Arbitrary Waveforms using a Tri-State Transmit Pulser

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Verasonics®

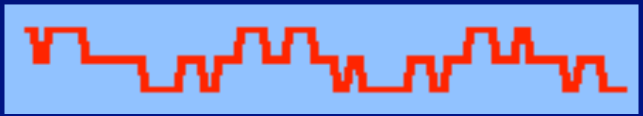
Prelude

Debate: Tri-state Switching Transmit vs. DAC + Linear Amp

- Can Tri-state Transmitter make “Analog” waveform?
- Exploit BL transducer – smooth out
- Goal: parity with DAC+LA into Transducer / medium

How to do in practice?

- Estimate transducer impulse response
- Build encoder for transducer: Deconvolution “Equalizer”
- Encoder output: tri-state sequence



Prior work: 1-bit, single channel, TR pulse compression (Encoding: zero-crossing)

Derode, A.; Tourin, A.; Fink, M., "Ultrasonic pulse compression with one-bit time reversal through multiple scattering," Journal of Applied Physics , vol.85, no.9, pp. 6343,6352, May 1999

Intro / Outline

Verasonics Vantage System Transmitter

- Arbitrary Tri-State sequences: [-V, 0, +V] @ 250 MHz
- PWM with 4 ns phase control
- Long sequences (dep. on spectrum, power, memory, aperture)
- Caveat: 3-clock dwell to achieve voltage state

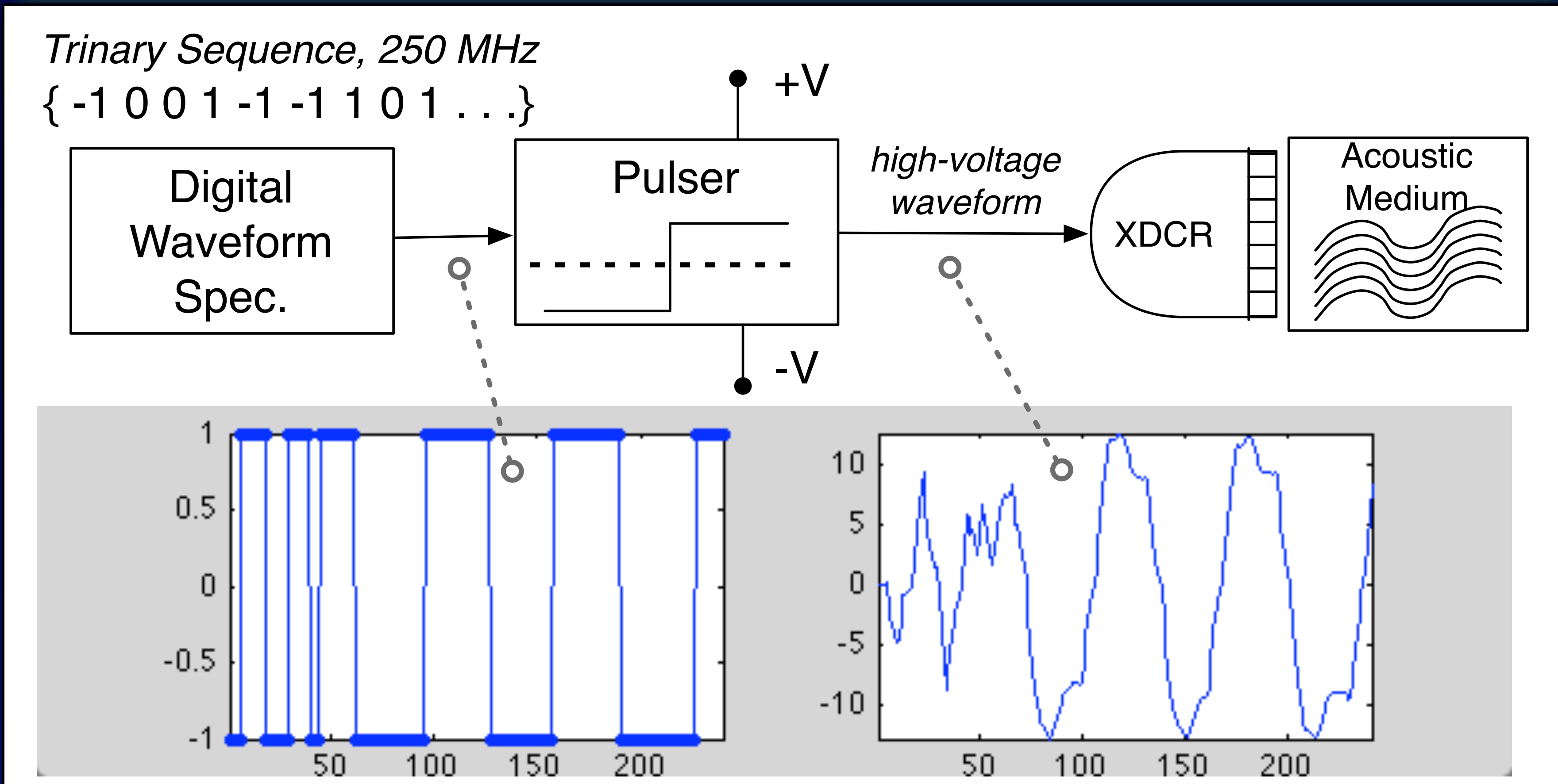
Making analog arbitrary waveforms –

- Algorithm, Performance criterion (Usage models)
- Water tank: Waveform fidelity vs. DAC vs. predicted
- Imaging application (phantom): **Complimentary Golay Sequence**
- Imaging application (phantom): **Equalized Gaussian Pulse**

Usage Models
Waveform fidelity in 1-way and 2-way propagation

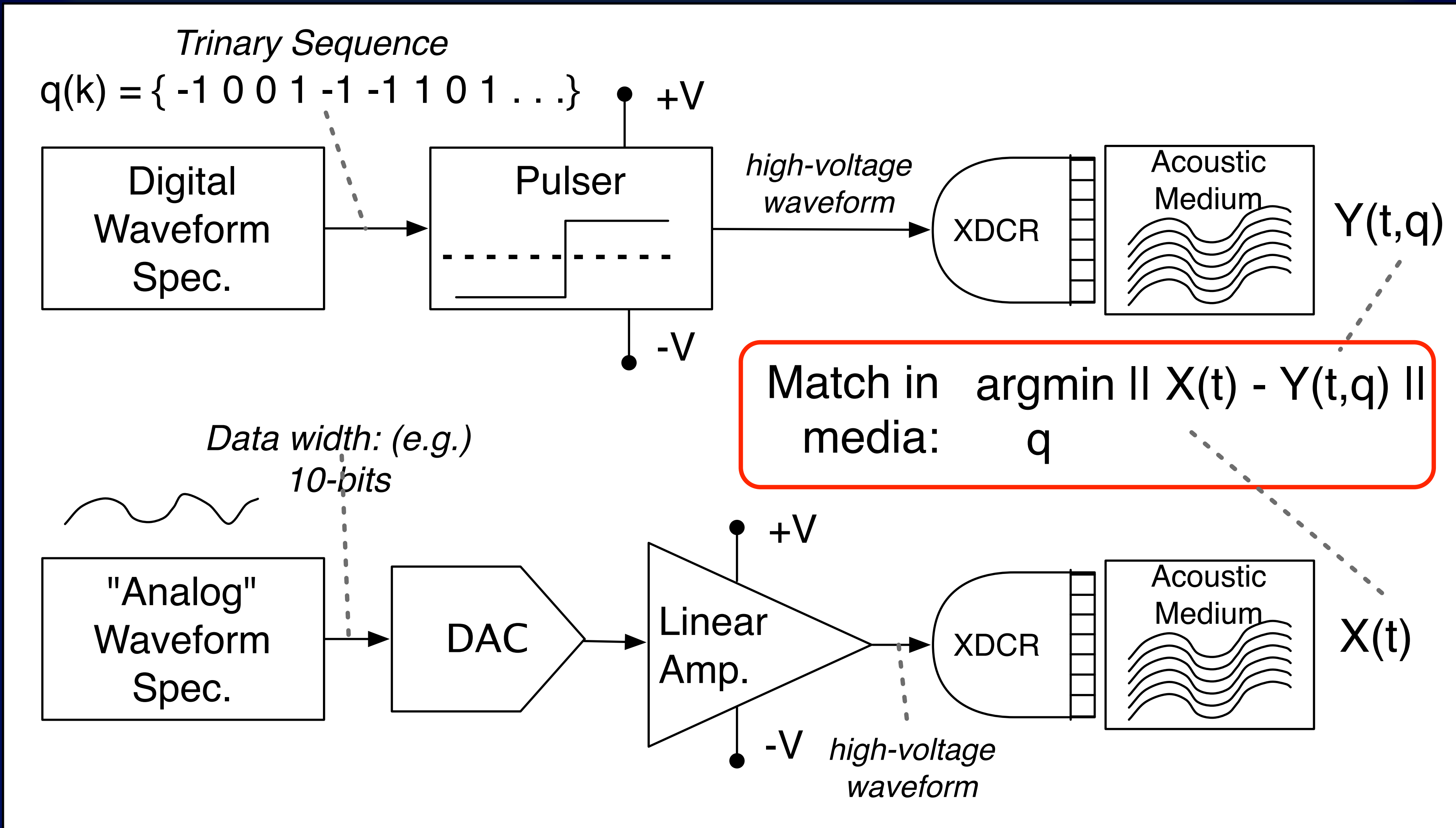
- **Usage Model: Digital Symbol code (e.g. Golay-coded pulses)**
- **Usage Model: Encoding "analog" waveform to mimic a DAC (requires Impulse Response model)**
  - Goal – mimic {DAC + Linear Amplifier} with Tri-State Pulser
  - Achieve fidelity In medium (requires probe forward impulse response)
  - Achieve fidelity at receiver (need round trip impulse response)
- **Usage Model: Encoding "analog" waveform into medium (requires Impulse Response model)**
  - Goal: reproduce the specified analog waveform (harder)
  - Achieve fidelity to design waveform in medium or at receiver

