# Application of time-reversal methods to communication in hostile environments

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**Auspices**

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# ORGANIZATION

- COMMUNICATION PROBLEM
- REVIEW OF TIME-REVERSAL
- TIME-REVERSAL POINT-TO-POINT (P2P) RECEIVERS
- TIME-REVERSAL ARRAY-TO-ARRAY (A2A) RECEIVERS
- WIDEBAND TIME-REVERSAL RECEIVERS
- SUMMARY AND FUTURE DIRECTIONS

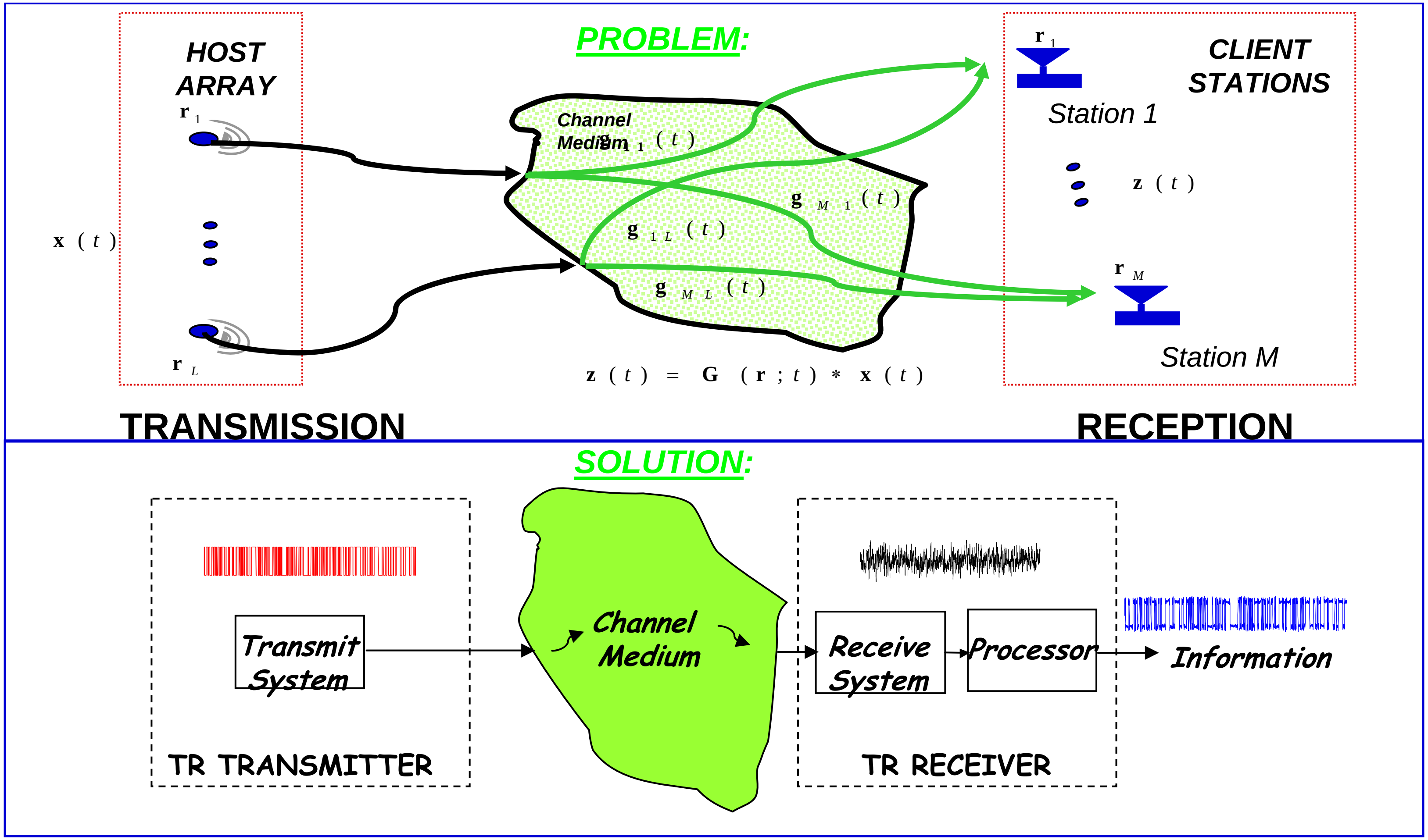
# COMMUNICATION PROBLEM

**PROBLEM:**

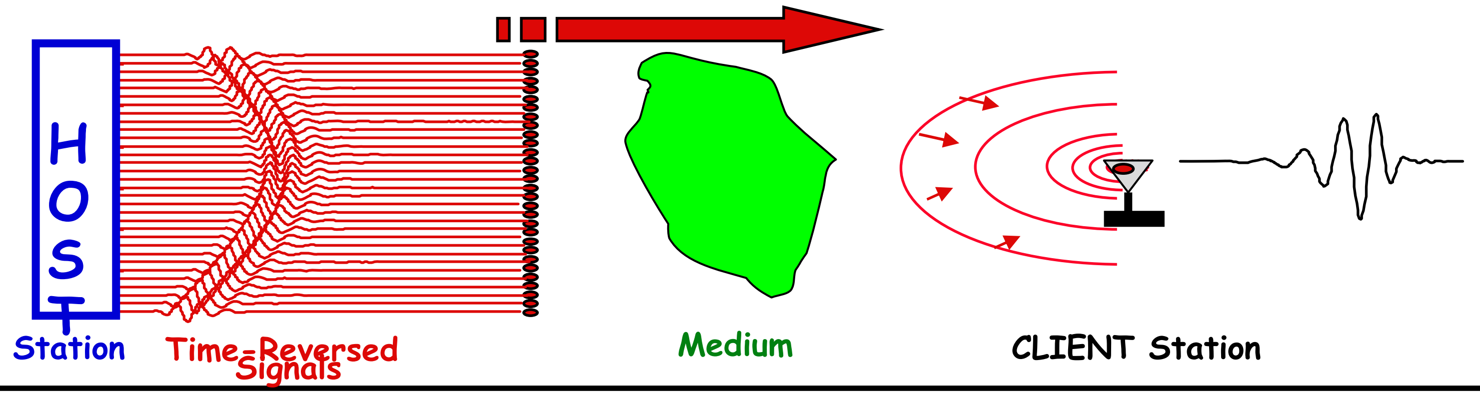
*Transmit information in a hostile medium (mpath,mscatterers,reverb,noise) and extract it with minimal symbol/bit error*

**APPROACH:**

*Time reversal (TR) communication system*

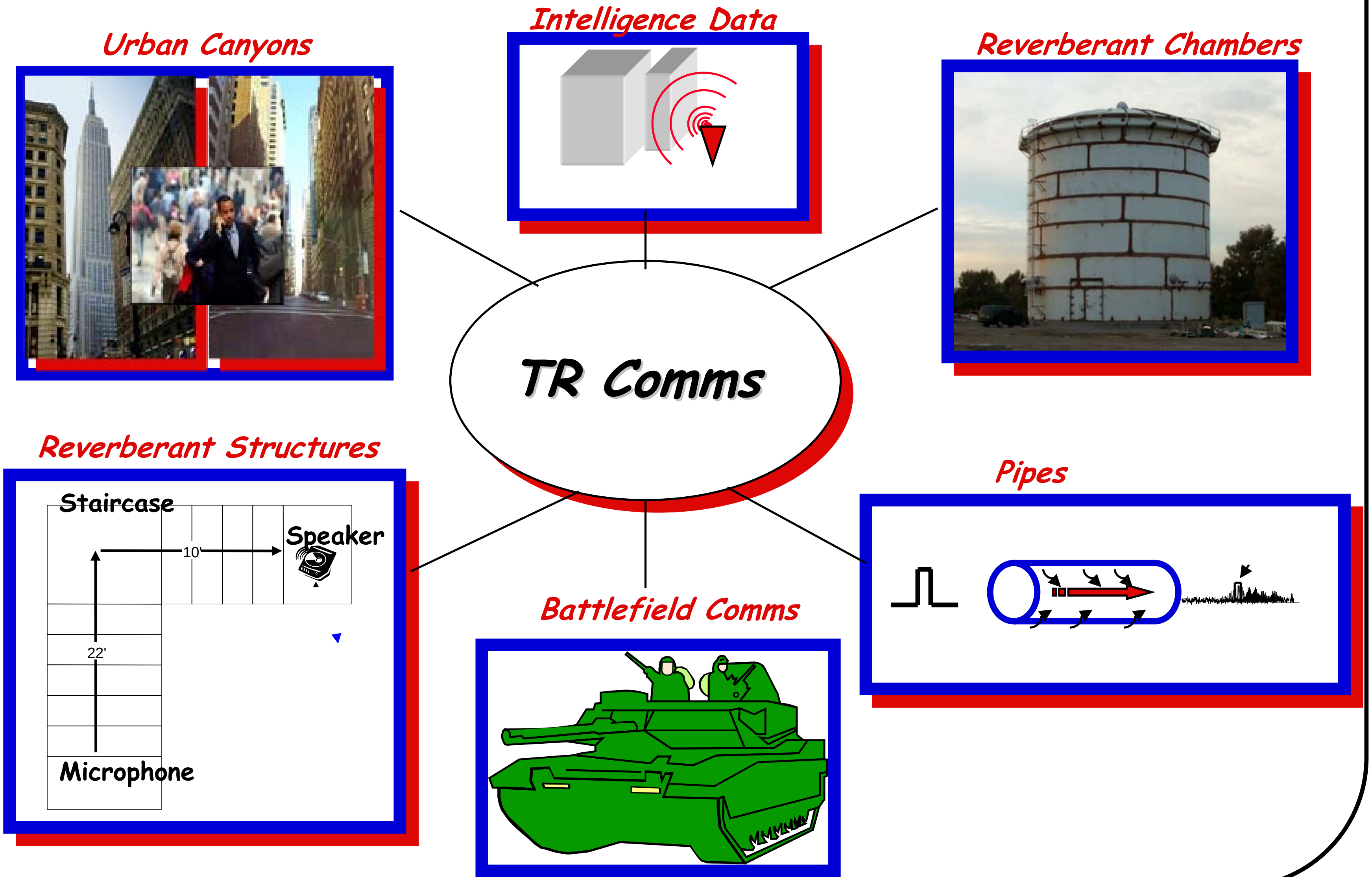


# TR communication systems can:




- 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

# TR offers an alternate solution to the communications problem in hostile environments

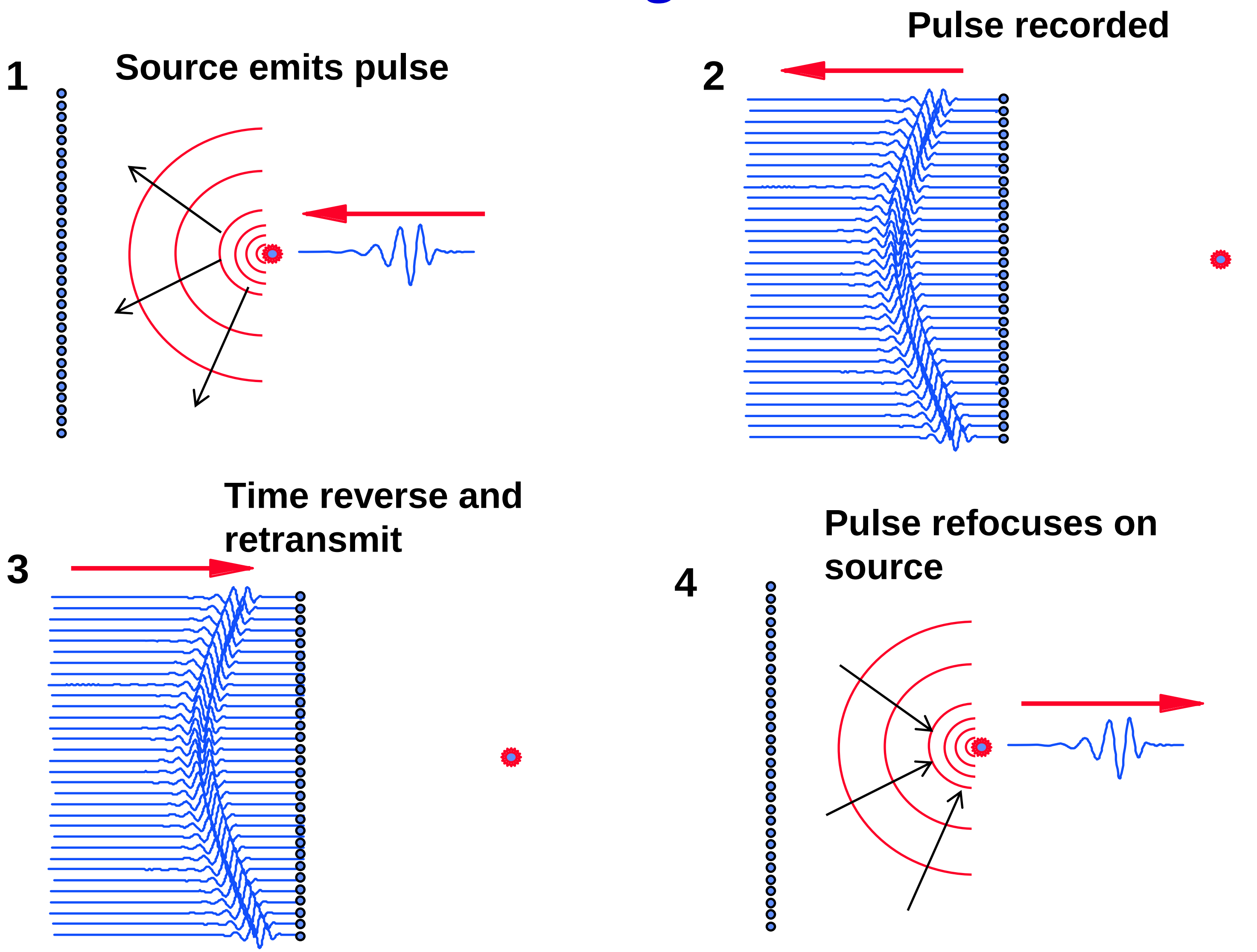


# TIME-REVERSAL

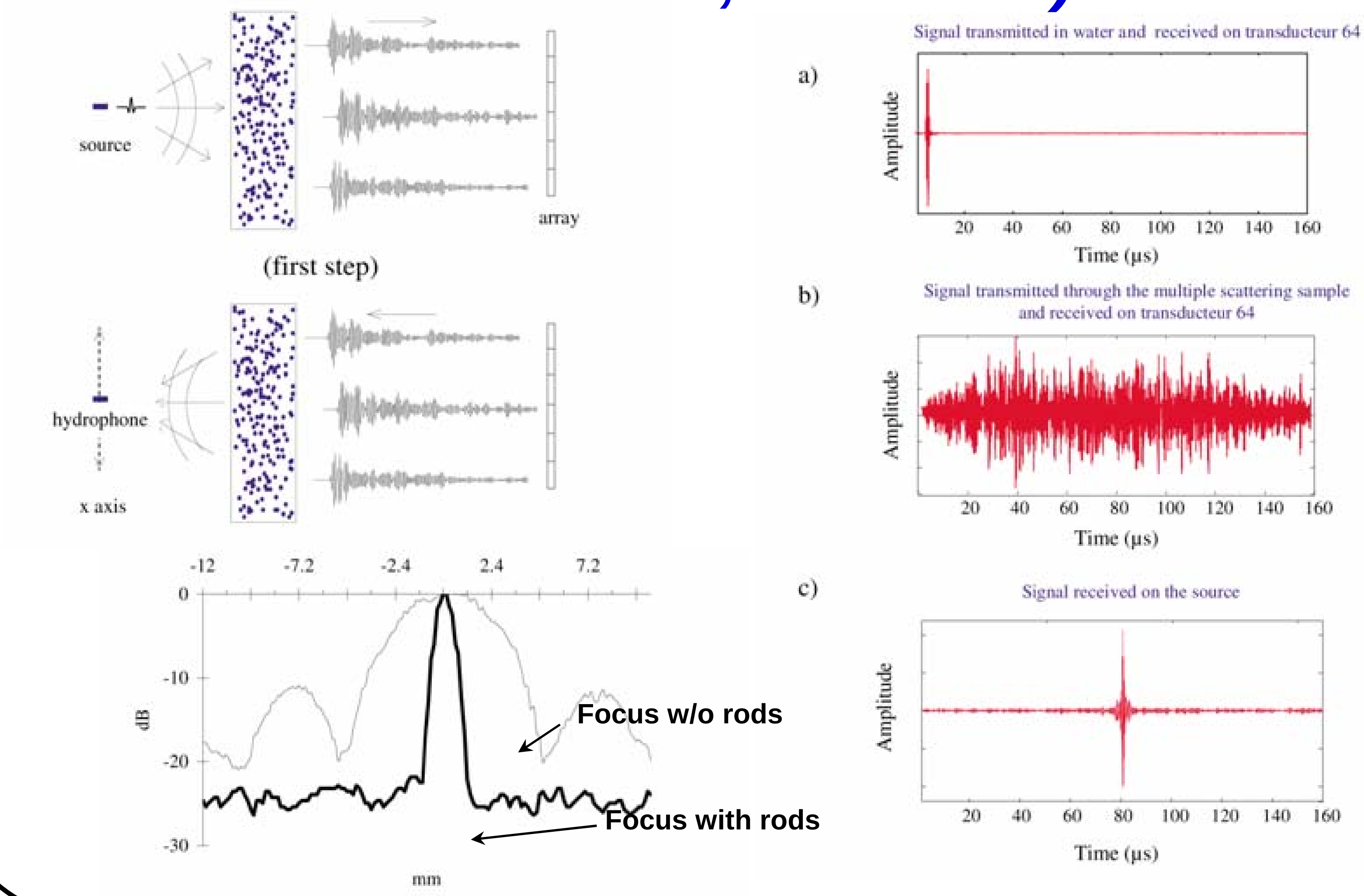
# *What is time reversal wave propagation?*

- **Time reversal techniques exploit the symmetry of wave propagation to the direction of time (time invariance, reciprocity) to enhance focusing, imaging, and target characterization**
- **Experimentalist: A simple technique for focusing energy on a target through an uncharacterized or complicated media**
- **Signal processor: A hardware implementation of a broadband spatio-temporal matched filter for multi-channel array data (minimal calculation)**
- **Applied mathematician: A symmetry of propagation and scattering useful for understanding scattering in difficult media and designing inversion and imaging methods ==> target characterization**

# Operation of a time reversal array (mirror) for a single source



# Time reversal allows focusing through complicated media (experiment by Derode, Roux, and Fink; PRL 1995)



# *Time reversal as a spatio-temporal matched filter (1)*

- **Simple matched filter**

  **Given data u(t) = s(t) + n(t);   s(t): signal,    n(t): white noise**

  **Determine filter h(t) so that y(t) = h(t)*u(t) has maximum SNR at time T:**

$$SNR(T) = \frac{\left| \int_0^T h(t')s(T-t')dt' \right|^2}{\sigma^2 \int_0^T |h(t')|^2 \, dt'}$$

  $\sigma$ **: noise variance**

  **Answer is h(t) = s(T-t); time-reversed version of signal**

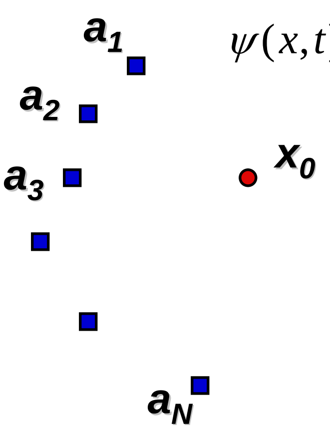
- **Generalization to multi-channel data $u_n(t)$ gives MMSE beamformer**

# *Time reversal as a spatio-temporal matched filter (2)*

- **Spatio-temporal matched filter**

  **Given an array with elements at positions $a_n$: $n = 1,2,\ldots,N$**

  **Determine excitations $E_n(t)$ that maximize SNR of the transmitted field at time $T$ AND position $x_0$**




$$\psi(x,t) = \sum_{n=1}^{N} \int_0^t G(x, a_n, t - t') E_n(t') dt'$$

**Field at x and t generated by array**

***$G(x,t;a_n,t)$ Green's function (impulse response)***

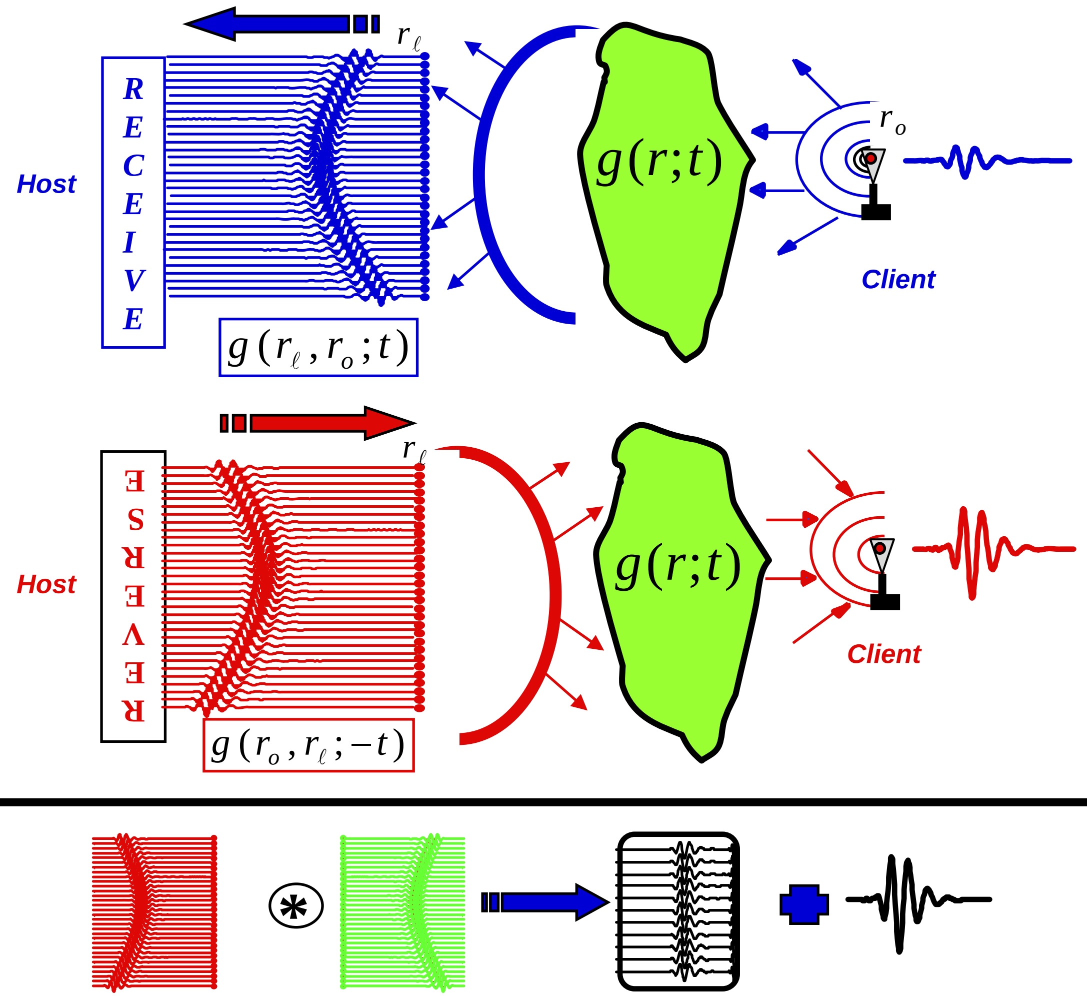
$$SNR(x_0, T) = \frac{\left| \sum_{n=1}^{N} \int_0^T G(x_0, a_n, T - t') E_n(t') dt' \right|^2}{\sum_{n=1}^{N} \int_0^T \left| E_n(t') \right|^2 dt'}$$

