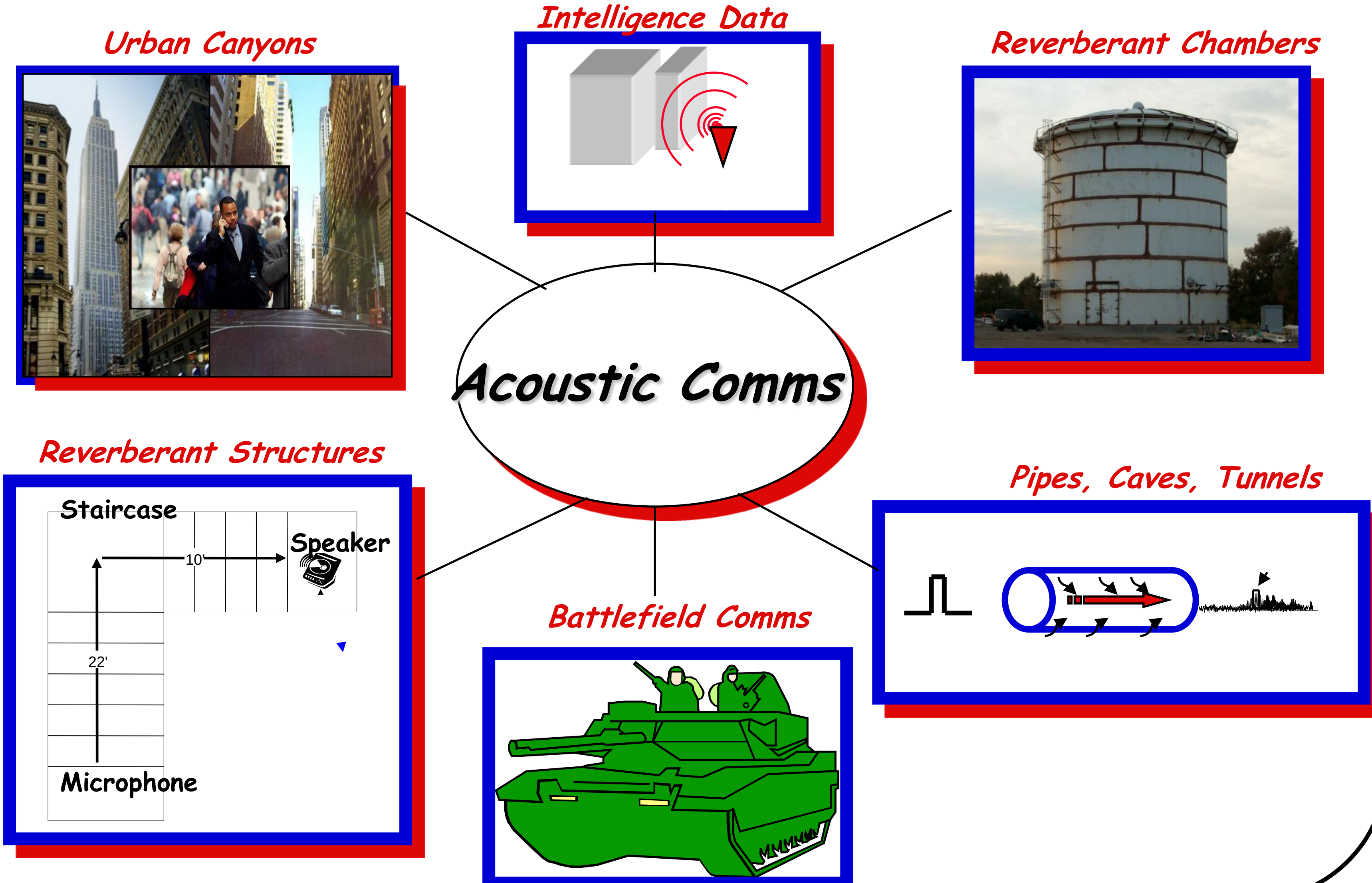
The application of acoustical processing techniques to ultrasonic data more detail for analysis



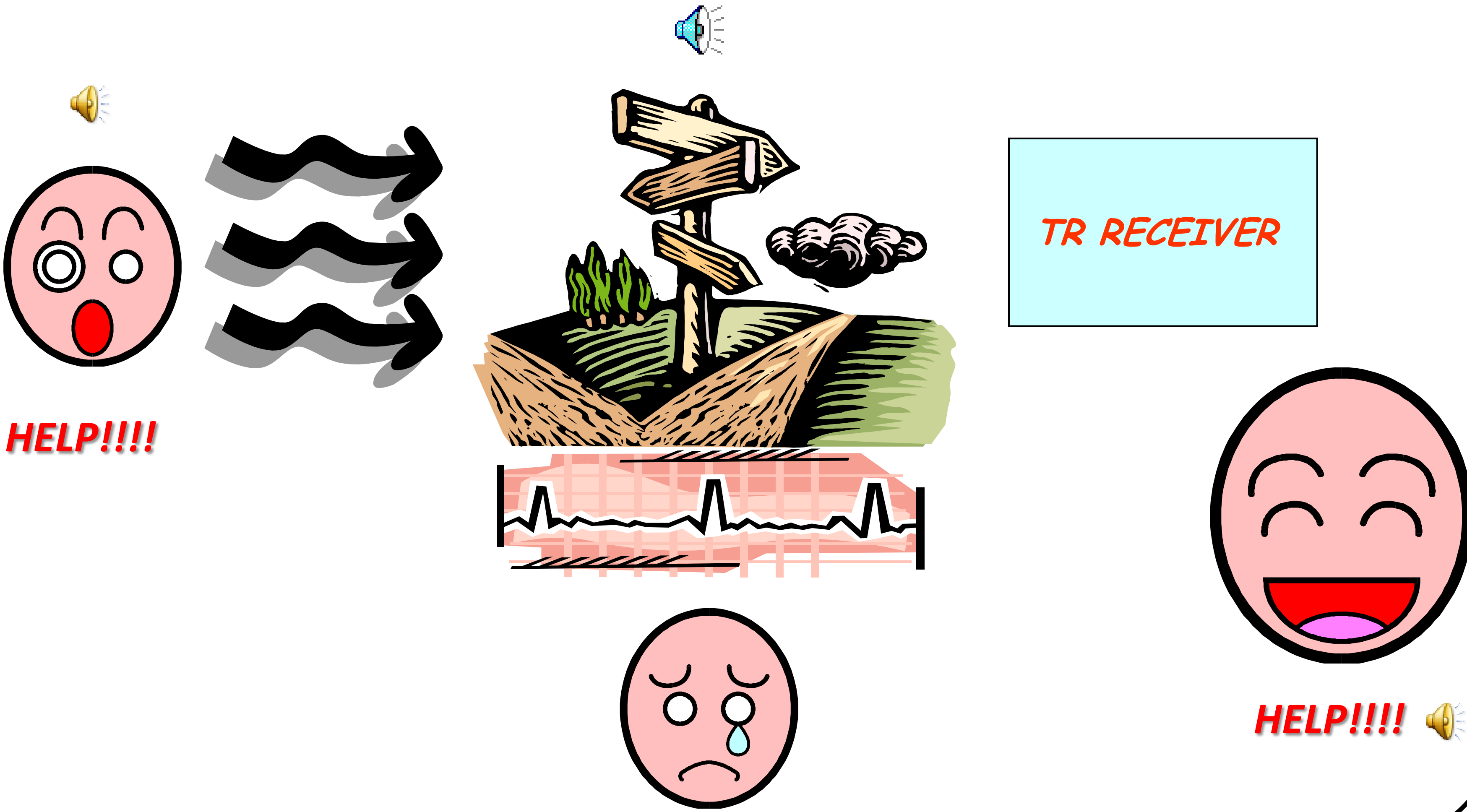

Sound Input from Microphone
Medium Distortion from Room
ECHO Sound Input from Room

BACKGROUND

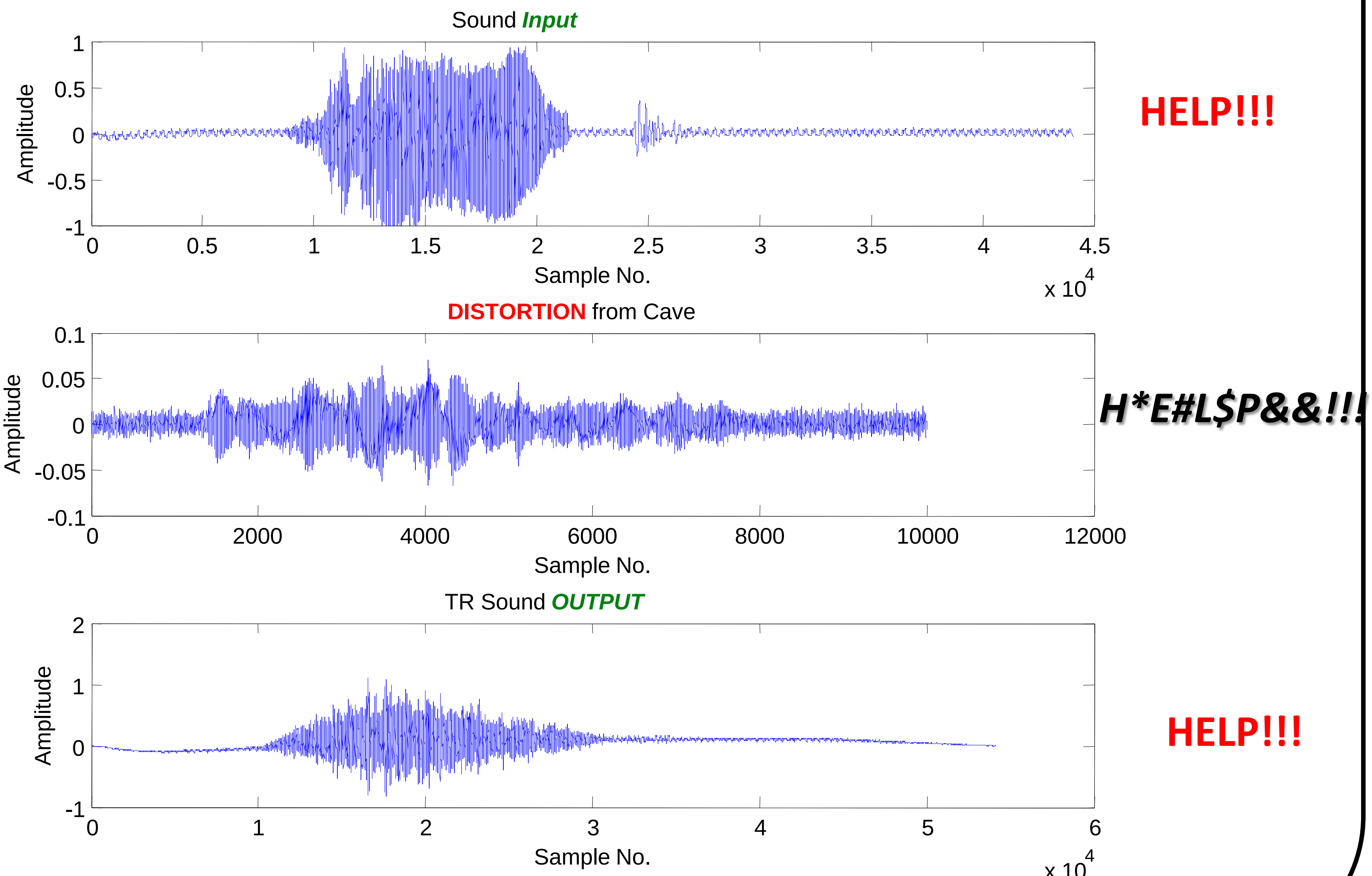
Signal processing enables a solution to the communications problem in hostile environments



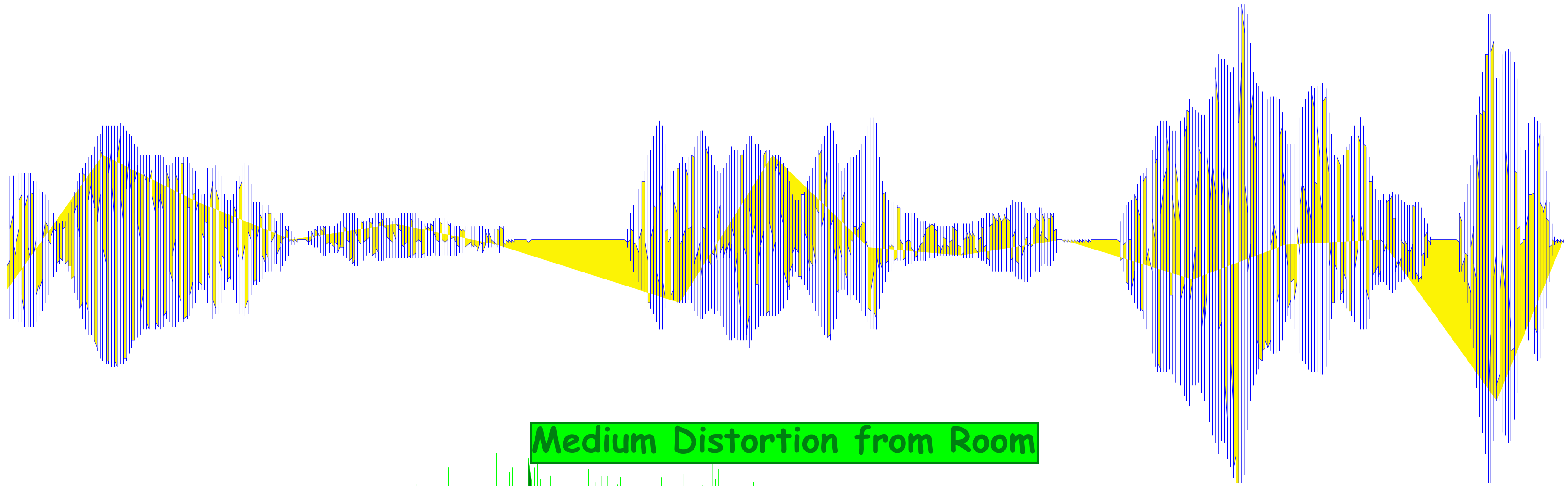
Time reversal processing enables such a solution since it re-traces paths to increase SNR and "unravel" distortions



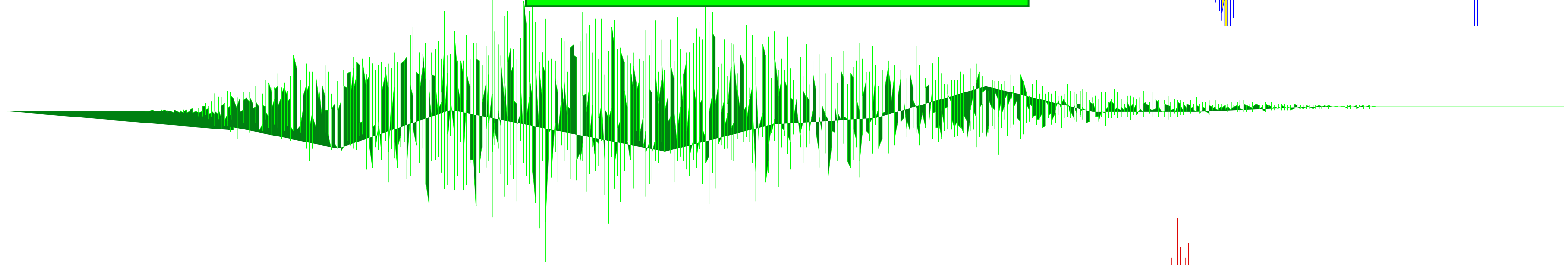
Reverberation and scattering can lead to unwanted distortion that time-reversal processing can "fix"