Usage Model: Digital Symbol Sequence

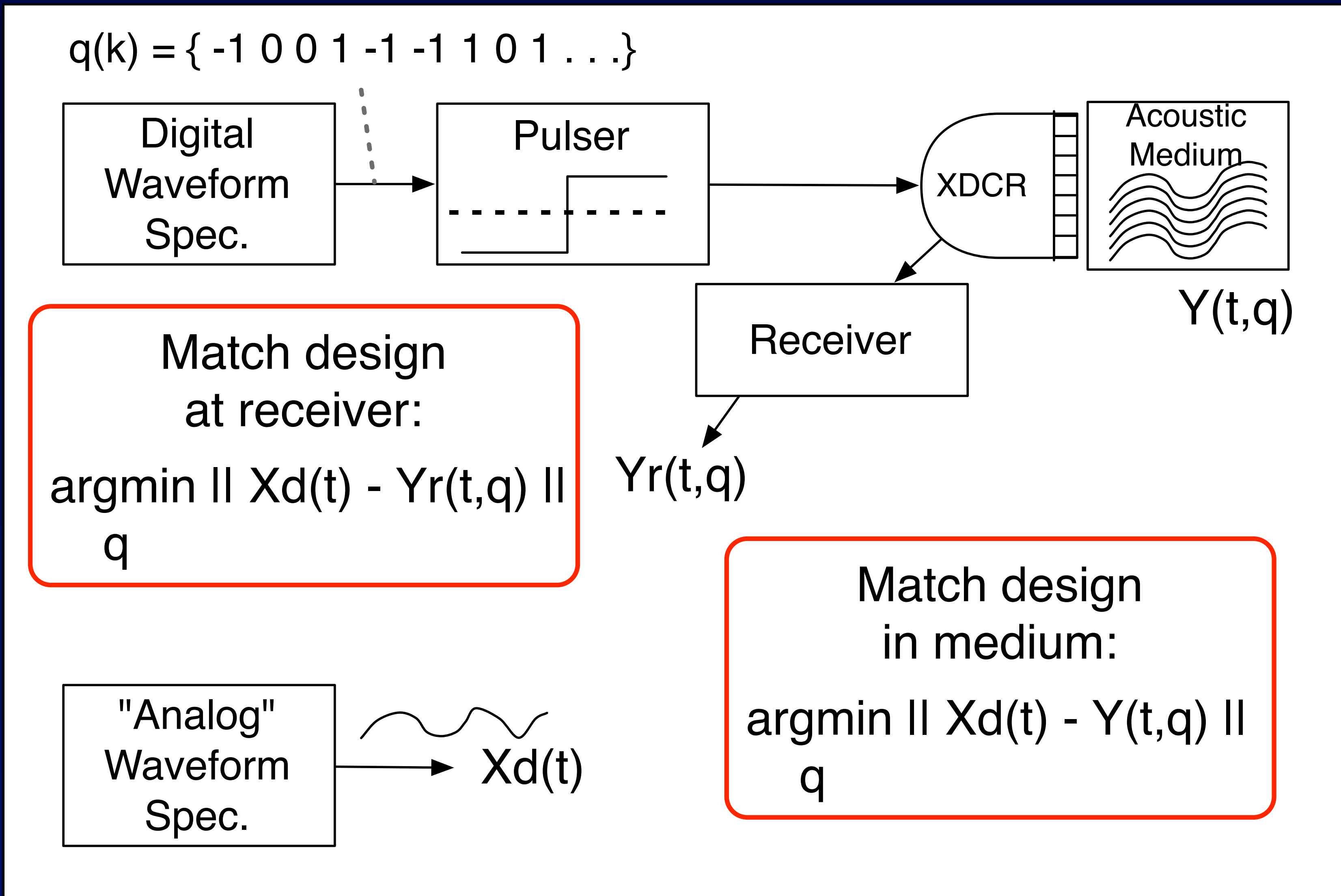


- "Open Loop" design examples:
- Conventional B-Mode, Doppler with PWM apodized tone burst
- Codes for channel sounding
- Codes for imaging (Golay)
- Push Sequence / ARFI
- LFM construction by zero-crossing detection

Usage Model: DAC synthesis/mimic (1-way)



Usage Model: Transducer Compensation



DAC synth/Probe Compensation: Equalizer Concept

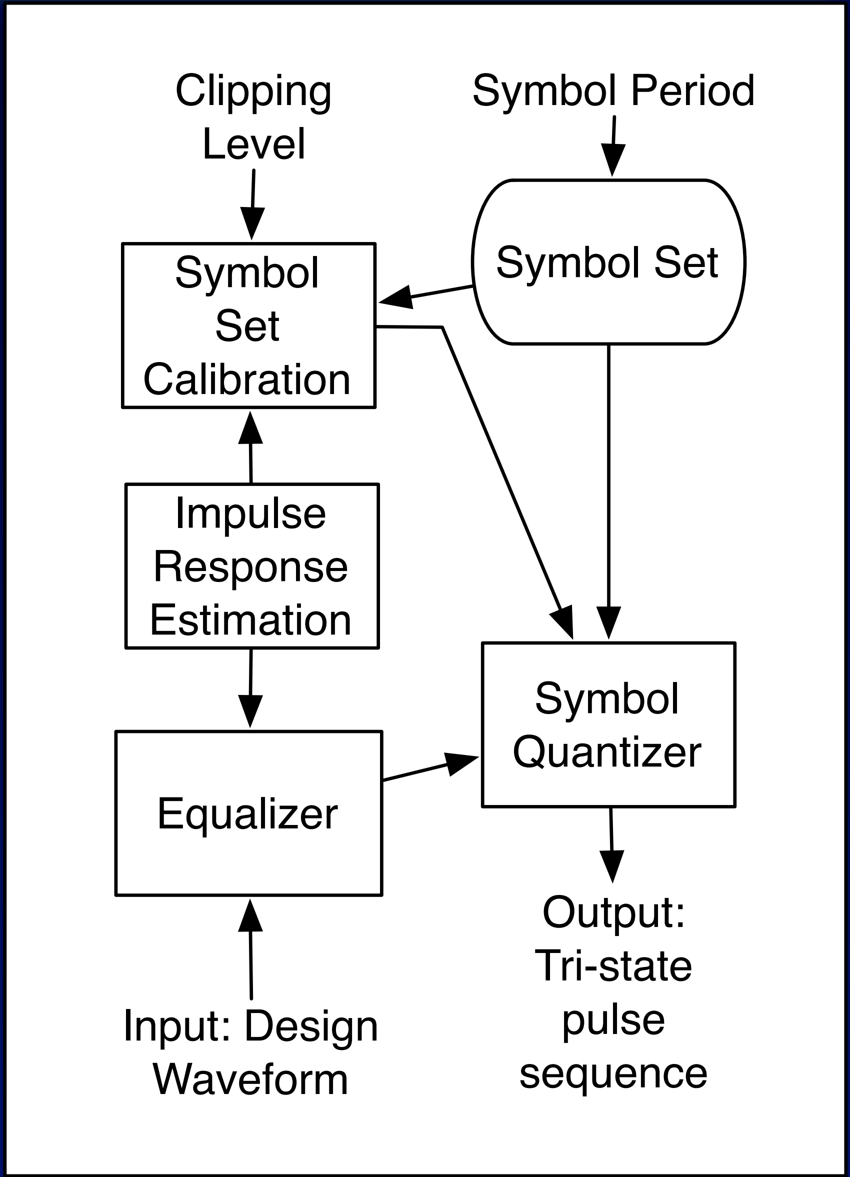
Problem: optimize transmitter pulse sequence, given

