The Response of LMS Adaptation to Distortions in PRML Optical Storage Channels

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Abstract

Integrators of PRML read channels for magnetic tape and optical disc storage devices are experiencing familiar problems as well as new challenges unique to their storage systems.

This presentation shows the dynamic behavior of unconstrained Least Mean Square (LMS) adaptation of a 9-Tap FIR. It is observed that the d=2 constraint in the RLL code causes insufficient signal energy to be present to properly drive filter adaptation at higher frequencies.

The signal is composed of Gaussian pulses of density PW50/T = 4.5, transition (edge) jitter and additive white gaussian noise. DC is removed before adding noise to provide a “bi-polar” signal. Standard EPR4 targets are used for both data- and decision-directed adaptation.

The first distortion studied is modulation. We observe that LMS mostly adjusts the lower frequencies of the FIR’s magnitude response.

Large PW50/T variation of ±50% is shown to cause only a minimal response from the LMS algorithm.

Disk defects that almost completely eliminate the signal cause less disruption to the LMS loop than do defects that attenuate large signals to approximately “inner” target values.

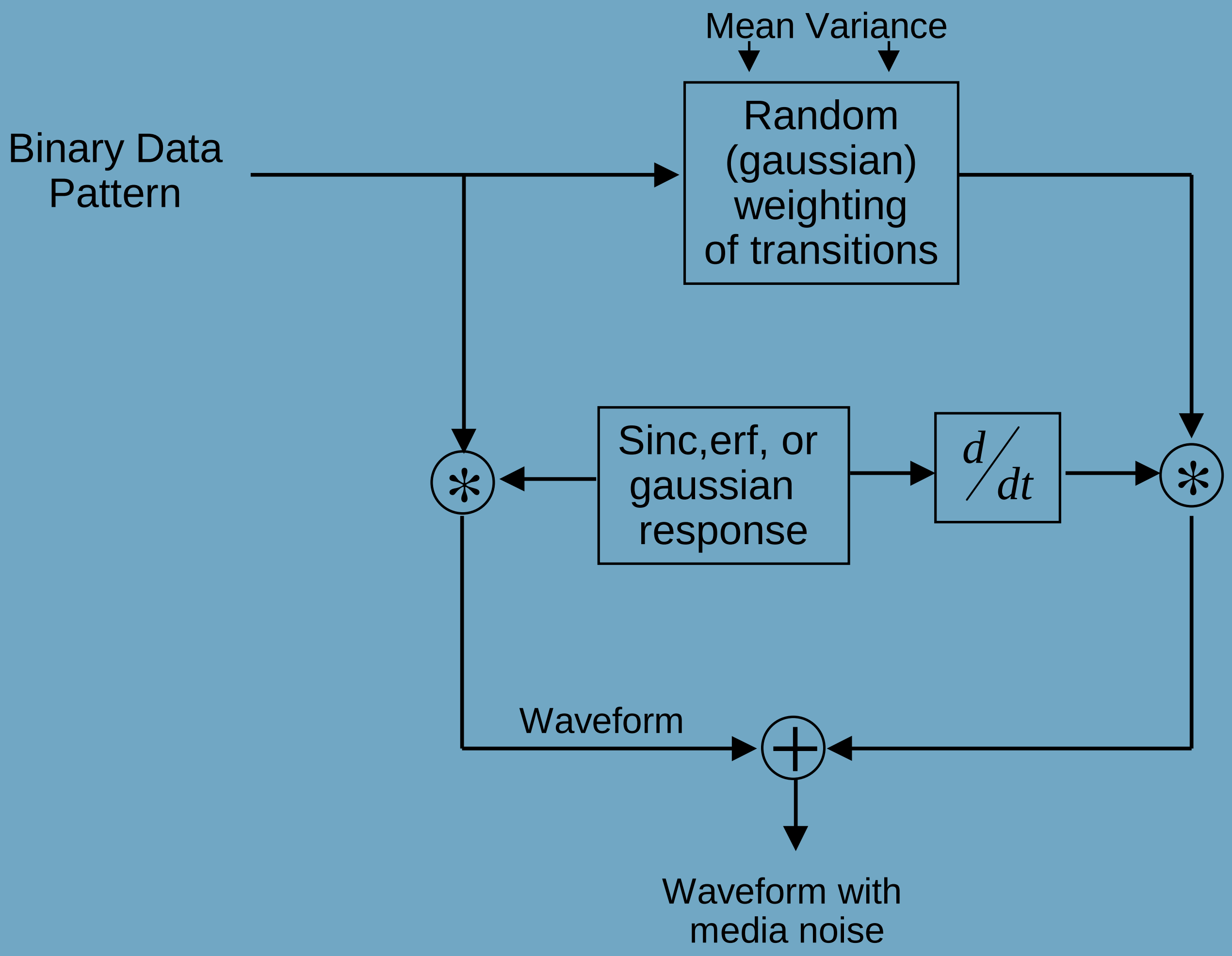
Signal Models

- Gaussian Pulses
  - PW50/T = 4.5
- Sinc Pulses
  - $1+D+D^2+D^3$ Target
  - Used for Data-directed LMS Adaptation

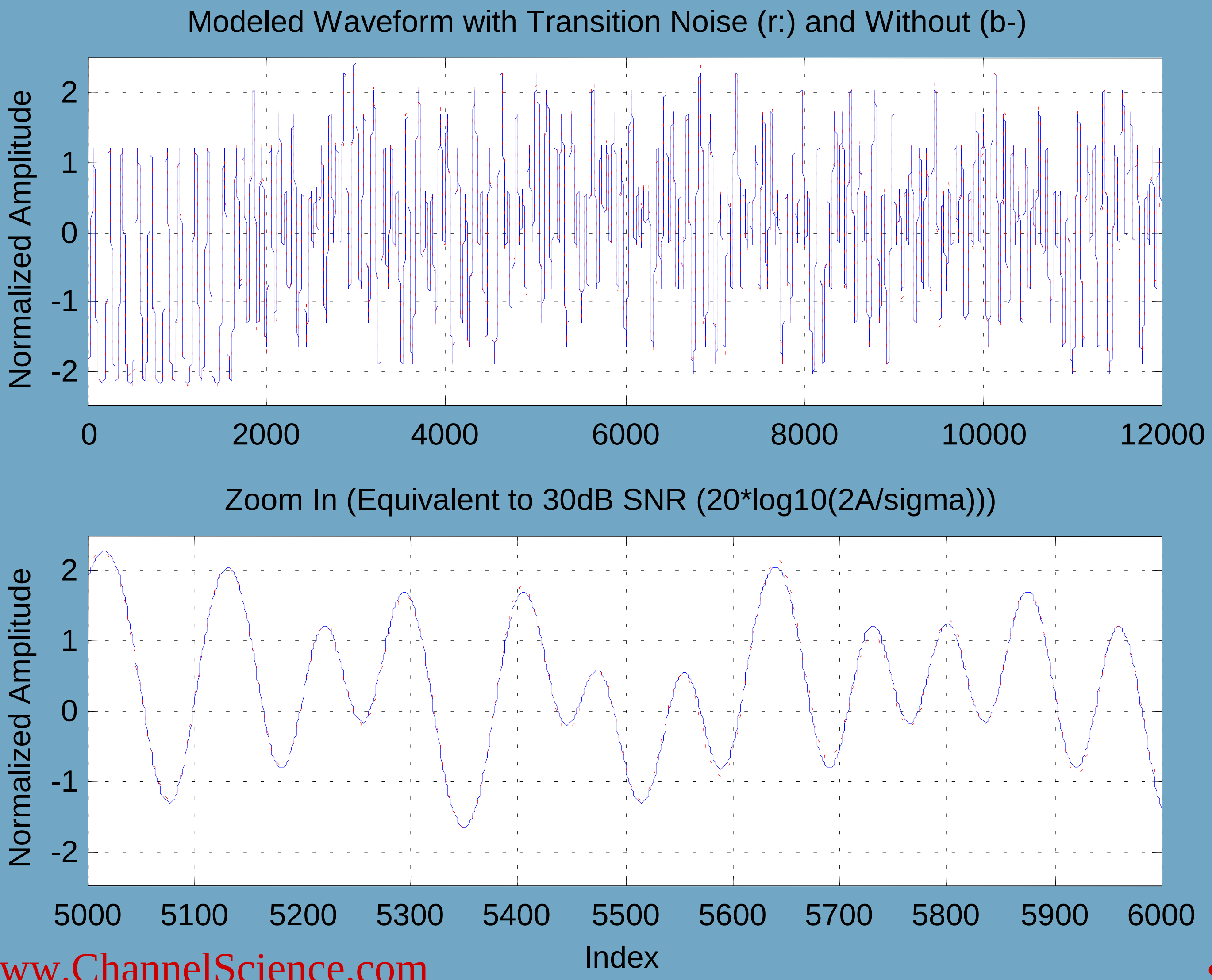
The Waveform

- DVD-like 32-bit Frame Sync Pattern
  - 4T-14T-4T-10T (repeated 5 times)
- 511-bit PRBS, pad
- RLL Code
  - d=2 Constraint
  - Using HDD Code 1/2(2,7)
- NRZI
- 30dB SNR ($V_{0\text{-}p}$/rms)
- Transition (Edge) Jitter