**Answer is $E_n(t) = G(x_o, a_n, T-t)$ : time-reversed Green's function**

$$\psi_{MF}(x,t) = \sum_{n=1}^{N} \int_0^t G(x, a_n, t - t') G(x_0, a_n, T - t') dt'$$

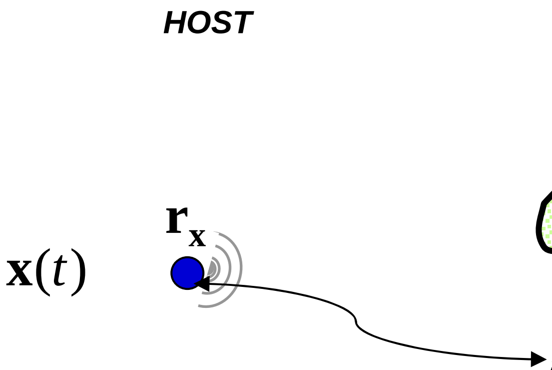
# TIME-REVERSAL POINT-TO-POINT (P2P) RECEIVERS

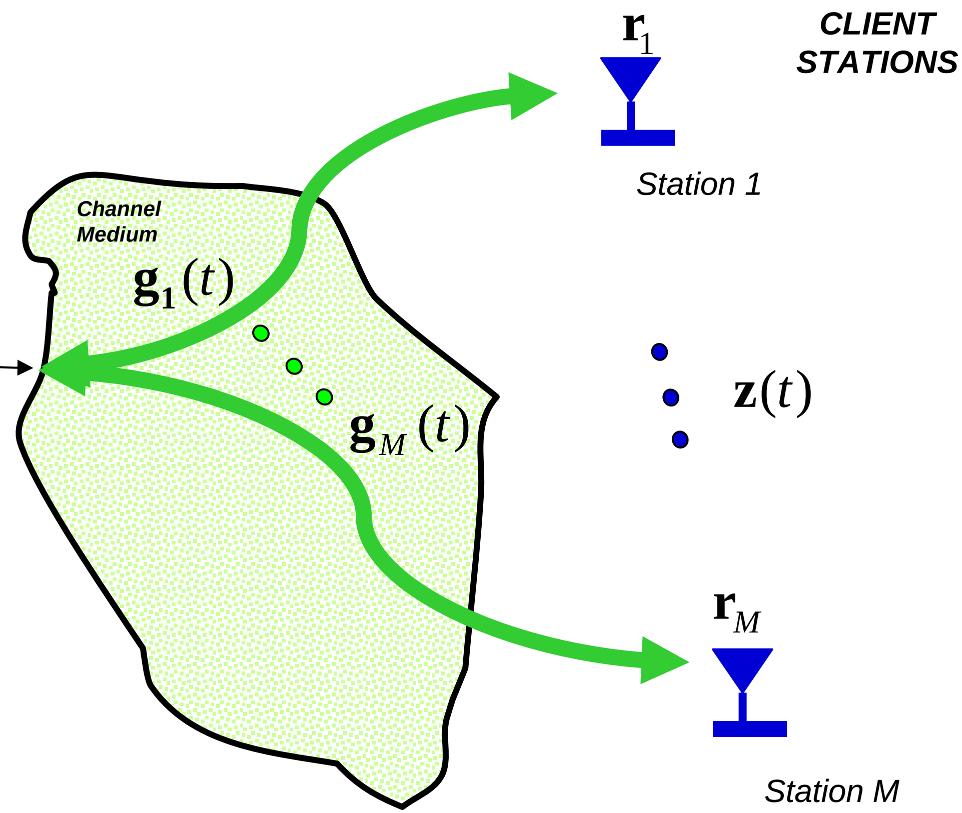
## A TR communication system is an intelligent, *optimal*, space-time, matched-filter that "learns" the medium




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

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




**If medium is highly reverberant, channels to neighboring stations can be uncorrelated (Tourin, Derode, Fink, *et al.*). Host could communicate solely with a single station using the Green's function (impulse response) for the associated channel.**

$$\mathbf{z}_m(t) = \mathbf{g}_m(\mathbf{r};t) * \mathbf{x}(t)$$

**TRANSMISSION** **RECEPTION**

# TR processing - time and frequency domains

**MEDIUM:** $z(t) = g(r;t) * i(t) \iff Z(\omega) = G(r;\omega) \times I(\omega)$

Impulsive for highly reverberant medium

**In the time domain, the TR processor is:**

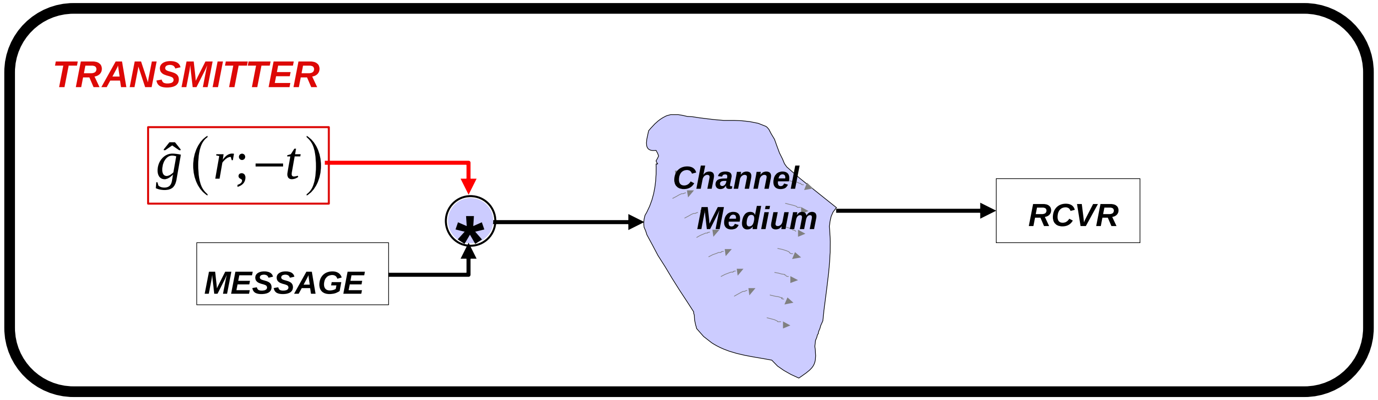
$$\hat{i}(t) \approx z(t) * \hat{g}(r;-t) = \left[ g(r;t) * \hat{g}(r;-t) \right] * i(t) = C_{gg}(t) * i(t)$$

**While in the temporal frequency domain it looks more familiar:**

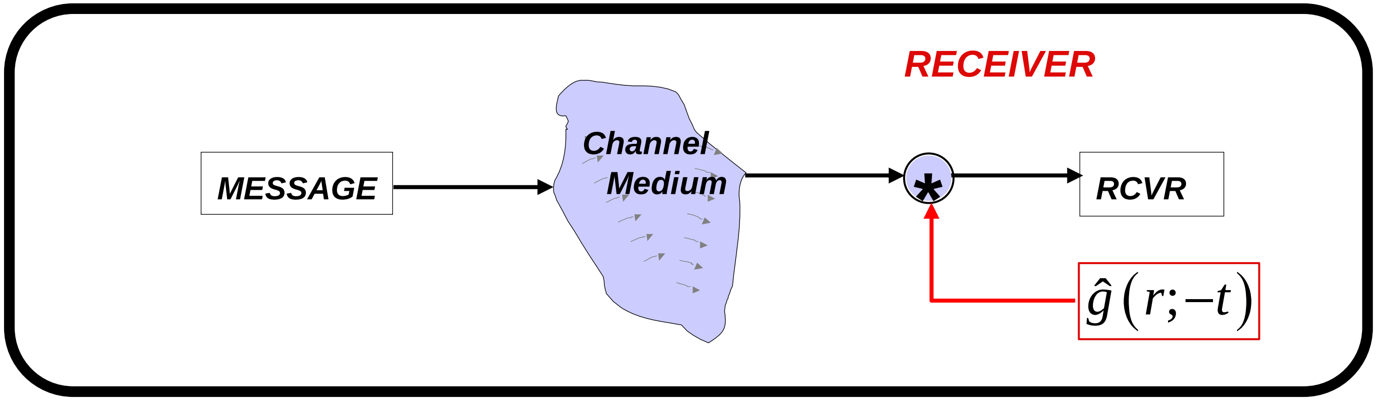
$$\hat{I}(\omega) = Z(\omega) \times G^*(r;\omega) = \left[ G(r;\omega) \times G^*(r;\omega) \right] \times I(\omega) = \left| G(r;\omega) \right|^2 \times I(\omega)$$

Spectral Phase Conjugation

# TR signal processing can be applied at either the transmitter or receiver:

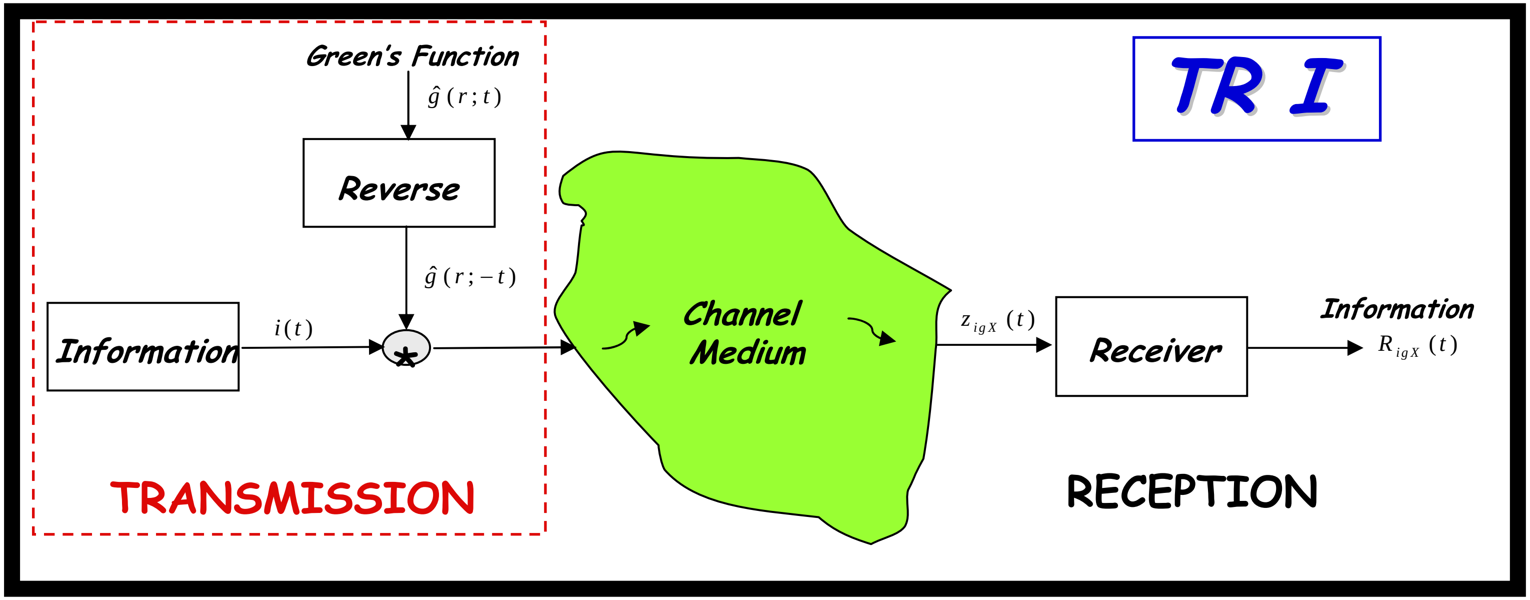



$$R(t) = g(r;t) * \left[\hat{g}(r;-t) * i(t)\right] = \left[g(r;t) * \hat{g}(r;-t)\right] * i(t) = C_{g\hat{g}}(r;t) * i(t) \approx i(t)$$



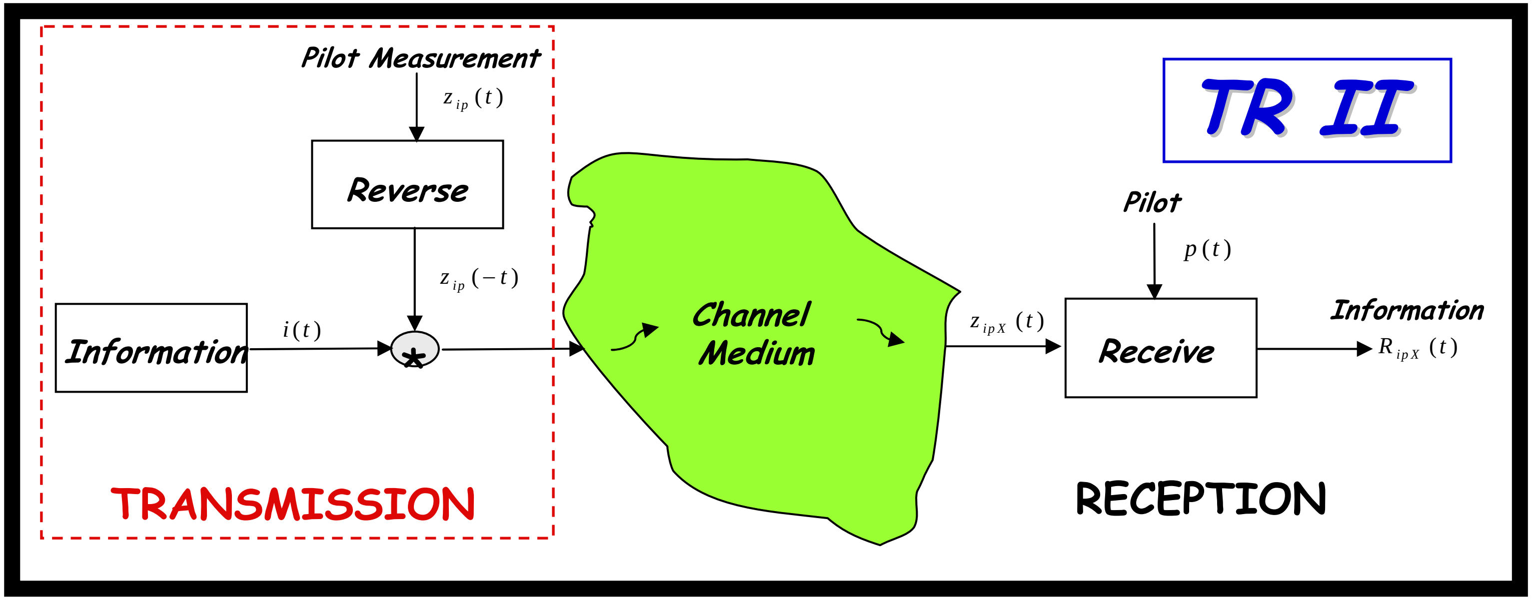

$$R(t) = \hat{g}(r;-t) * \left[g(r;t) * i(t)\right] = \left[\hat{g}(r;-t) * g(r;t)\right] * i(t) = C_{g\hat{g}}(r;t) * i(t) \approx i(t)$$

## We have implemented two versions of TR receivers on transmission:




1. Receiver *j* sends pilot to transmitter
2. Transmitter estimates Green's function: $\hat{g}_j(t)$
3. Transmitter sends $\hat{g}_j(-t) * I(t)$
4. Receiver *j* records $g_j(t) * \hat{g}_j(-t) * I(t) = \hat{C}_{jj}(t) * I(t) \approx I(t)$

   Receiver *k* records $g_k(t) * \hat{g}_j(-t) * I(t) = \hat{C}_{jk}(t) * I(t) \neq I(t)$




1. Receiver *j* sends pilot *p(t)* to transmitter, $p(t) * p(-t) = C_{pp}(t) \approx \delta(t)$

2. Transmitter receives $z_{jp}(t) = p(t) * g_j(t)$

3. Transmitter sends $z_{jp}(-t) * I(t)$

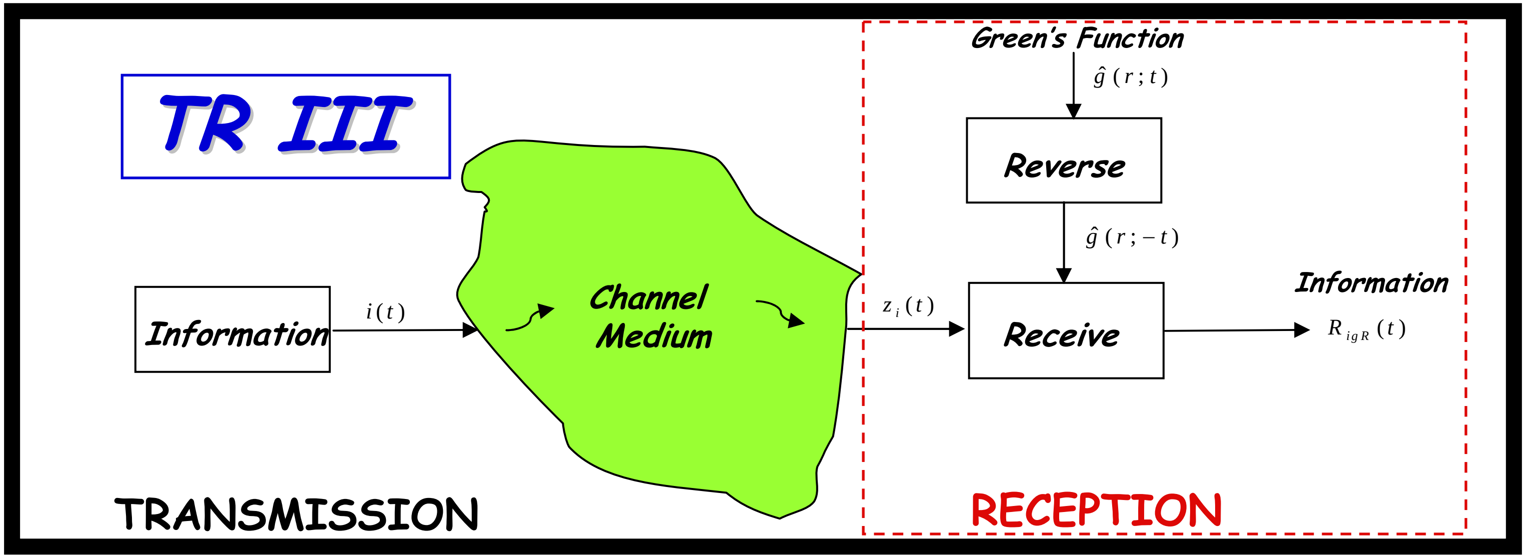
4. Receiver *j* records signal and convolves it with pilot

$$p(t) * g_j(t) * z_{jp}(-t) * I(t) = C_{pp}(t) * C_{jj}(t) * I(t) \approx I(t)$$

Receiver *k* produces

$$p(t) * g_k(t) * z_{jp}(-t) * I(t) = C_{pp}(t) * C_{jk}(t) * I(t) \neq I(t)$$

## … and we have implemented 2 TR receiver versions on reception:




1. Transmitter sends pilot *p(t)*

2. Receiver *j* records $p(t) * g_j(t)$ and estimates Green's function $\hat{g}_j(t)$

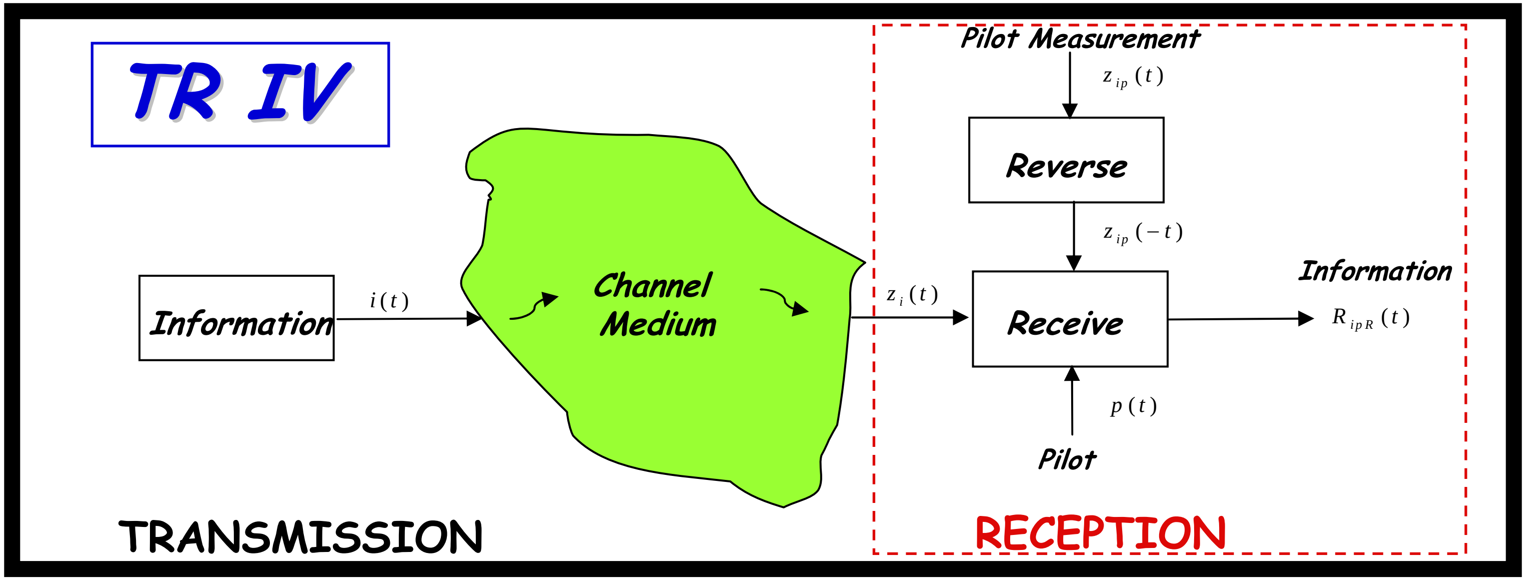
3. Transmitter sends *I(t)*

4. Receiver *j* records signal and convolves it with $\hat{g}_j(-t)$

$$\hat{g}_j(-t) * g_j(t) * I(t) = \hat{C}_{jj}(t) * I(t) \approx I(t)$$

Receiver *k* does the same:

$$\hat{g}_k(-t) * g_k(t) * I(t) = \hat{C}_{kk}(t) * I(t) \approx I(t)$$




1. Transmitter sends pilot *p(t)*, $p(t) * p(-t) = C_{pp}(t) \approx \delta(t)$

2. Receiver *j* records $z_{jp}(t) = p(t) * g_j(t)$

3. Transmitter sends $p(t) * I(t)$

4. Receiver *j* records signal and convolves it with $z_j(-t)$

$$z_{jp}(-t) * g_j(t) * p(t) * I(t) = C_{jj}(t) * C_{pp}(t) * I(t) \approx I(t)$$