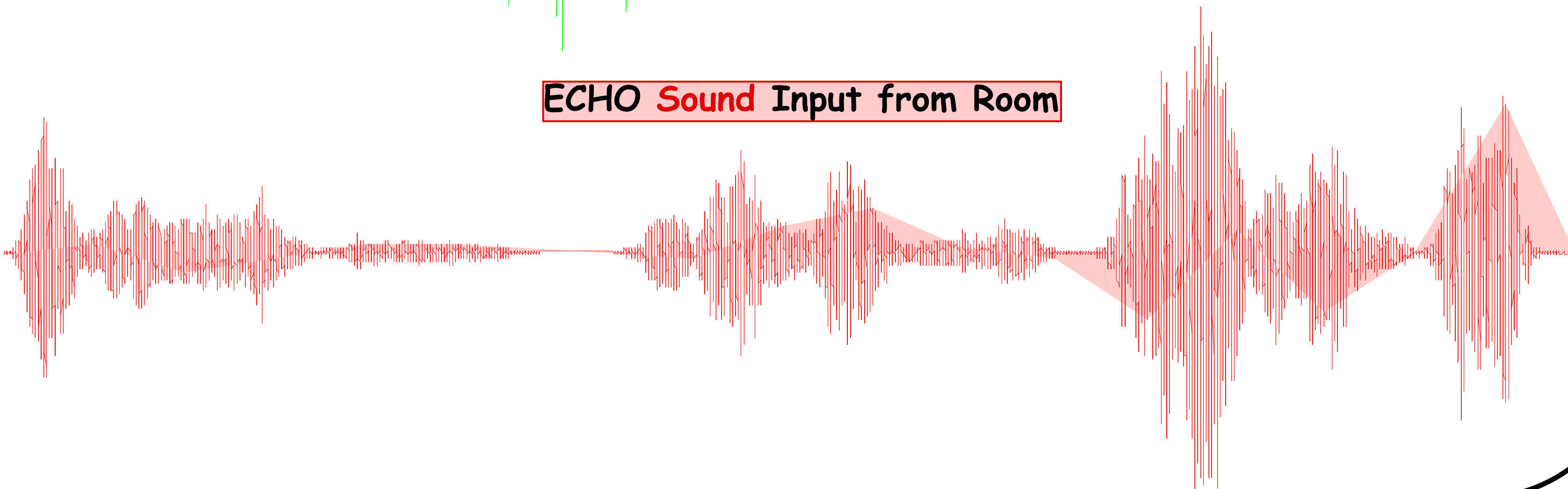
Sound Input from Microphone



Medium Distortion from Room

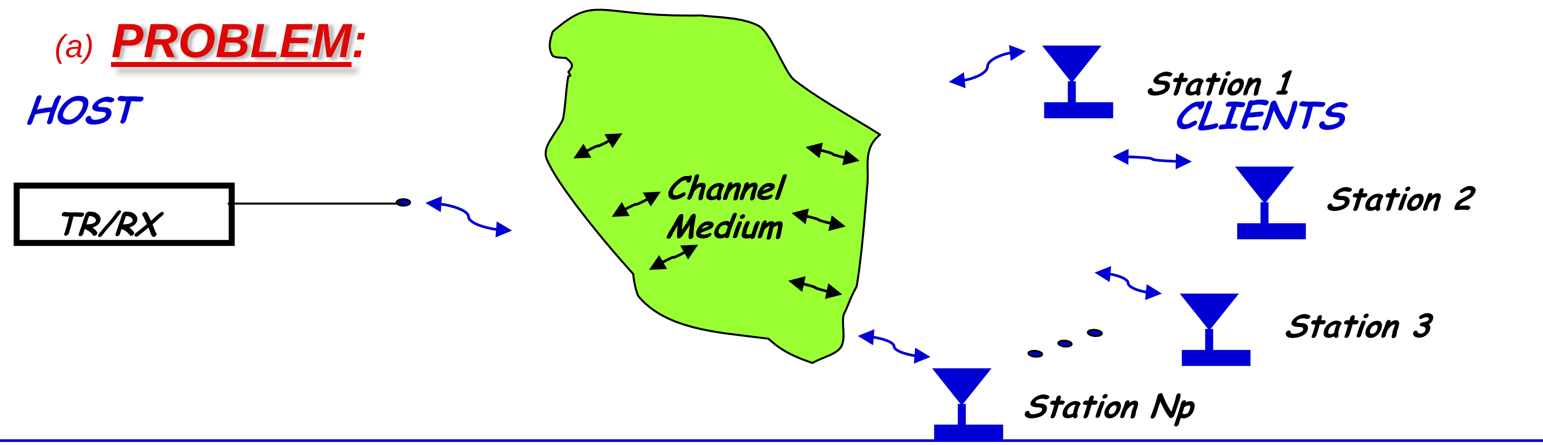


ECHO Sound Input from Room

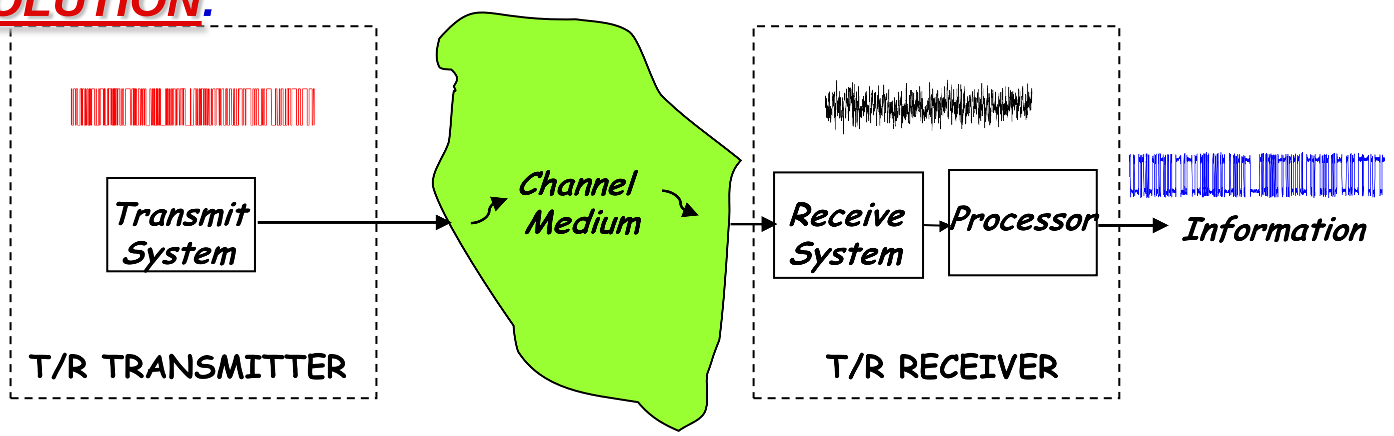


PROBLEM:
Transmit information in a hostile medium (mpath, mscatterers, reverb, noise) and extract it with minimal error
APPROACH:
Time reversal (T/R) communication system

(a) **PROBLEM:**



(b) **SOLUTION:**



TIME-REVERSAL

Background & Theory

Time-Reversal Methods enable Communications in Severe Multipath Environments

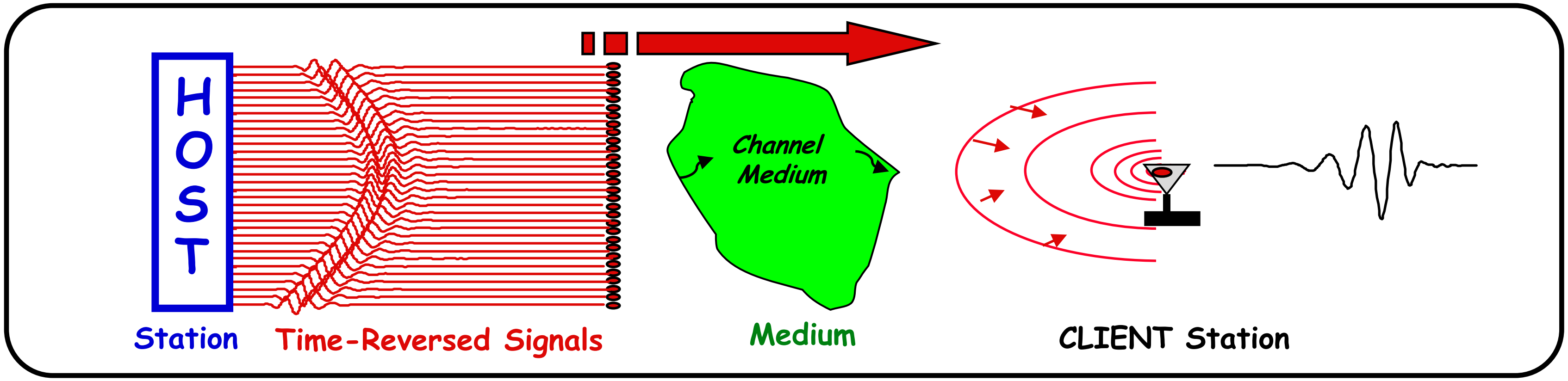
ADVANTAGES

- **Communication in the presence of multipath and an inhomogeneous medium**
- **Application of Time Reversal Signal Processing (space-time equivalent of matched-filter in software)**
- **For example,transmission from remote, embedded sensors and point-to-point communications**
- **Can be extended to the RF spectrum**
- **Reasonably straightforward software receiver designs can carry out system functions**

ISSUES

- **Signals must be collected, digitized, time-reversed and processed on transmission and/or reception**
- **External noise, TX/RX dynamic range, power levels and medium losses**
- **Digitization will be the cost driver**

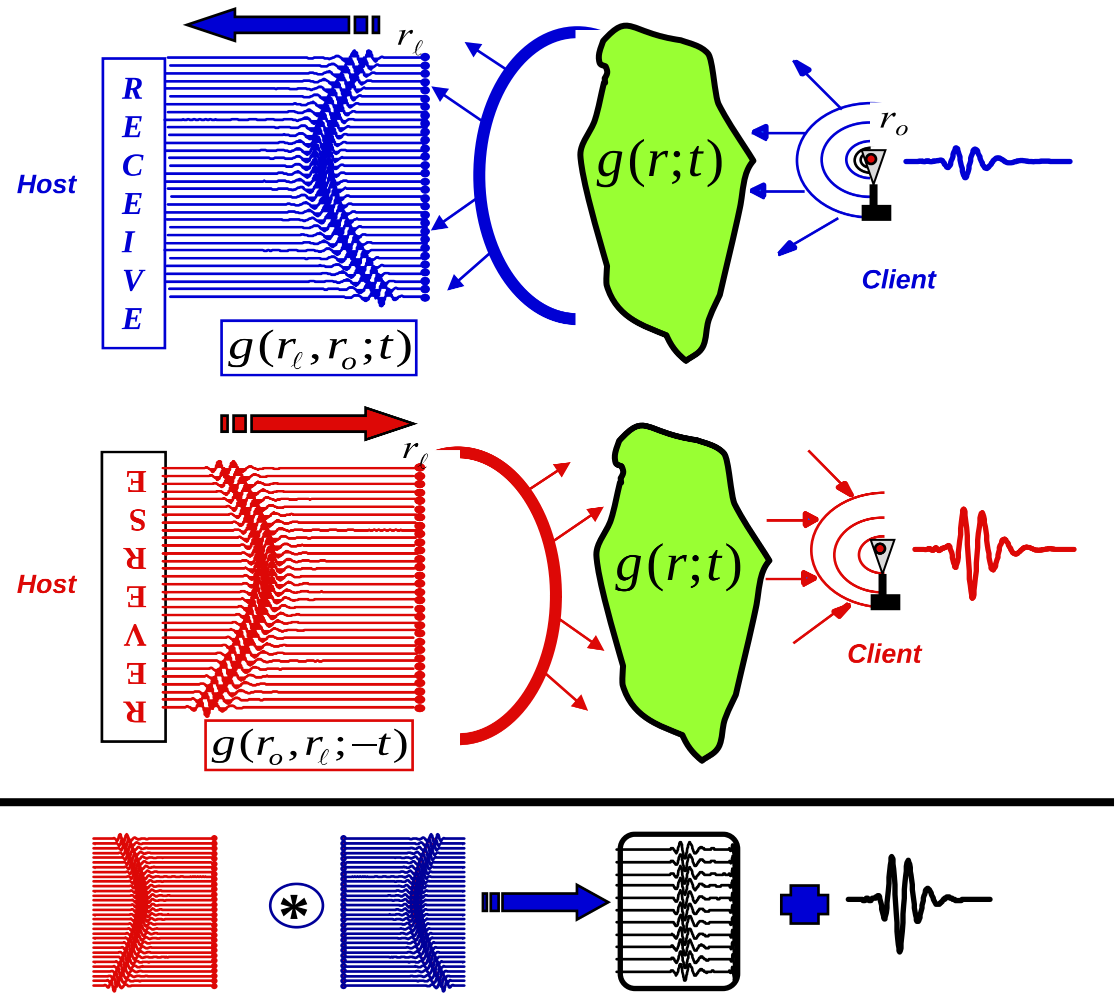
T/R communication systems can:



- mitigate multipath, multiple scattering, inhomogeneous effects
- focus signal energy at a client station through a hostile medium
- provide a secure link (unique medium function) from host-to-client
- be deployed in point-to-point (P2P) or array configurations (A2P,A2A)
- compliment existing communications technology
- be implemented in software

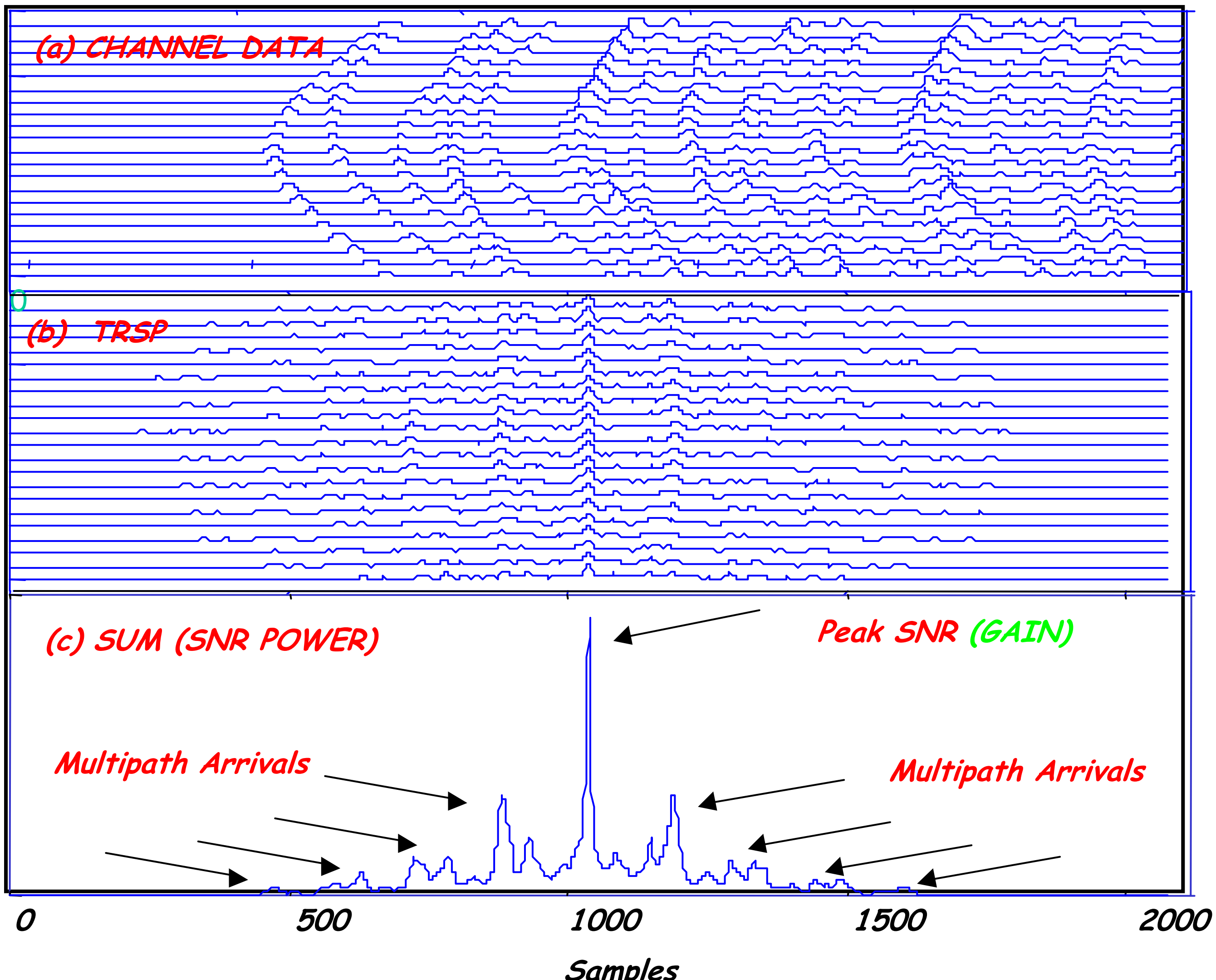
WHAT IS TIME-REVERSAL???