Jitter Model



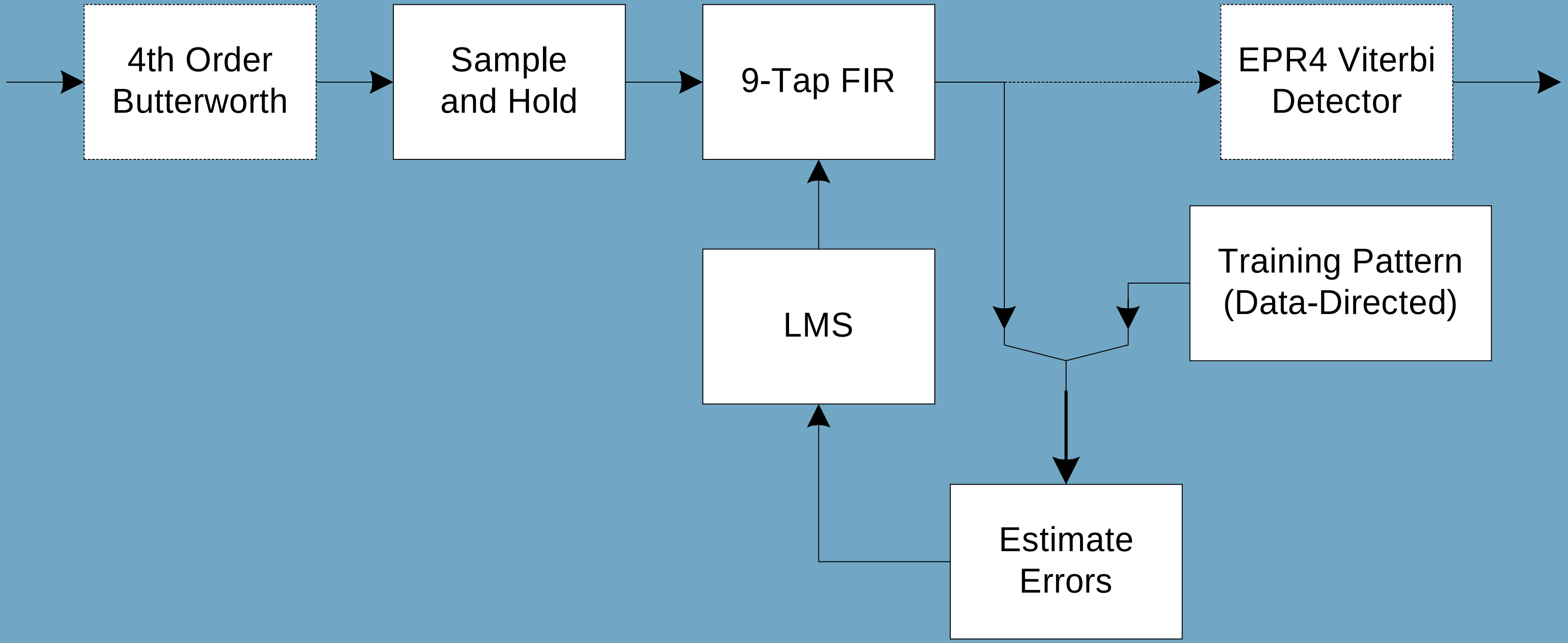
The Waveform: With and Without Jitter



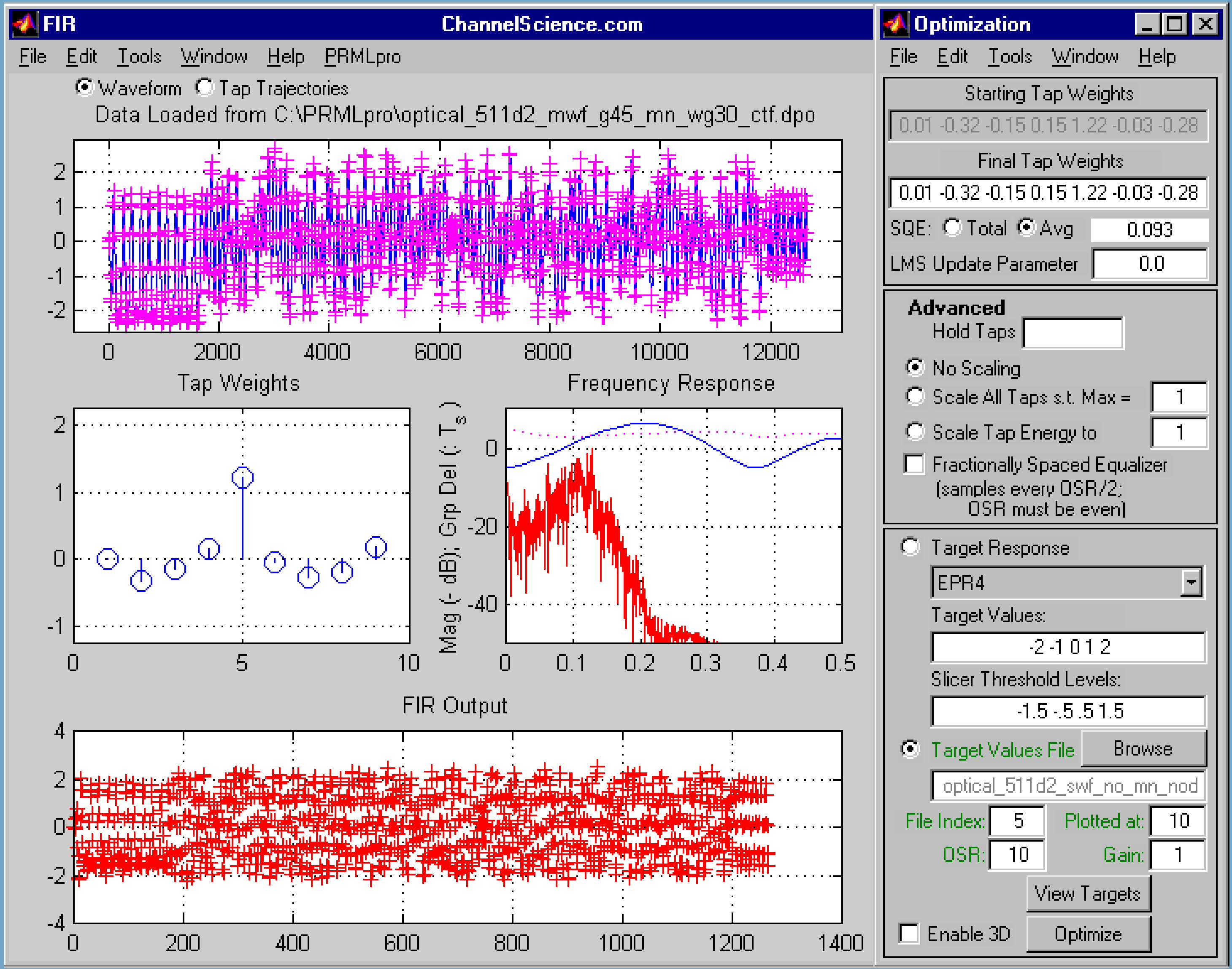
System Model - PRML*pro*™

- No AGC, No PLL
- 4th Order Butterworth
  - 3dB Boost; f_c=0.15*f_s
  - Skipped in Some Examples to let Noise Help Drive LMS to Attenuate Higher Frequencies
- Sample-and-Hold (No Quantization)
- 9-tap FIR
  - Nominal setting
    - Determined by LMS (Step-sizes 0.001, 0.0005) 0.01 -0.32 -0.15 0.15 1.22 -0.03 -0.28 -0.2 0.19
- LMS Step-size Parameter = 0.01

System Model



Results of LMS Adaptation on Undistorted Waveform



● Waveform ○ Tap Trajectories

Data Loaded from C:\PRMLpro\optical_511d2_mwf_g45_mn_wg30_ctf.dpo

Starting Tap Weights: 0.01 -0.32 -0.15 0.15 1.22 -0.03 -0.28

Final Tap Weights: 0.01 -0.32 -0.15 0.15 1.22 -0.03 -0.28

SQE: ○ Total ● Avg 0.093

LMS Update Parameter 0.0

Advanced

Hold Taps

● No Scaling

○ Scale All Taps s.t. Max = 1

○ Scale Tap Energy to 1

☐ Fractionally Spaced Equalizer (samples every OSR/2; OSR must be even)