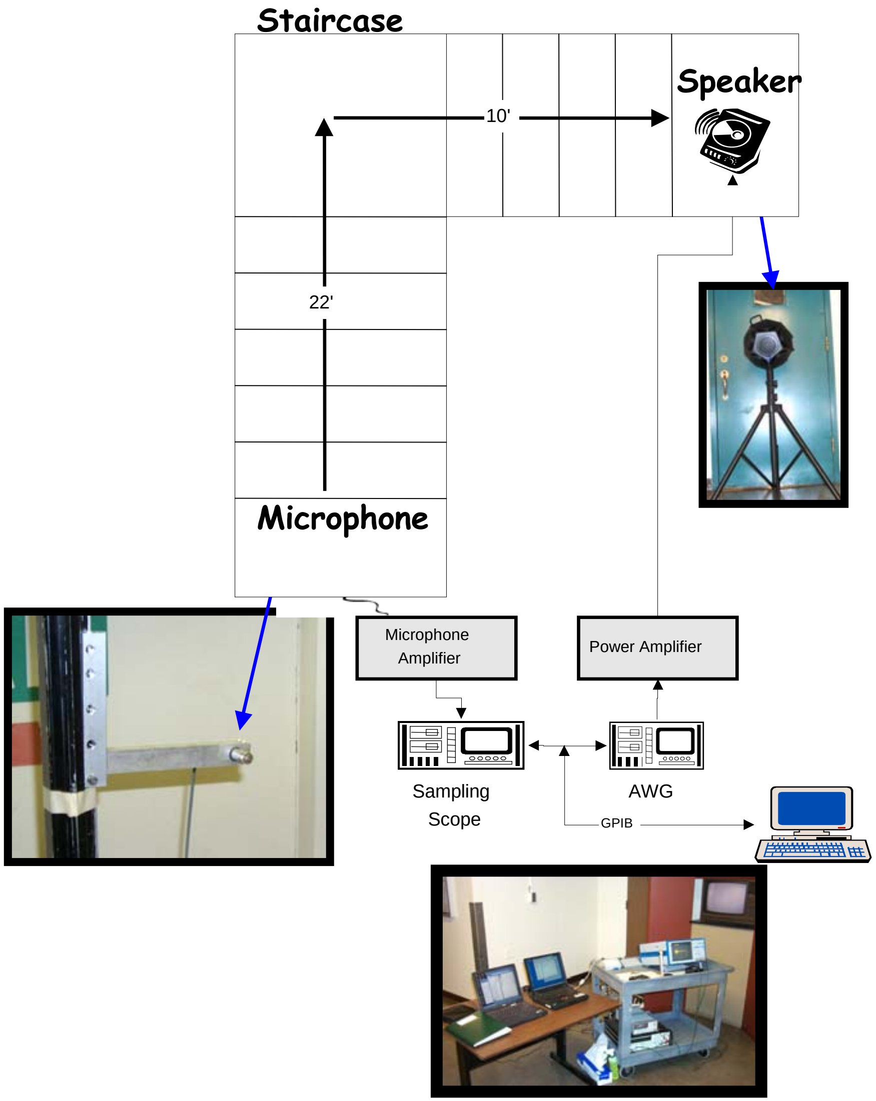
Receiver *k* does the same:

$$z_{kp}(-t) * g_k(t) * p(t) * I(t) = C_{kk}(t) * C_{pp}(t) * I(t) \approx I(t)$$

# Summary of TR receiver types

| | TR Green's function g | TR g*pilot |
|---|---|---|
| Transmission (focused) | Type I | Type II |
| Reception (broadcast) | Type III | Type IV |

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



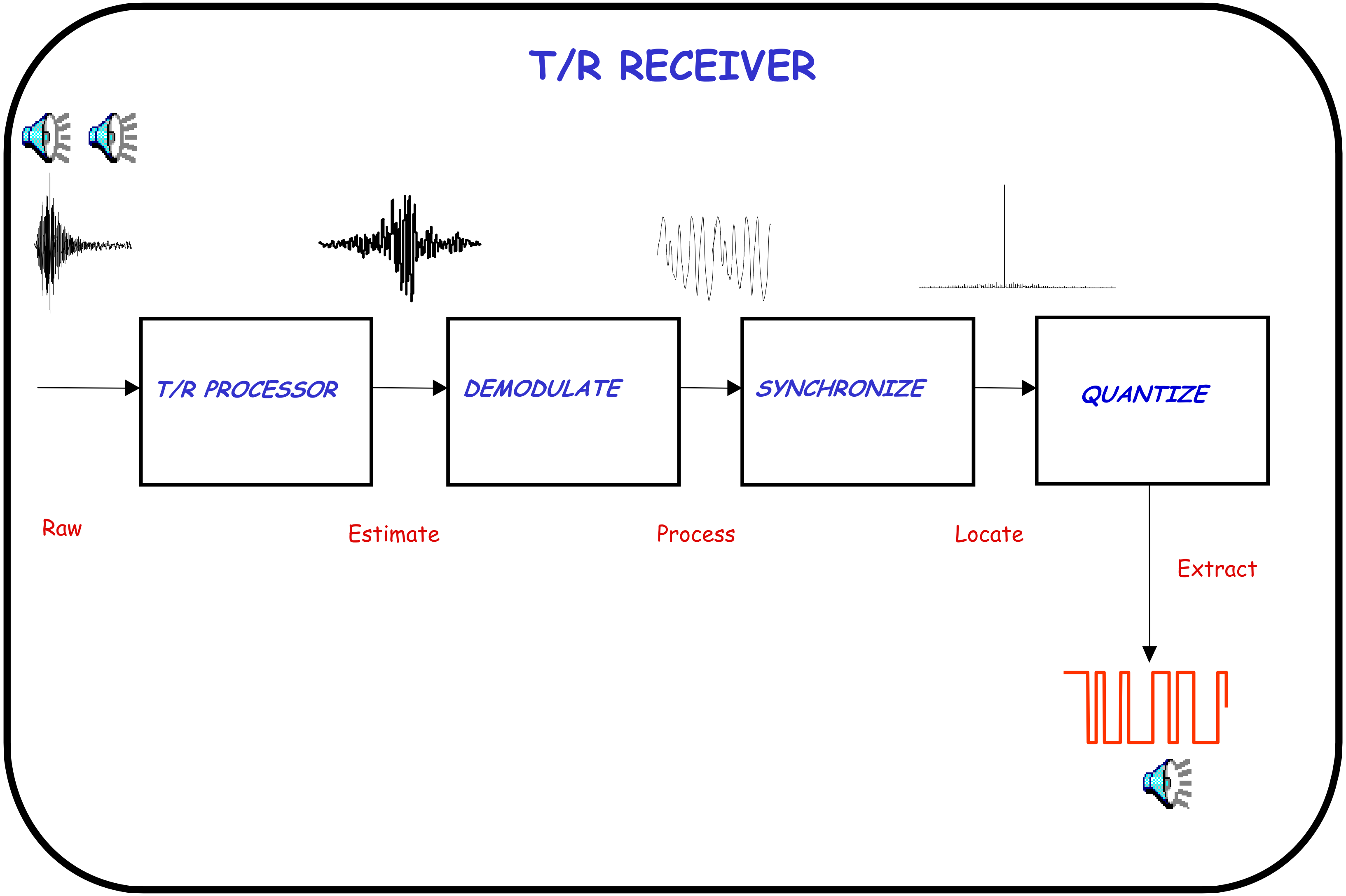
# The experiment was accomplished with:

- SOURCE/AMP: B&K 4296/2716 20dB
- PILOT/CODE: Analogic 2020 arbitrary waveform generator
- MICROPHONE: B&K 2716
- DIGITIZER: LeCroy 8-bit

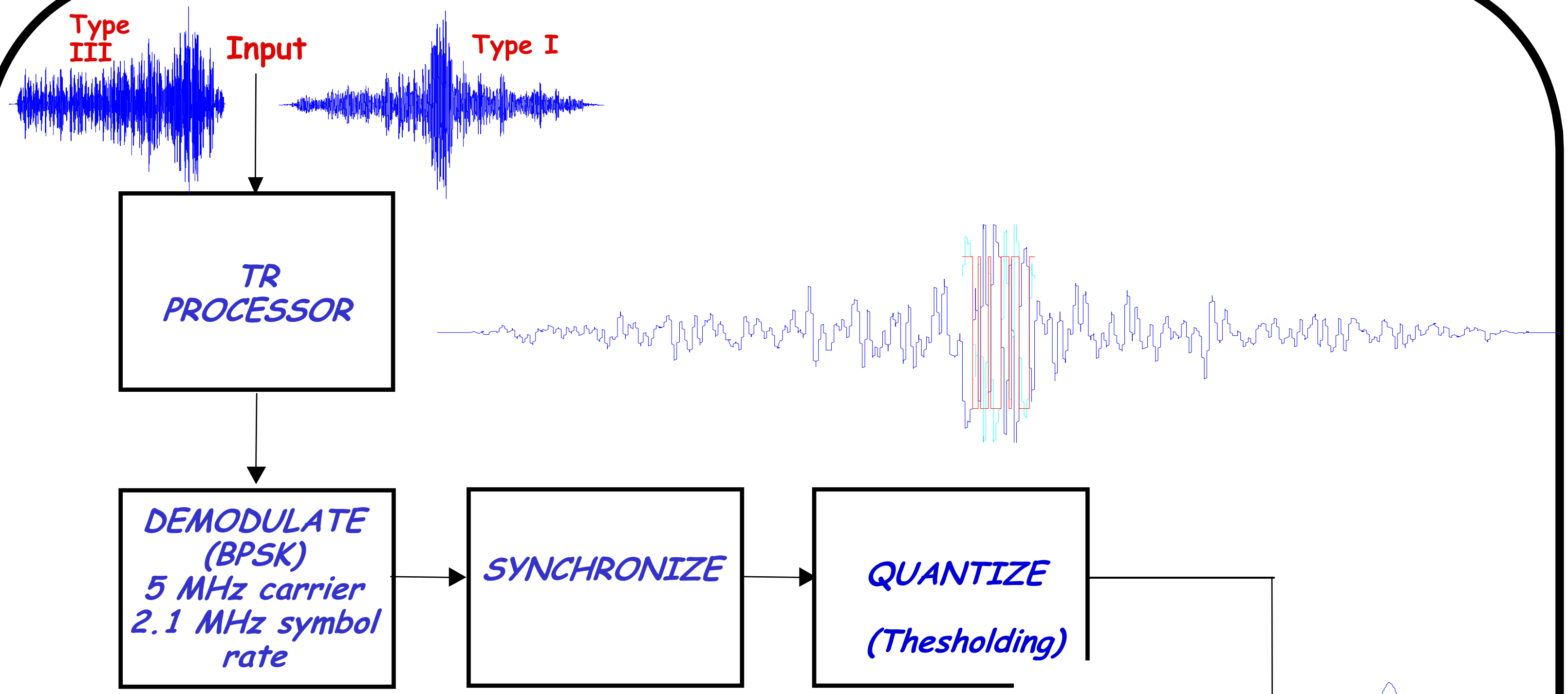
- ------------------------------------------------------------

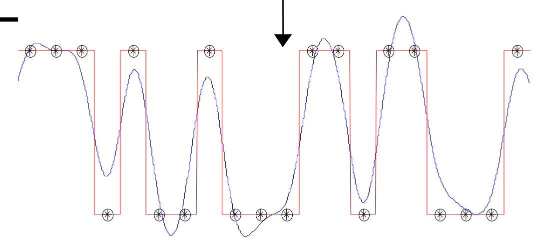
- PILOT: Chirp pulse swept from 0.1-2KHz
- CODE: BPSK 0.1KHz BW
- MODULATION: AM center frequency at 1.207KHz
- SAMPLING FREQUENCY: 10KHz
- SYMBOL/BIT RATE: 100 samples/symbol

# T/R acoustic receiver for stairwell experiment



# TR acoustic receiver implementation

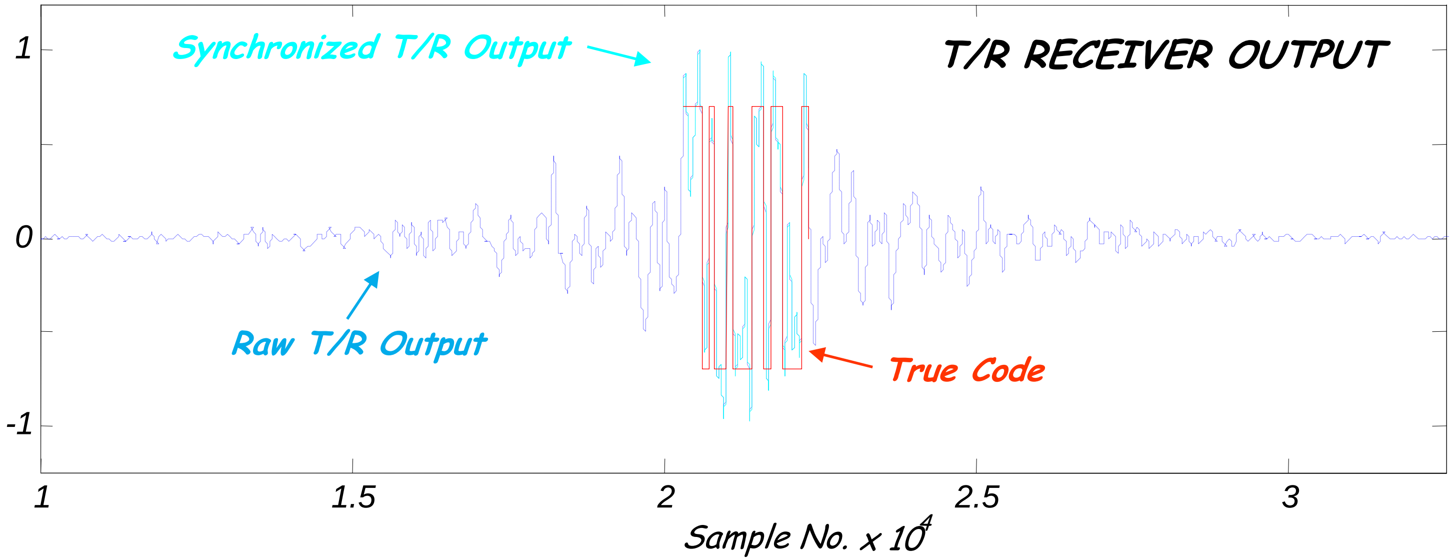


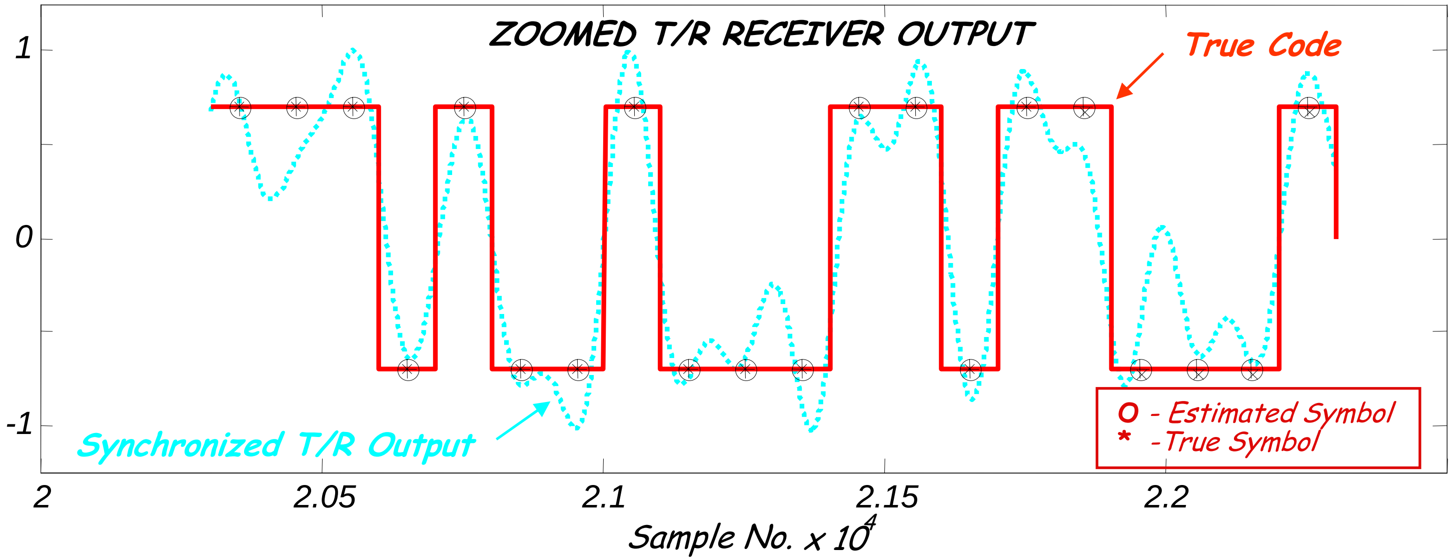



Choose threshold to convert analog to digital (quantize)

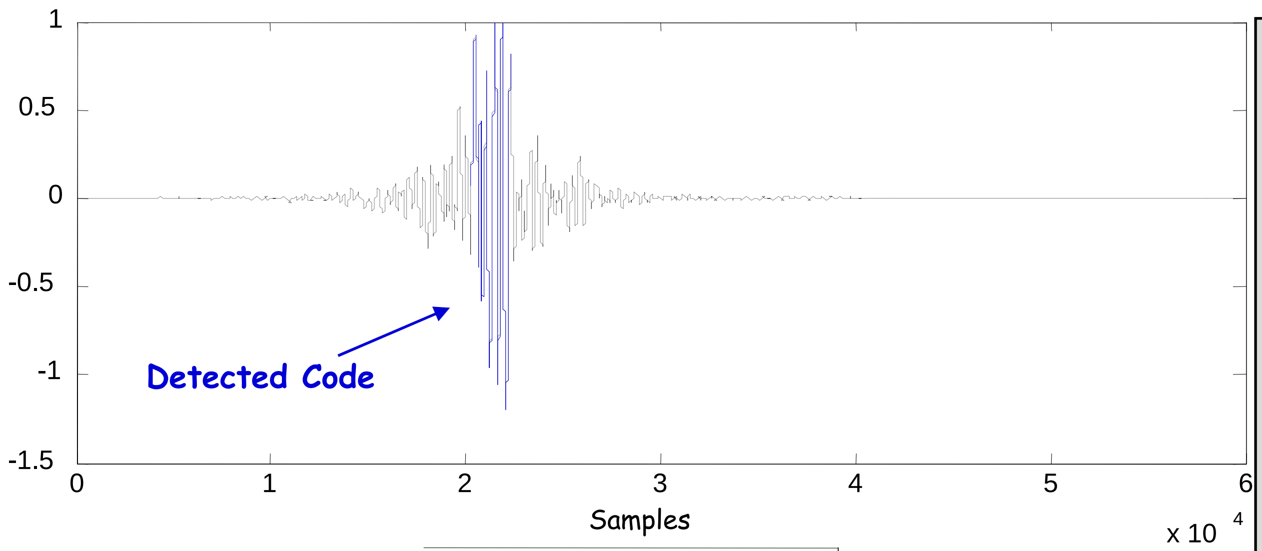
$$\hat{i}(t) = \begin{cases} 1, & s(t) \geq \tau \\ -1, & s(t) < \tau \end{cases}$$

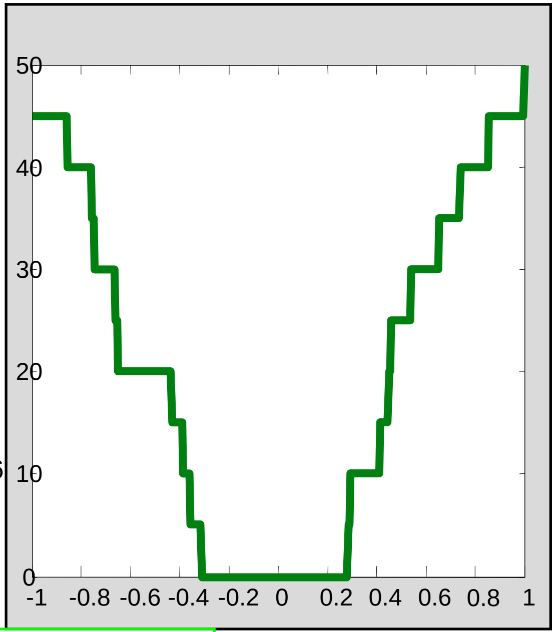
Receiver performance measured by range of thresholds that give zero symbol error

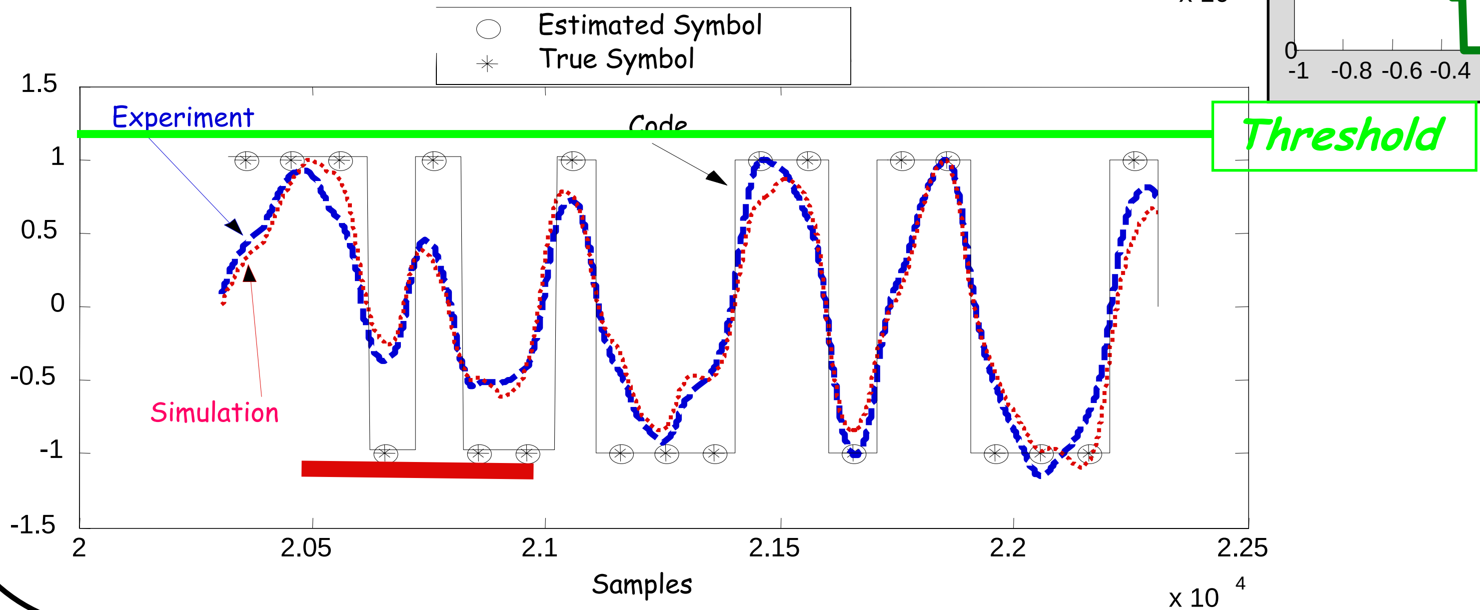

T/R RECEIVER OUTPUT
Synchronized T/R Output
Raw T/R Output
True Code
1
0
-1
1
1.5
2
2.5
3
Sample No. x 10^4