- Transducer Impulse Resp.
- Desired Reference Waveform

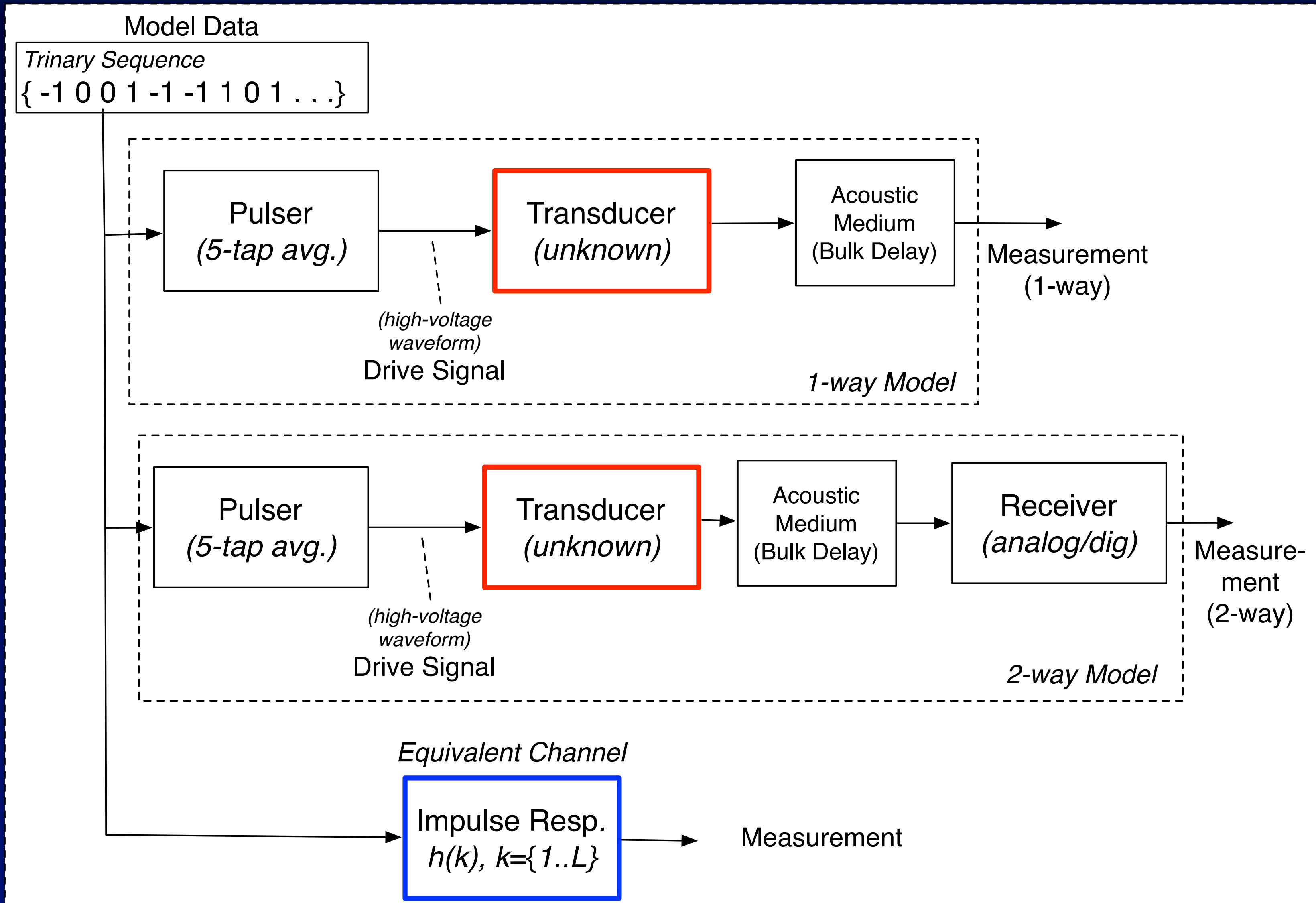
Analogy: Symbol Equalization
(communication in BL channel)

Approach:

- Linear Equalization
- symbol mapping



Models Needed for Signal Design



Convolution Model: Impulse Response Estimation

Convenient to use Toeplitz matrix T(q) of TX vector q
=> Linear Model estimation by Least Squares

$$\mathbf{Y} = \begin{bmatrix} y(1) \\ \vdots \\ y(N+L-1) \end{bmatrix} = \begin{bmatrix} q(1) & 0 & \cdots & 0 \\ \vdots & q(1) & & \vdots \\ q(N) & \vdots & & \\ 0 & q(N) & \ddots & 0 \\ & 0 & \ddots & q(1) \\ \vdots & & & \vdots \\ 0 & \cdots & 0 & q(N) \end{bmatrix} \begin{bmatrix} h(1) \\ \vdots \\ h(L) \end{bmatrix} + errors$$

$$\mathbf{Y} = T(\mathbf{q})\,\mathbf{h} + errors \quad \Rightarrow \quad \hat{\mathbf{h}} = T(\mathbf{q})^{+}\,\mathbf{Y}$$

Single Transmission

$$\begin{bmatrix} \mathbf{Y}_1 \\ \vdots \\ \mathbf{Y}_K \end{bmatrix} = \begin{bmatrix} T(\mathbf{q}_1) \\ \hline \vdots \\ \hline T(\mathbf{q}_K) \end{bmatrix} \mathbf{h} + \begin{bmatrix} errors_1 \\ \vdots \\ errors_K \end{bmatrix} \Rightarrow \hat{\mathbf{h}} = \begin{bmatrix} T(\mathbf{q}_1) \\ \hline \vdots \\ \hline T(\mathbf{q}_K) \end{bmatrix}^{+} \begin{bmatrix} \mathbf{Y}_1 \\ \vdots \\ \mathbf{Y}_K \end{bmatrix}$$

K Multi - WF Transmits

"Equalizer" Concept: synthesize DAC, Compensate Probe, or both

Reference waveform

Decimated Toeplitz Convolution Matrix

"Soft" symbols

$$\mathbf{W} = \begin{bmatrix} w(1) \\ \vdots \\ w(L+PD-1) \end{bmatrix} = \begin{bmatrix} h(1) & 0 & \cdots & & 0 \\ \vdots & & & & \vdots \\ h(L) & \ddots & h(1) & & \\ 0 & & \ddots & & 0 \\ & 0 & h(L) & \ddots & h(1) \\ \vdots & & & & \vdots \\ 0 & & \cdots & 0 & h(L) \end{bmatrix} \begin{bmatrix} r(1) \\ \vdots \\ r(P) \end{bmatrix} + \begin{bmatrix} \text{approximation} \\ \text{errors} \end{bmatrix}$$

$$\mathbf{W} = \mathbf{H}_d\,\mathbf{r} + \mathbf{e}$$

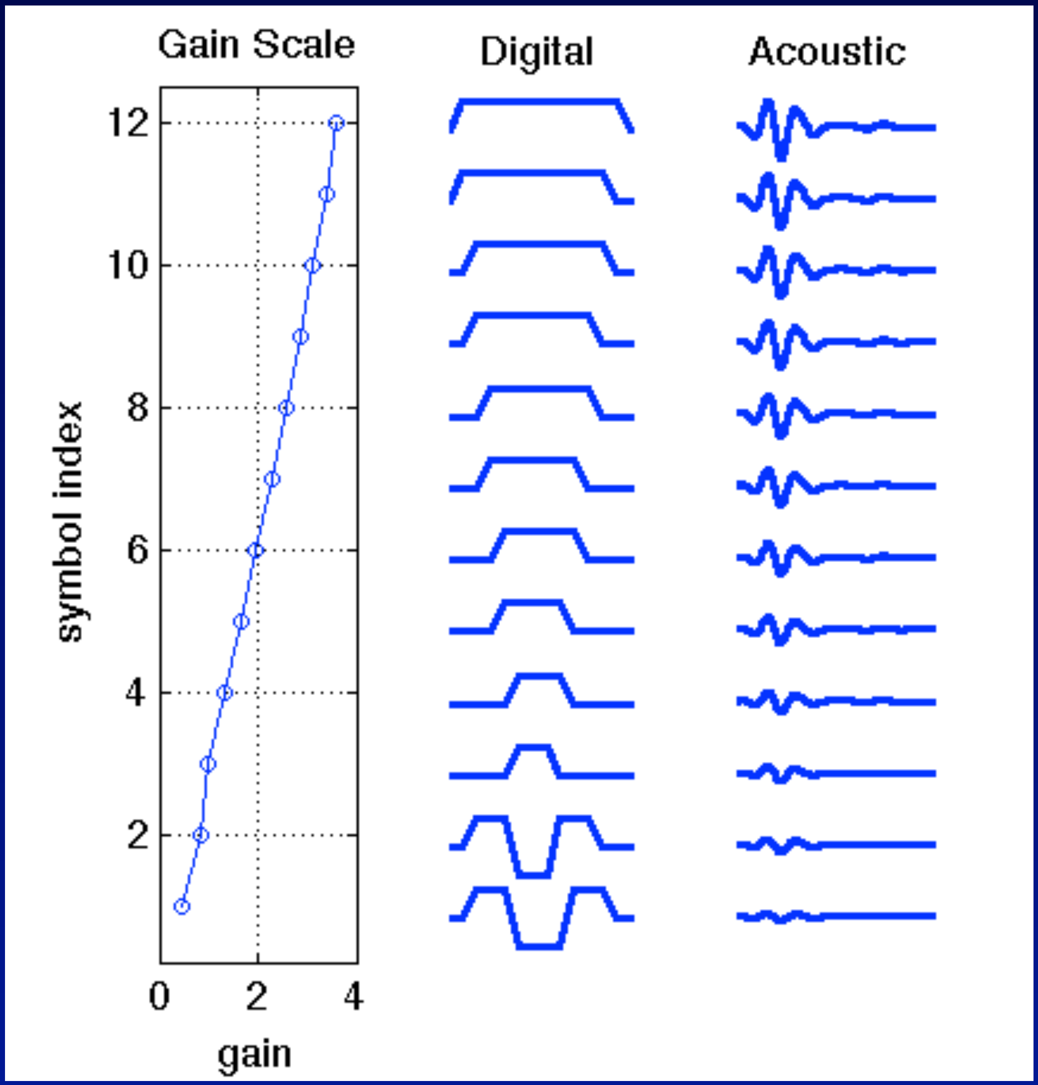
Ordinary LS Solution:

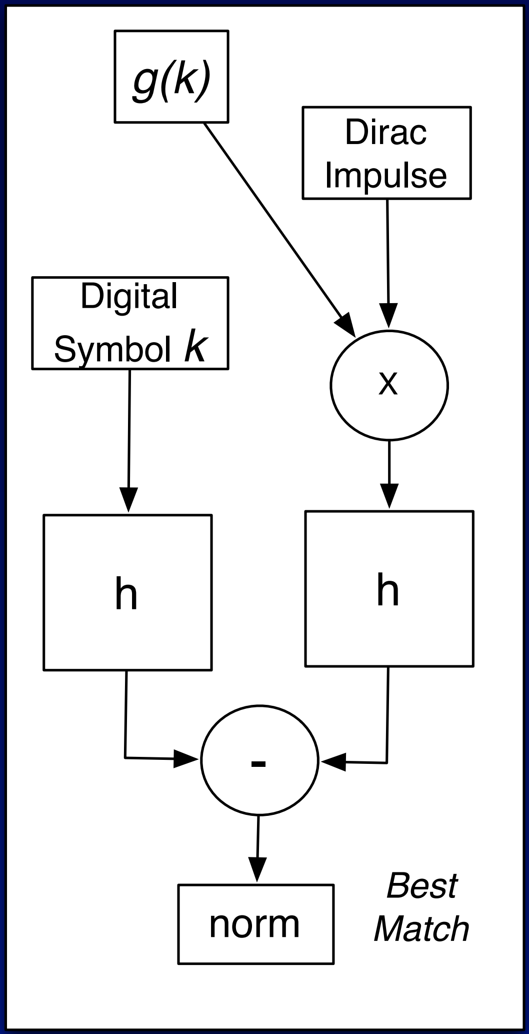
$$\hat{\mathbf{r}} = \mathbf{H}_d^{+}\mathbf{W}$$