○ Target Response

EPR4

Target Values: -2 -1 0 1 2

Slicer Threshold Levels: -1.5 -.5 .5 1.5

● Target Values File

optical_511d2_swf_no_mn_nod

File Index: 5 Plotted at: 10

OSR: 10 Gain: 1

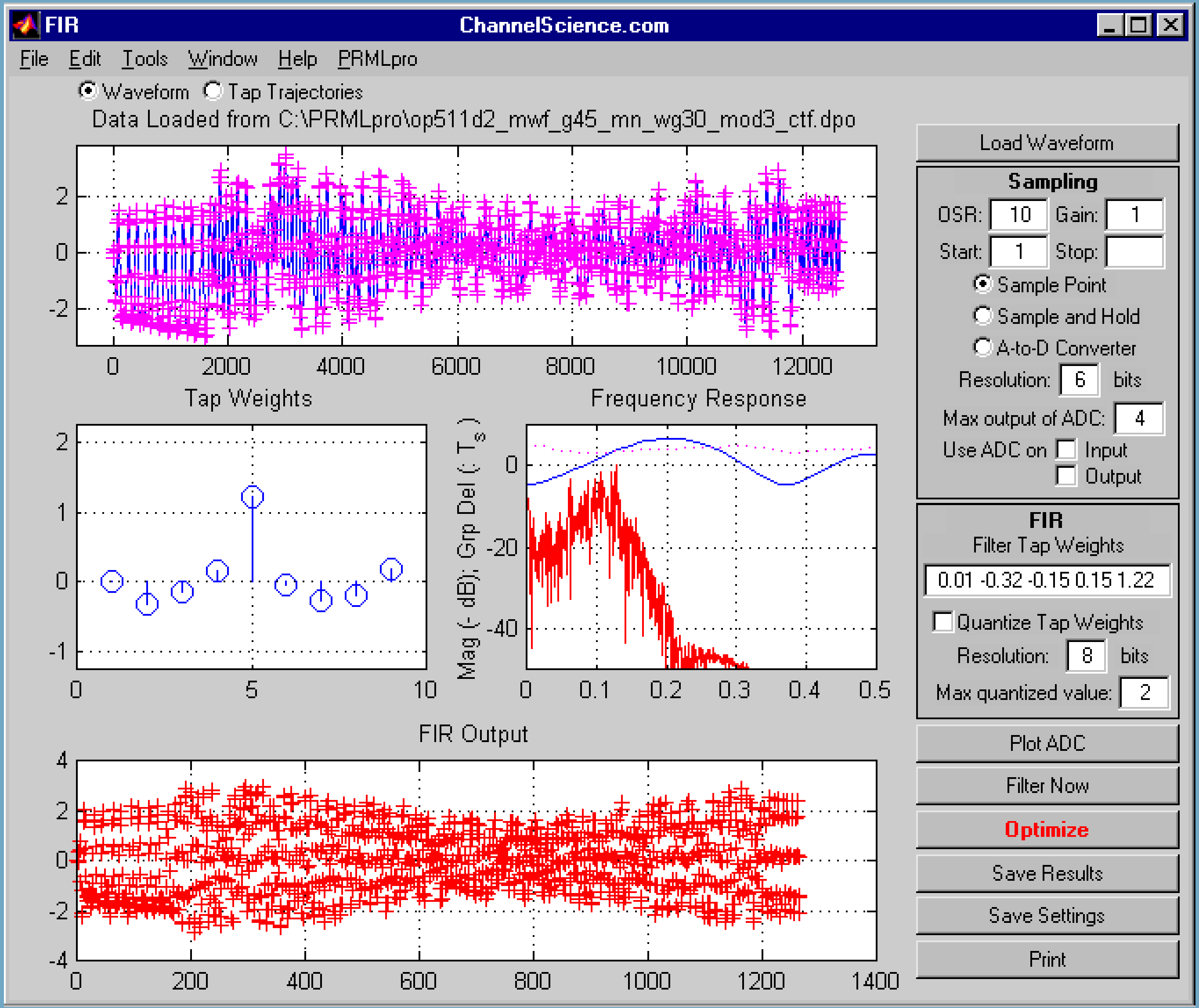
☐ Enable 3D

Note lack of HF rolloff.

Modulation

- Models Wobble and Periodic Intensity Variations
- Multiply Waveform by Sinusoid
- $1+0.3*\sin(2\pi*(0.001T_s)*t)$
  - 30% Amplitude Variation
  - 100 Bits / Modulation Period

Modulation Without LMS: MSE=0.152



● Waveform ○ Tap Trajectories

Data Loaded from C:\PRMLpro\op511d2_mwf_g45_mn_wg30_mod3_ctf.dpo

Sampling

OSR: 10 Gain: 1

Start: 1 Stop:

● Sample Point

○ Sample and Hold

○ A-to-D Converter

Resolution: 6 bits

Max output of ADC: 4

Use ADC on ☐ Input

☐ Output

FIR

Filter Tap Weights

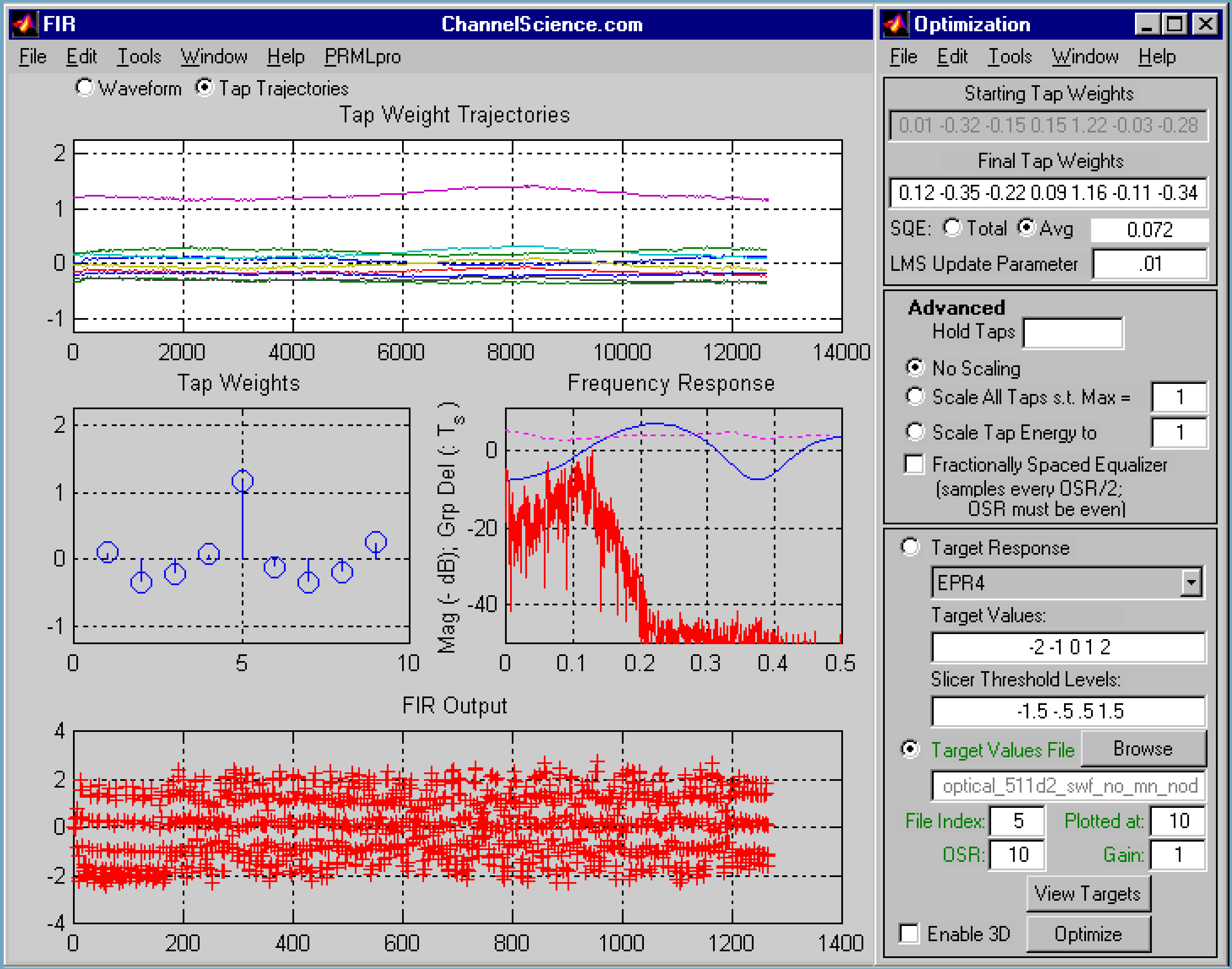
0.01 -0.32 -0.15 0.15 1.22

☐ Quantize Tap Weights

Resolution: 8 bits

Max quantized value: 2

Modulation with Data-directed LMS



○ Waveform ● Tap Trajectories

Starting Tap Weights: 0.01 -0.32 -0.15 0.15 1.22 -0.03 -0.28

Final Tap Weights: 0.12 -0.35 -0.22 0.09 1.16 -0.11 -0.34

SQE: ○ Total ● Avg 0.072

LMS Update Parameter .01

Advanced

Hold Taps

● No Scaling

○ Scale All Taps s.t. Max = 1

○ Scale Tap Energy to 1

☐ Fractionally Spaced Equalizer (samples every OSR/2; OSR must be even)