ZOOMED T/R RECEIVER OUTPUT
True Code
Synchronized T/R Output
O - Estimated Symbol
* - True Symbol
1
0
-1
2
2.05
2.1
2.15
2.2
Sample No. x 10^4

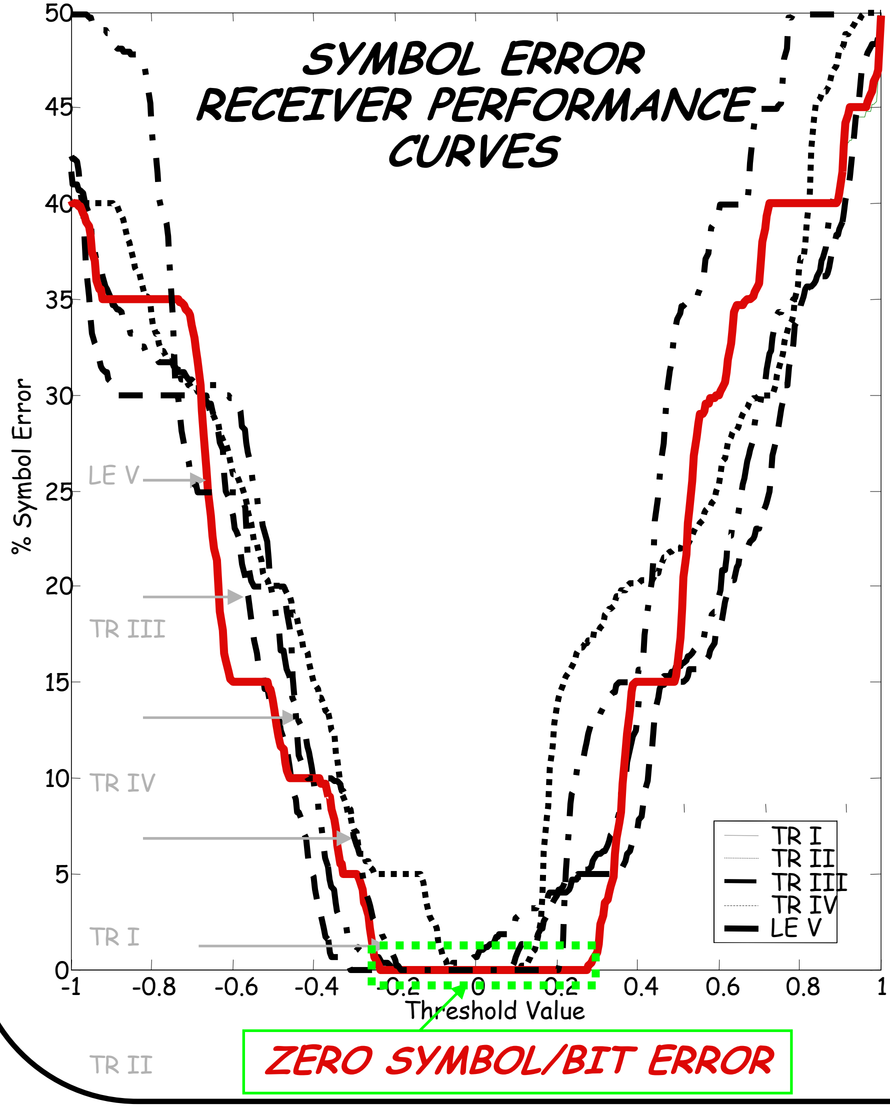
# Calculate symbol error as a function of threshold

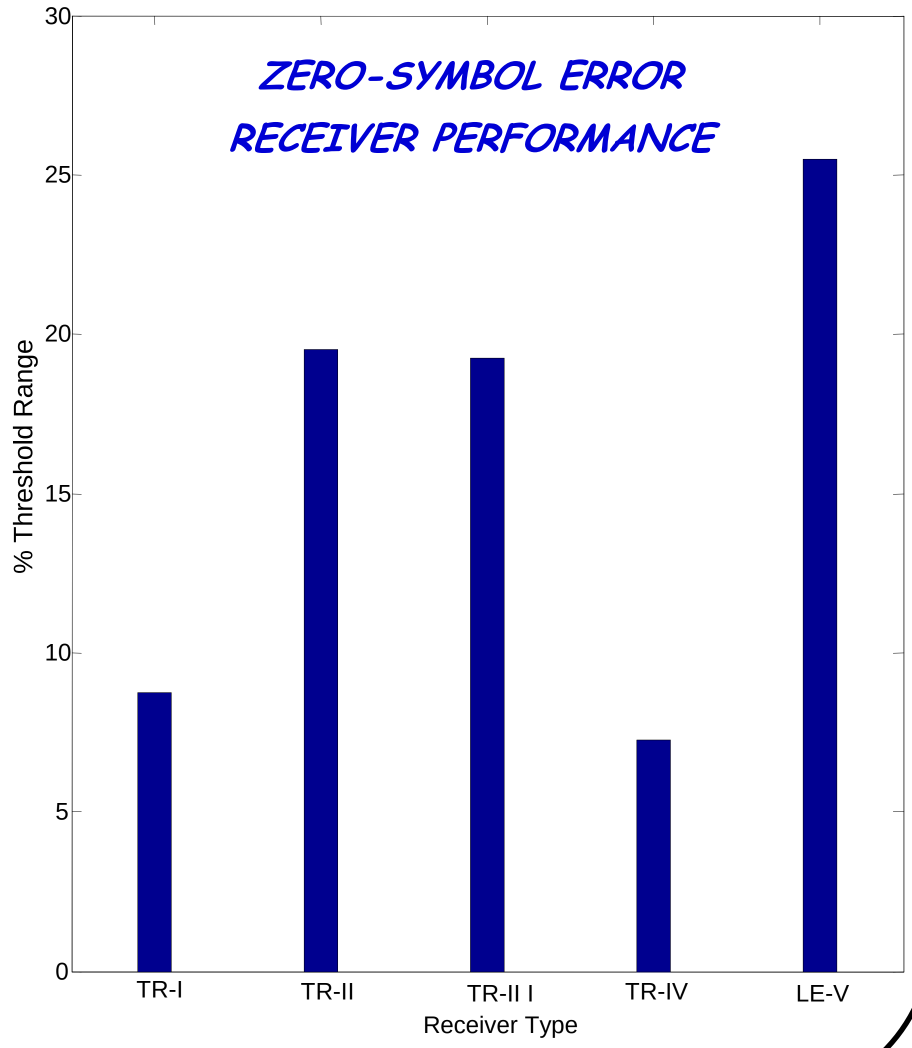


# TR acoustic receiver performance compares favorably with the optimal linear equalizer (inverse filter)



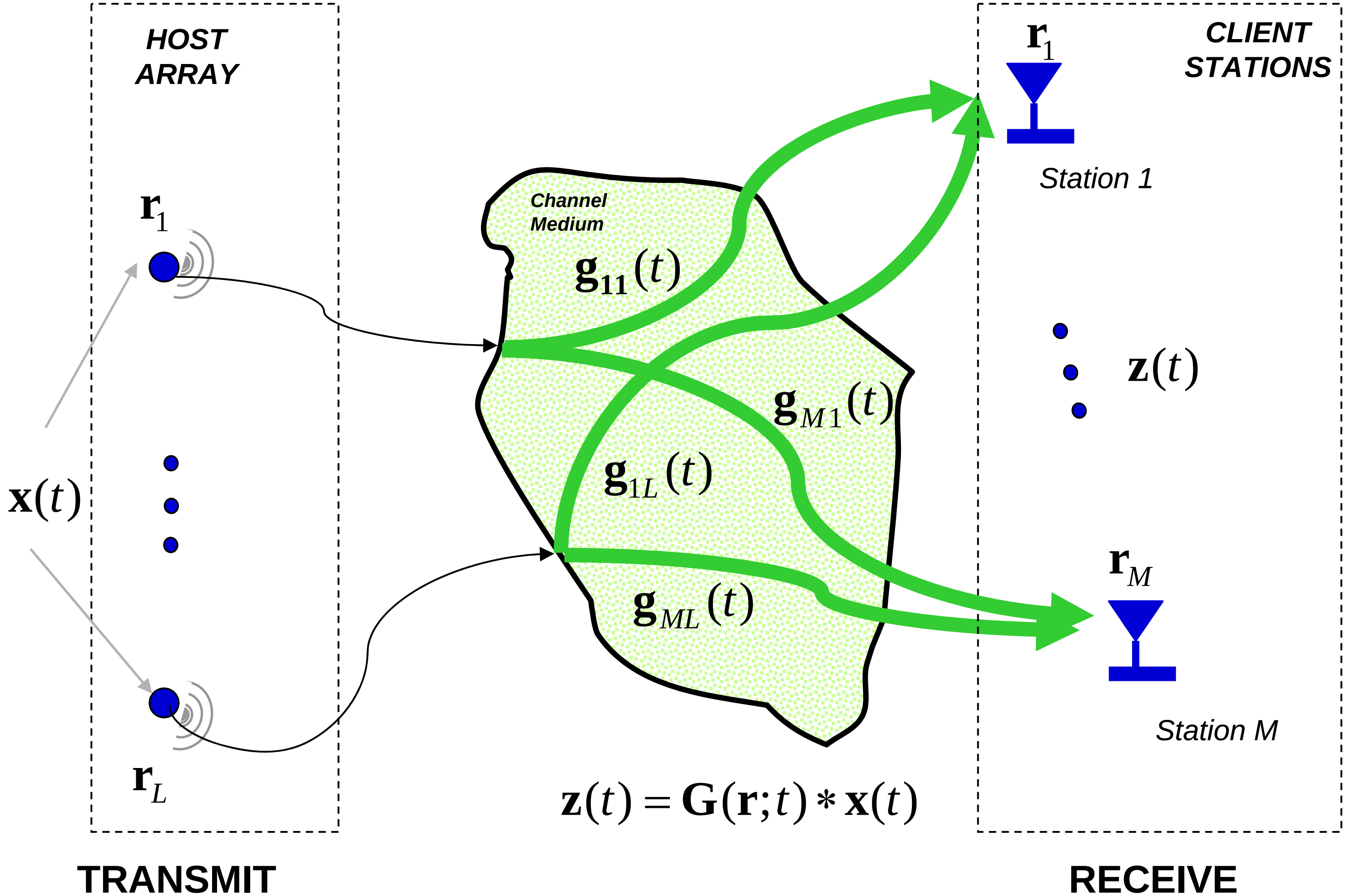



# Summary of P2P results:

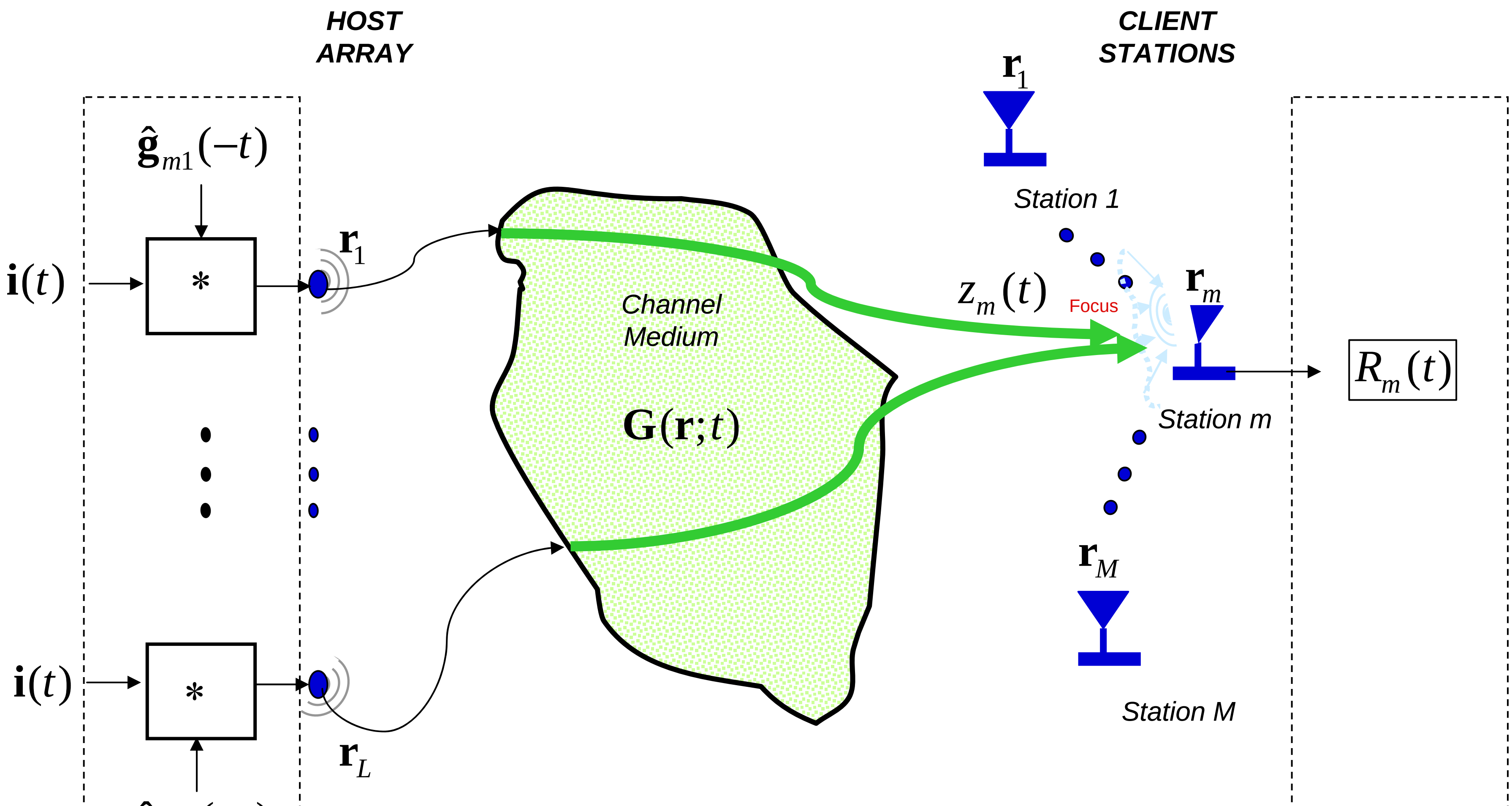
- We have discussed the idea of communications in a hostile environment using *time-reversal processing* with *multi-channel* (intelligent array) *signal processing*
- We have discussed the approach using theory and experiment to evaluate the performance of 4 TR receiver realizations
- We have evaluated receiver performance using a set of metrics based on symbol error. Performance compares favorably with more complex linear equalization (inverse filter).

# TIME-REVERSAL ARRAY-TO-ARRAY (A2A) RECEIVERS

**The medium (Green's function) provides UNIQUE paths (channels) from the host array to each client station---this is the key in TR communications**

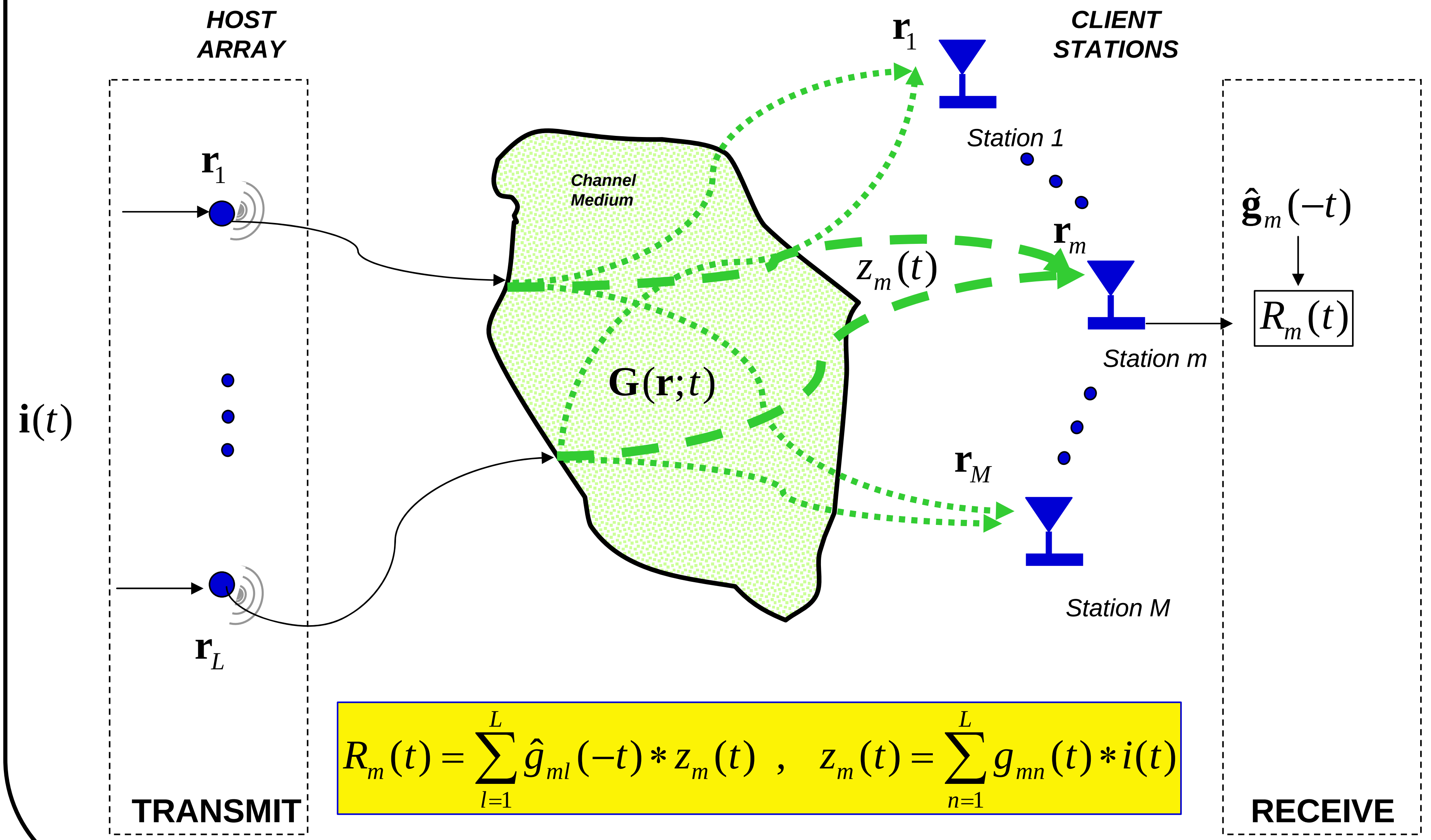


# TR Receiver I: G-function on Tx




$$z_m(t) = \sum_{l=1}^{L} g_{ml}(t) * x_l(t) = \left[ \sum_{l=1}^{L} g_{ml}(t) * \hat{g}_{ml}(-t) \right] * i(t)$$

# TR Receiver III: G-function on Rcv




$$R_m(t) = \sum_{l=1}^{L} \hat{g}_{ml}(-t) * z_m(t) \quad , \quad z_m(t) = \sum_{n=1}^{L} g_{mn}(t) * i(t)$$

# ANALYSIS of TR Receiver Operation

*TR Receiver I: focus at receiver m, calculate response at receiver k*

$$z_k(t) = \left[\sum_{l=1}^{L} g_{kl}(t) * \hat{g}_{ml}(-t)\right] * i(t) = \left[\sum_{l=1}^{L} \hat{C}_{ll}^{km}(t)\right] * i(t) \approx L\delta_{km} i(t)$$

$$\hat{C}_{nl}^{km}(t) \equiv g_{kn}(t) * \hat{g}_{ml}(-t) \approx \delta_{km}\delta_{nl}\delta(t)$$ *(for high multipath)*

*TR Receiver III:*

$$R_m(t) = \sum_{l=1}^{L} \hat{g}_{ml}(-t) * z_m(t) = \left[\sum_{l=1}^{L}\sum_{n=1}^{L} \hat{g}_{ml}(-t) * g_{mn}(t)\right] * i(t) = \left[\sum_{l=1}^{L}\sum_{n=1}^{L} \hat{C}_{nl}^{km}(t)\right] * i(t)$$