Symbol Set Cal. & Map: Quantize the “soft” symbols

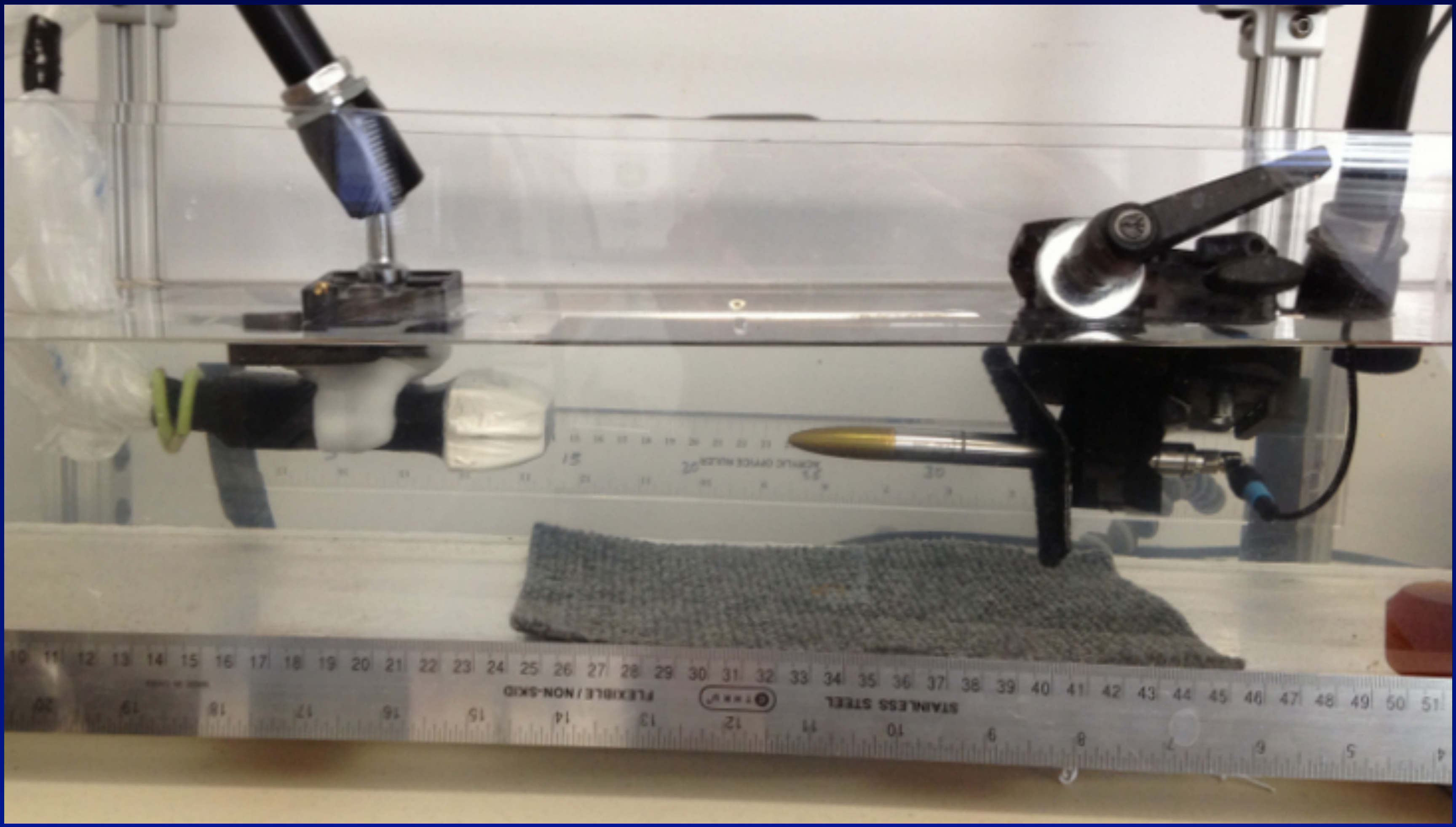
(1) L.S. fit symbols to h

(2) Closest *g(k)* to *r*



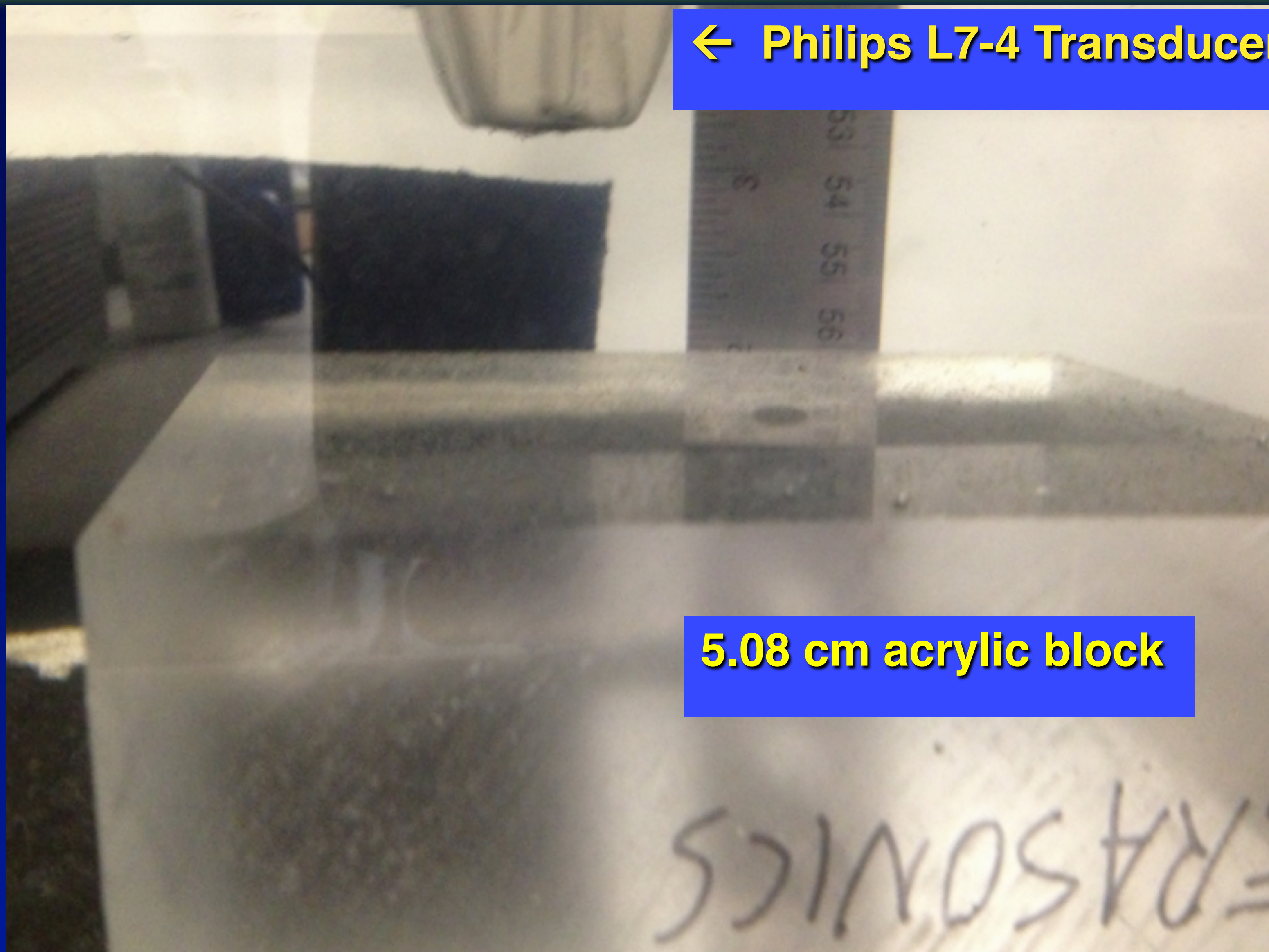


Experimental Setup
1-way propagation in water tank

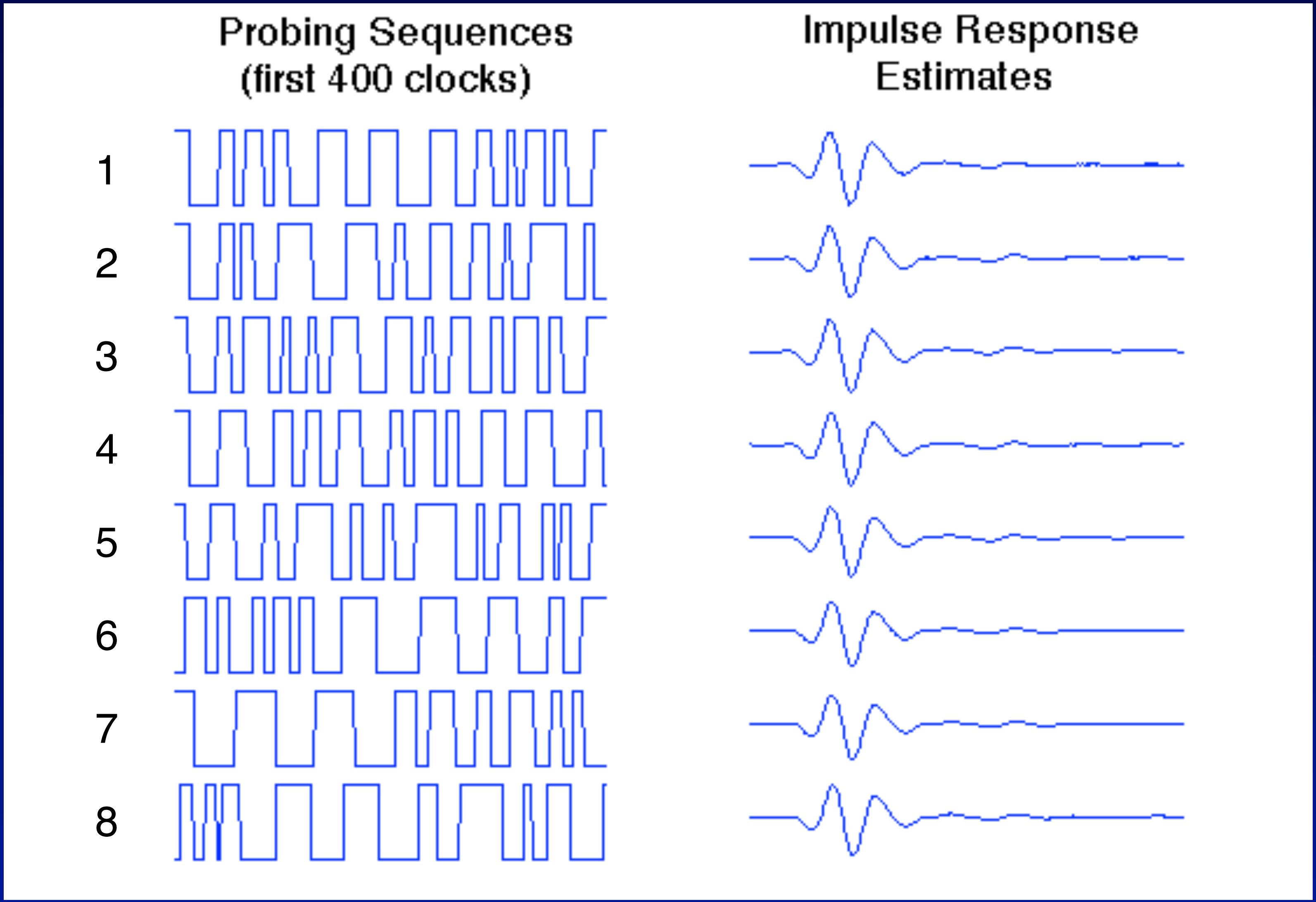


Philips L7-4 Transducer **Onda Hydrophone**

Experimental Setup
2-way propagation in water tank – acoustic mirror



Results: Transducer Impulse Responses
Probing with Broadband Random Sequences



Nonlinearities: Tristate vs DAC

Impulse Response Estimation: RSS/DOF >> quiescent noise variance

Indicates Nonlinearity in probe or medium

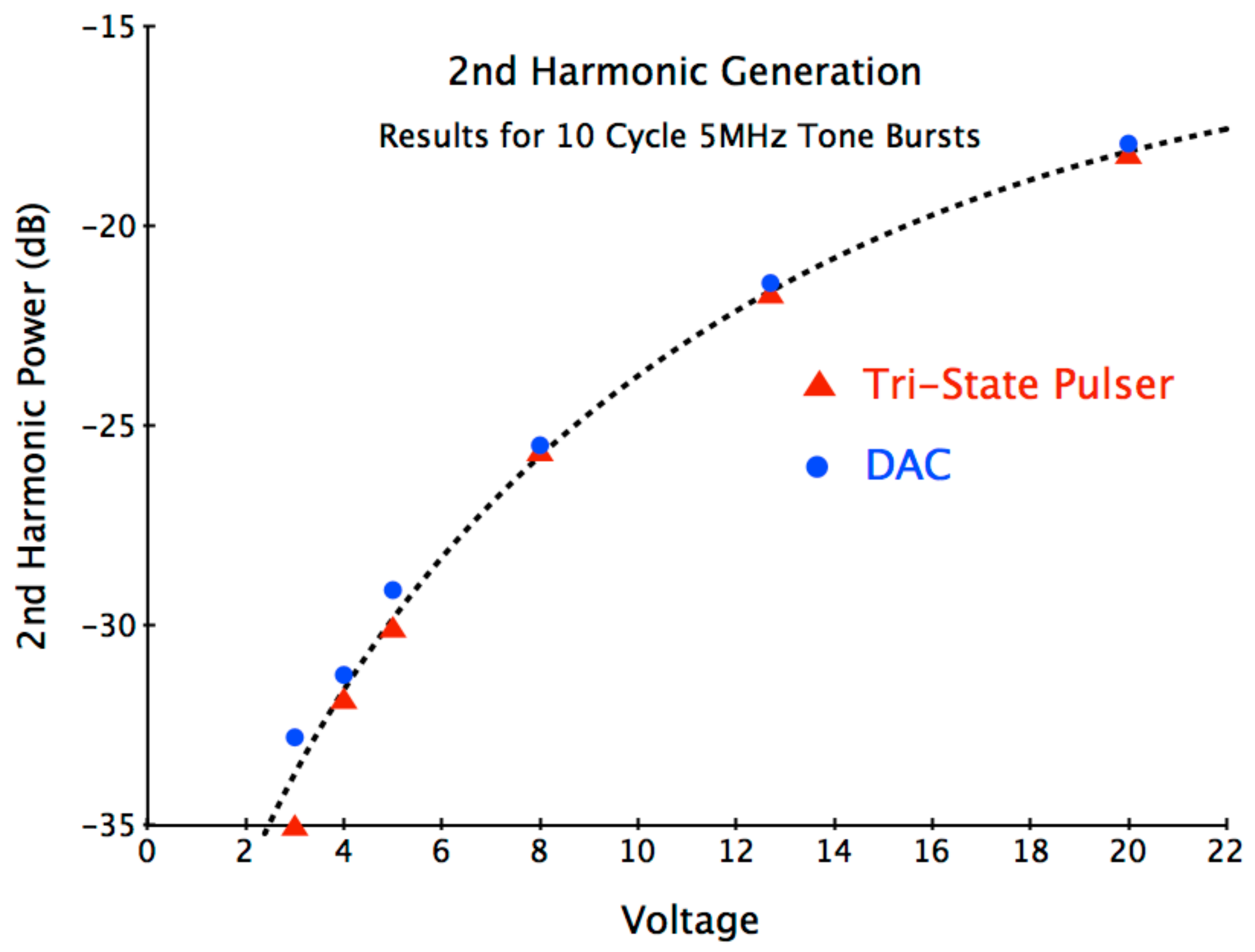
Does Tristate Spectrum Induce In-band Distortion?