○ Target Response: EPR4

Target Values: -2 -1 0 1 2

Slicer Threshold Levels: -1.5 -.5 .5 1.5

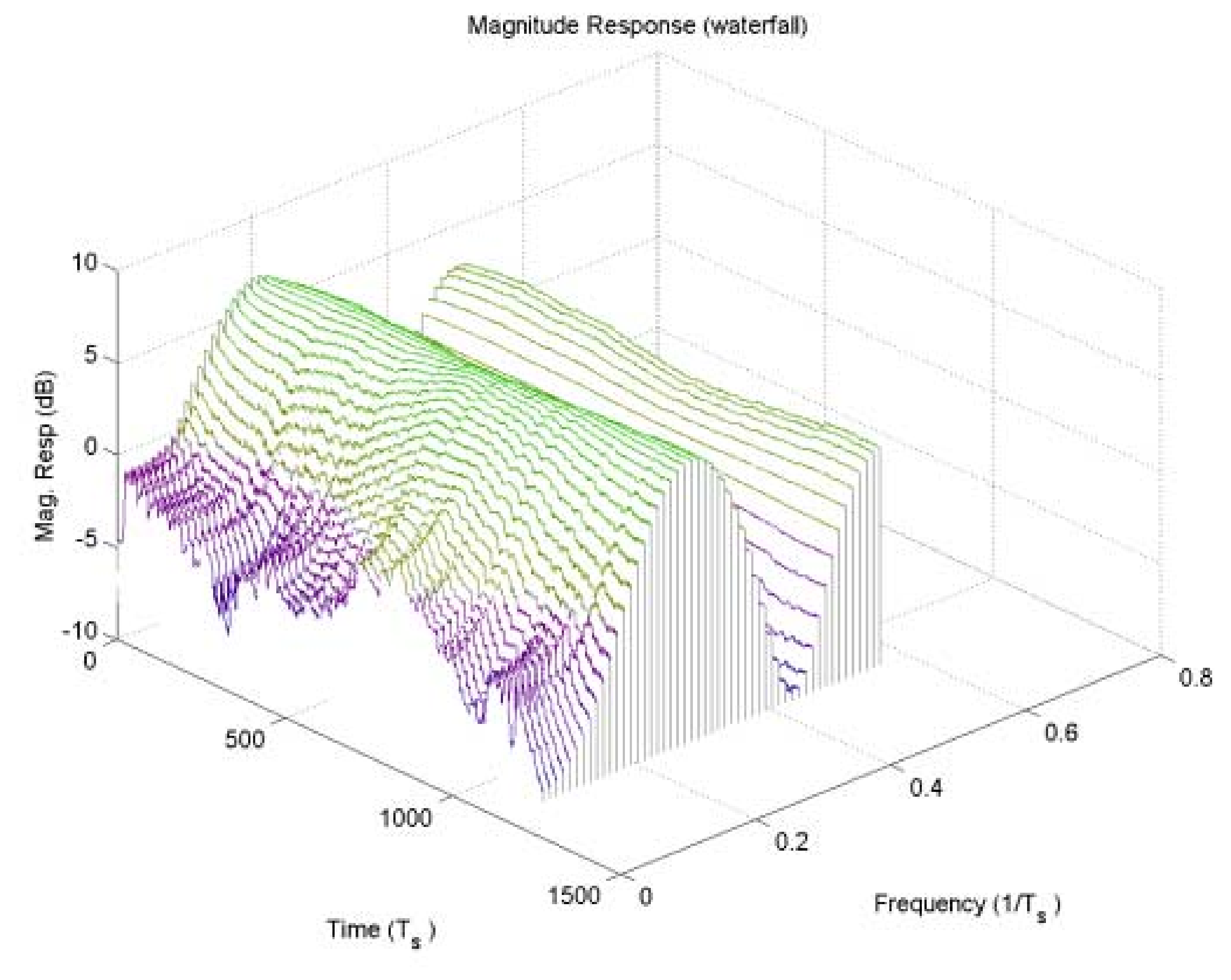
● Target Values File: optical_511d2_swf_no_mn_nod

File Index: 5 Plotted at: 10

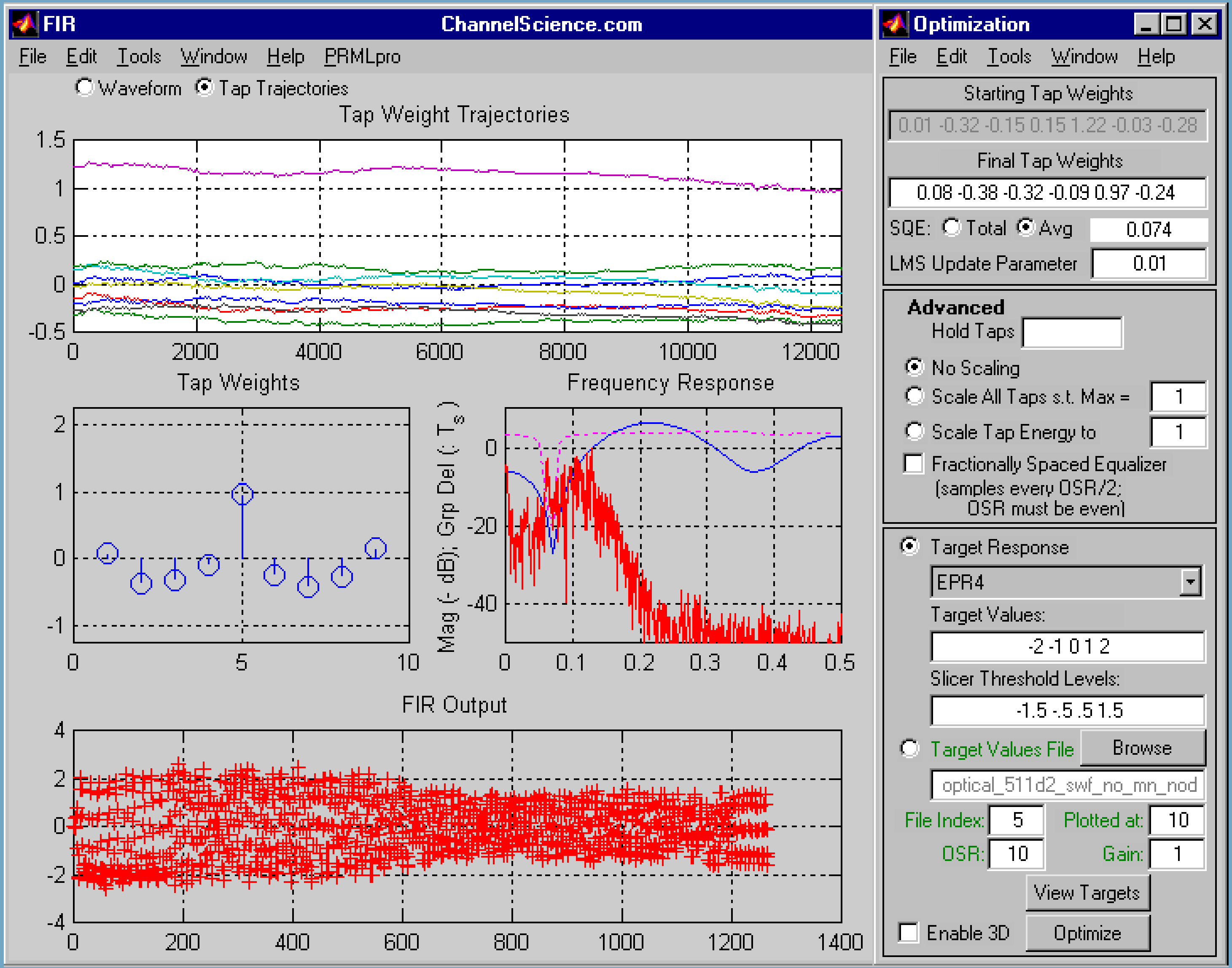
OSR: 10 Gain: 1

☐ Enable 3D

Modulation with Data-directed LMS



Modulation with Decision-directed LMS



Starting Tap Weights

0.01 -0.32 -0.15 0.15 1.22 -0.03 -0.28

Final Tap Weights

0.08 -0.38 -0.32 -0.09 0.97 -0.24

SQE: ○ Total ● Avg 0.074

LMS Update Parameter 0.01

Advanced

Hold Taps

● No Scaling

○ Scale All Taps s.t. Max = 1

○ Scale Tap Energy to 1

☐ Fractionally Spaced Equalizer (samples every OSR/2; OSR must be even)

● Target Response

EPR4

Target Values:

-2 -1 0 1 2

Slicer Threshold Levels:

-1.5 -.5 .5 1.5

○ Target Values File

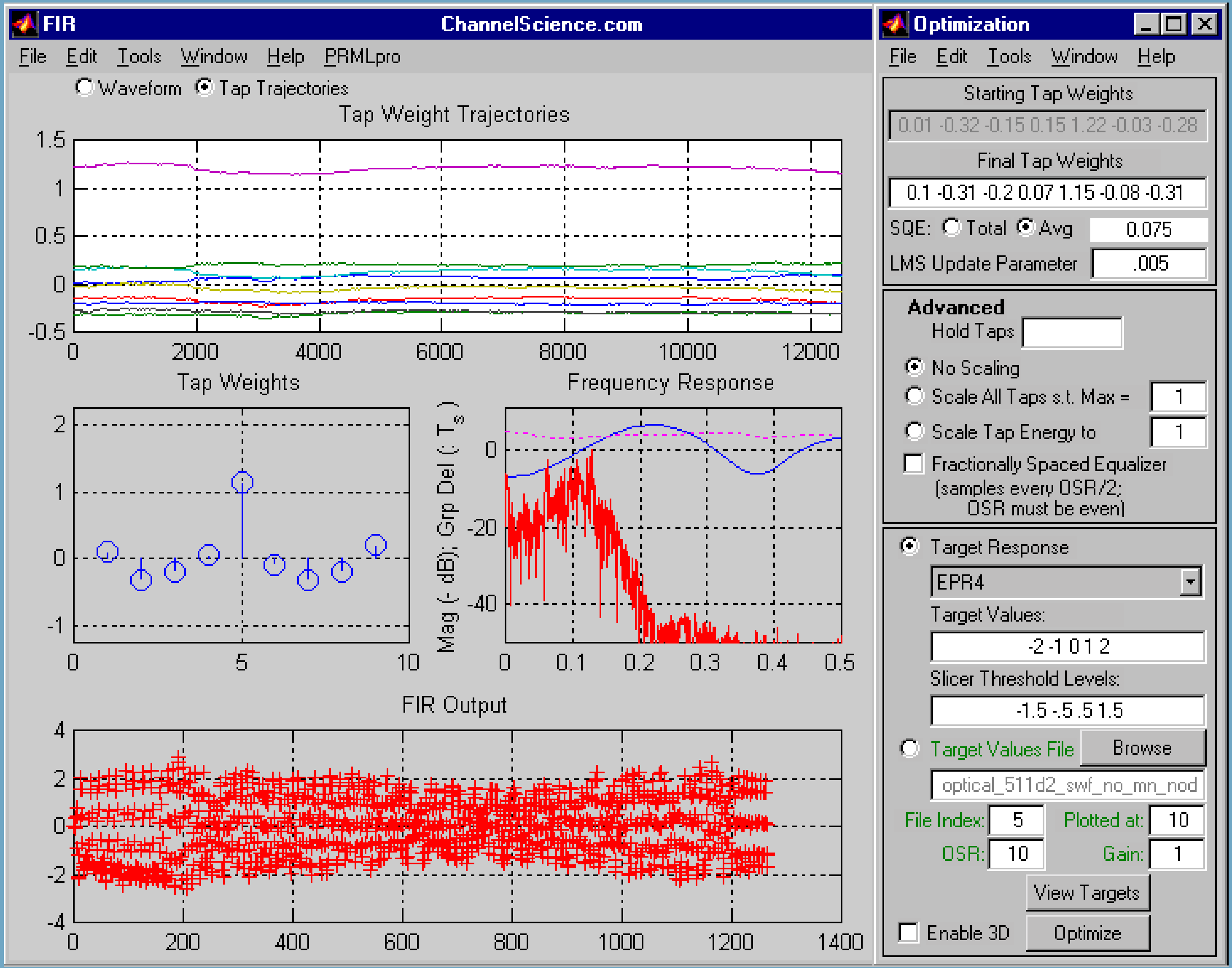
optical_511d2_swf_no_mn_nod

File Index: 5 Plotted at: 10

OSR: 10 Gain: 1

☐ Enable 3D

Decision-directed LMS with Smaller BW



○ Waveform ● Tap Trajectories

Starting Tap Weights: 0.01 -0.32 -0.15 0.15 1.22 -0.03 -0.28

Final Tap Weights: 0.1 -0.31 -0.2 0.07 1.15 -0.08 -0.31

SQE: ○ Total ● Avg 0.075

LMS Update Parameter: .005

Hold Taps:

● No Scaling

○ Scale All Taps s.t. Max = 1

○ Scale Tap Energy to 1

☐ Fractionally Spaced Equalizer (samples every OSR/2; OSR must be even)

● Target Response: EPR4

Target Values: -2 -1 0 1 2

Slicer Threshold Levels: -1.5 -.5 .5 1.5

○ Target Values File: optical_511d2_swf_no_mn_nod

File Index: 5 Plotted at: 10

OSR: 10 Gain: 1

☐ Enable 3D

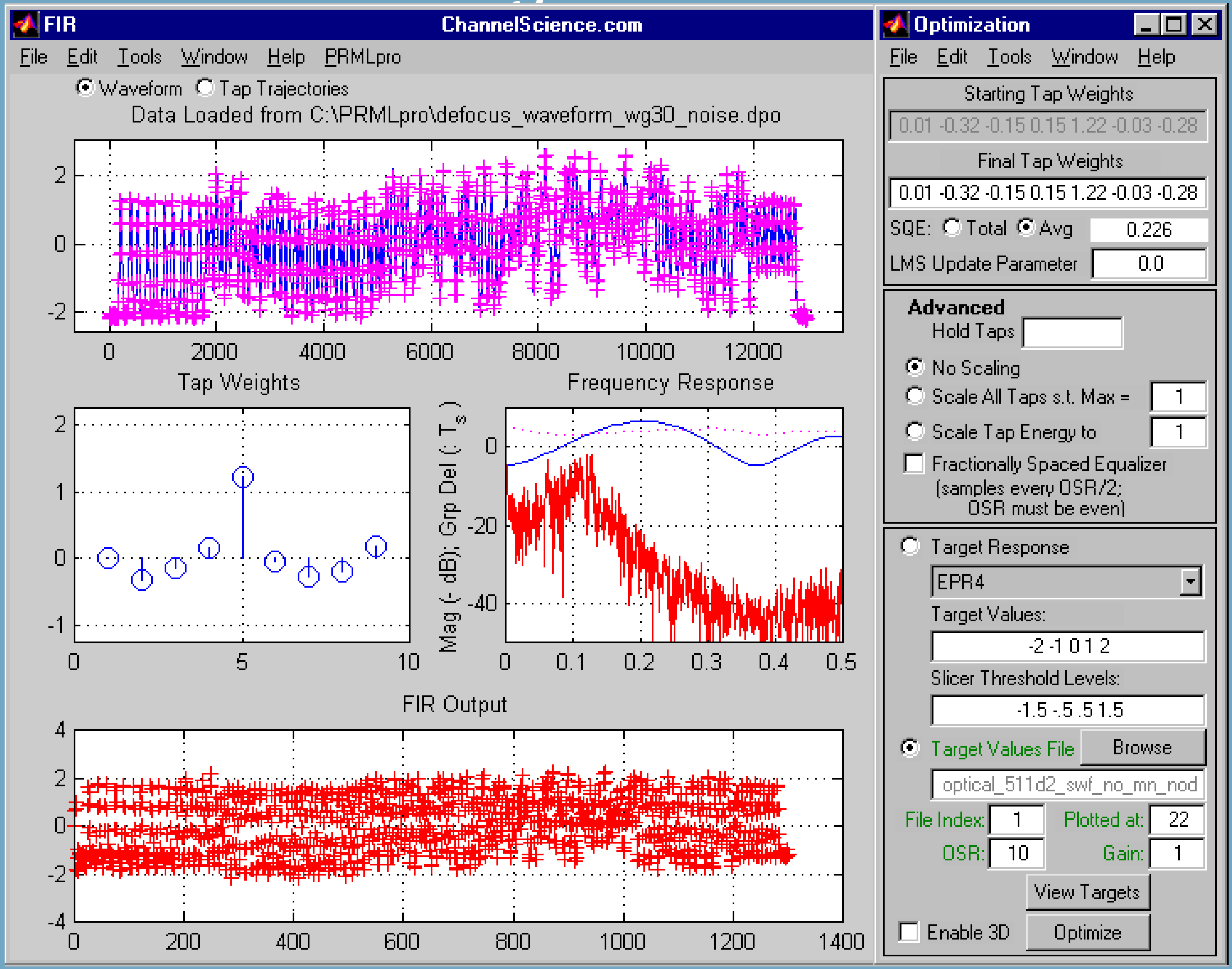
Observations: Modulation

- There is Not Sufficient Signal Energy to Properly Drive Adaptation at Higher Frequencies
- Decision-directed LMS Removes the Modulation Effects
- LMS Mostly Affects the Magnitude Response at Lower Frequencies - In Opposite Phase, Relative to the Magnitude of Modulation
- Data-directed LMS Adapts to Lower Amplitude “inner” Targets During Attenuation Phase of Modulation
- Lower LMS Bandwidth can Improve Data-directed Performance, under the Conditions Modeled

Defocusing

- Models Domain Bloom, Wobble and Focus Servo
- Four Sections of Different PW50/T
  - PW50/T = 4.5 (nominal to bit 250)
  - PW50/T = 2.25 (50% narrow to bit 500)
  - PW50/T = 4.5 (nominal to bit 750)
  - PW50/T = 6.25 (50% wide to bit 1000)
  - PW50/T = 4.5 (nominal to end)
- Abrupt Jump Between Each PW50/T Section
- No Transition Jitter

Defocusing without LMS



● Waveform ○ Tap Trajectories

Data Loaded from C:\PRMLpro\defocus_waveform_wg30_noise.dpo

Starting Tap Weights

0.01 -0.32 -0.15 0.15 1.22 -0.03 -0.28

Final Tap Weights

0.01 -0.32 -0.15 0.15 1.22 -0.03 -0.28

SQE: ○ Total ● Avg 0.226

LMS Update Parameter 0.0

Advanced

Hold Taps

● No Scaling

○ Scale All Taps s.t. Max = 1

○ Scale Tap Energy to 1

☐ Fractionally Spaced Equalizer (samples every OSR/2; OSR must be even)