T/R system is an intelligent, *optimal*, space-time, matched-filter that "learns" the medium

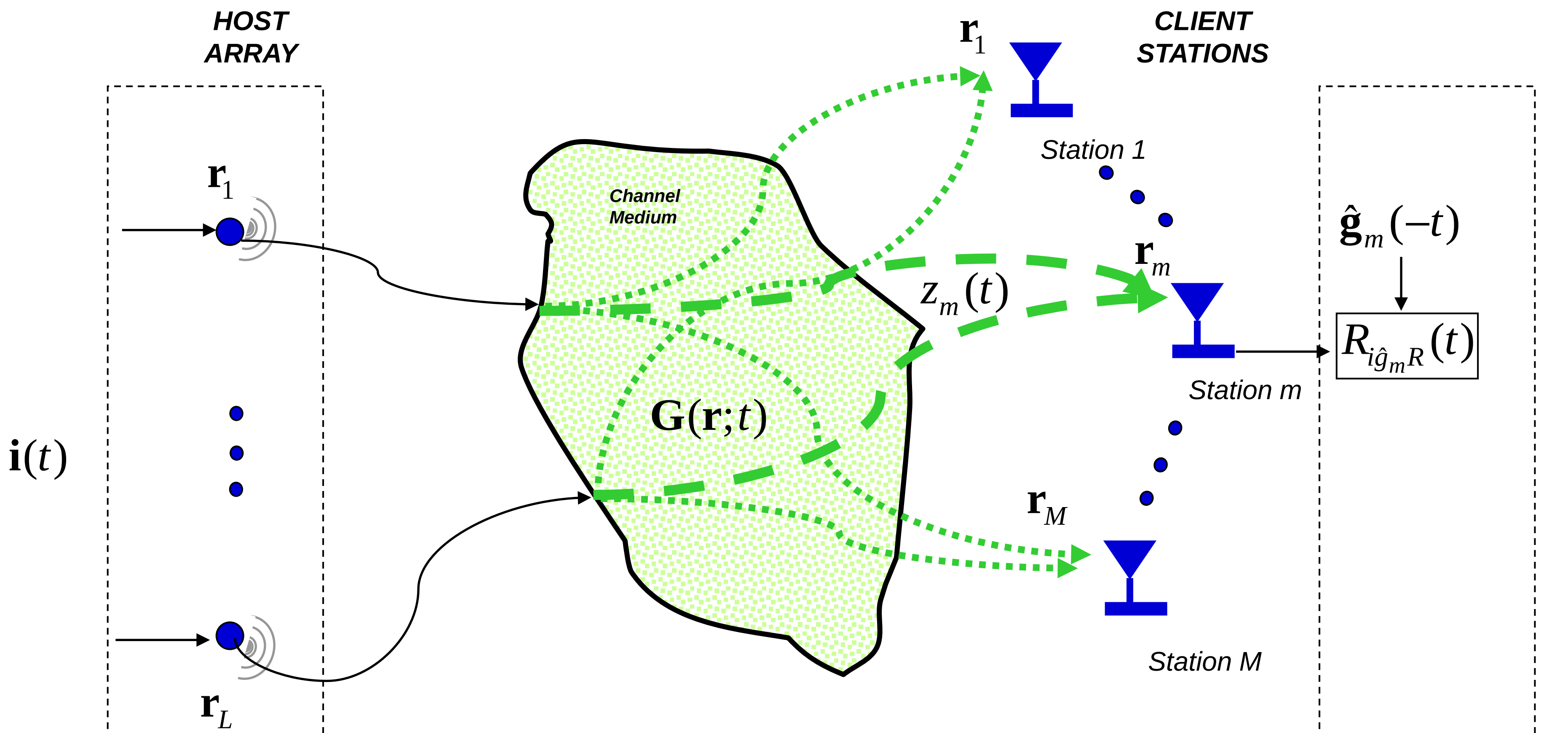


$$g(r_o, r_\ell; -t) * g(r_\ell, r_o; t) = \sum_\ell C_{g_\ell g_\ell}(t) \circledast i(t)$$

T/R operations are equivalent to using the medium to "physically" estimate multichannel autocorrelations providing both TEMPORAL (multiple arrivals) GAIN & SPATIAL (array) GAIN

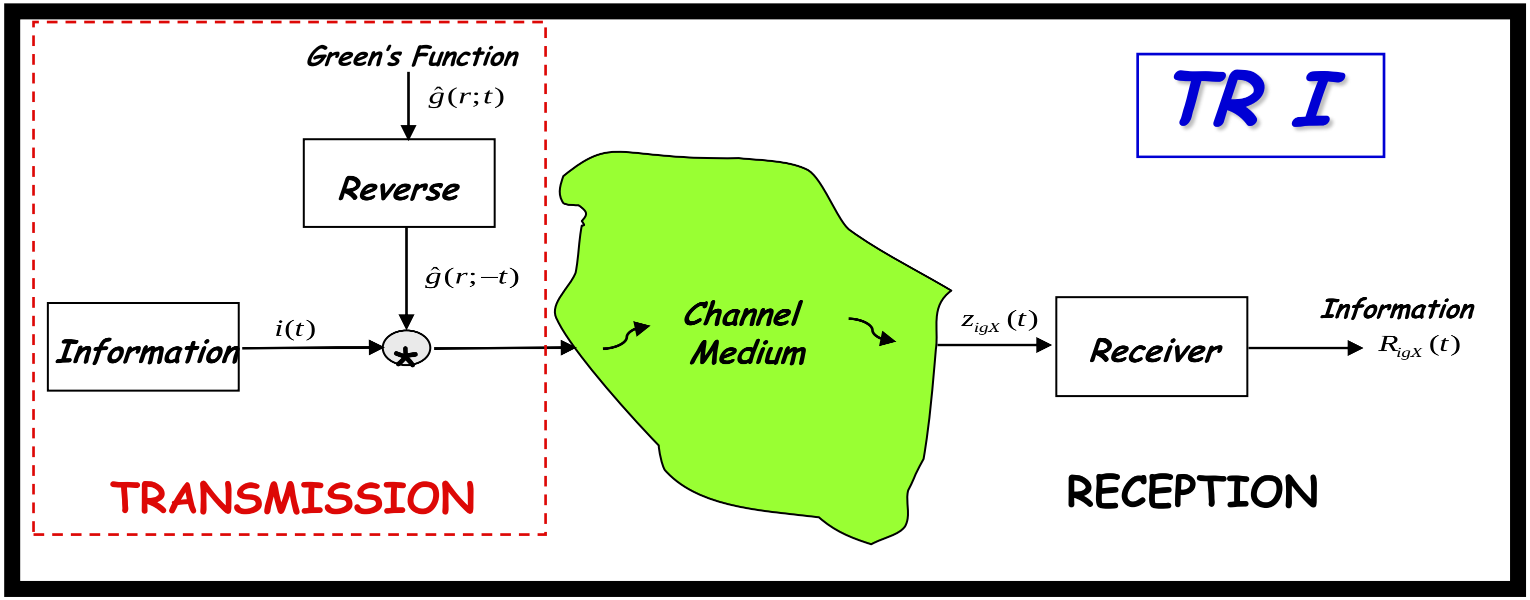


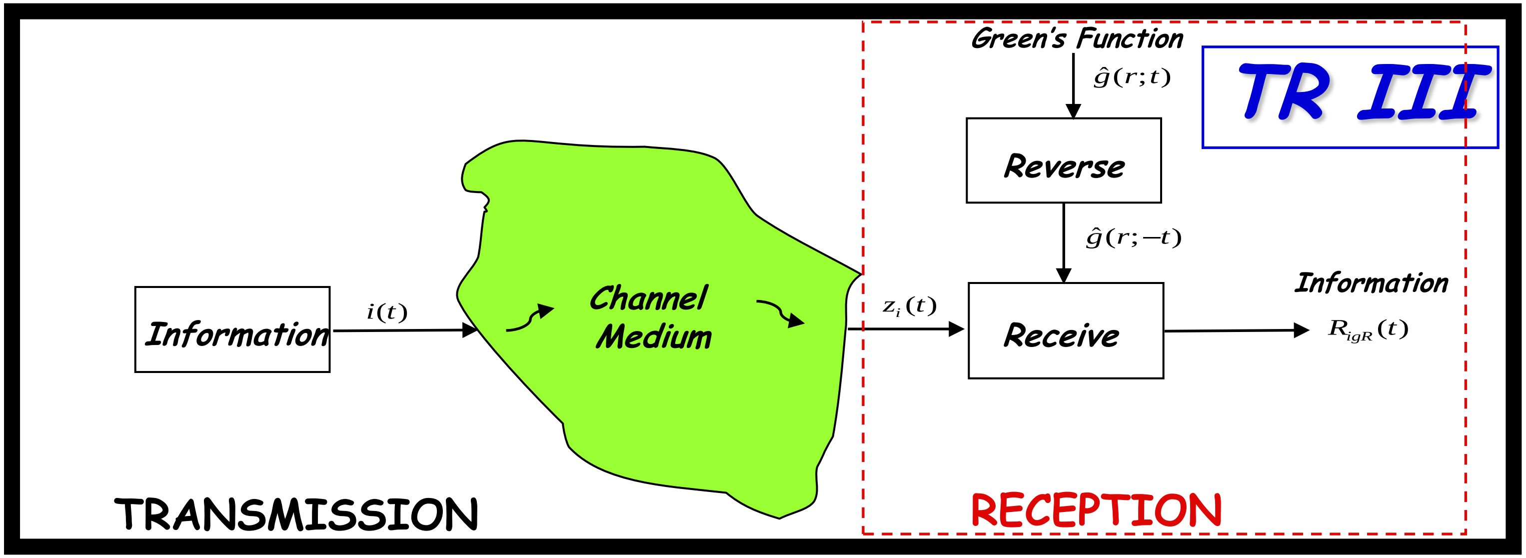
The medium (Green's function) provides UNIQUE paths (channels) from the host array to each client station---this is the key to be exploited in T/R communications



$$\mathbf{R}_{i\hat{g}_m R}(t) = z_m(t) * \hat{\mathbf{g}}_m(-t) = \left(\mathbf{g}_m^T(t) * \mathbf{i}(t)\right) * \hat{\mathbf{g}}_m(-t)$$

T/R receiver realizations can implemented on transmission or reception:



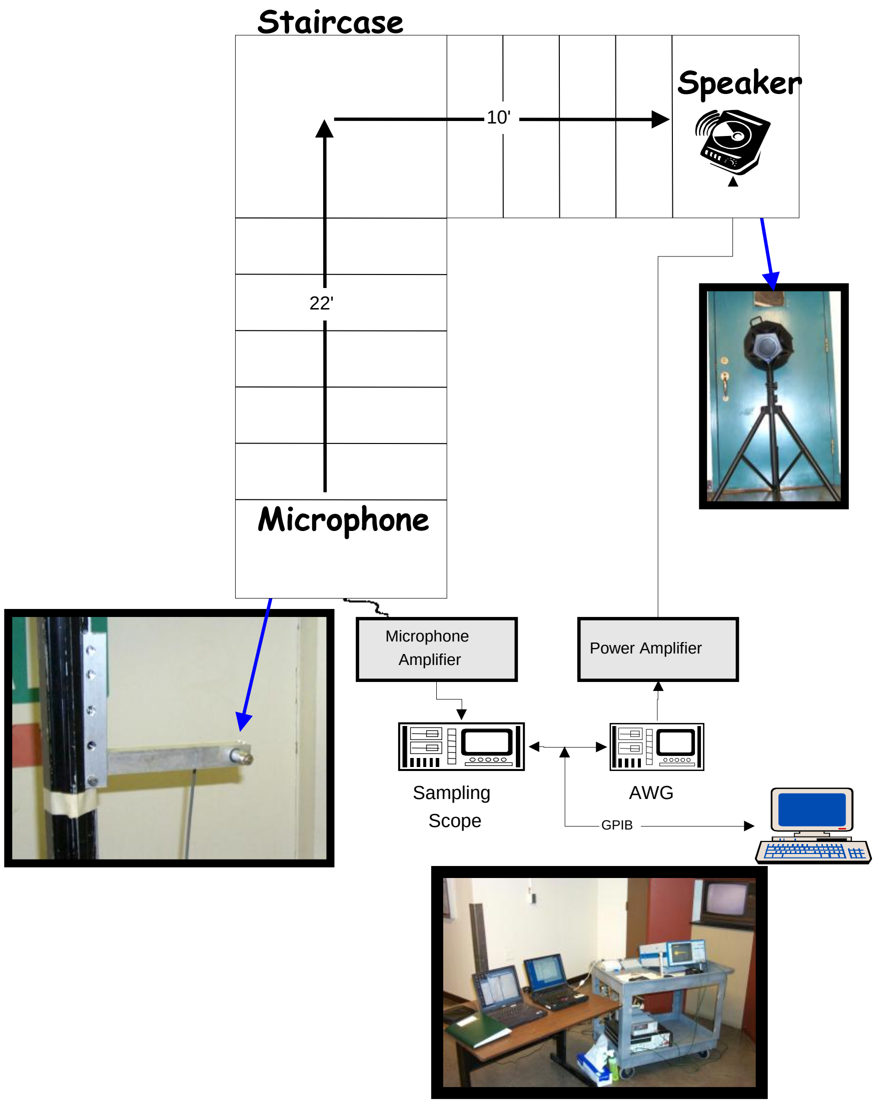


I. POINT-TO-POINT EXPERIMENTS IN A REVERBERATIVE STAIRWELL

We define the following terms:

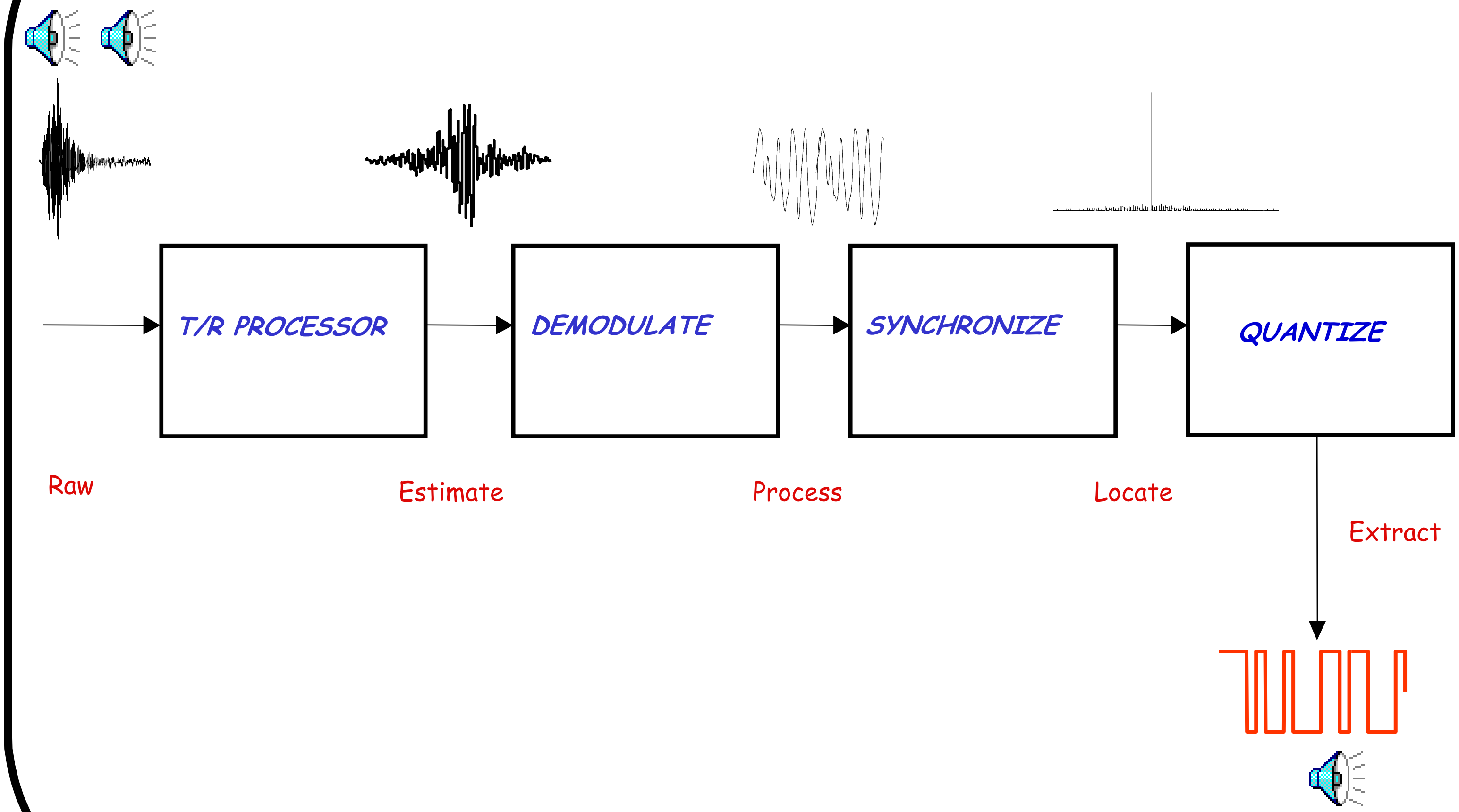
- ***Symbol Error*** – *error between true symbol sample transmitted and sample extracted by recvr (made up of bits)*
- ***Bit Error*** – *error between true bit transmitted and actual bit extracted by recvr*
- ***Open Communications*** – *both host & clients can broadcast openly in the environment (city, urban env.,etc.) and everyone can listen*
- ***Secure Communications*** – *both host & client broadcast but NO ONE can listen*
- ***Covert Communications*** – *host broadcasts & ONLY client can listen*