Experiment: 1-way water tank, DAC vs tristate pulser

Signal: 10 cycle square (3-state), sin (DAC)

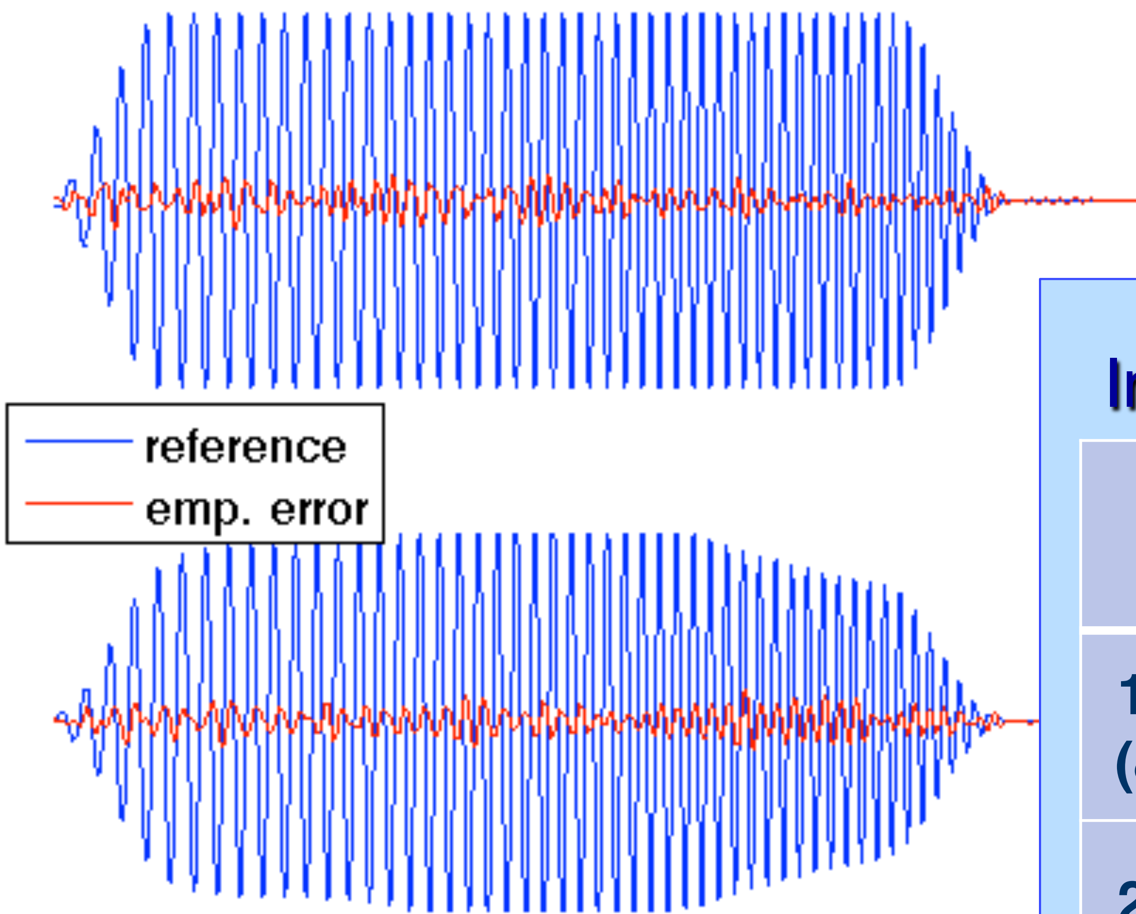
Pulse Inversion at low voltage (not shown)

Result: Same power in 2^{nd} harmonic (high Volt)



Results: LFM DAC synthesis & Probe Compensation

Example: L7-4 Probe Compensation



Example: L7-4 DAC Synthesis

LFM Water Tank example

- Taylor Weighting
- 10 μSec duration
- 3.5 < F (MHz) < 6.5

In-band NRMSE (dB)

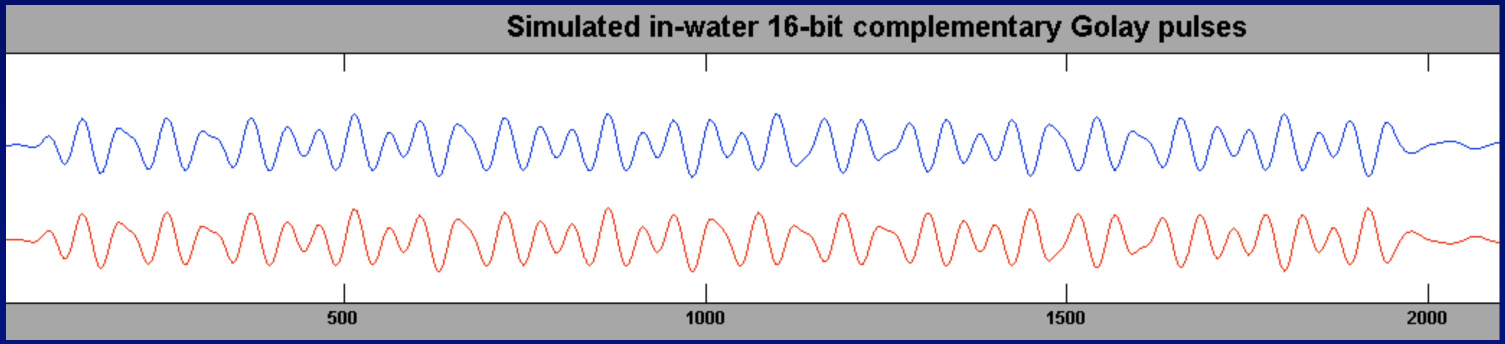
	Probe Comp.	DAC Synth.
1-Way (8.0 V)	-23.8	-24.1
2-Way (5.0 V)	-22.5	-21.6

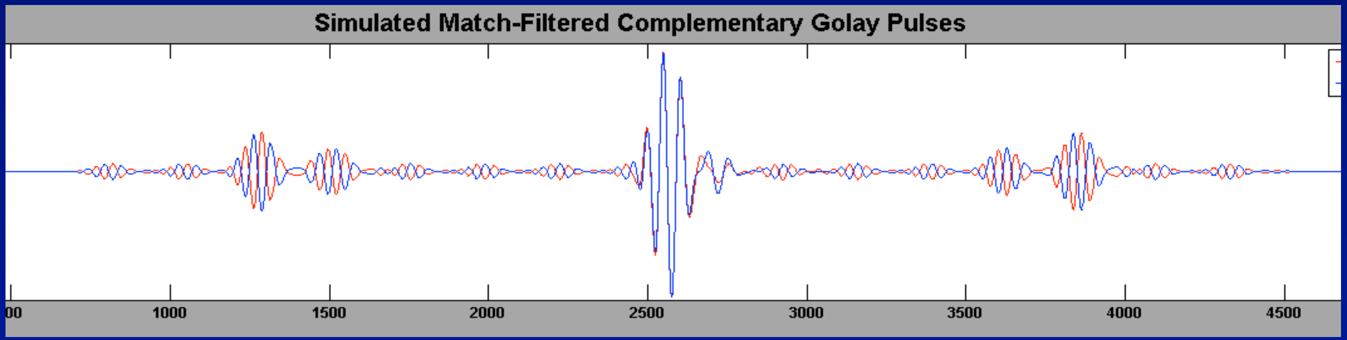
Imaging Example: Complementary Golay Pulses
Background

Matched-Filter pulse compression of coded sequences suffers from sidelobes

Complementary Golay Sequences: Autocorrelation sidelobes are equal and opposite, so use 2 complementary transmissions to cancel sidelobes

Following Nowicki *et al.*, use 16-bit pair for imaging example using an impulse response wavelet.