○ Target Response

EPR4

Target Values: -2 -1 0 1 2

Slicer Threshold Levels: -1.5 -.5 .5 1.5

● Target Values File Browse

optical_511d2_swf_no_mn_nod

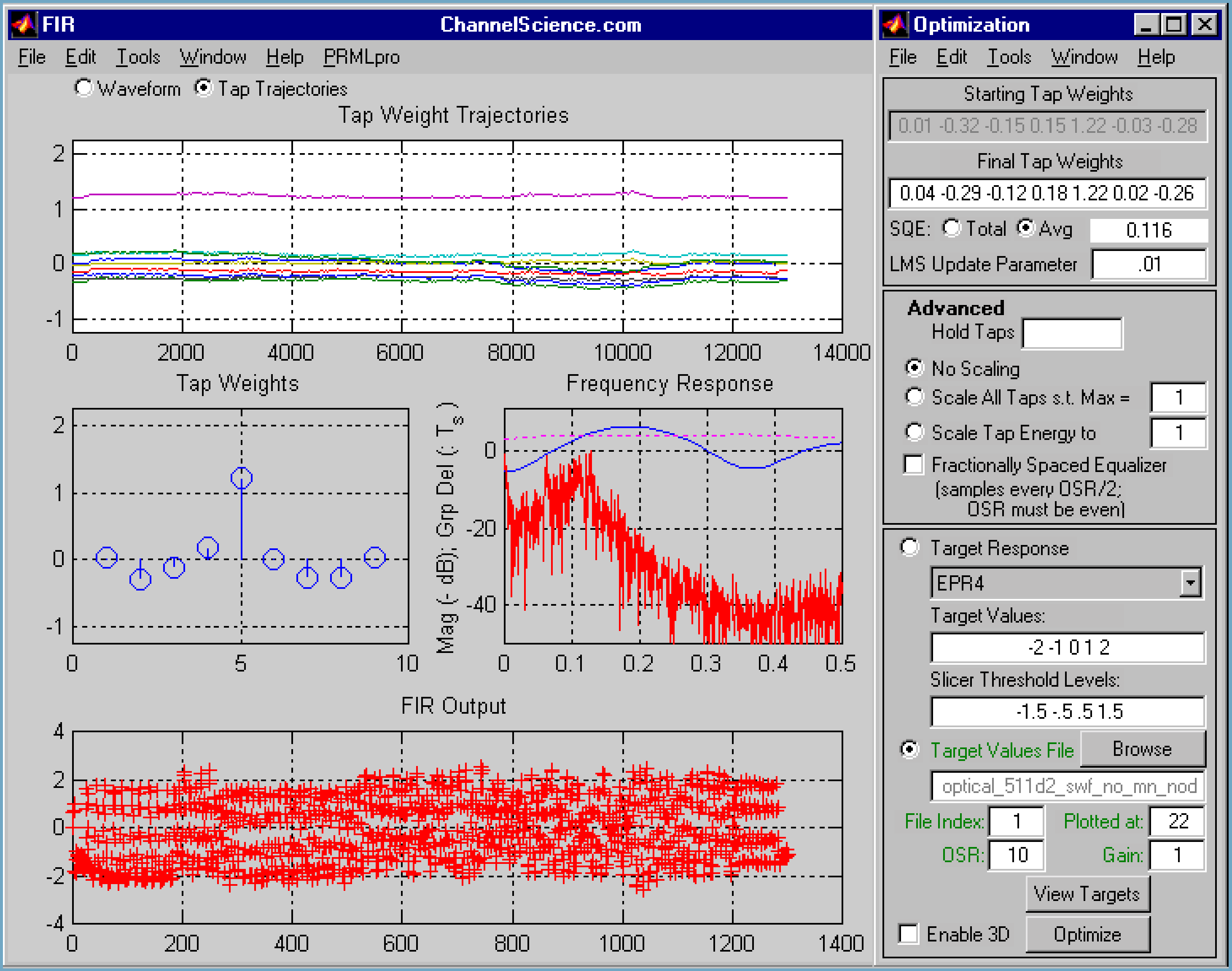
File Index: 1 Plotted at: 22

OSR: 10 Gain: 1

View Targets

☐ Enable 3D Optimize

Defocusing with Data-directed LMS



○ Waveform ● Tap Trajectories

Starting Tap Weights: 0.01 -0.32 -0.15 0.15 1.22 -0.03 -0.28

Final Tap Weights: 0.04 -0.29 -0.12 0.18 1.22 0.02 -0.26

SQE: ○ Total ● Avg 0.116

LMS Update Parameter .01

Hold Taps

● No Scaling

○ Scale All Taps s.t. Max = 1

○ Scale Tap Energy to 1

☐ Fractionally Spaced Equalizer (samples every OSR/2; OSR must be even)

○ Target Response: EPR4

Target Values: -2 -1 0 1 2

Slicer Threshold Levels: -1.5 -.5 .5 1.5

● Target Values File: optical_511d2_swf_no_mn_nod

File Index: 1 Plotted at: 22

OSR: 10 Gain: 1

☐ Enable 3D

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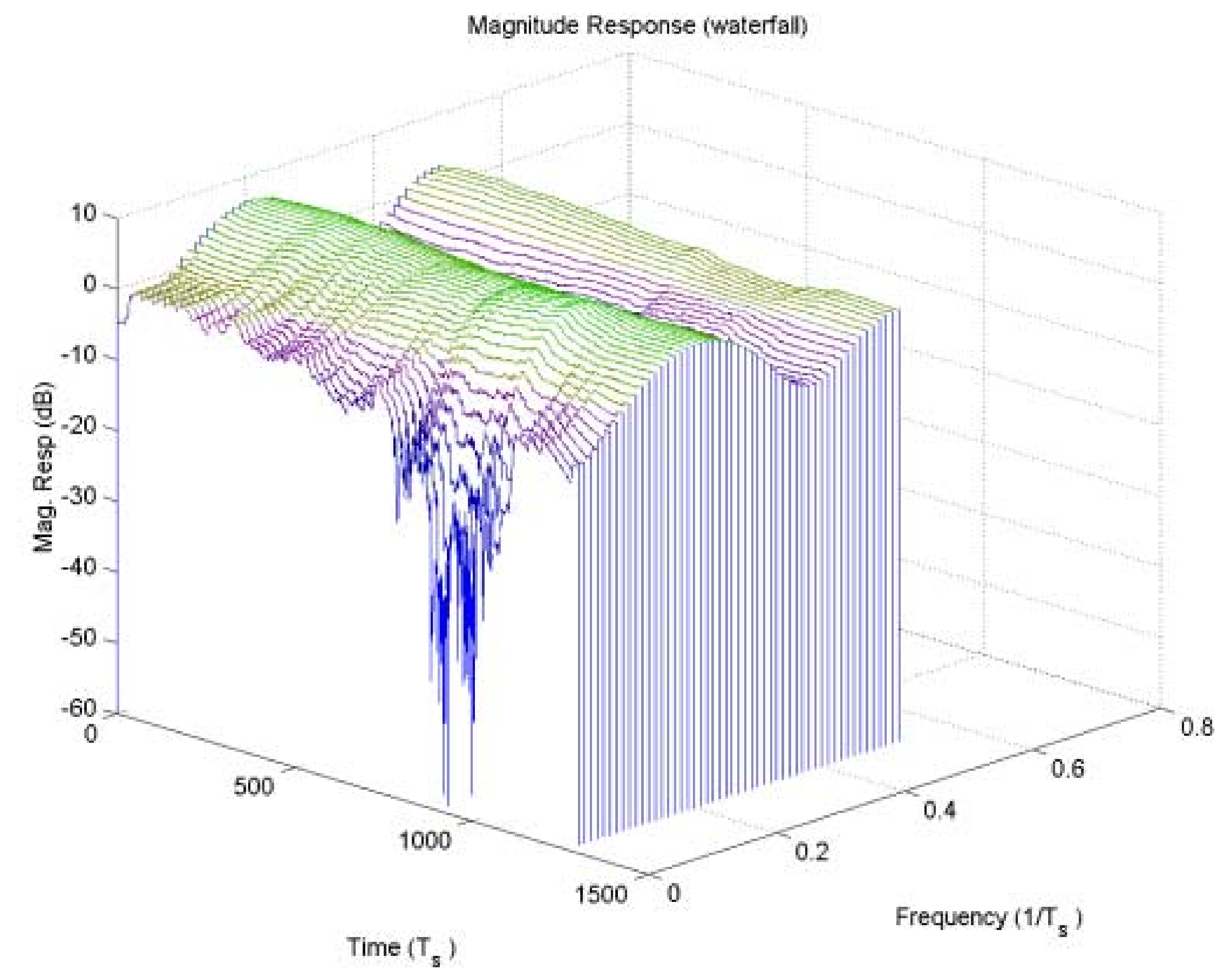
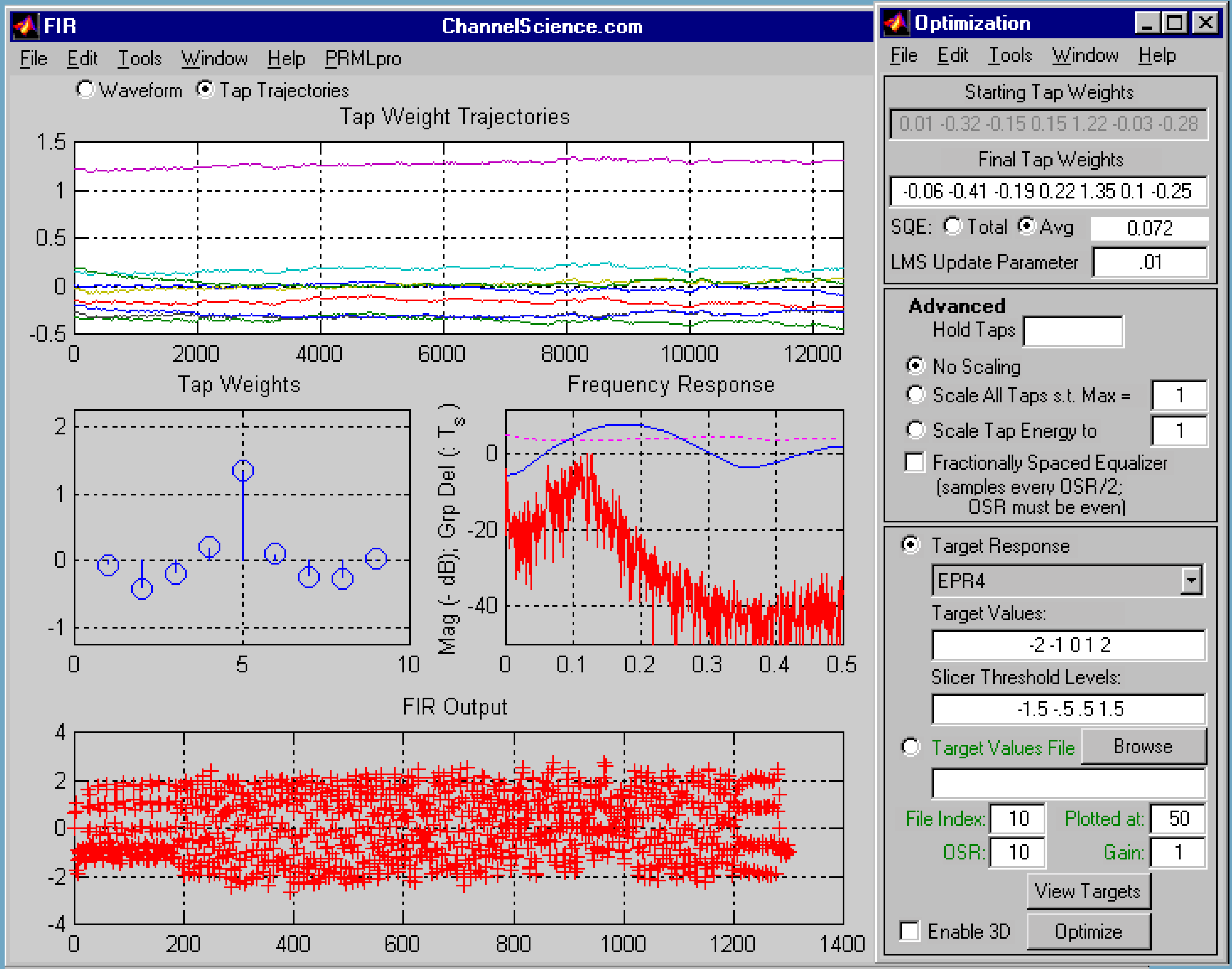
Defocusing with Data-directed LMS