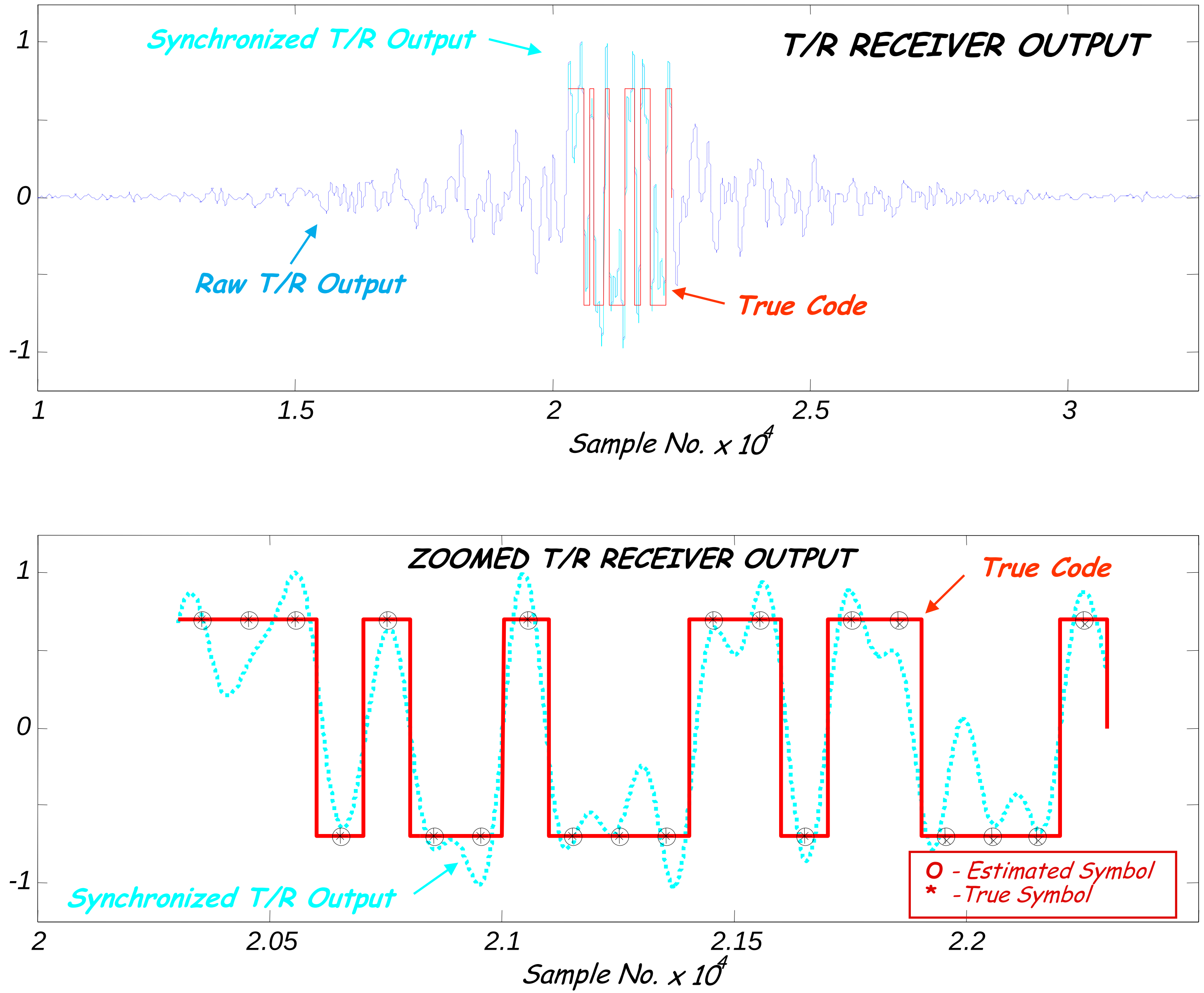
We developed a P2P ACOUSTICS experiment in a hostile, highly reverberant free space environment to evaluate the T/R receiver:



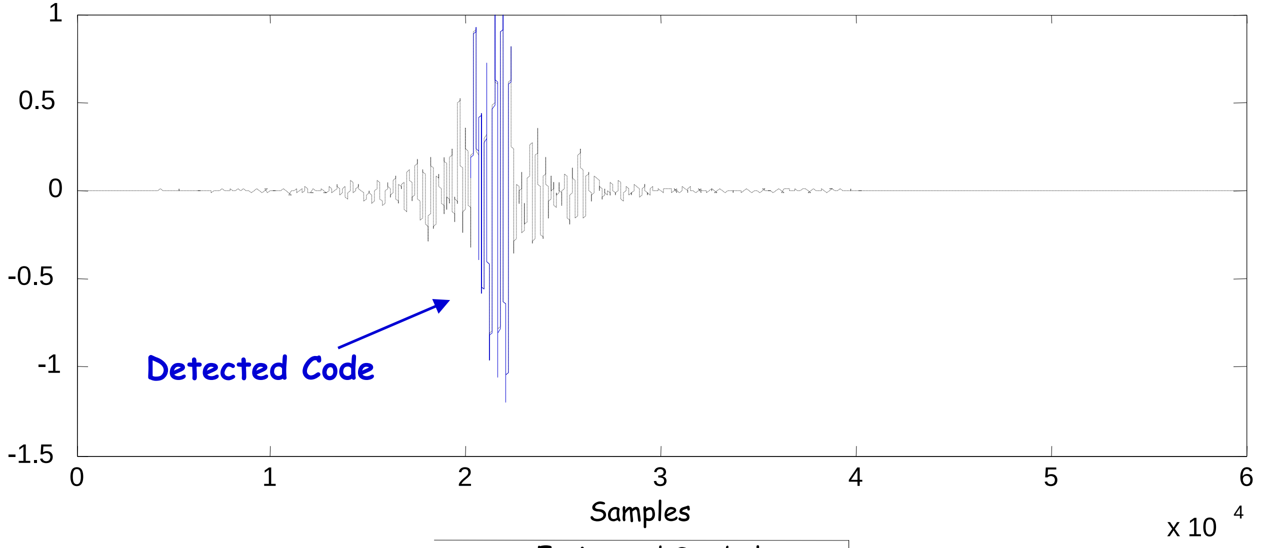
T/R acoustic receiver for stairwell experiment

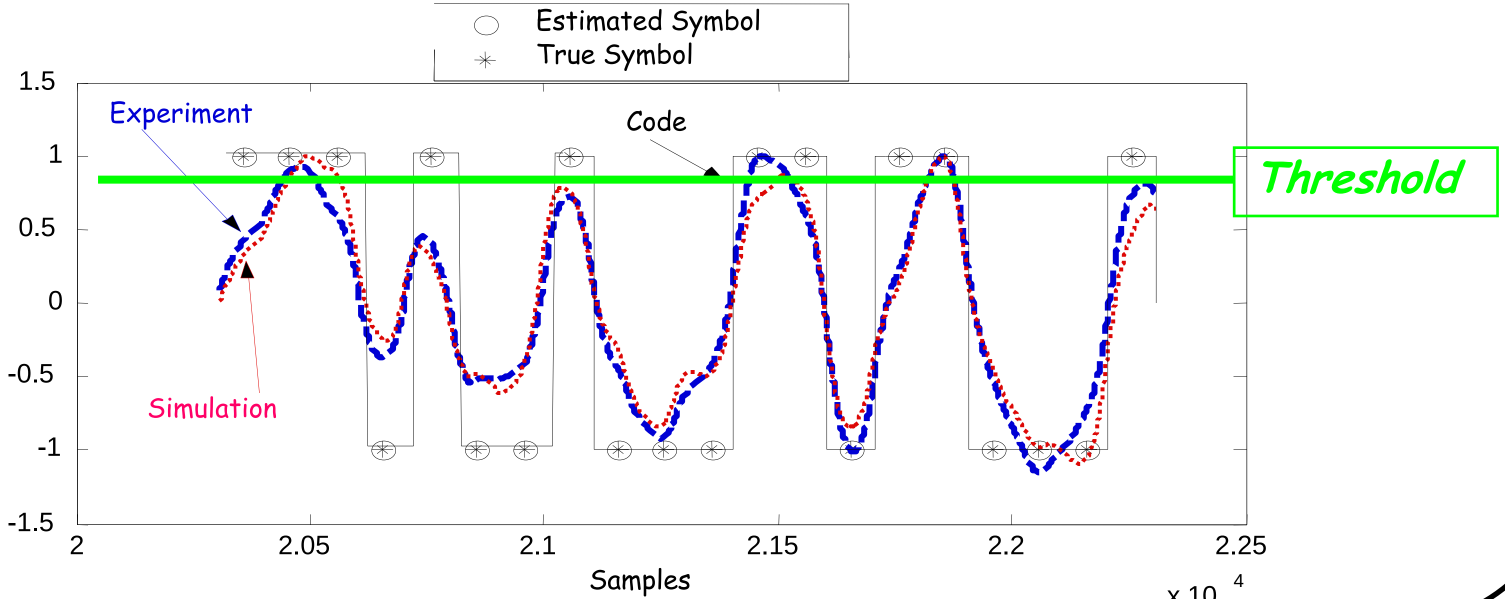
T/R RECEIVER



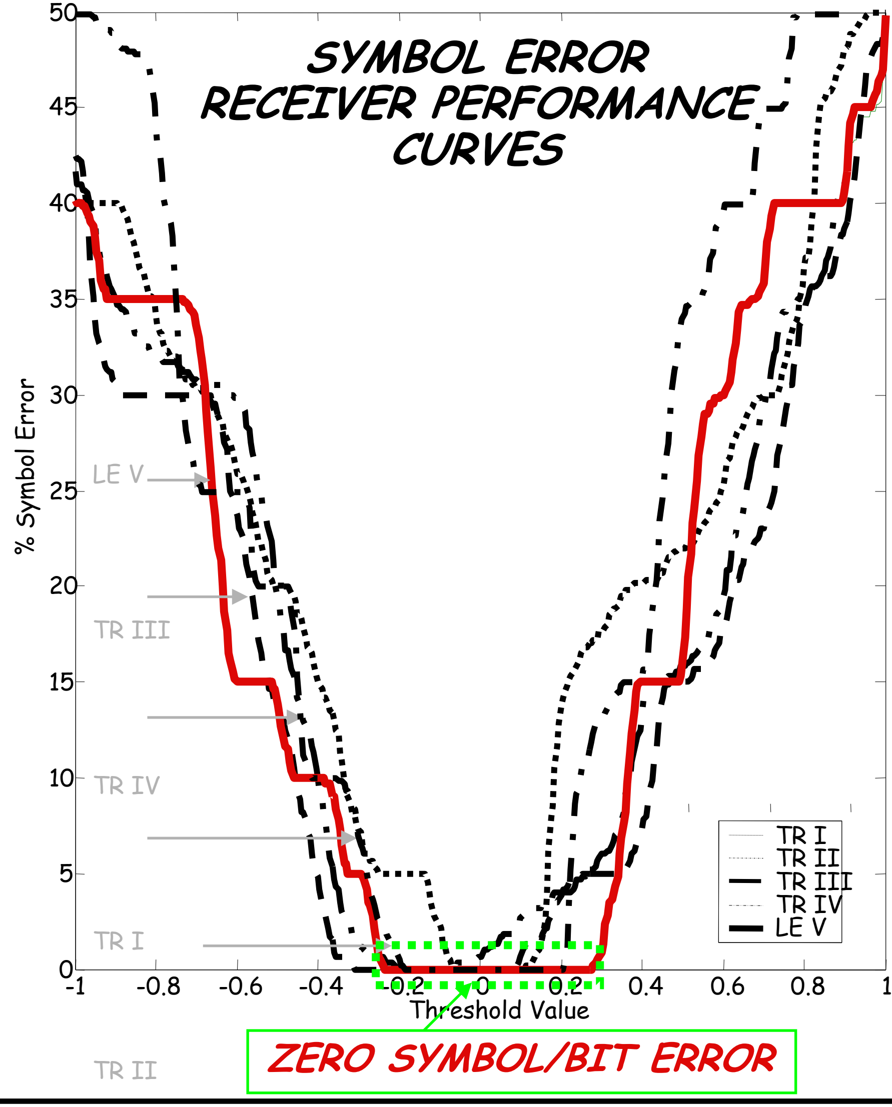

T/R RECEIVER OUTPUT
Synchronized T/R Output
Raw T/R Output
True Code
Sample No. x 10^4
ZOOMED T/R RECEIVER OUTPUT
True Code
Synchronized T/R Output
O - Estimated Symbol
* - True Symbol
Sample No. x 10^4

Typical T/R acoustic receiver performance on experimental data is quite reasonable



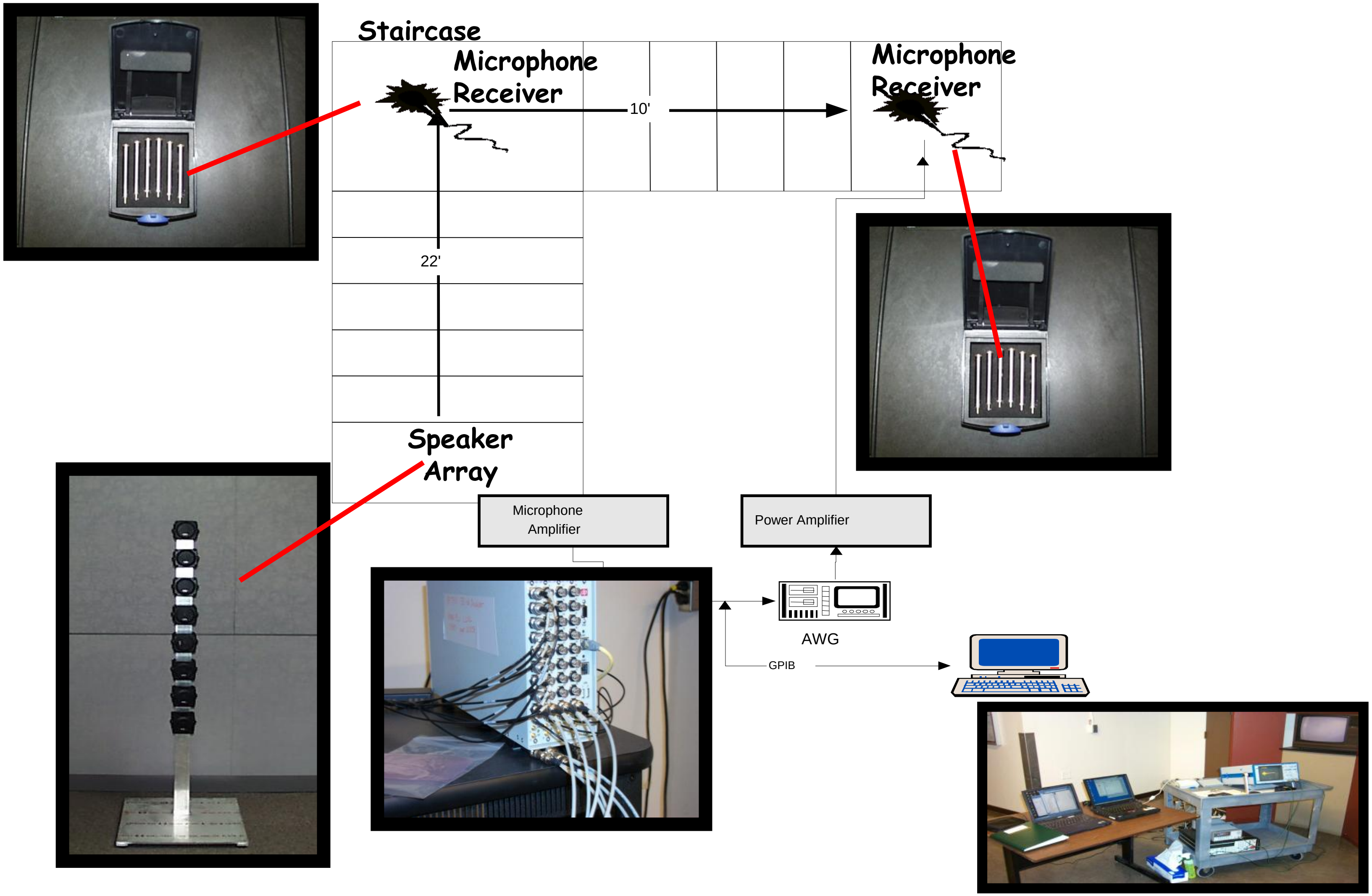


T/R acoustic receiver performance comparison (ensemble average) of Symbol Error vs. Threshold