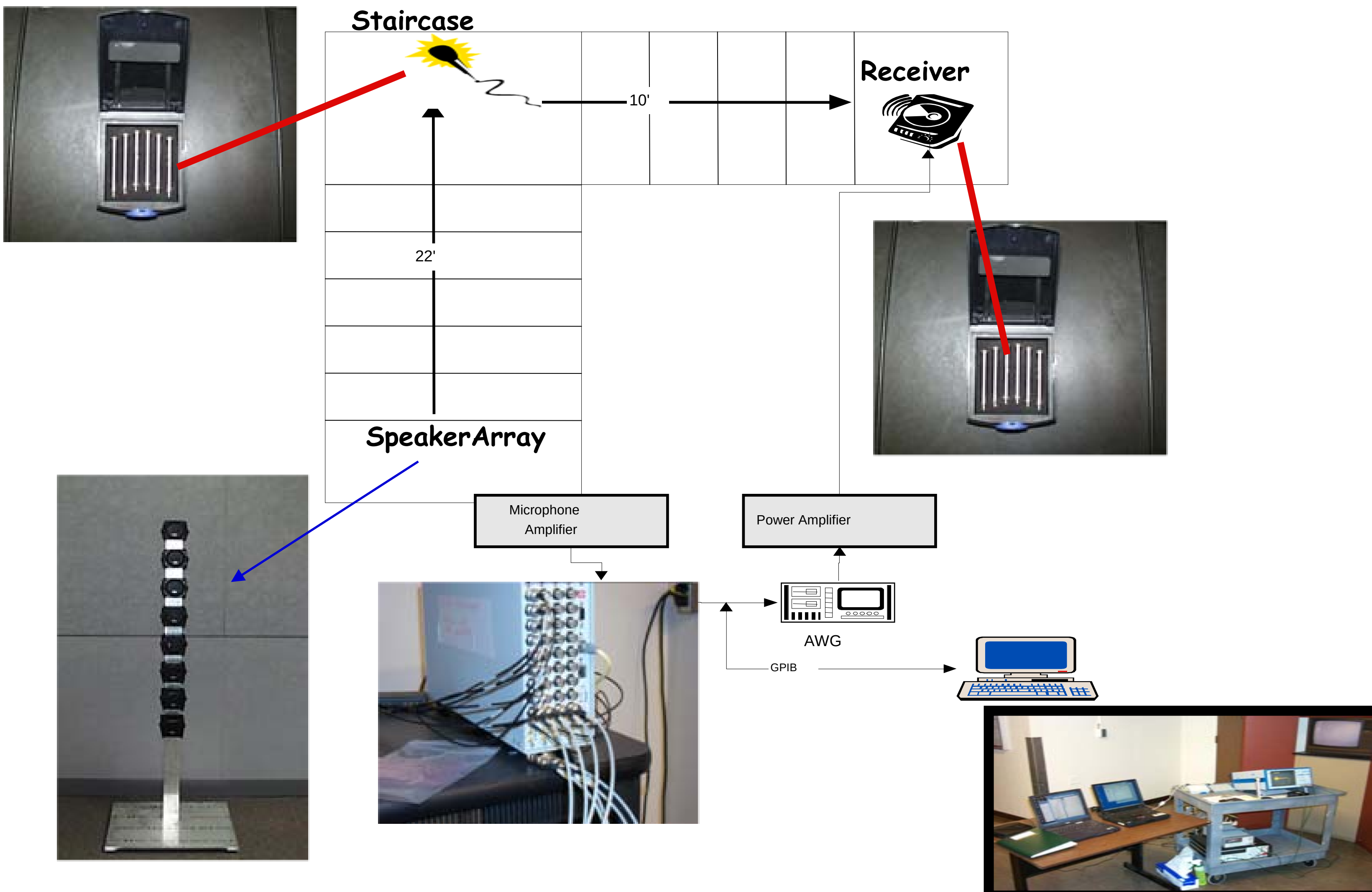
$$= \left[\sum_{l=1}^{L} \hat{C}_{ll}^{mm}(t)\right] * i(t) + \left[\sum_{\substack{l,n=1 \\ l \neq n}}^{L} \hat{C}_{nl}^{mm}(t)\right] * i(t)$$

$$\approx L\ \ i(t) + \text{"noise"}$$

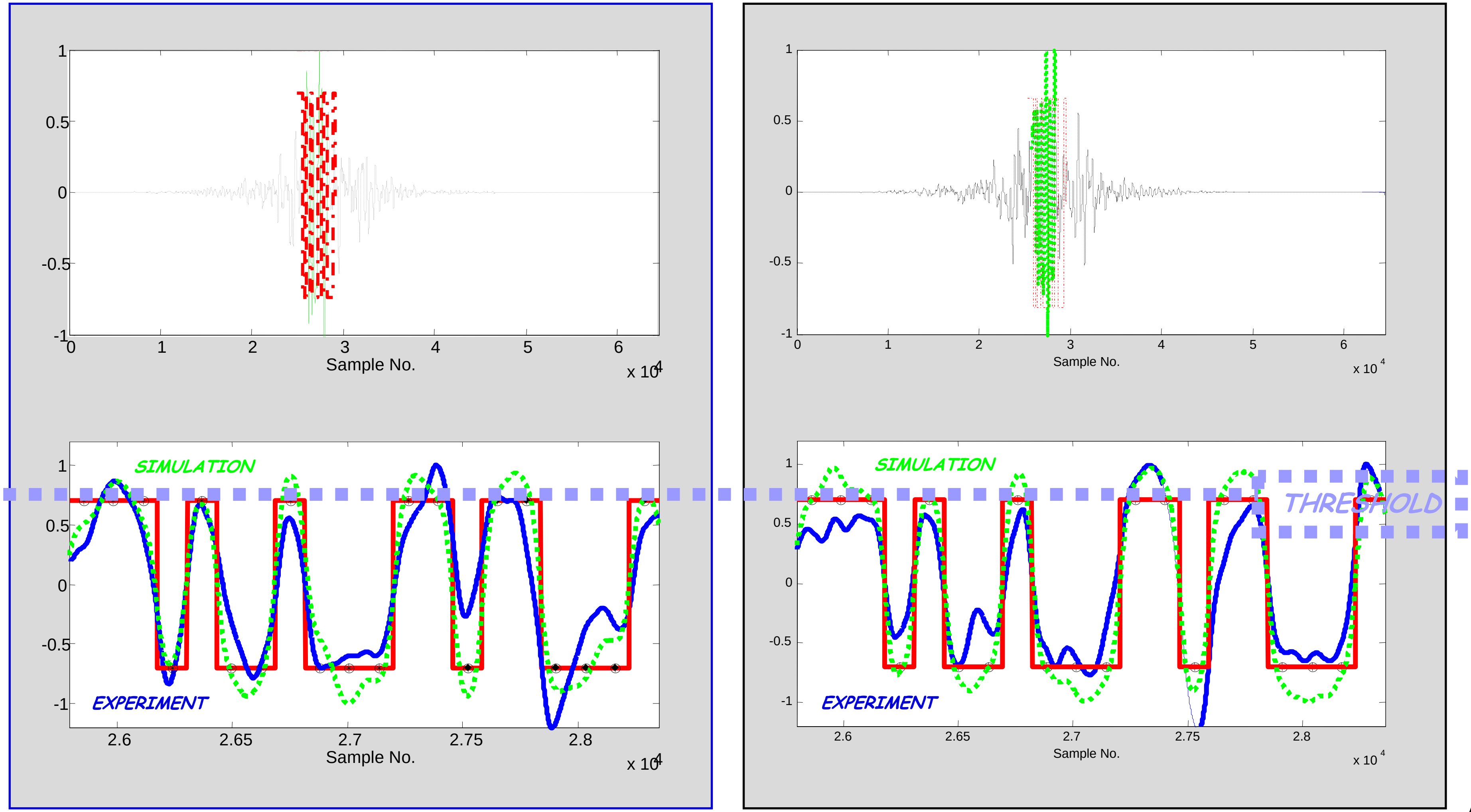
*(TR I result)*

***Outputs of active (I) and passive (III) receivers are not equivalent***

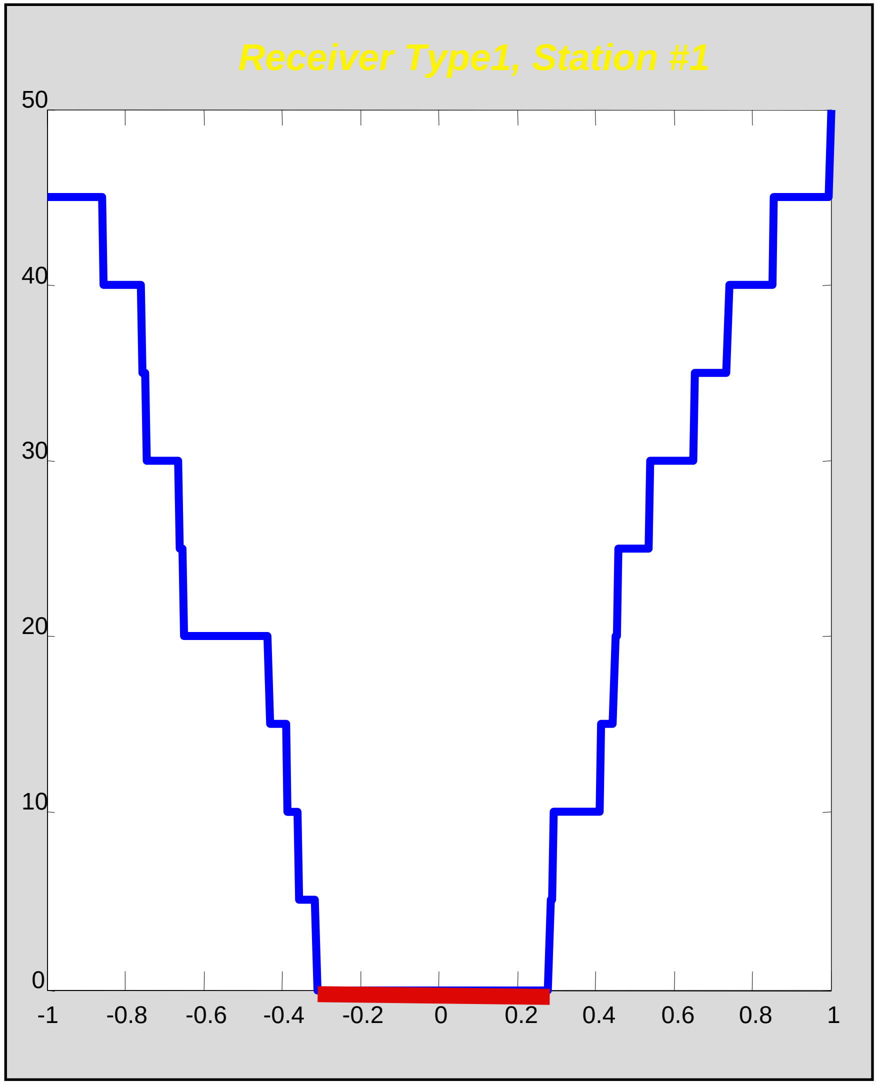
**We developed A2P ACOUSTICS experiment in a hostile, highly reverberant free space environment to evaluate the T/R receiver:**

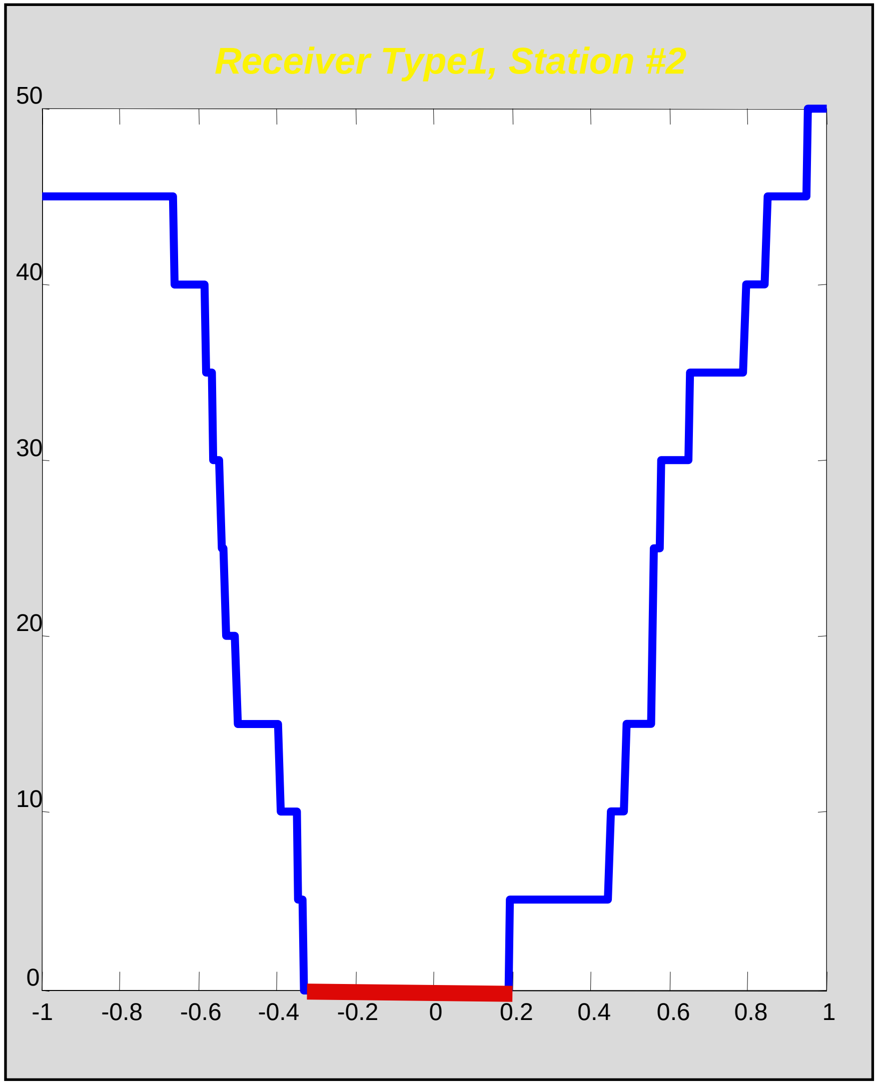


# TR RECEIVER I: Focuses on Each Client

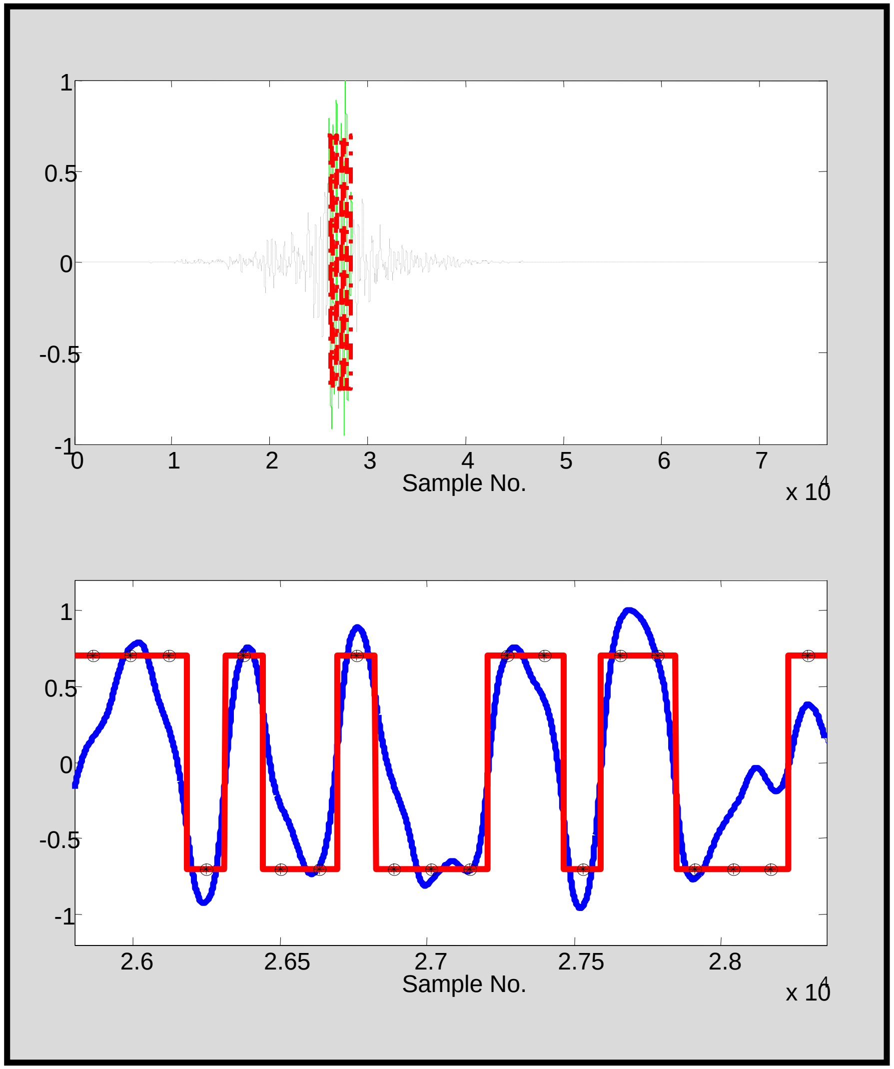


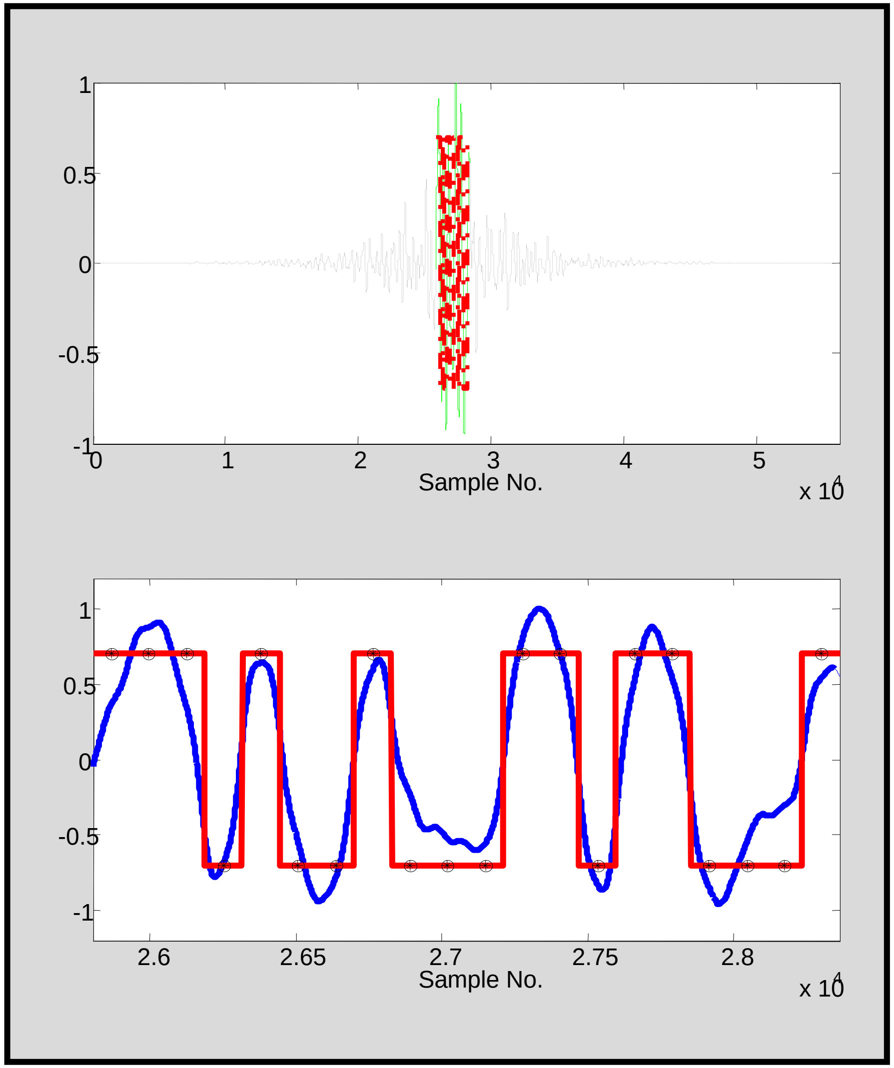
# TR Receiver I: Performance



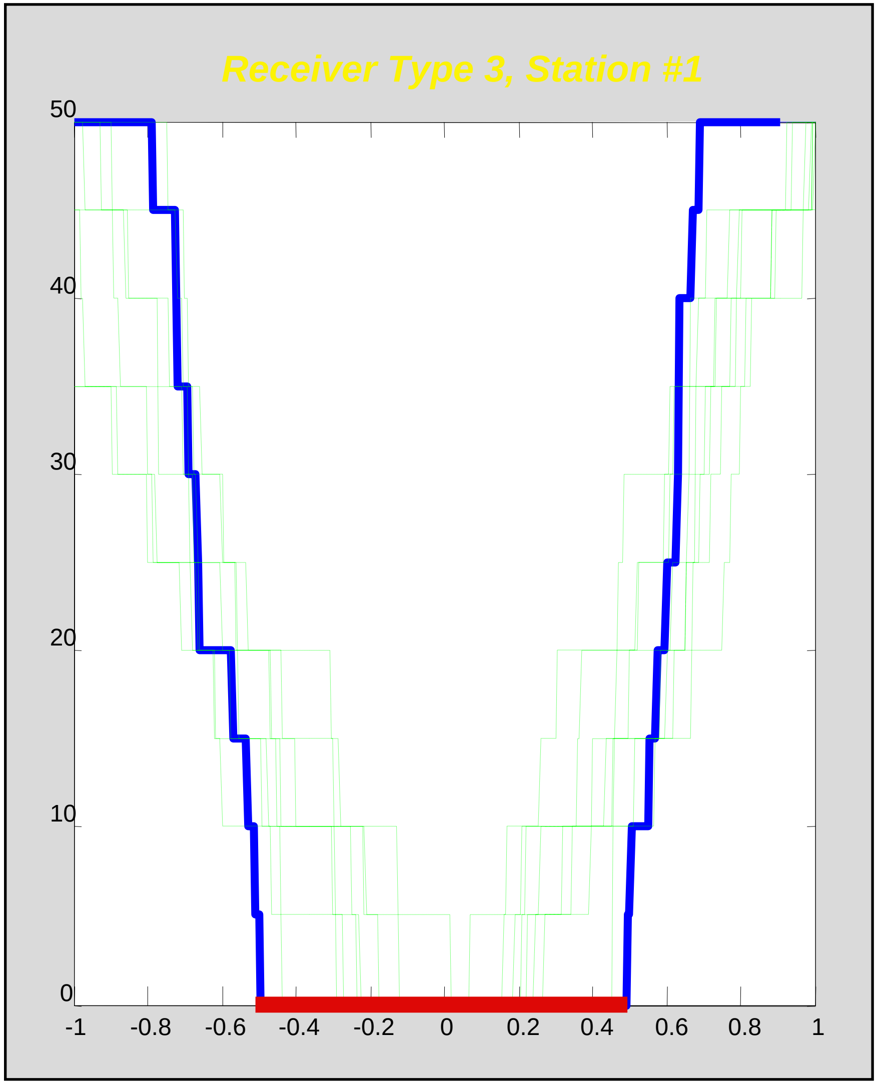



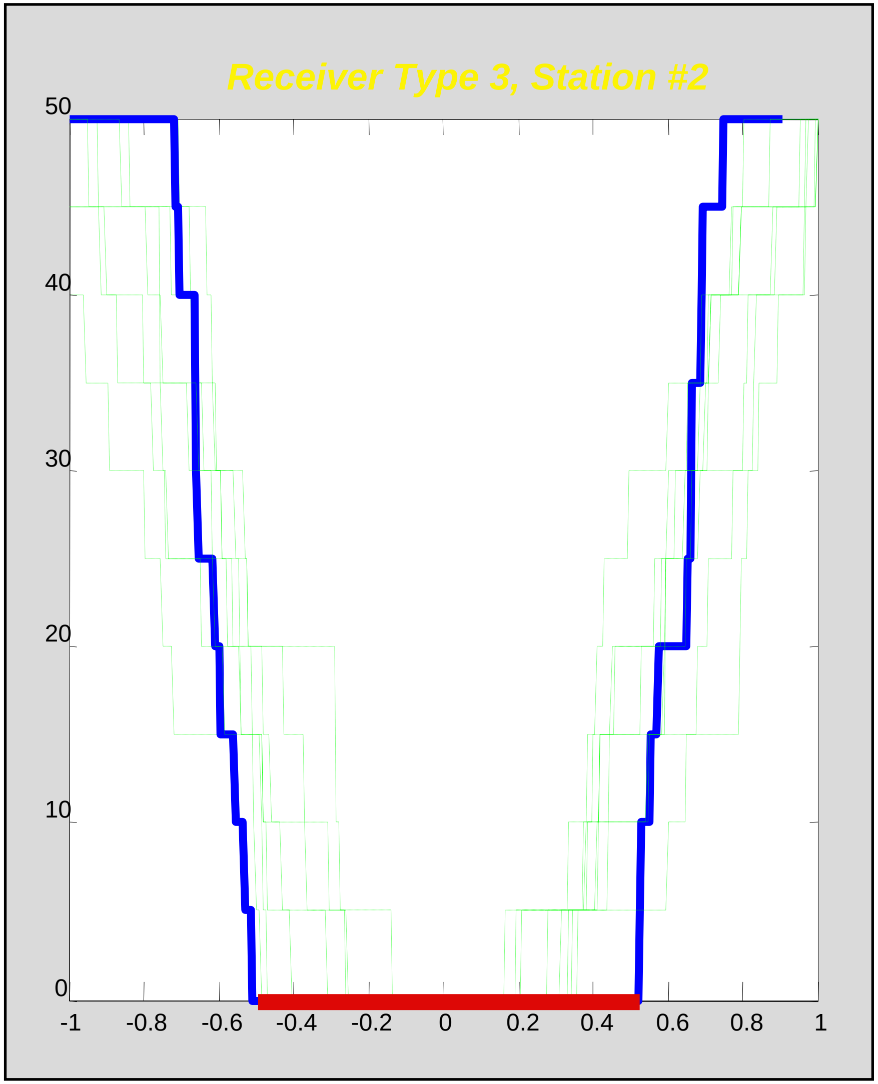
# TR RECEIVER III: Focus on Client Receiver