Defocusing with Decision-directed LMS



○ Waveform ● Tap Trajectories

Starting Tap Weights: 0.01 -0.32 -0.15 0.15 1.22 -0.03 -0.28

Final Tap Weights: -0.06 -0.41 -0.19 0.22 1.35 0.1 -0.25

SQE: ○ Total ● Avg 0.072

LMS Update Parameter: .01

Hold Taps:

● No Scaling

○ Scale All Taps s.t. Max = 1

○ Scale Tap Energy to 1

☐ Fractionally Spaced Equalizer (samples every OSR/2; OSR must be even)

● Target Response: EPR4

Target Values: -2 -1 0 1 2

Slicer Threshold Levels: -1.5 -.5 .5 1.5

○ Target Values File

File Index: 10 Plotted at: 50

OSR: 10 Gain: 1

☐ Enable 3D

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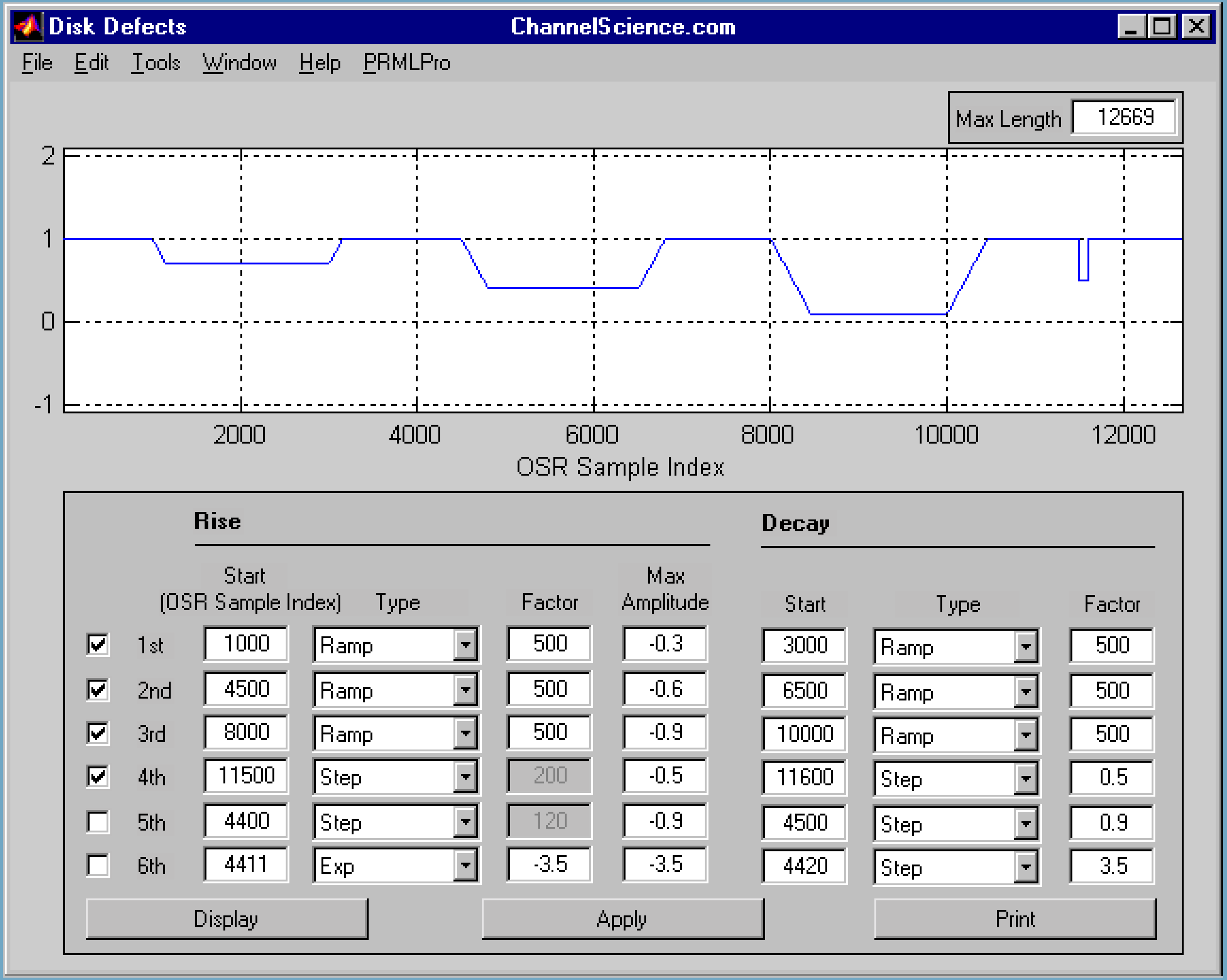
Observations: Defocusing

- There is Not Sufficient Signal Energy to Properly Drive Adaptation at Higher Frequencies
- As Modeled, the Filter Magnitude Response Change is Minimal, Even for Large PW50T Fluctuations
- Decreased PW50/T has Less of an Effect on LMS than does Increased PW50/T
- Increased PW50/T Causes the Filter to Attenuate Lower Frequencies More, but Little Additional High Frequency Boost is Applied

Disk Defects

- Models Pits and Scratches (Pinholes and Wedges)
- Linear Slopes, Flat “Bottoms”
- Defect 1
  - 2%/T; Attenuated to 70%; Total Duration 200 T
- Defect 2
  - 2%/T; Attenuated to 40%; Total Duration 200 T
- Defect 3
  - 2%/T; Attenuated to 10%; Total Duration 200 T
- Defect 4
  - Step; Attenuated to 50%; Total Duration 10 T