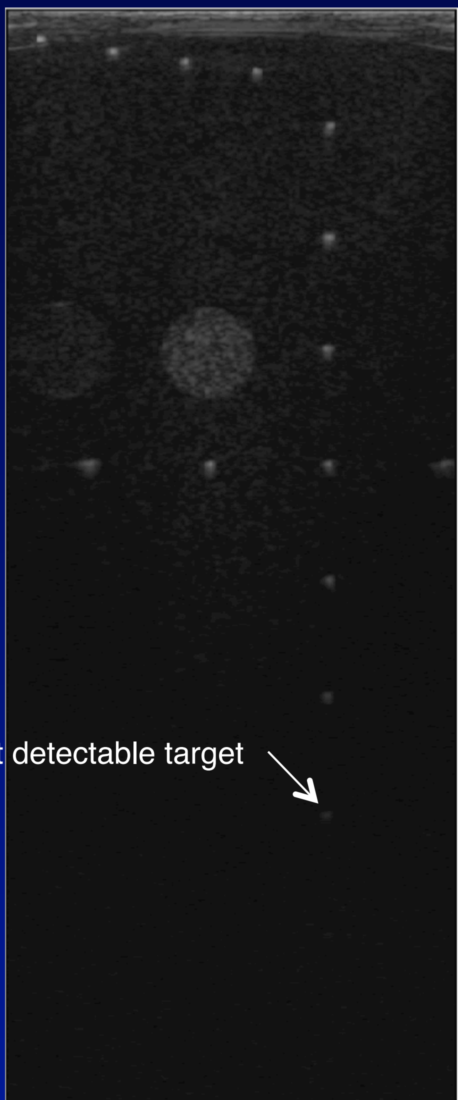




Nowicki, A. et al., 2004. Extending penetration depth using coded ultrasonography. *Bull. Pol. Ac.: Tech., 52(3).*

Imaging Example: Complementary Golay Pulses
0.7 dB/cm/MHz Resolution Phantom @ 5 Volts

5 MHz Monopulse



16-bit Golay

Transmit Burst

2 cm

10 cm

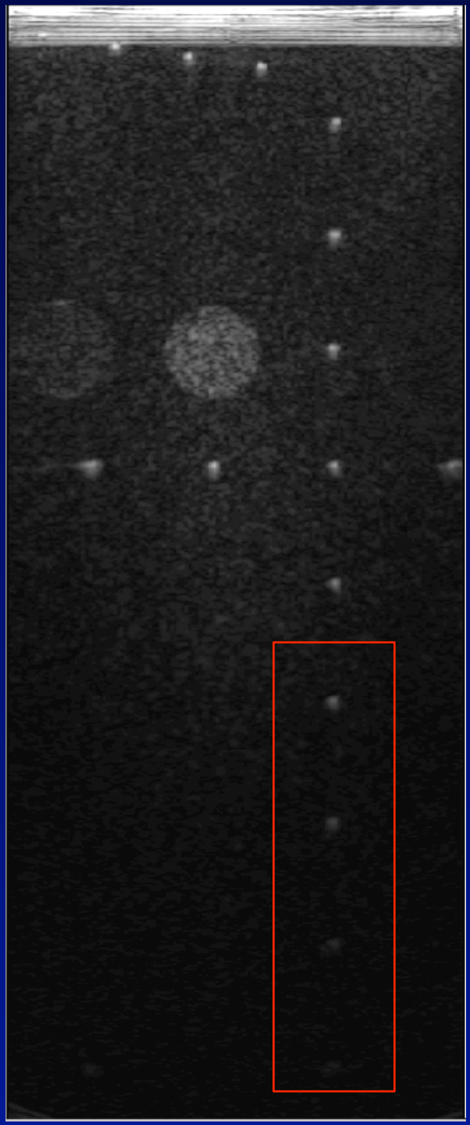
Last detectable target

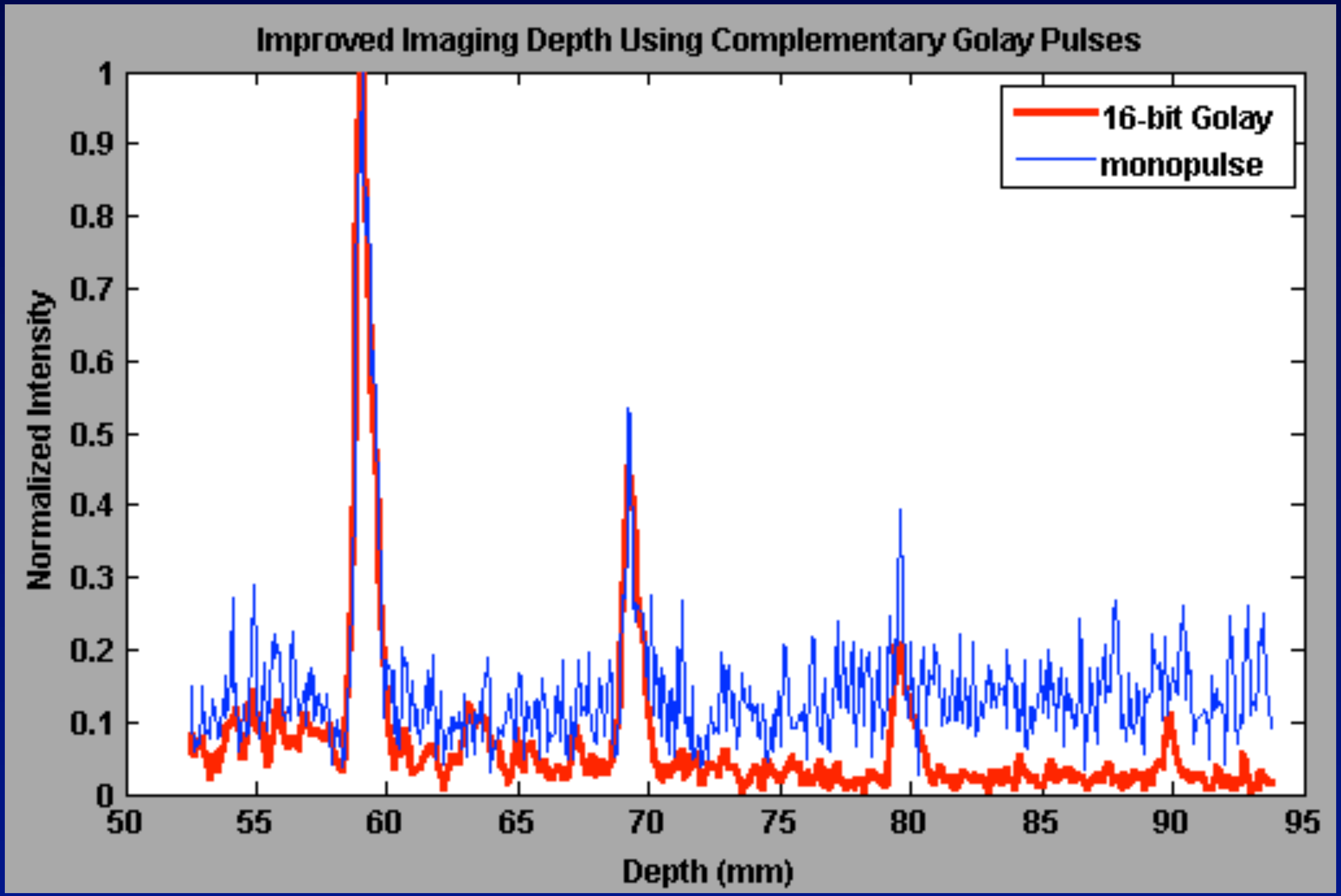
Last detectable target

- L7-4 Transducer, 5 Volts
- Golay RF data match-filtered, averaged, and normalized by 16
- All other settings equal (e.g. TGC, image brightness and contrast)
- Improved signal to noise results in deeper imaging range