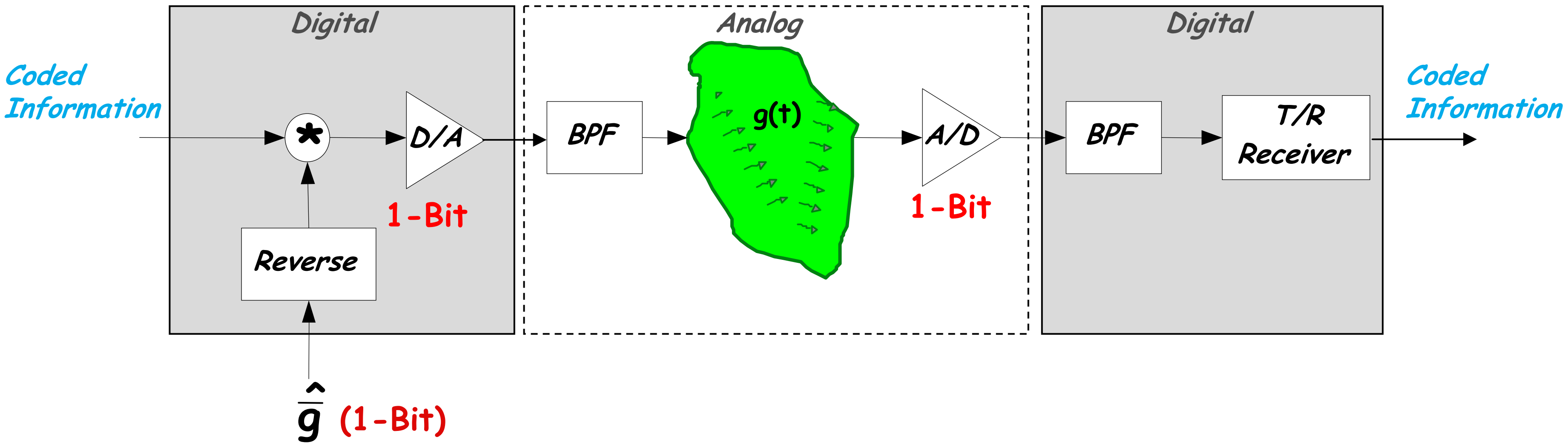



# TR Receiver III: Performance

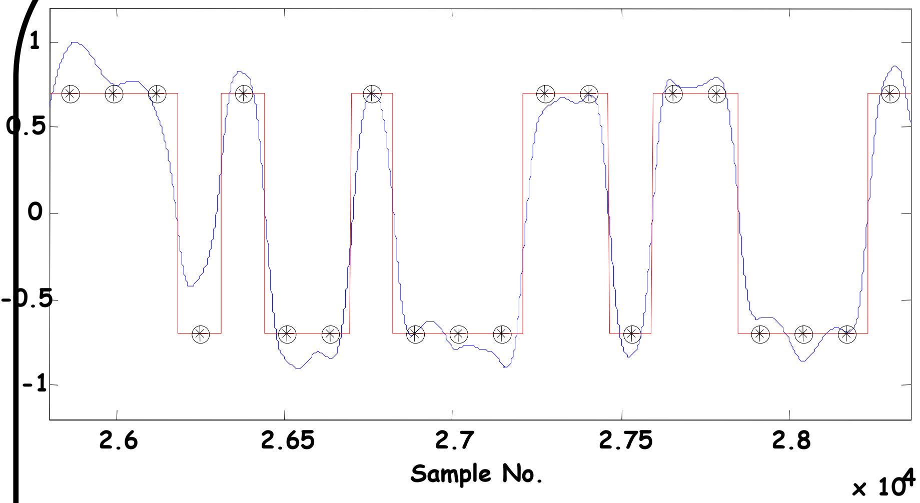


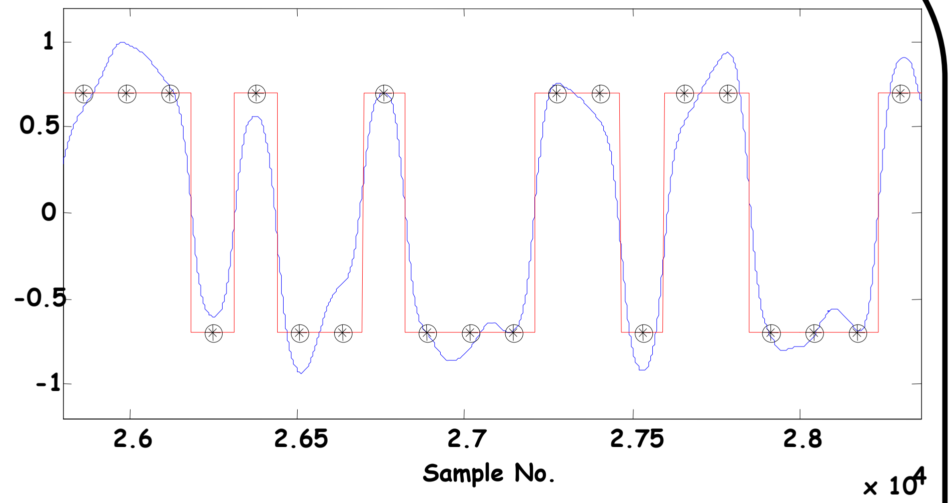
# TR I realization in a 1-bit implementation



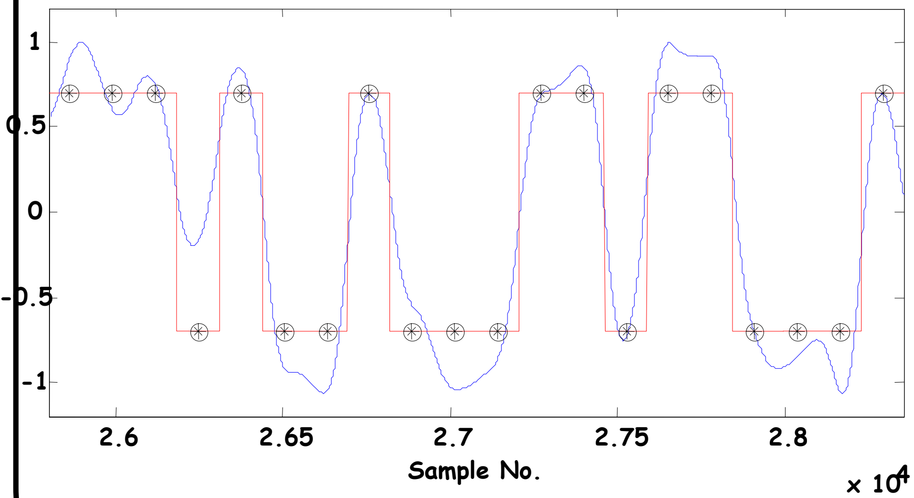
## TR I: Client One (24-BIT)



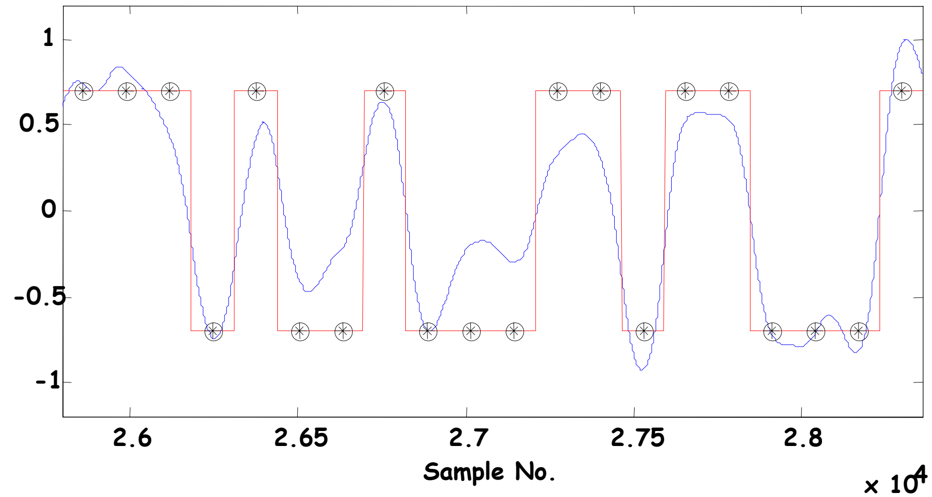

## TR I: Client Two (24-BIT)




## TR I: Client One (1-BIT)

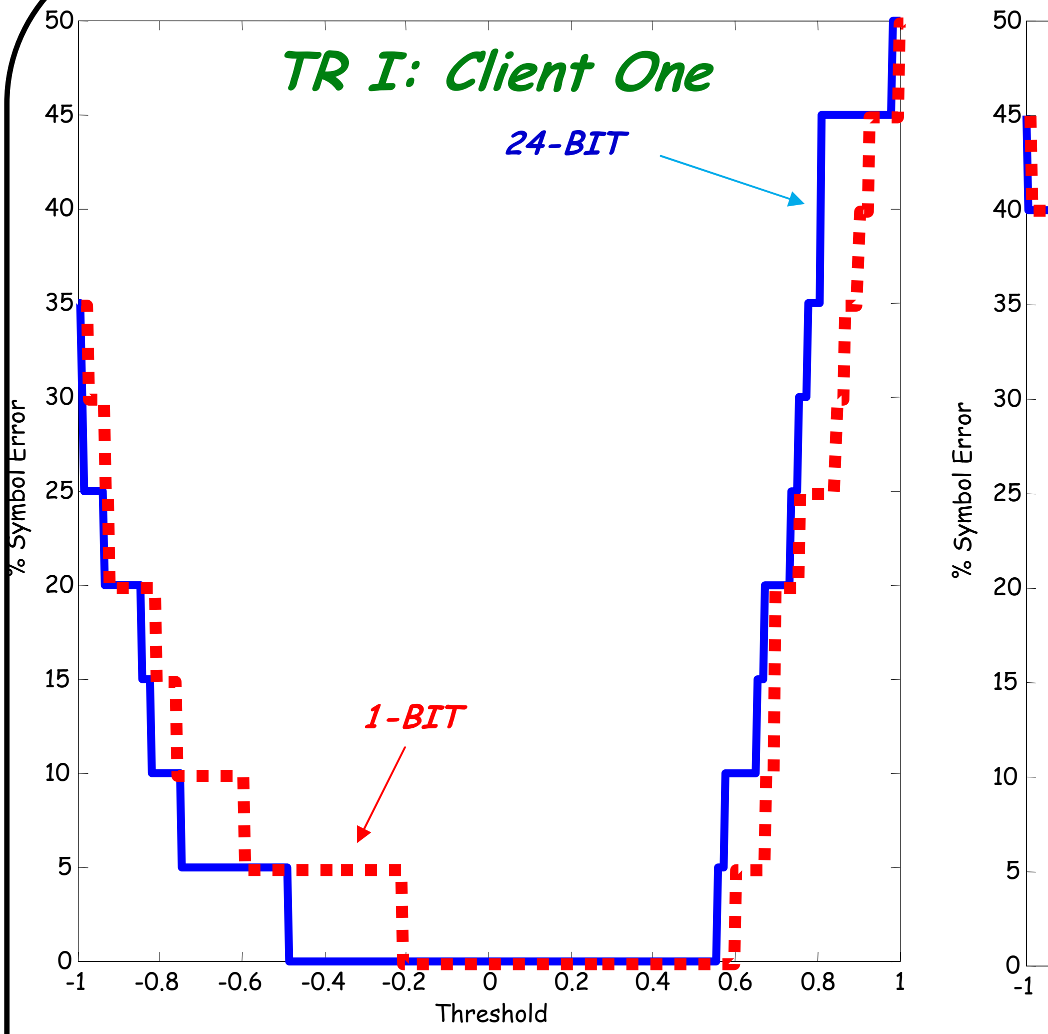



## TR I: Client Two (1-BIT)

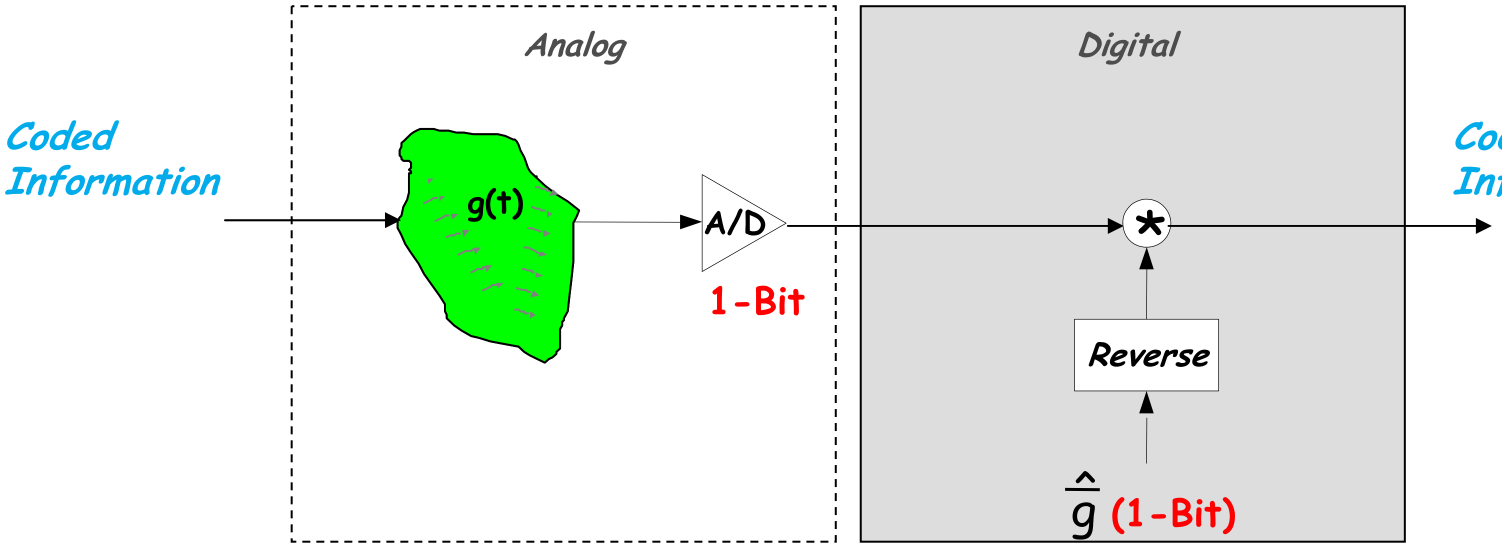


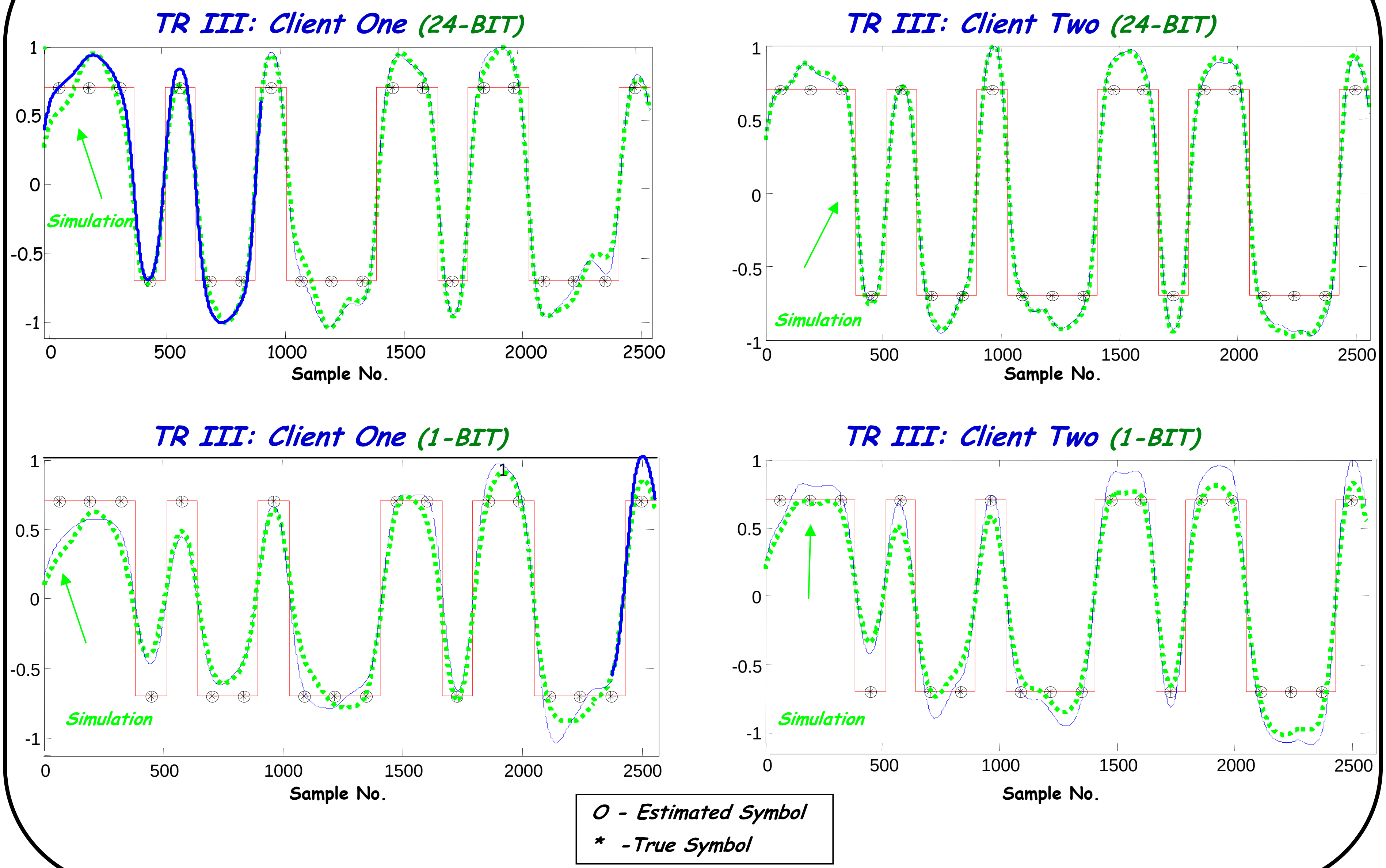

*O - Estimated Symbol*

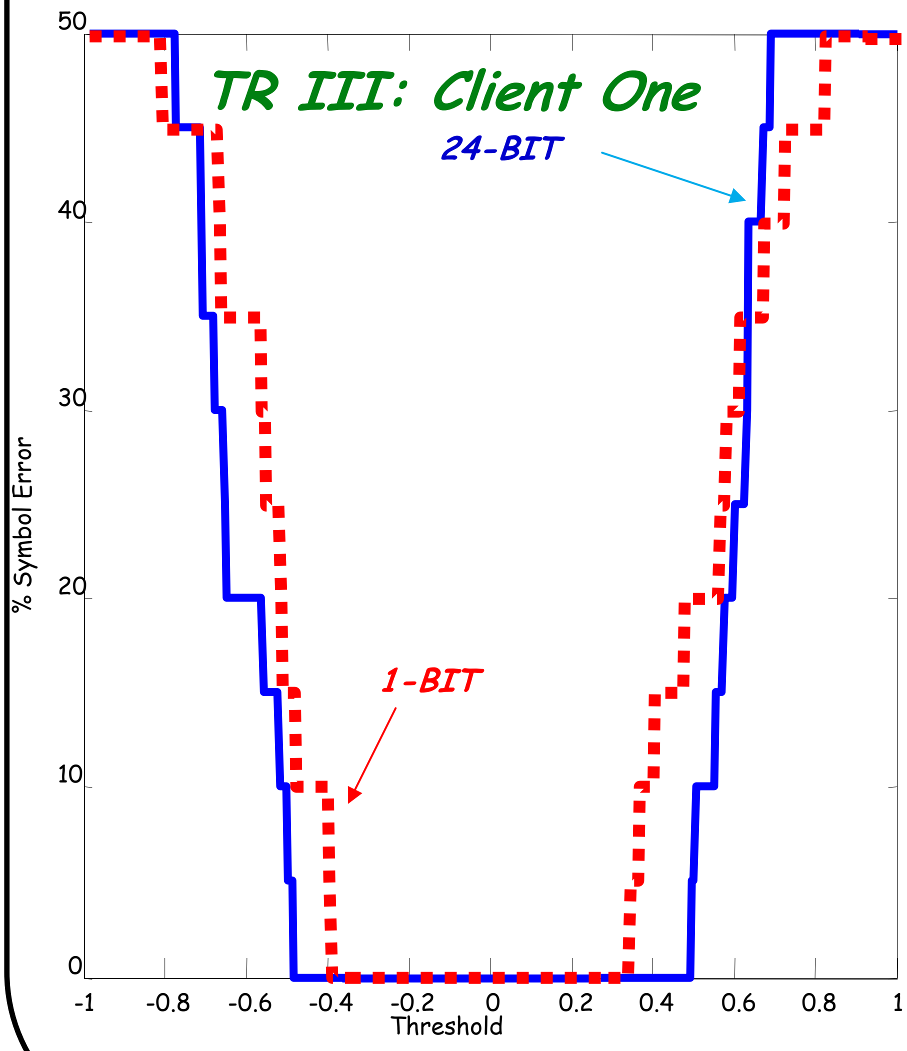
** -True Symbol*


TR I: Client One
24-BIT
1-BIT
% Symbol Error
Threshold
TR I: Client Two
1-BIT
24-BIT
% Symbol Error
Threshold