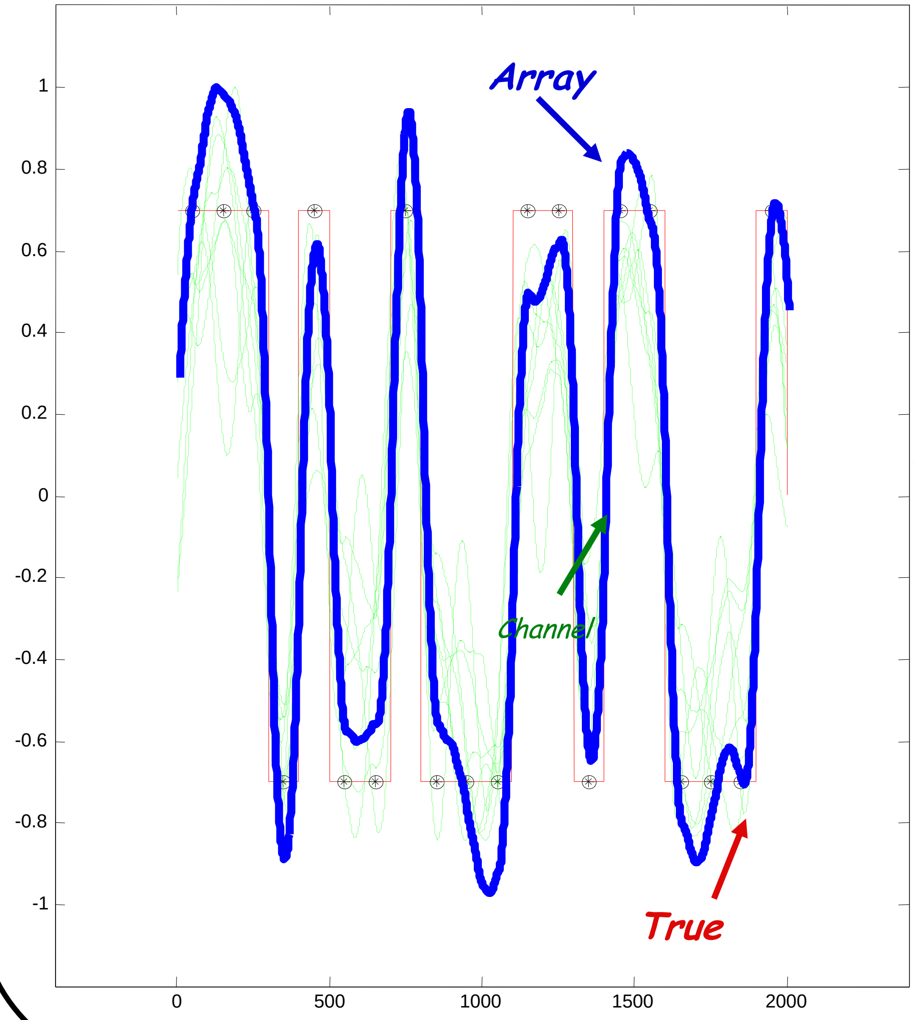


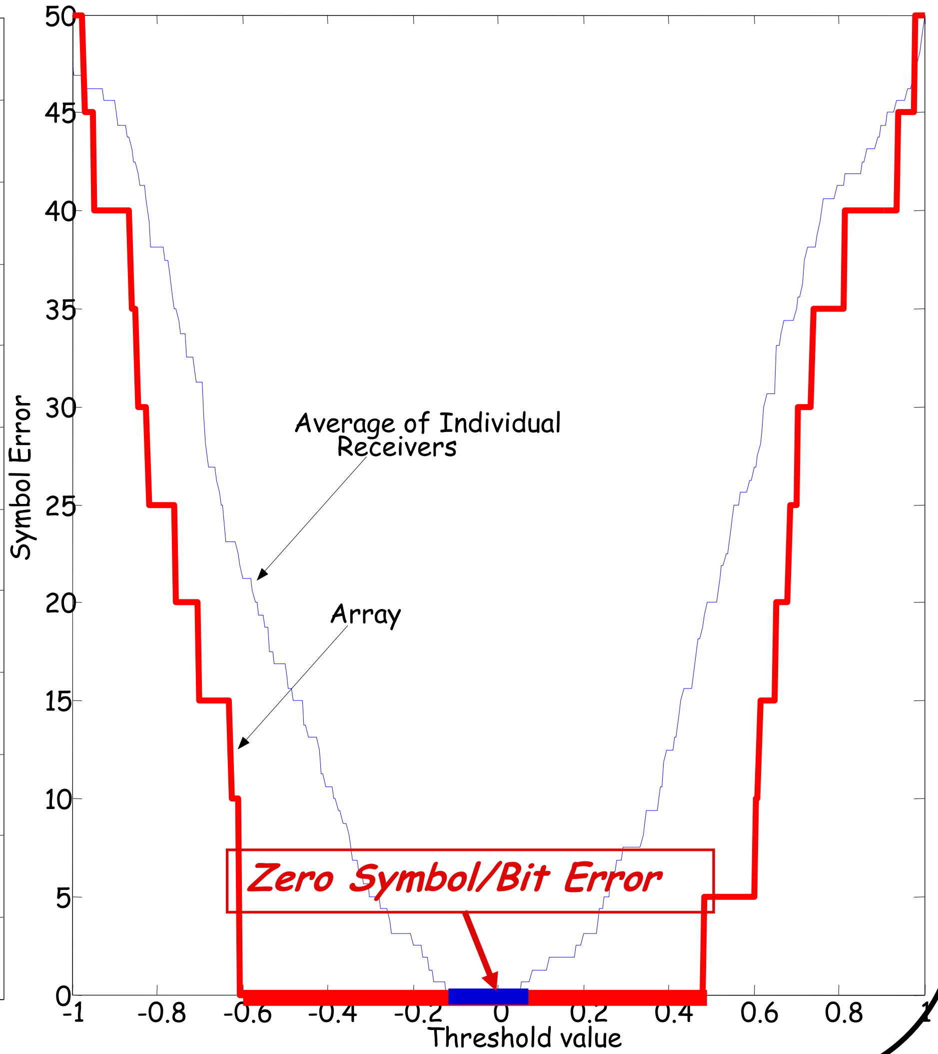
II. ARRAY-TO-POINT EXPERIMENTS IN A REVERBERATIVE STAIRWELL

We developed A2P ACOUSTICS experiment in a hostile, highly reverberant free space environment to evaluate the T/R receiver:

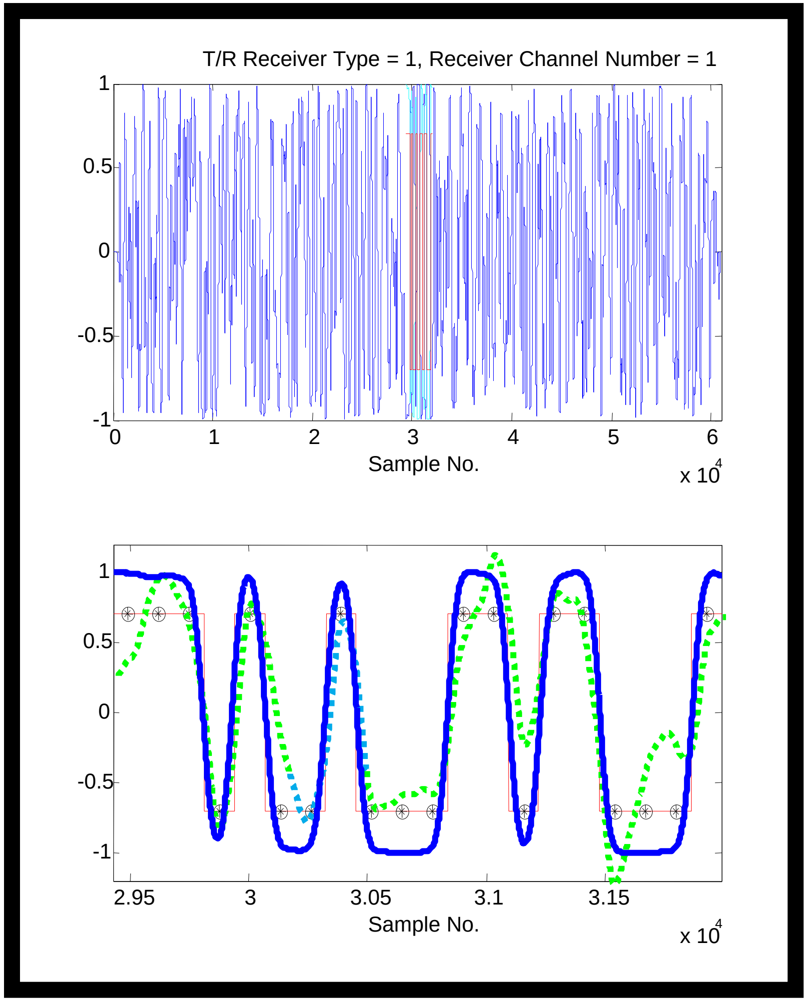


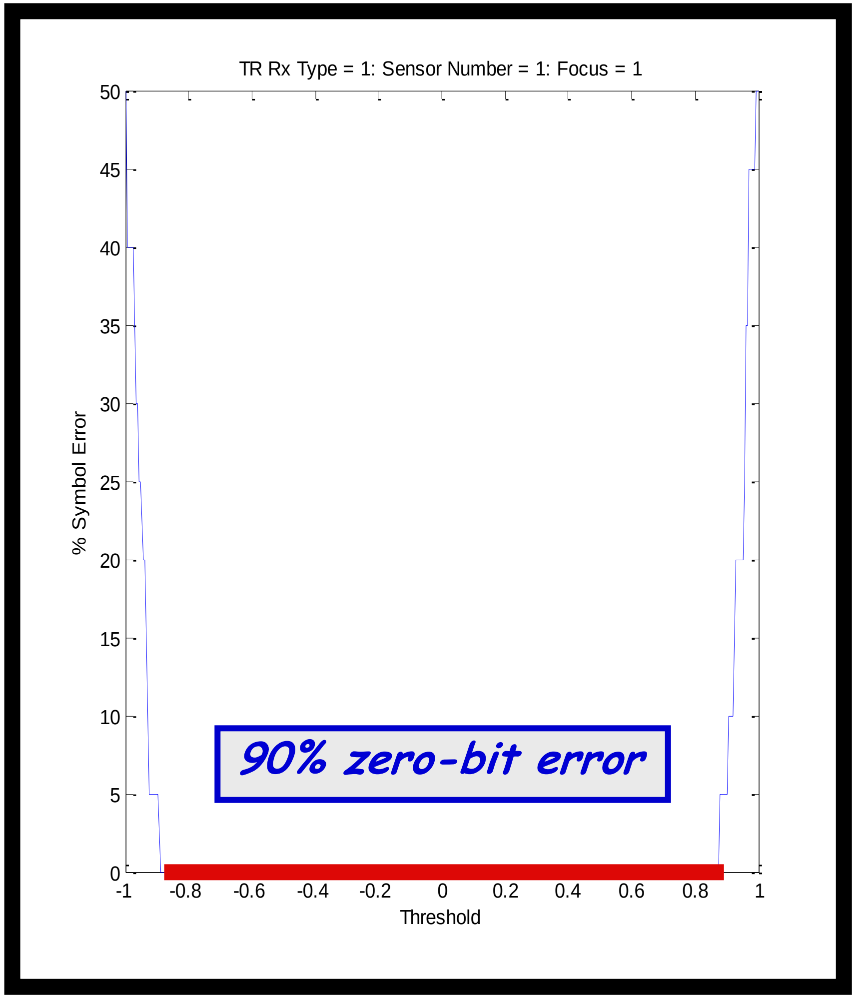
T/R Arrays can provide significant SNR gain and performance over a single channel (sensor) reception in a hostile environment



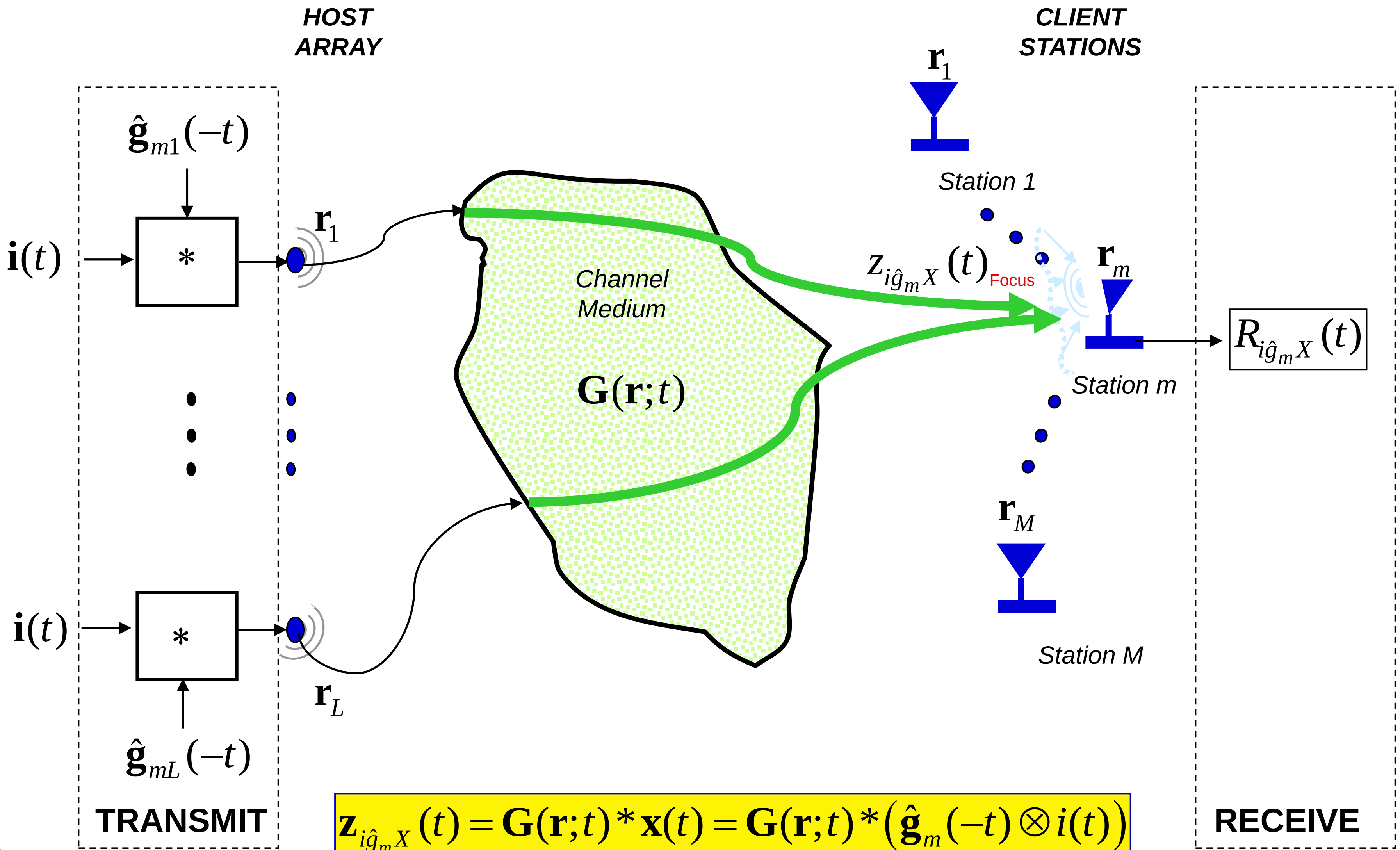


1-BIT Performance is possible and works!