Imaging Example: Complementary Golay Pulses

Results in a resolution phantom

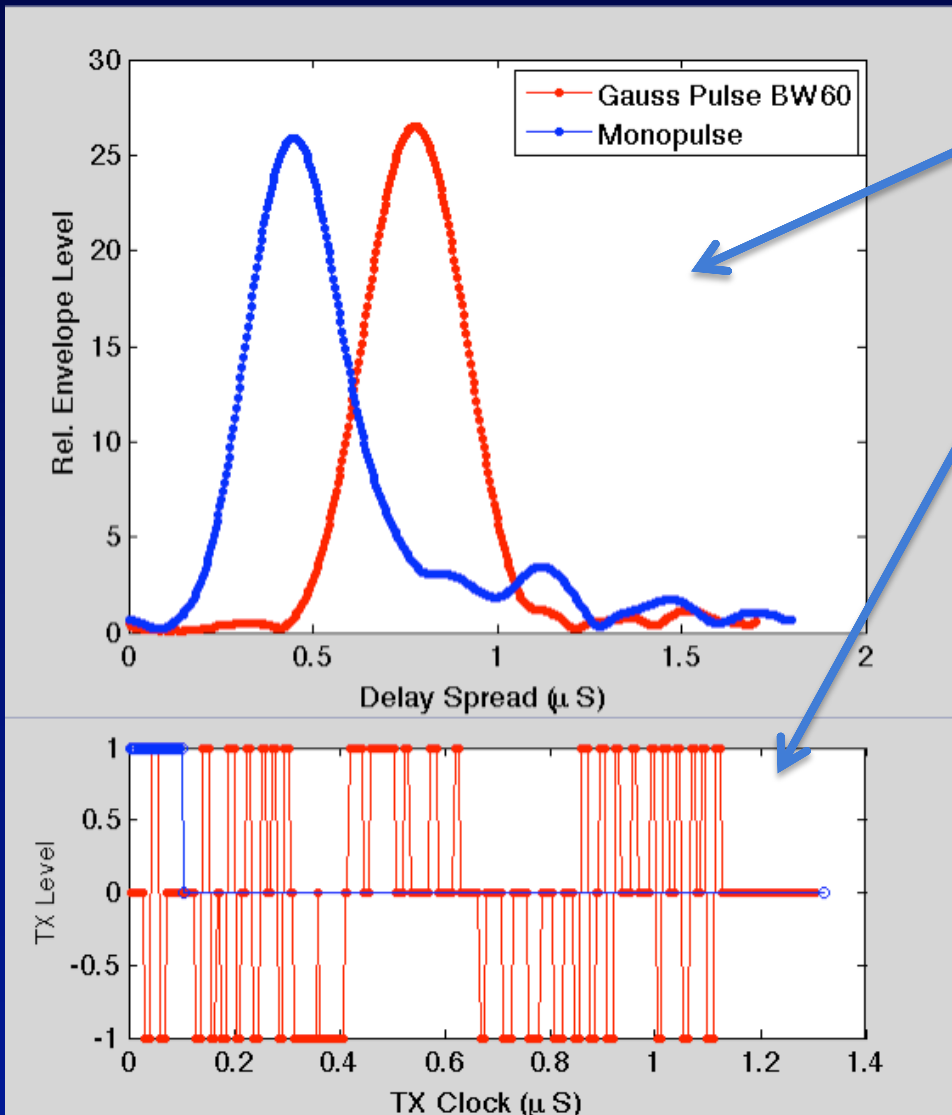




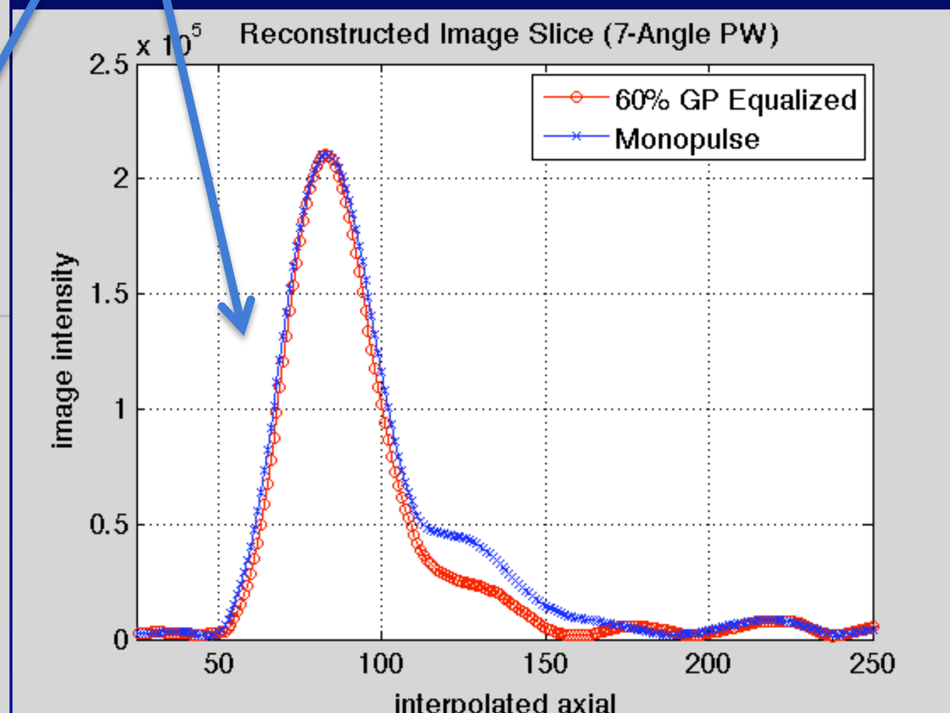
Golay Pulse Encoding Results:

- Reduced noise floor
- Improved imaging depth of penetration

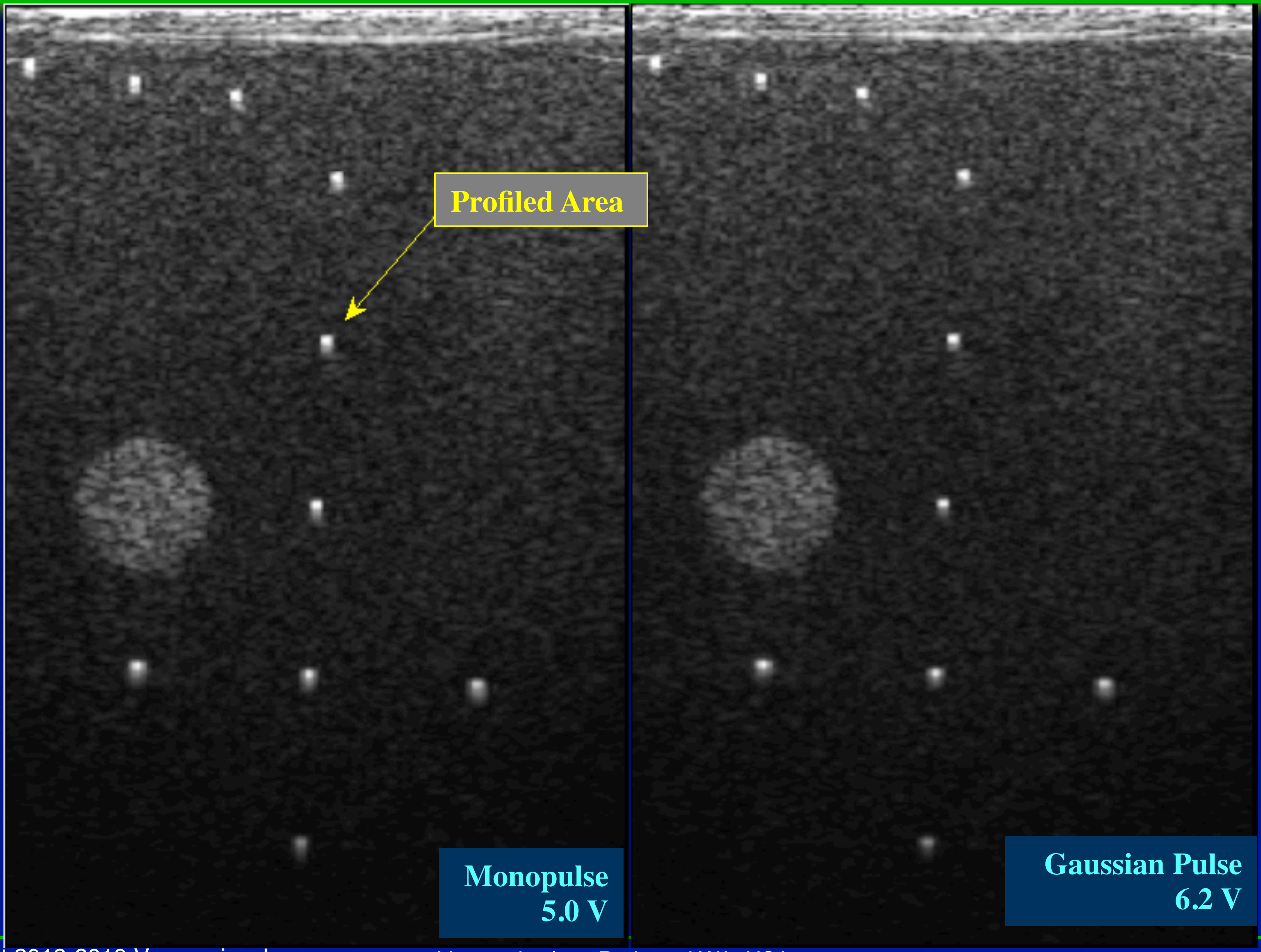
Imaging Example: Transducer Compensation
Gaussian Pulse vs. Monopulse (7-Angle Planewave)



- **Predicted: monopulse vs. equalized GP (60% BW)**
- **Transmitter pulse sequences**
- **Reconstructed Image Slice (7-Angle Planewave)**



Example: Transducer Compensation
Monopulse vs. Gaussian Pulse (60% BW) (7-angle PW image)



Summary

The Verasonics "Vantage" Ultrasound System Transmitter has Arbitrary Waveform capability

- Arbitrarily long pulses defined using a compact tri-state pulse code
- 250 MHz clock sets state transitions for accurate phasing
- Use PWM to adjust amplitude

Described Analog waveform encoding problems and methods

Simulations of waveform fidelity use transducer Impulse Response

Measurements of in-water waveforms

- Measurements consistent with simulation within quantified nonlinear effects
- Increased transmitter distortion at very low voltages due to circuitry

Imaging Examples: Golay Sequence, Gaussian Pulse

Future work

- Evaluation in attenuating media, emphasizing 2-Way propagation, improved short-waveform

Patent Pending USPTO App. #61856488