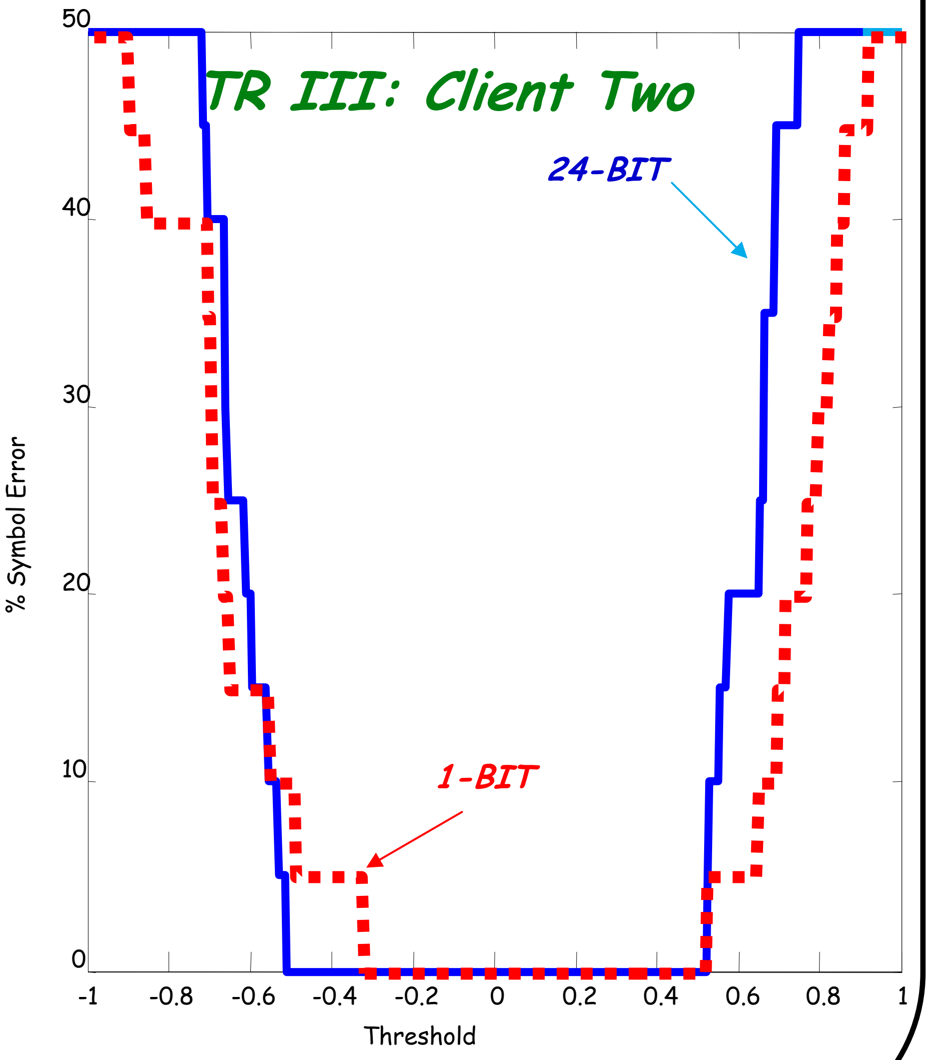
# TR III realization in a 1-bit implementation




TR III: Client One (24-BIT)
TR III: Client Two (24-BIT)
TR III: Client One (1-BIT)
TR III: Client Two (1-BIT)
Simulation
Sample No.
1
0.5
0
-0.5
-1
0
500
1000
1500
2000
2500
O - Estimated Symbol
* -True Symbol



TR III: Client One
24-BIT
1-BIT
% Symbol Error
Threshold

TR III: Client Two
24-BIT
1-BIT
% Symbol Error
Threshold

# Proof-of-principle experiments have shown great results!

- 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 array-to-point (A2P) communications the concept of a time-reversal (T/R) receiver is capable of operating successfully in a highly reverberative environment

# Summary for A2A realizations:

- We have generalized the idea of P2P TR communications to an A2A configuration.
- We have discussed the approach using theory, simulation, and experiment to evaluate the performance of T/R receiver realizations
- We have shown improved performance using a host array over the P2P results.
- We have shown a “1-bit” realization of a TR receiver.

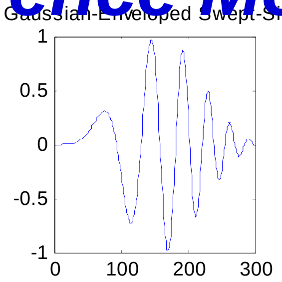
# WIDEBAND TIME-REVERSAL RECEIVERS

## *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 "time-reference" (XR) synchronization and modulation/demodulation scheme (2 pulses/bit; polarity check)**
- **performed experiments in the tunnel-like (cave) of B194 demonstrating the capability**

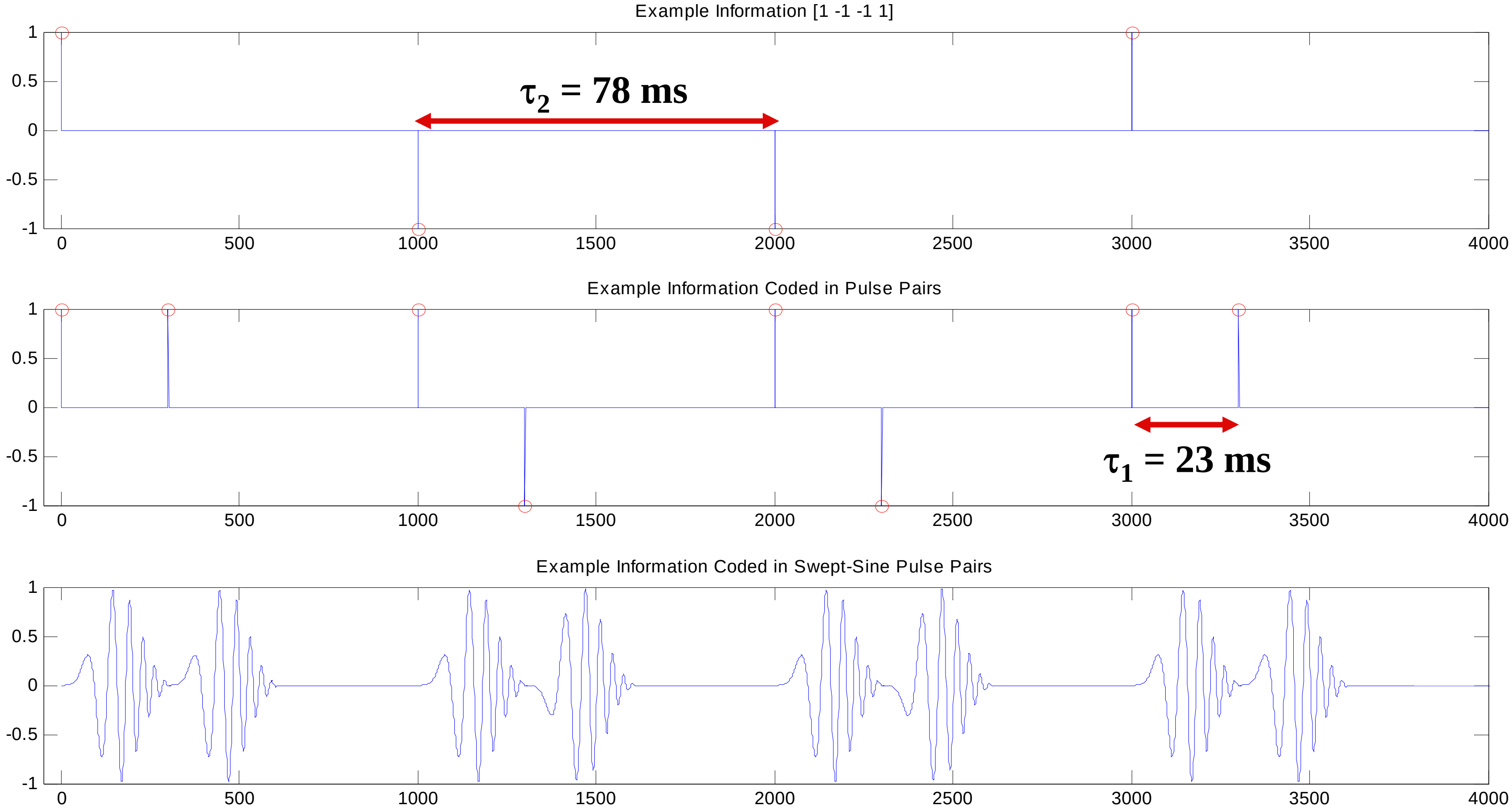
# Time Reference Modulation



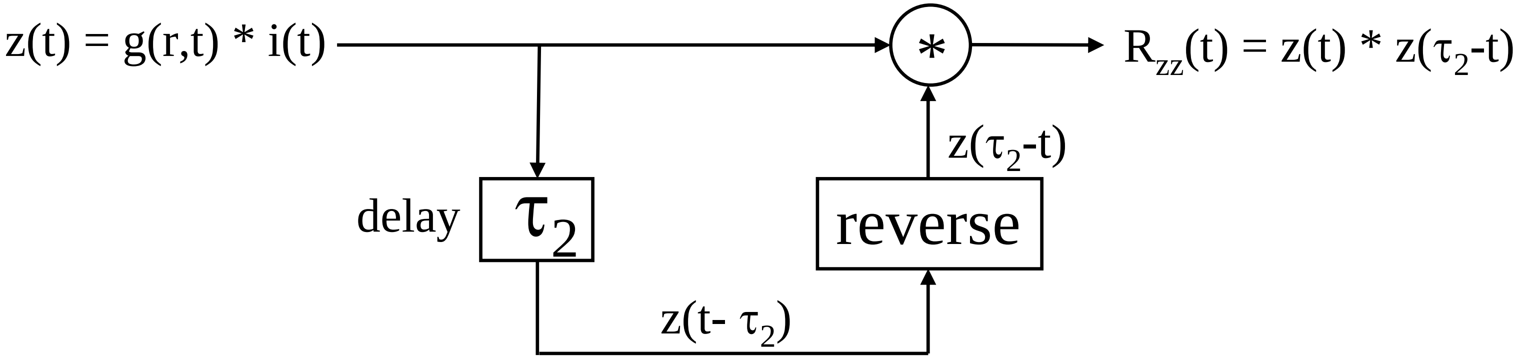

**Gaussian windowed swept sine**

**600-1800 Hz**

**(sampling frequency 12.8 kHz)**



# *Time Reference Demodulation*




$R_{zz}(t) = [g(r,t) * i(t)] * [\, g(r, \tau_2\text{-}t) * i(\tau_2\text{-}t)]$

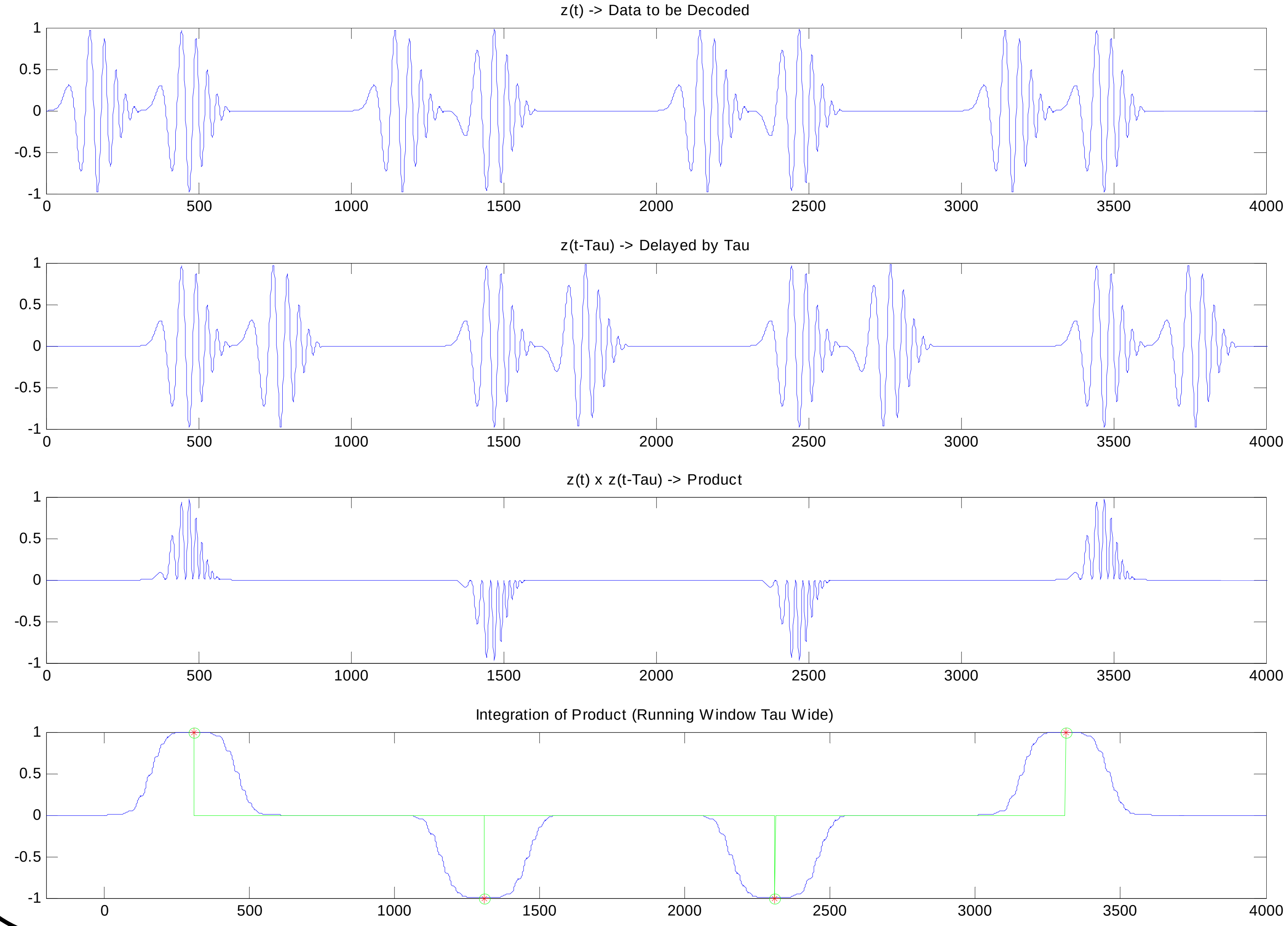
$R_{zz}(t) = [g(r,t) * g(r, \tau_2\text{-}t)] * [i(r,t) * i(\tau_2\text{-}t)]$

$R_{zz}(t) = R_{gg}(\tau_2 - t) * R_{ii}(\tau_2 - t)$

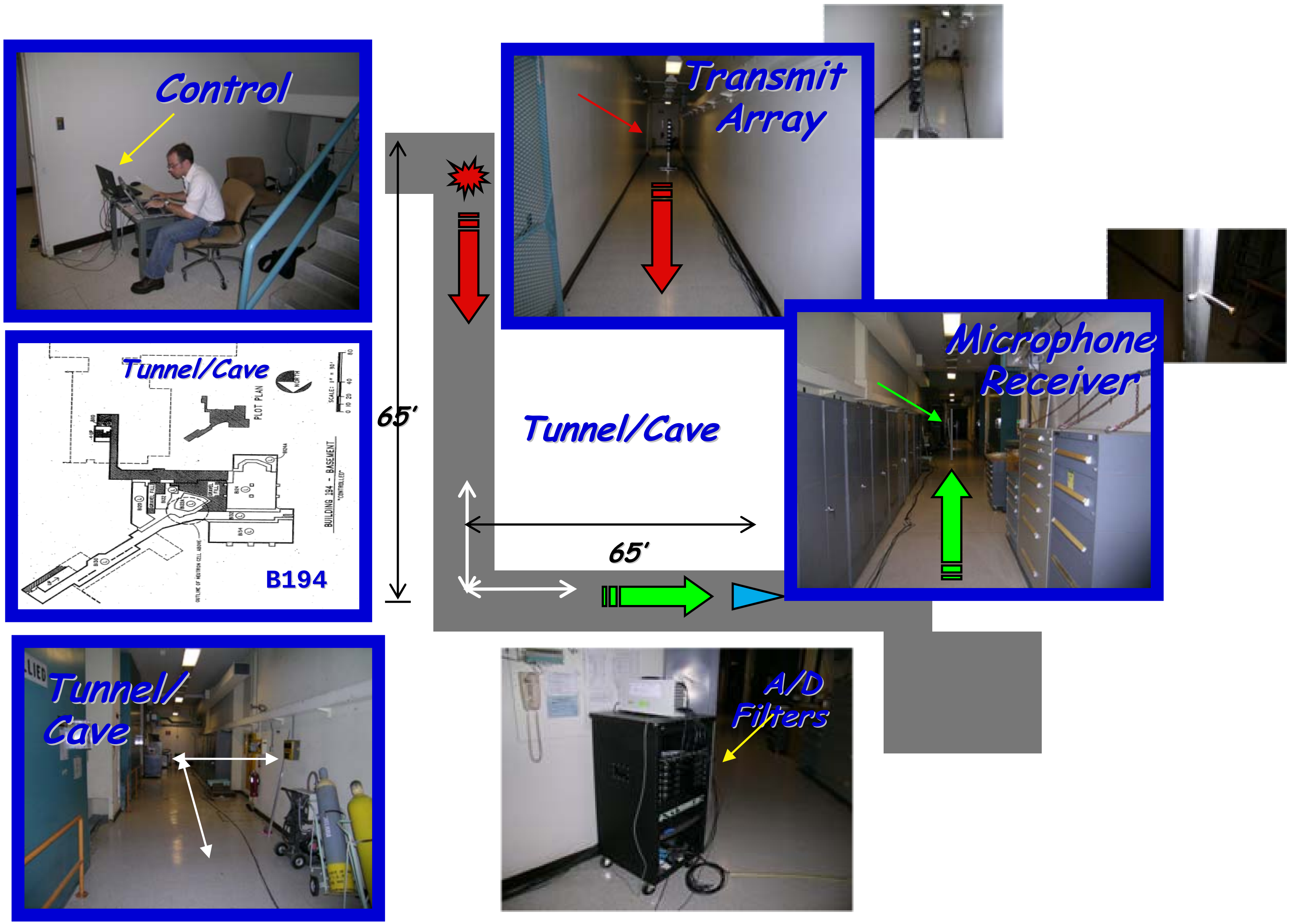
$\therefore$ $R_{zz}$ a maximum at $t = \tau_2$

 *Lawrence Livermore National Laboratory*

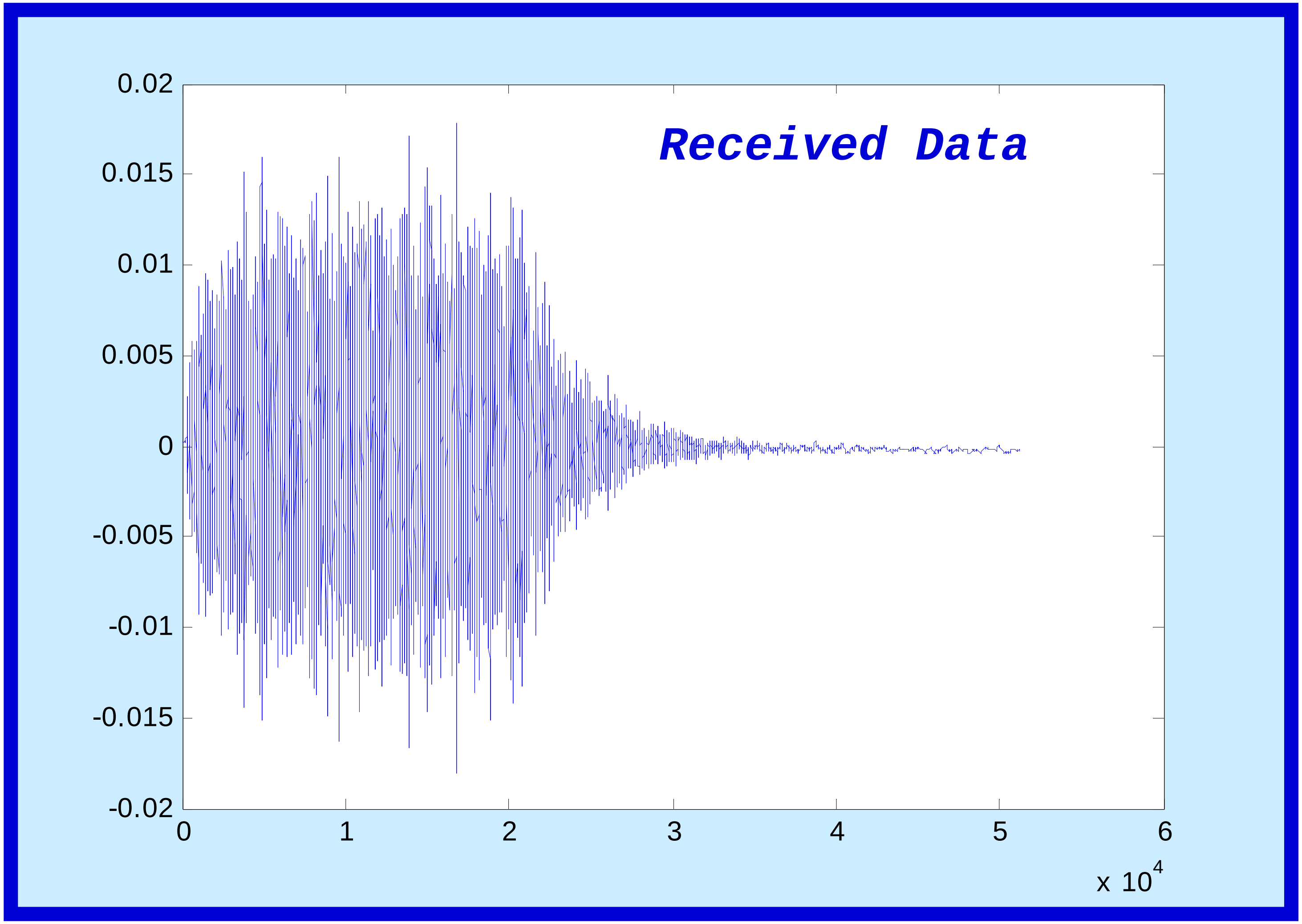
# Time Reference Demodulation



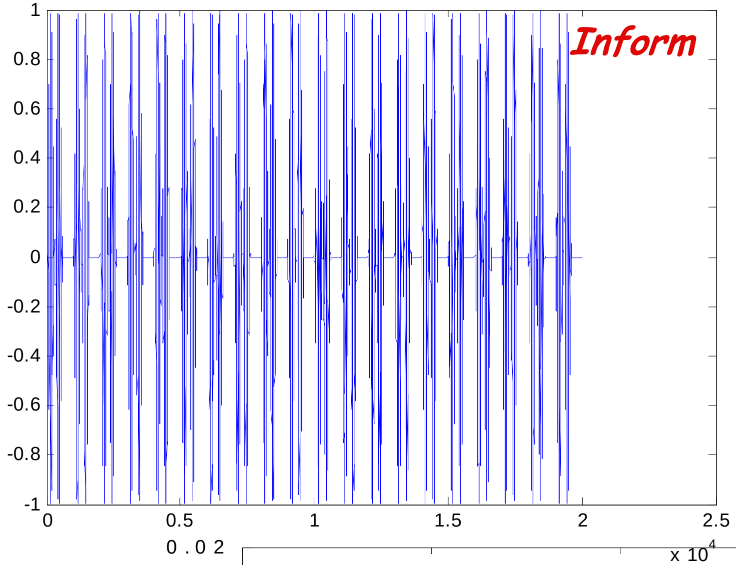
# We performed experiments in a hostile tunnel/cave environment