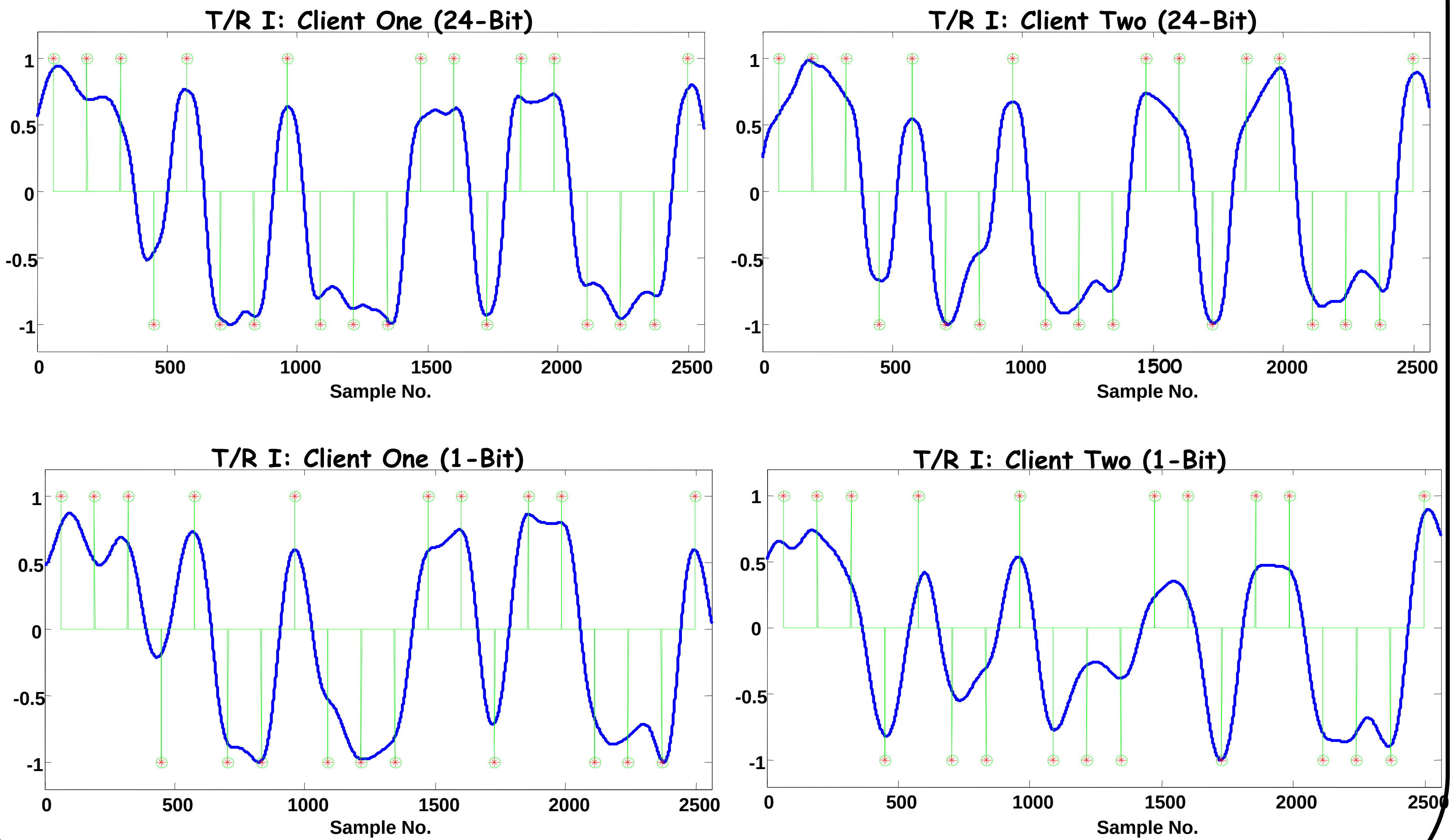


T/R Receiver Realization I: G-function on Tx

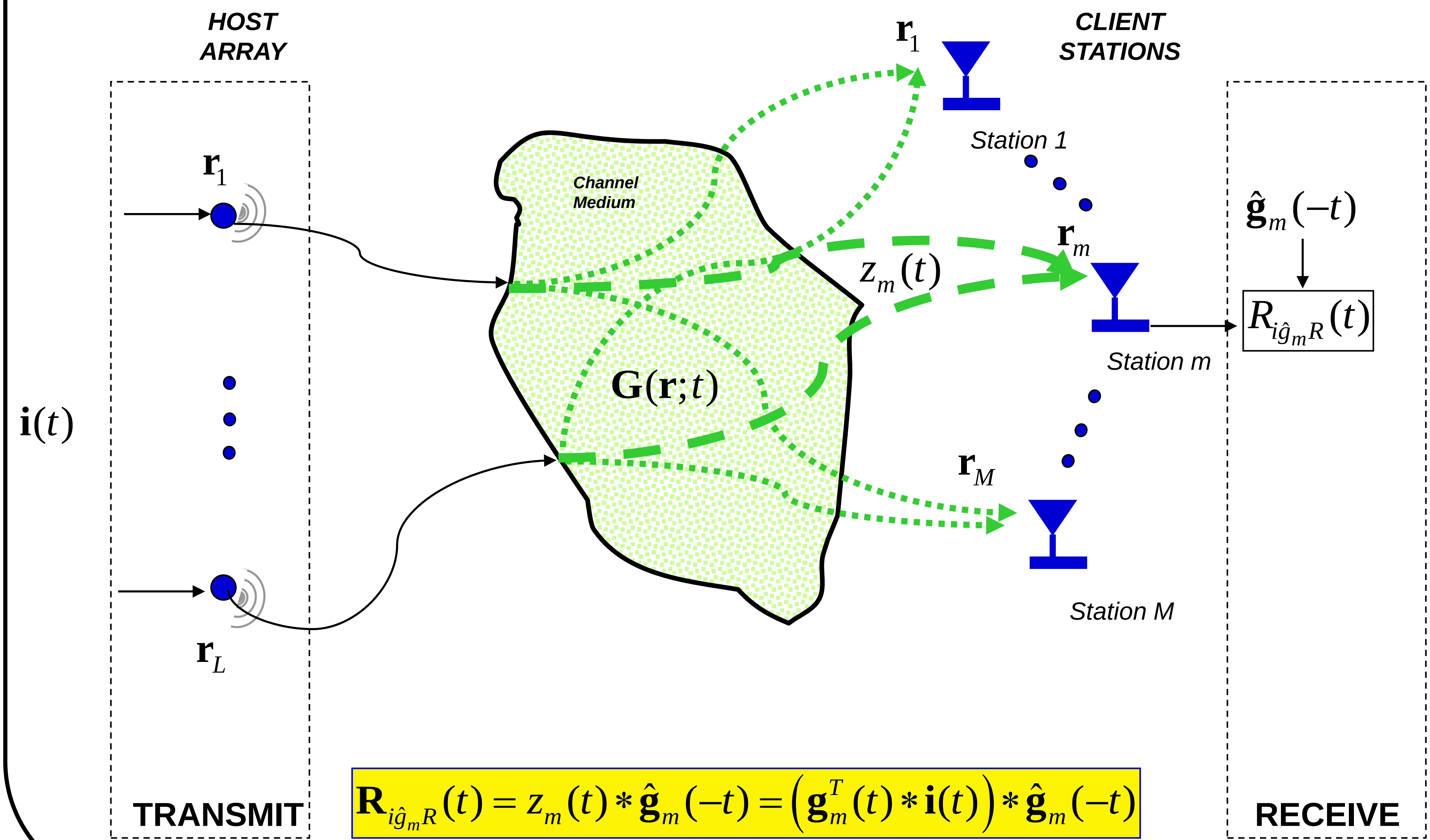


$$\mathbf{z}_{i\hat{g}_m X}(t) = \mathbf{G}(\mathbf{r};t) * \mathbf{x}(t) = \mathbf{G}(\mathbf{r};t) * \left(\hat{\mathbf{g}}_m(-t) \otimes i(t)\right)$$

T/R I focusing at clients 1 & 2:

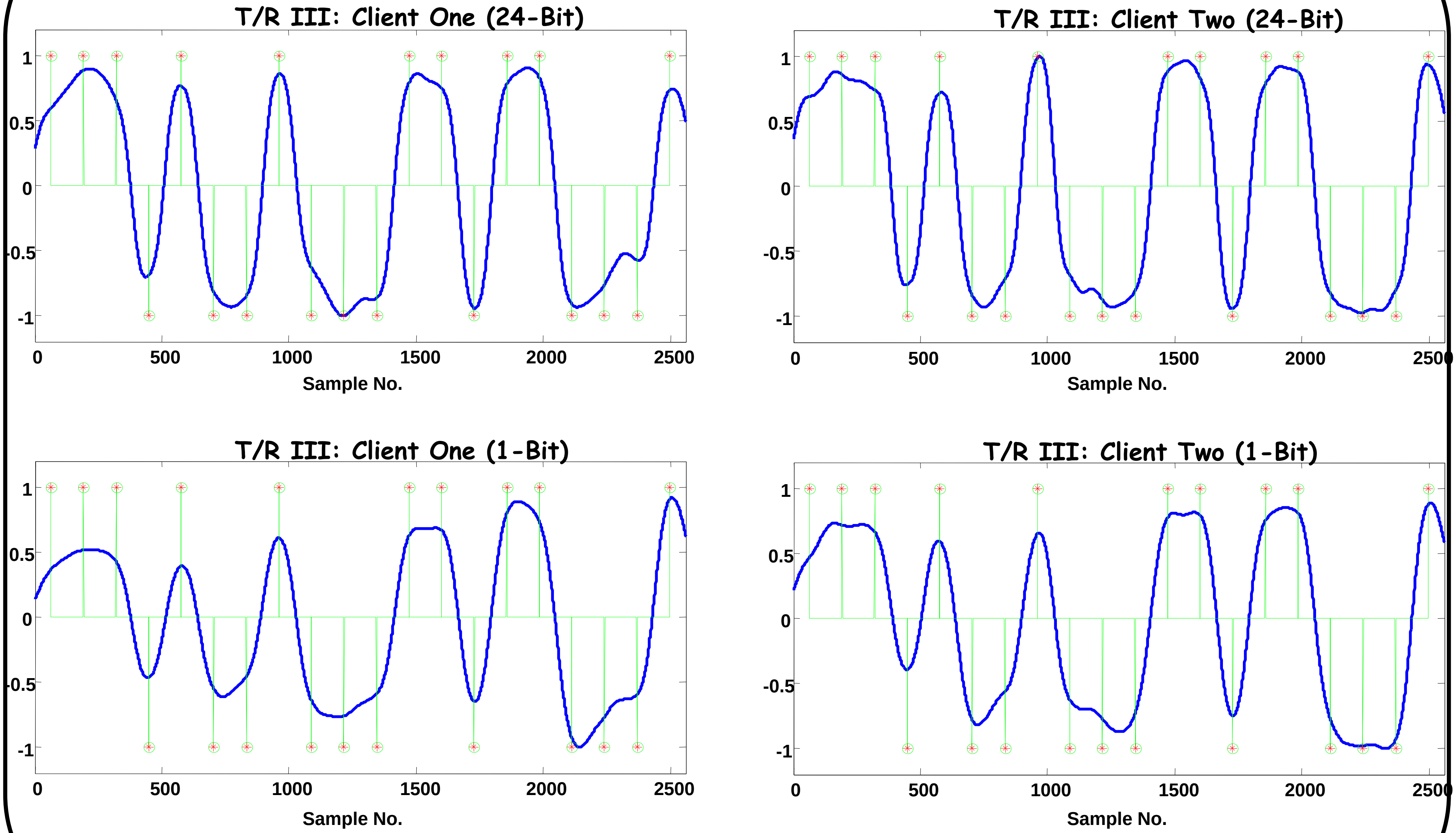


T/R Receiver Realization III: G-function on Rcv



$$\mathbf{R}_{i\hat{g}_m R}(t) = z_m(t) * \hat{\mathbf{g}}_m(-t) = \left(\mathbf{g}_m^T(t) * \mathbf{i}(t)\right) * \hat{\mathbf{g}}_m(-t)$$

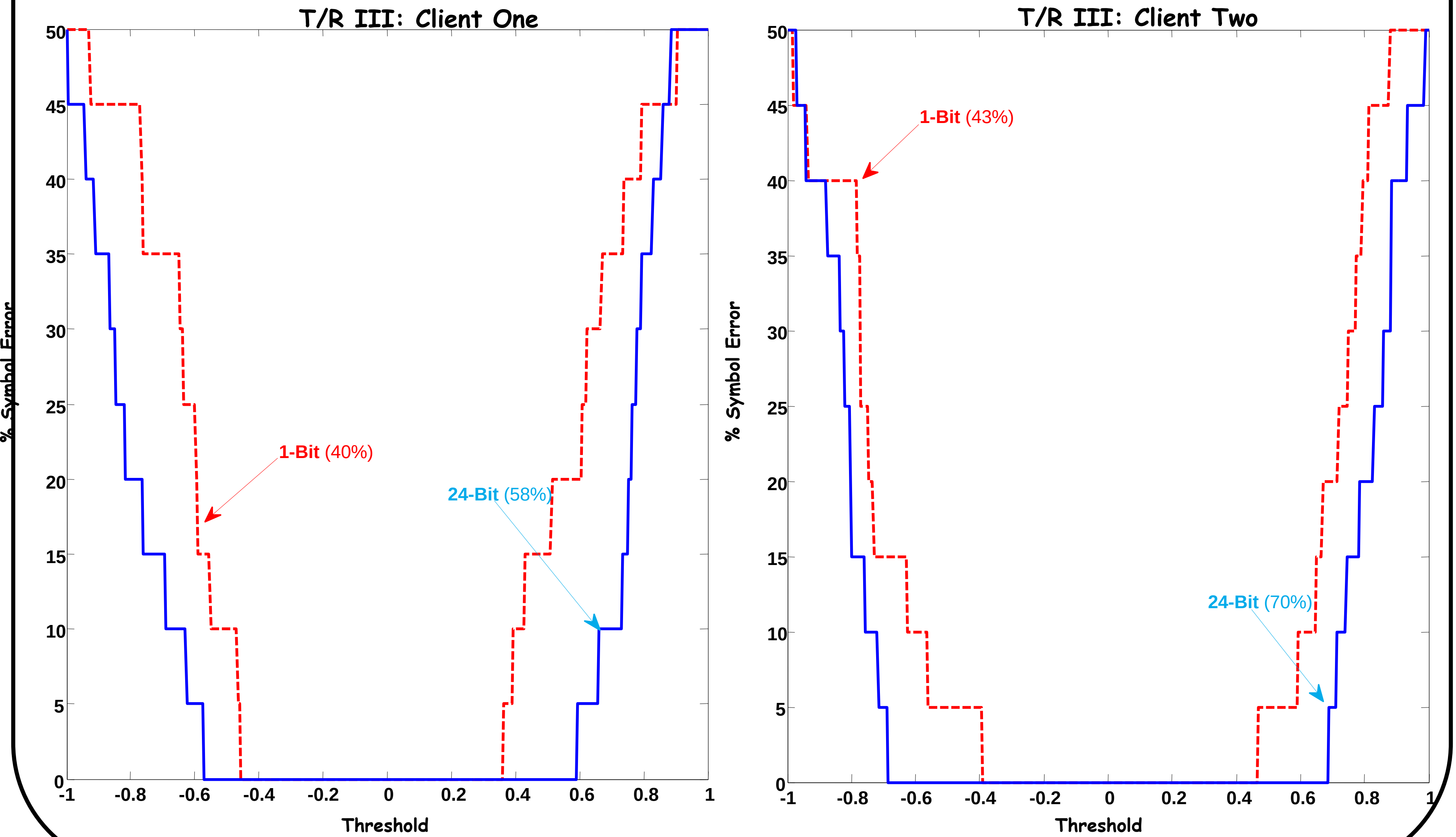
T/R III focusing at clients 1 & 2:



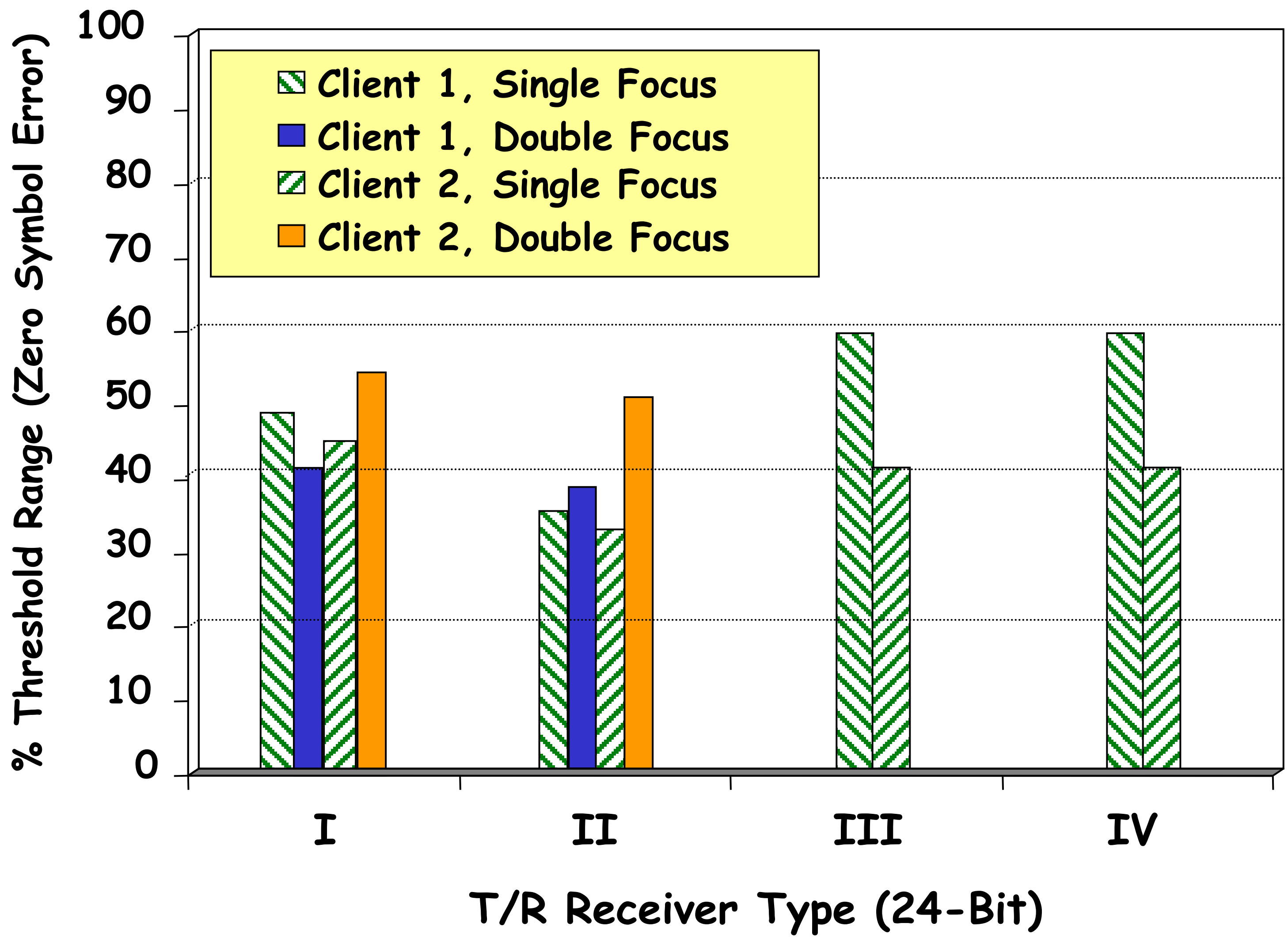
* - *Estimated Symbol*

O - *True Symbol*

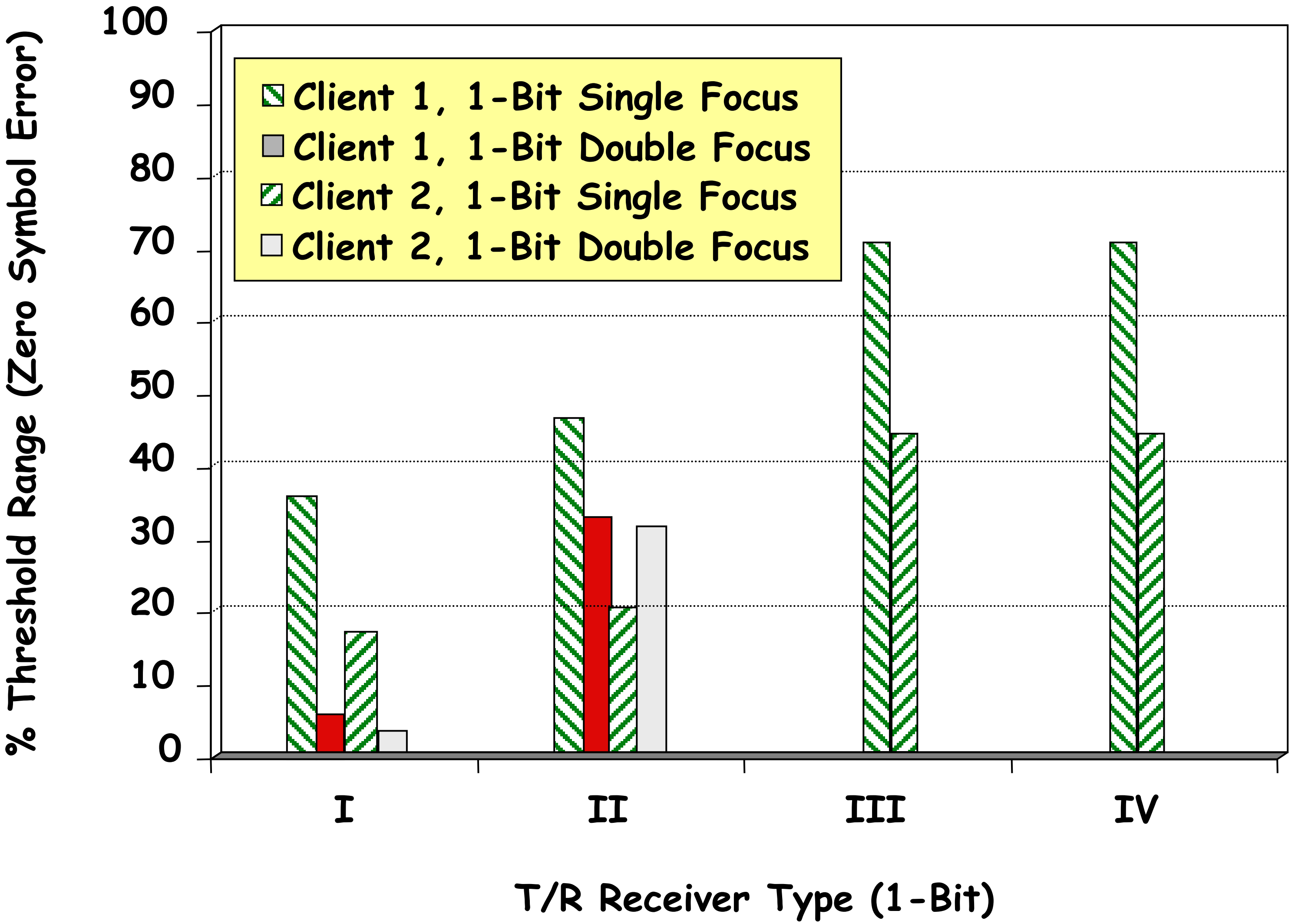
T/R III focusing at clients 1 & 2: % symbol error



Overall T/R receiver performance is encouraging for 24-bit designs:



Overall for T/R receivers focusing at clients 1 & 2 demonstrates the degradation:



Proof-of-principle experiments have shown outstanding results for these experiments

- *standard receivers try to "ignore" multipath by using only direct path information (time gating)*
- *arrays have been recently introduced into comms area, but not intelligent (learn Green's function) T/R arrays*

BUT

- *we have shown for P2P and A2P communications the concept of a time-reversal (T/R) receiver is capable of operating successfully in a highly reverberative environment even in a 1-BIT T/R receiver realization*

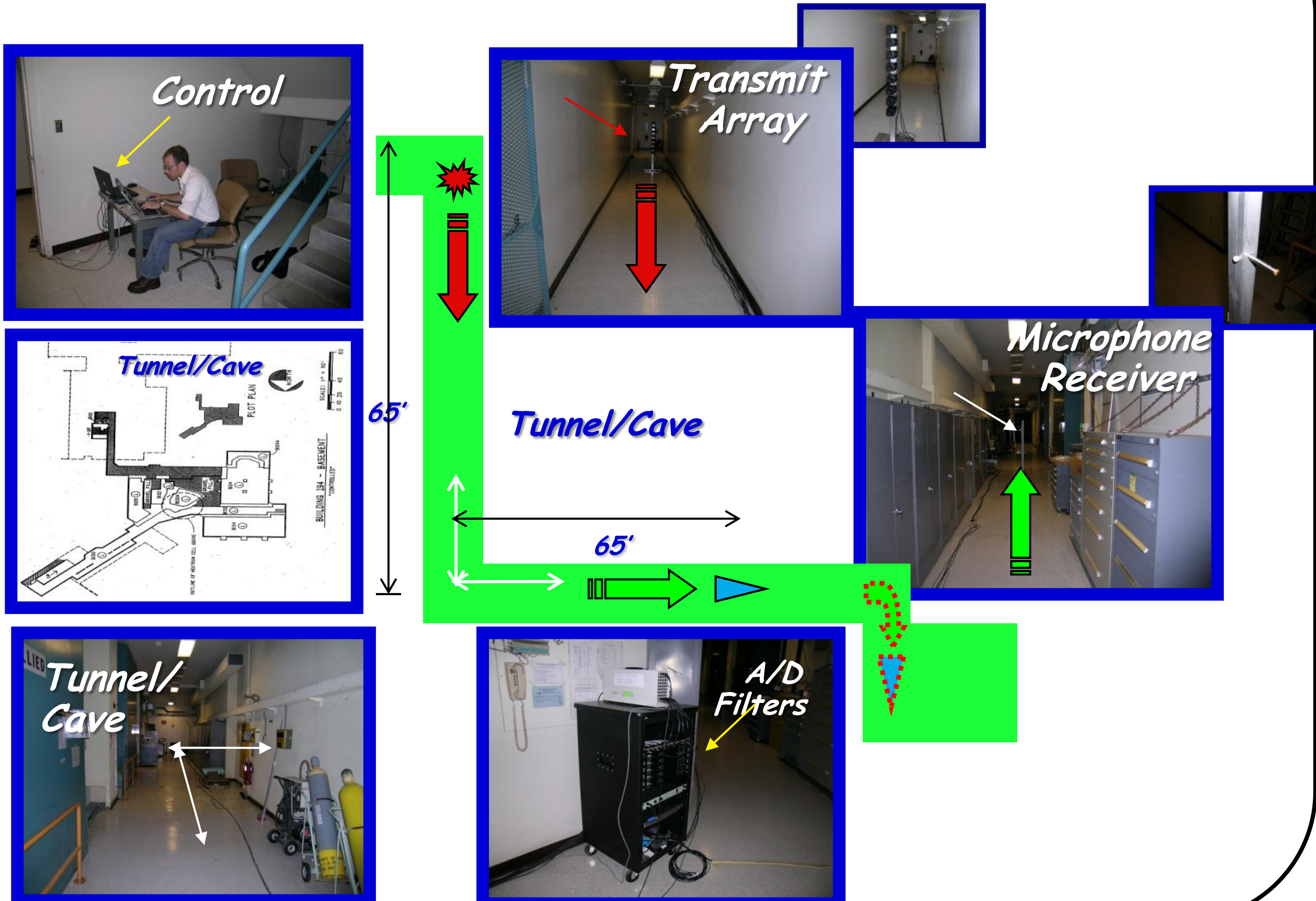
III. ARRAY-TO-POINT EXPERIMENTS IN A TUNNEL-LIKE STRUCTURE

Synchronization & demodulation create a significant problem for carrier-based NB receivers (collaborating with MIR people)

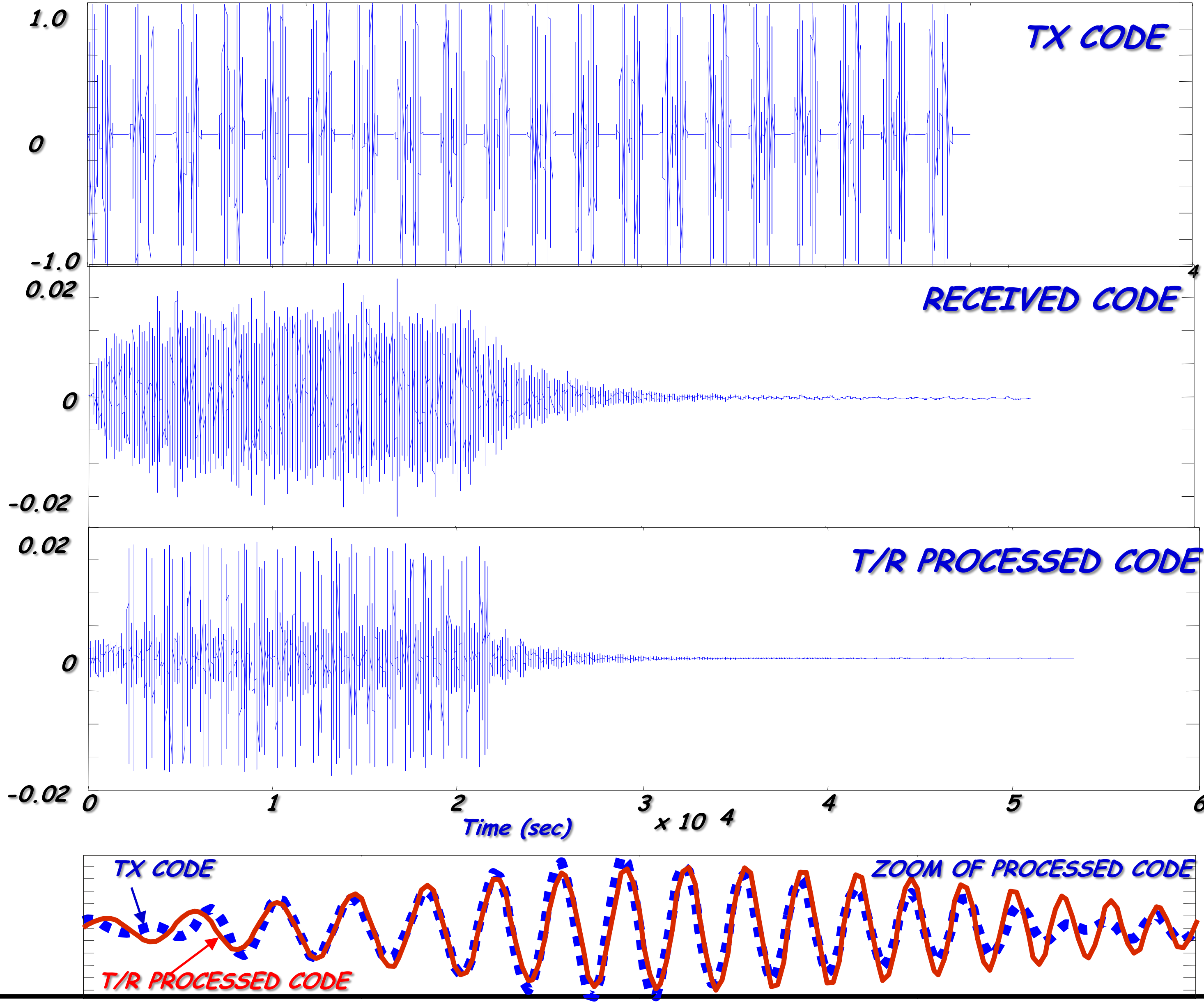
To **improve** our performance we:

- decided on a **wide-band** design (F_{BW}=BW/F_C>20%;F^{TR}>50%)
- chose to use a "**transmitter-reference**" (XR) synchronization and modulation/demodulation scheme (2 pulses/bit; polarity check)
- designed a gaussian-windowed chirp **pulse** for our BPSK codes
- performed **experiments** in our canonical stairway and compared performance to validate design
- performed experiments in the **tunnel-like** (cave) demonstrating the capability

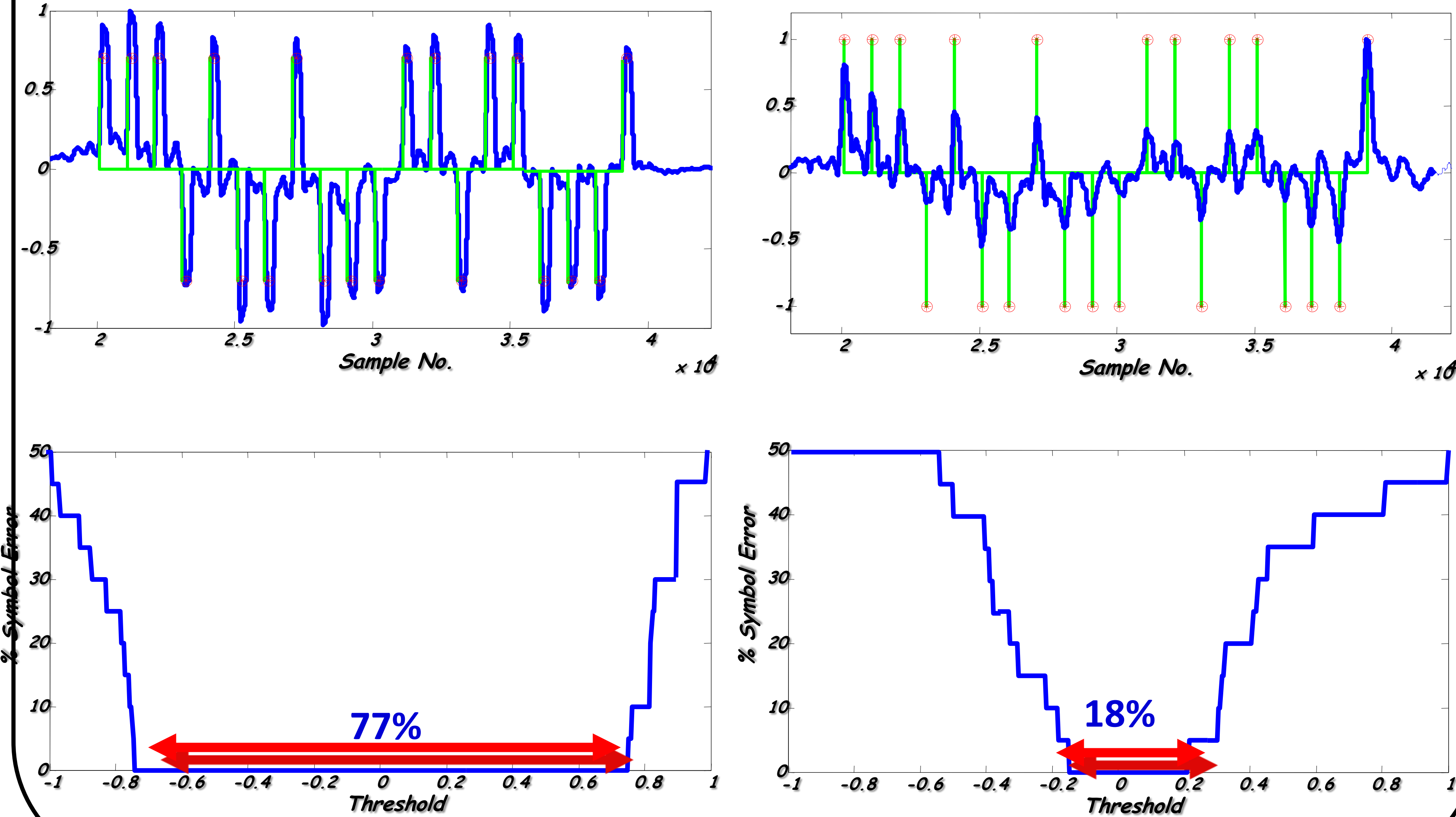
The raw transmitter-reference (XR) information is broadcast in the highly reverberant tunnel-like environment



Wide-band processing minimizes the synchronization problem



Wide-band T/R works for both 24 & 1-bit realizations



Summary:

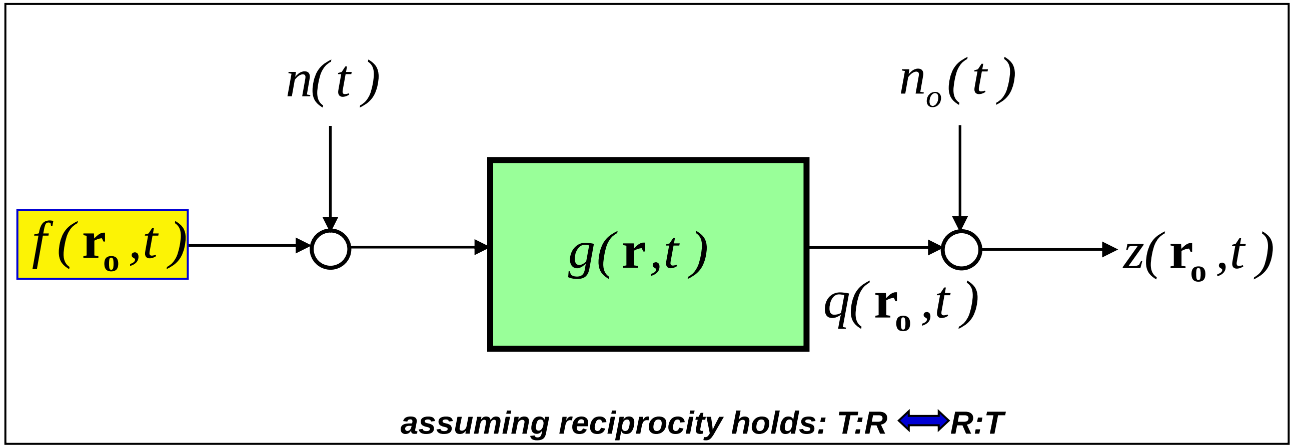
- **We have discussed the idea of communications in a hostile environment using *time-reversal processing* with *multi-channel* (intelligent array) *signal processing***
- **We have discussed the approach using theory, simulation, experiment and prototype design**
- ***We have performed :***
  - ***theory (T/R operators and multi-channel (array) signal processing)***
  - ***algorithms (processing)***
  - ***simulations***
  - ***experiments (media and test beds)***
  - ***prototype development***
- ***leading to a commercializable receiver for military and civilian applications***

BACK-UPs

T/R (on transmission) provides the MF solution to the problem of determining the optimal input to maximize the SNR at the source

<u>MF problem</u>:

GIVEN a "known" signal (Green's function) of the medium from source-to-transmitter in additive random noise, FIND the *input function* that *maximizes* the SNR at the source (focus)



$$\max_{f}\ \mathrm{SNR}_{\mathrm{out}} \equiv \frac{q^2(\mathbf{r}_o,t)}{E\left\{n_o^2(t)\right\}}$$

The T/R solution (transmission) in AWN to the MF problem is given by:

$$SNR_{out} = \frac{\left| \int_{-\infty}^{T} f(\mathbf{r}_o,\alpha) g(\mathbf{r}_o, T-\alpha) d\alpha \right|^2}{\frac{N_o}{2} \int_{-\infty}^{T} g^2(\mathbf{r}_o, T-\alpha) d\alpha} = \frac{\left| f(\mathbf{r}_o,t) * g(\mathbf{r}_o,t) \right|^2}{\frac{N_o}{2} \int_{-\infty}^{T} g^2(\mathbf{r}_o, T-\alpha) d\alpha}$$

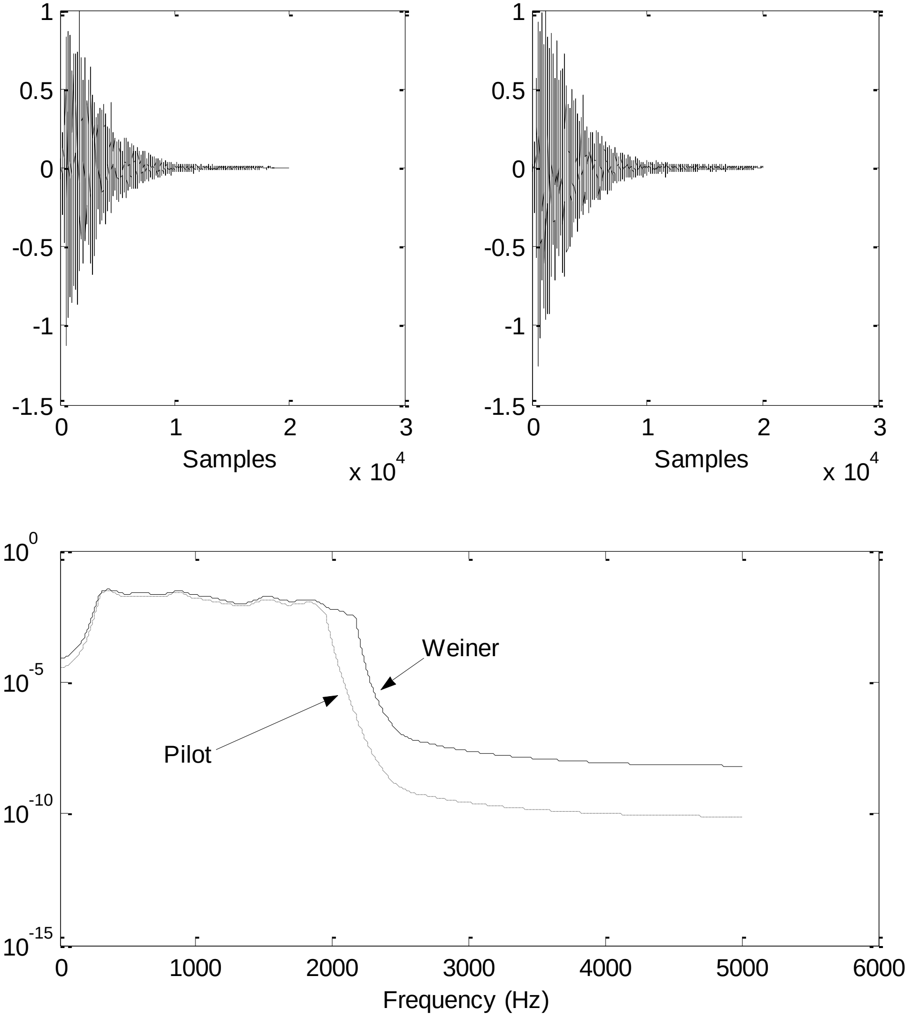
which leads to the maximization of the numerator (as before) giving the solution

$$f(\mathbf{r}_o,t) = g(\mathbf{r}_o, T-t)$$ ← **time-reversed Green's fcn**

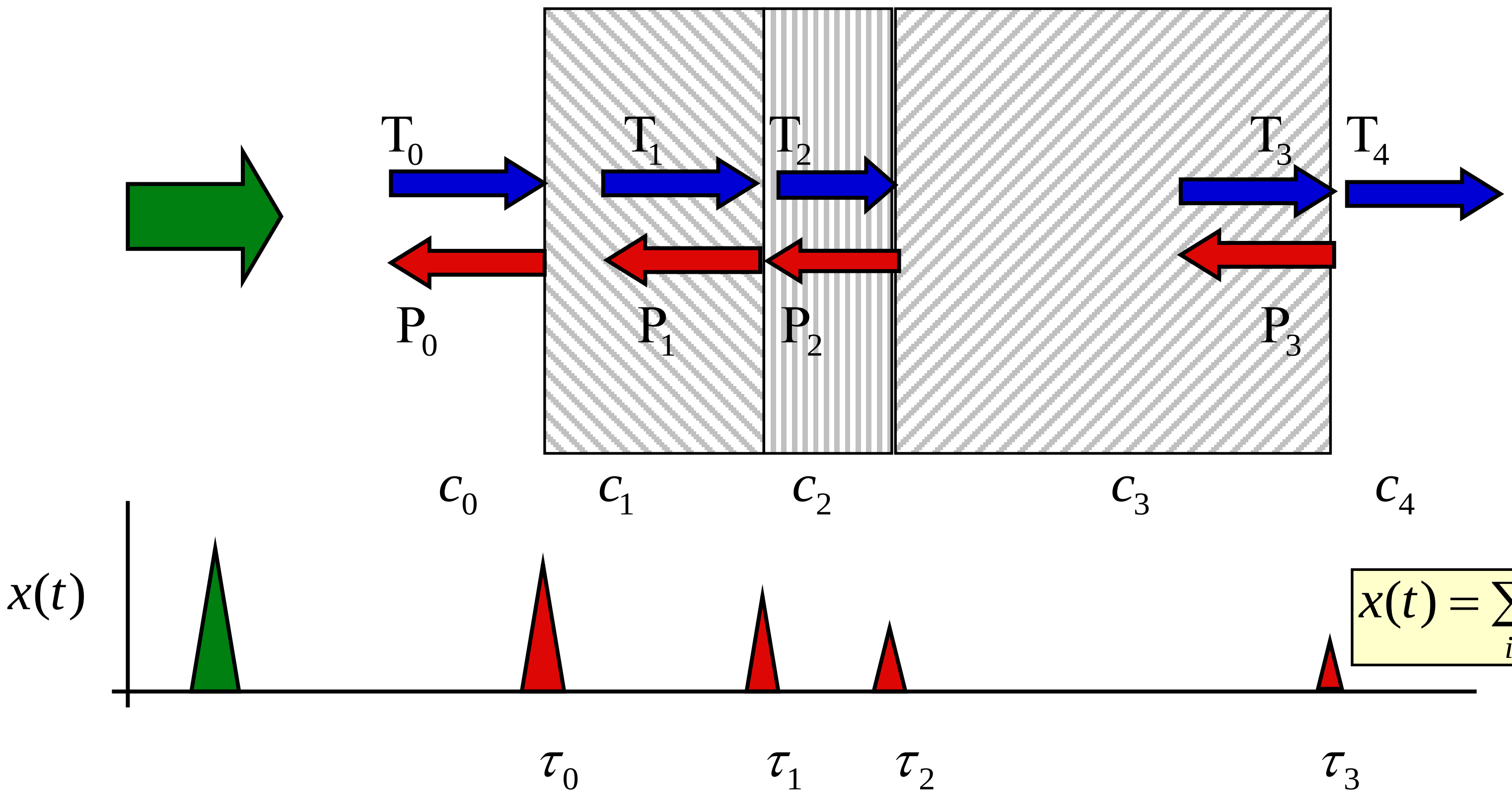
For a "known" signal (Green's fcn) the optimal SNR solution is the T/R processor.

$$z(\mathbf{r}_o,t) = f(\mathbf{r}_o,t) * g(\mathbf{r}_o,t) = g(\mathbf{r}_o,T-t) * g(\mathbf{r}_o,t)$$

The channel Green's function can be estimated optimally or using a simple pilot (chirp)



Wave propagation in media (water, air, tissue, materials etc.) causes reflections and transmissions of energy at each interface



$$x(t) = \sum_i \alpha_i s(t - \tau_i)$$

Knowledge of the media velocity enables us to detect and localize the interfaces using arrival times (time delays)