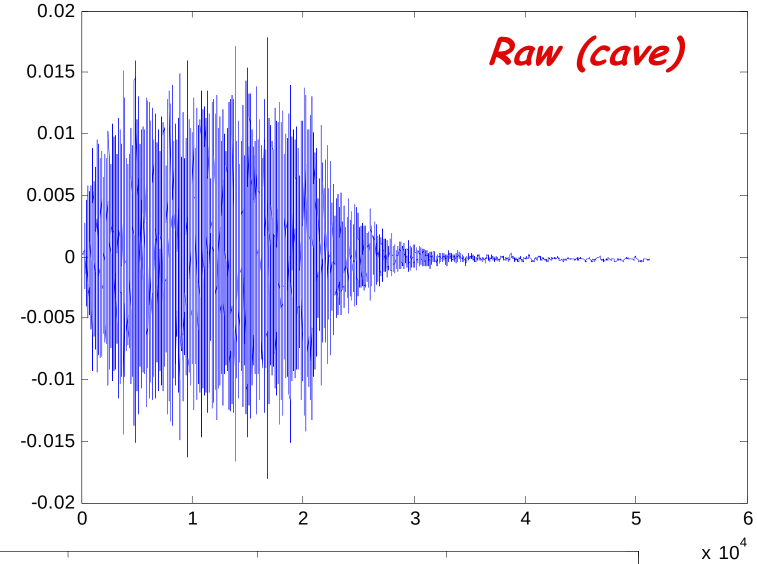


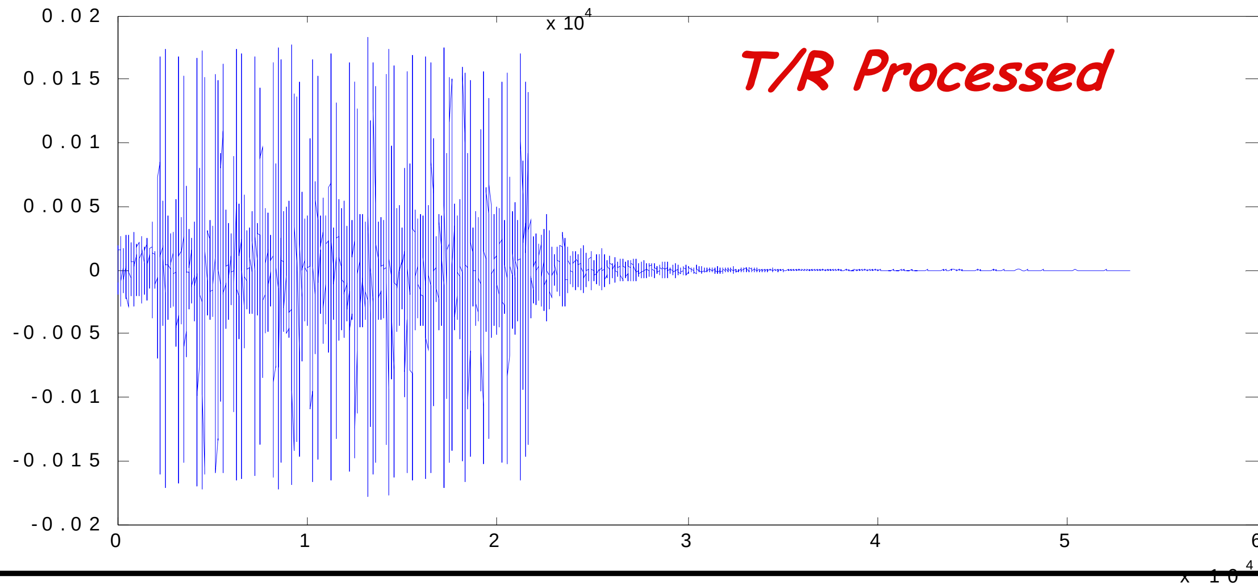
**The raw transmitter-reference (XR) information is broadcast in the highly reverberant tunnel-like environment**



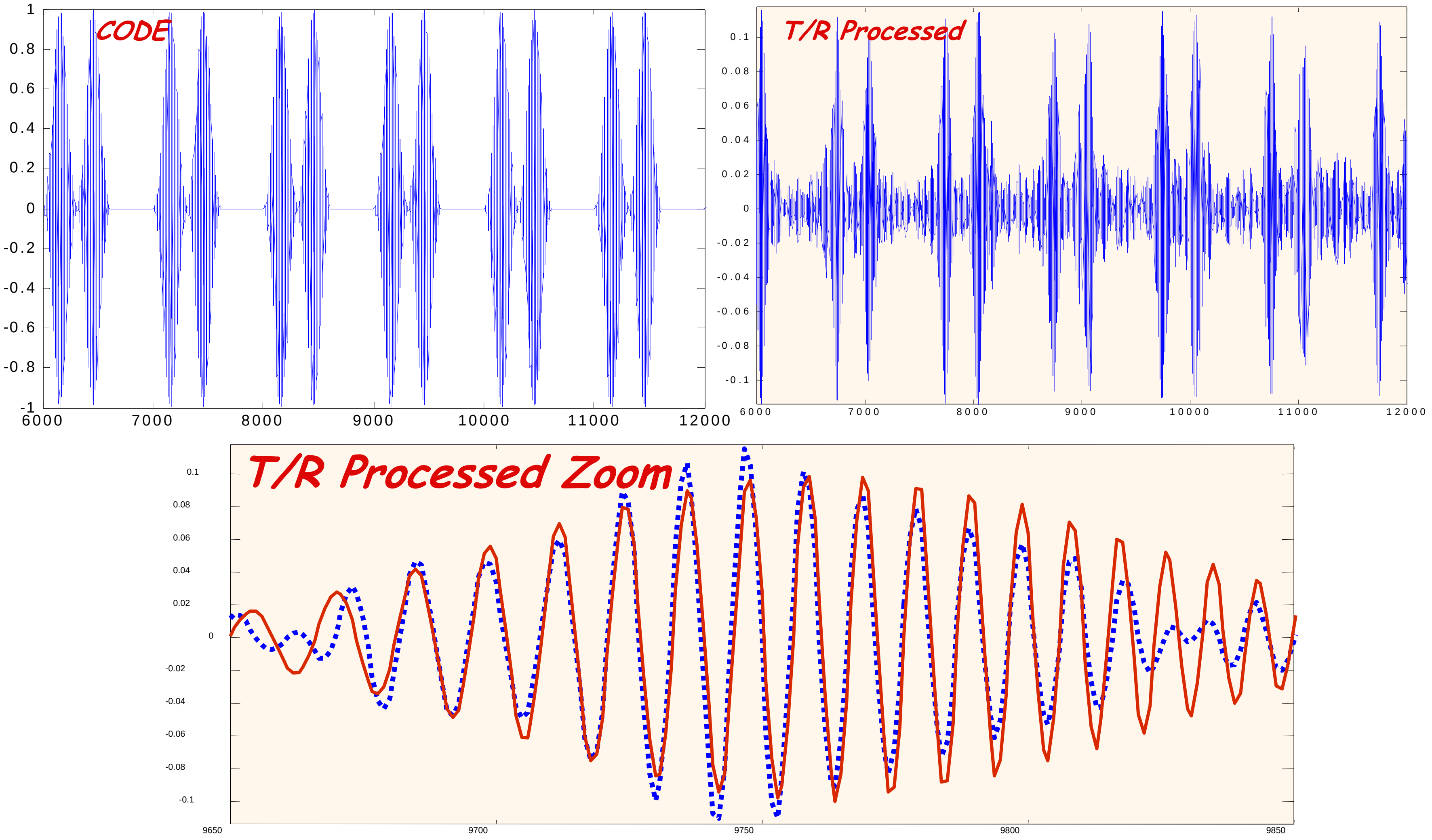
# Compare the original information signal with the T/R received Type III signal



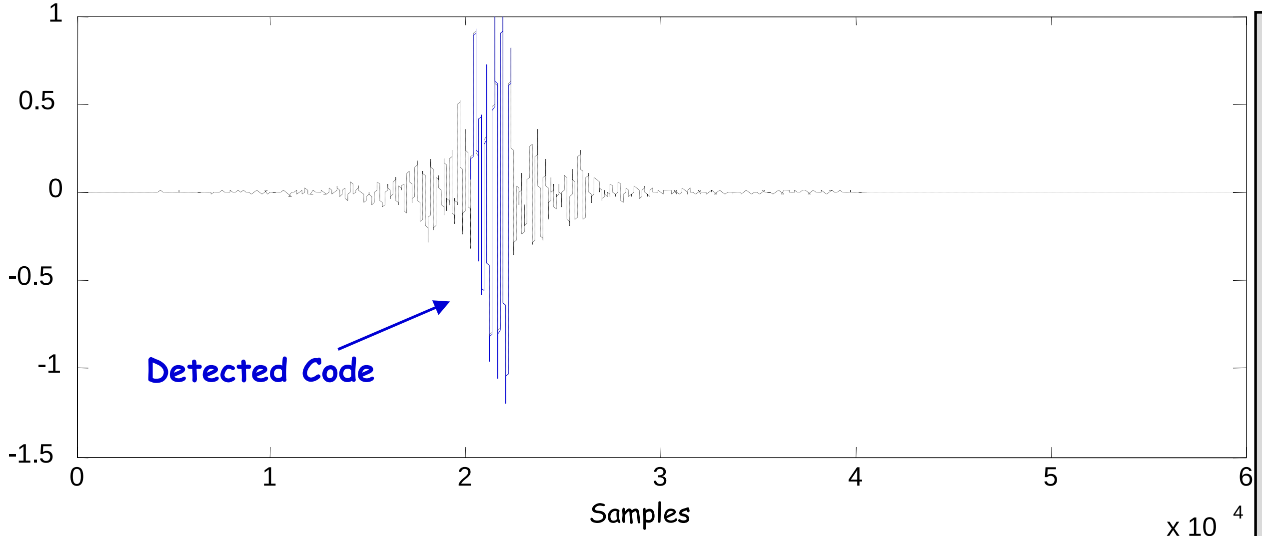



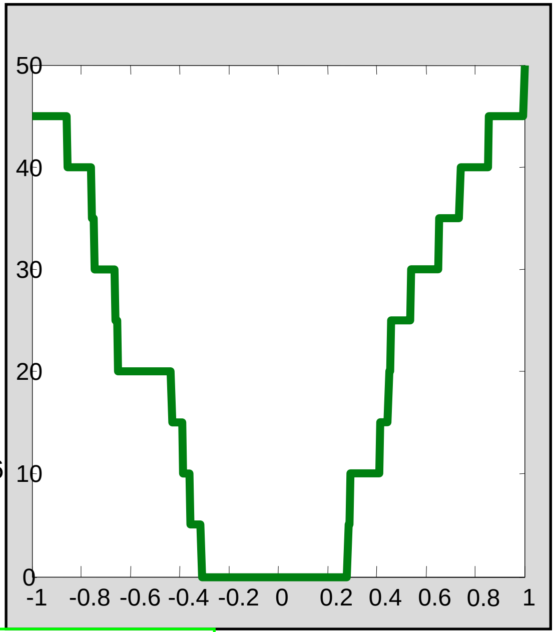



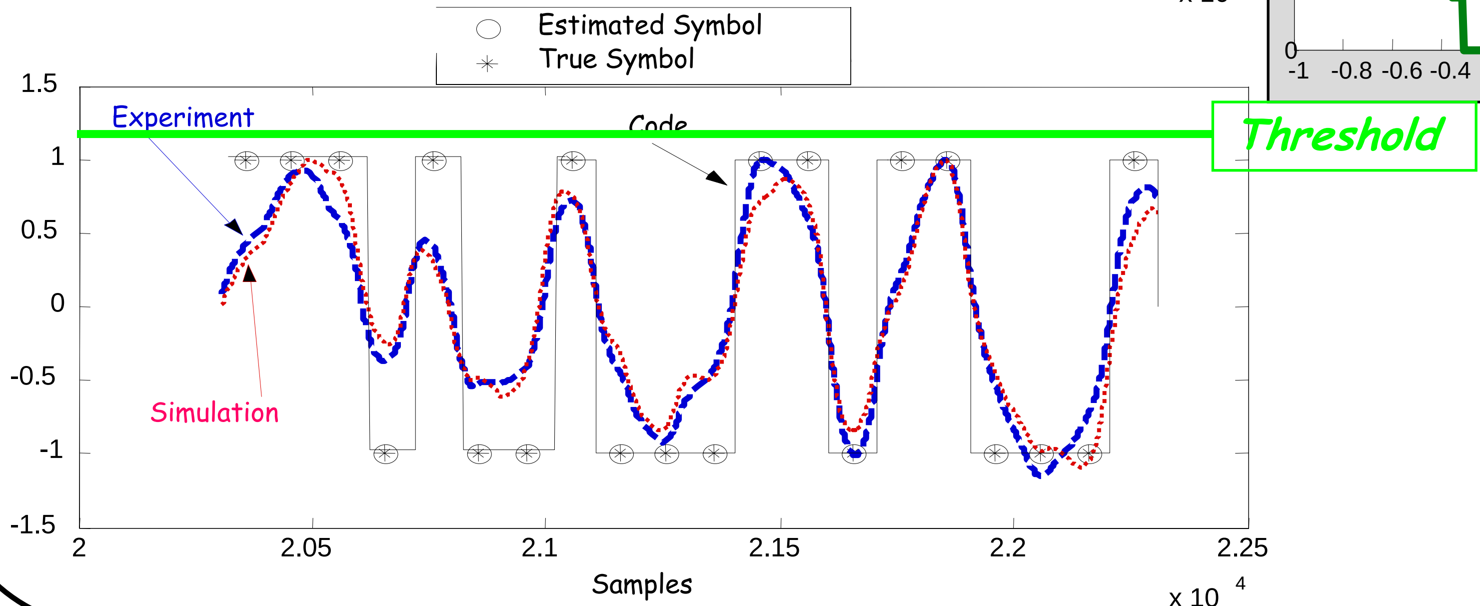
# A zoom of the original information and received Type I signals



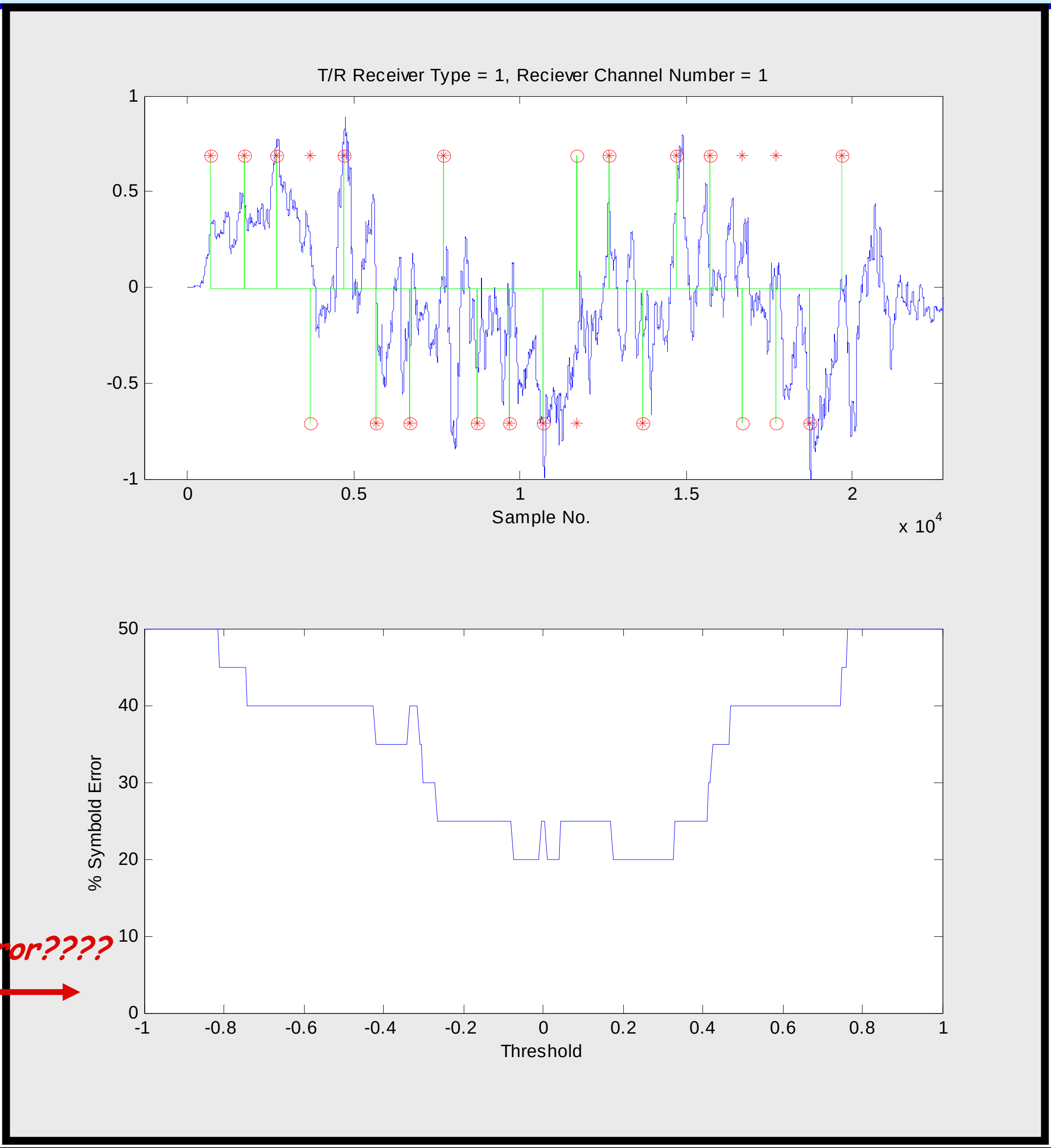
# Calculate symbol error as a function of threshold



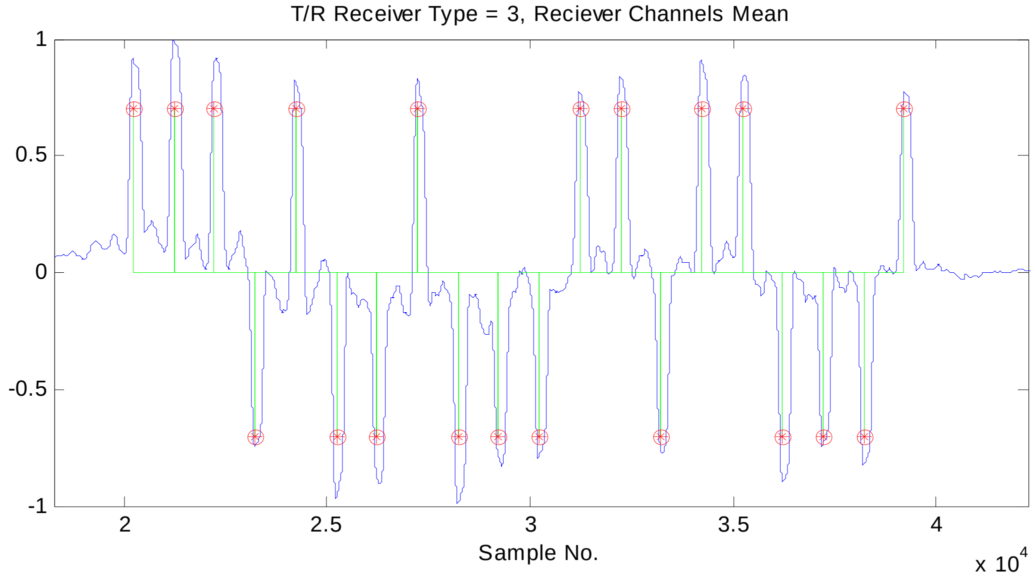


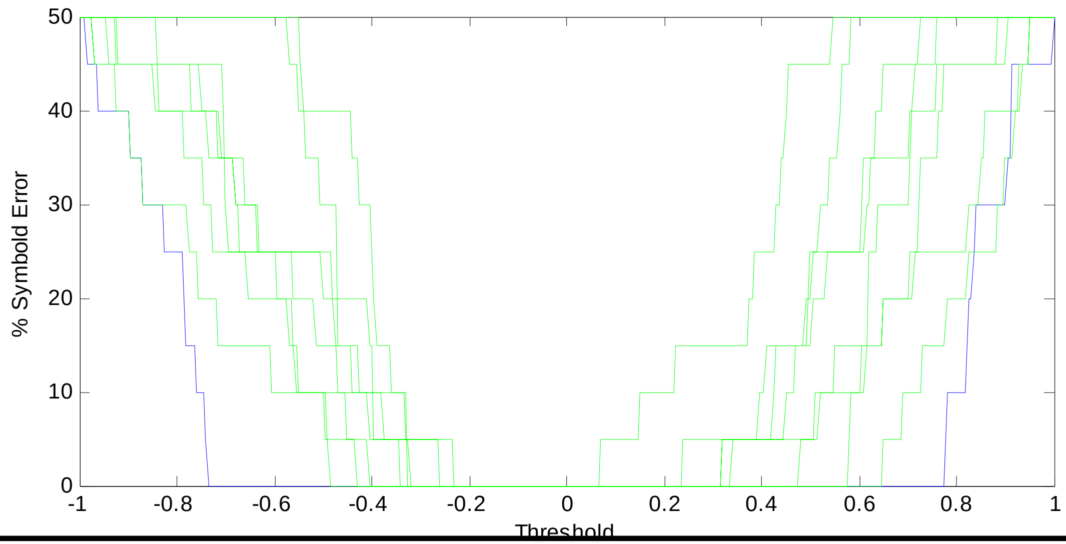
# XR demodulation without TR processing is unable to extract information




Zero-symbol error????

Un-averaged receiver result, Type 3 (Uses only one instance of BP filtered RxI)



# *Summary for wideband implementation:*

- **Showed the time-reversal can be implemented for wideband systems**

- **Time-reversal approach is compatible with a carrier-less modulation scheme**

- **Experiment in a tunnel-like environment shows array gain**

# *Conclusion*

- **TR communications schemes can be implemented either on transmit (active) or receive (passive)**
- **Performance approaches the ideal linear equalizer (inverse filter) for point-to-point implementation**
- **Performance improves for array-to-point implementation**
- **Receiver performs well even when signal range is restricted to 1-bit**
- **TR approach is compatible with wideband, carrier-less communications**