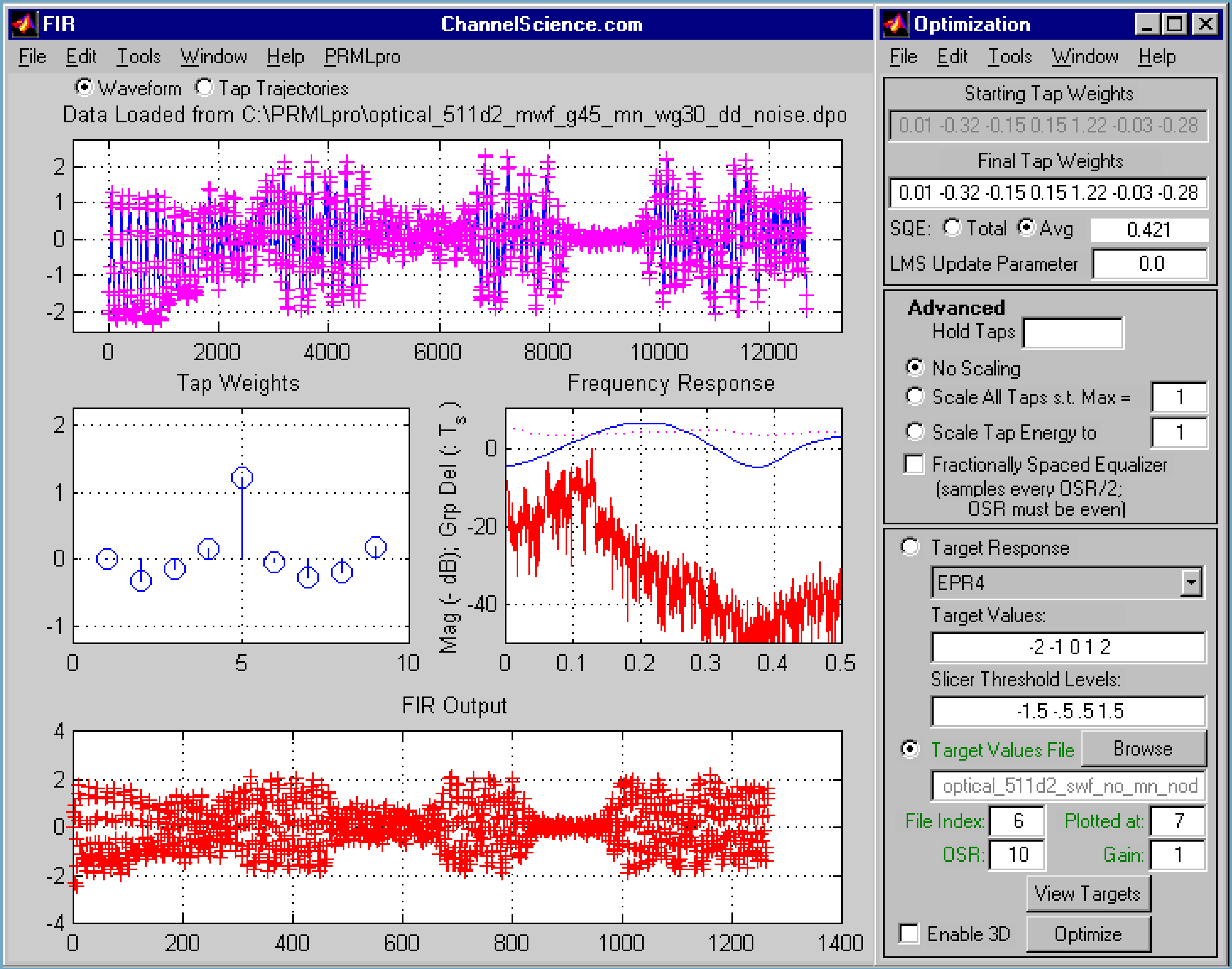
Disk Defect Profile



Max Length 12669

		Rise				**Decay**		
		Start (OSR Sample Index)	Type	Factor	Max Amplitude	Start	Type	Factor
☑	1st	1000	Ramp	500	-0.3	3000	Ramp	500
☑	2nd	4500	Ramp	500	-0.6	6500	Ramp	500
☑	3rd	8000	Ramp	500	-0.9	10000	Ramp	500
☑	4th	11500	Step	200	-0.5	11600	Step	0.5
☐	5th	4400	Step	120	-0.9	4500	Step	0.9
☐	6th	4411	Exp	-3.5	-3.5	4420	Step	3.5

Disk Defects without LMS



● Waveform ○ Tap Trajectories

Data Loaded from C:\PRMLpro\optical_511d2_mwf_g45_mn_wg30_dd_noise.dpo

Starting Tap Weights: 0.01 -0.32 -0.15 0.15 1.22 -0.03 -0.28

Final Tap Weights: 0.01 -0.32 -0.15 0.15 1.22 -0.03 -0.28

SQE: ○ Total ● Avg 0.421

LMS Update Parameter: 0.0

Advanced

Hold Taps:

● No Scaling

○ Scale All Taps s.t. Max = 1

○ Scale Tap Energy to 1

☐ Fractionally Spaced Equalizer (samples every OSR/2; OSR must be even)

○ Target Response: EPR4

Target Values: -2 -1 0 1 2

Slicer Threshold Levels: -1.5 -.5 .5 1.5

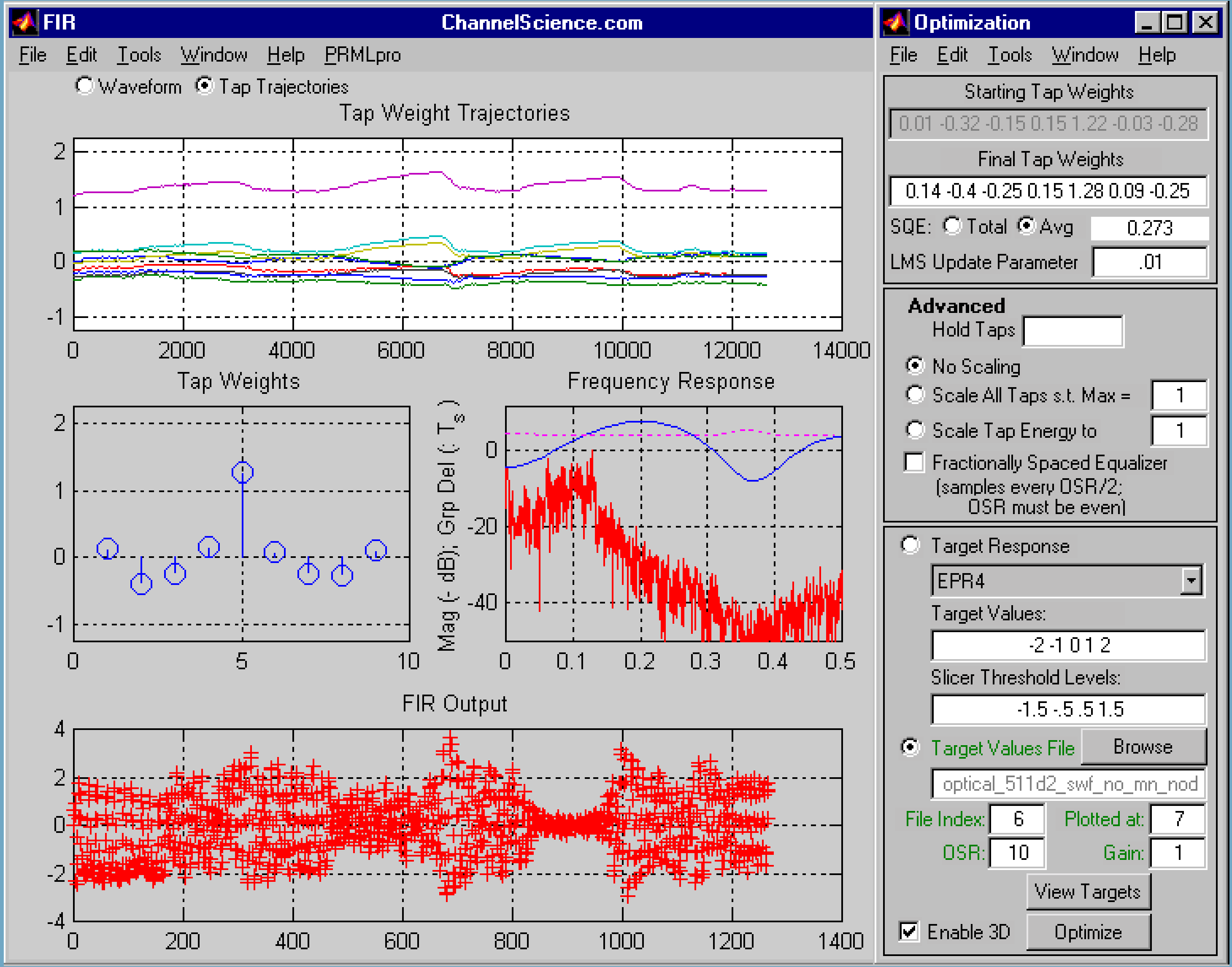
● Target Values File: optical_511d2_swf_no_mn_nod

File Index: 6 Plotted at: 7

OSR: 10 Gain: 1

☐ Enable 3D

Disk Defects with Data-directed LMS



○ Waveform ● Tap Trajectories

Starting Tap Weights

0.01 -0.32 -0.15 0.15 1.22 -0.03 -0.28

Final Tap Weights

0.14 -0.4 -0.25 0.15 1.28 0.09 -0.25

SQE: ○ Total ● Avg 0.273

LMS Update Parameter .01

Advanced

Hold Taps

● No Scaling

○ Scale All Taps s.t. Max = 1

○ Scale Tap Energy to 1

☐ Fractionally Spaced Equalizer (samples every OSR/2; OSR must be even)

○ Target Response

EPR4

Target Values: -2 -1 0 1 2

Slicer Threshold Levels: -1.5 -.5 .5 1.5

● Target Values File

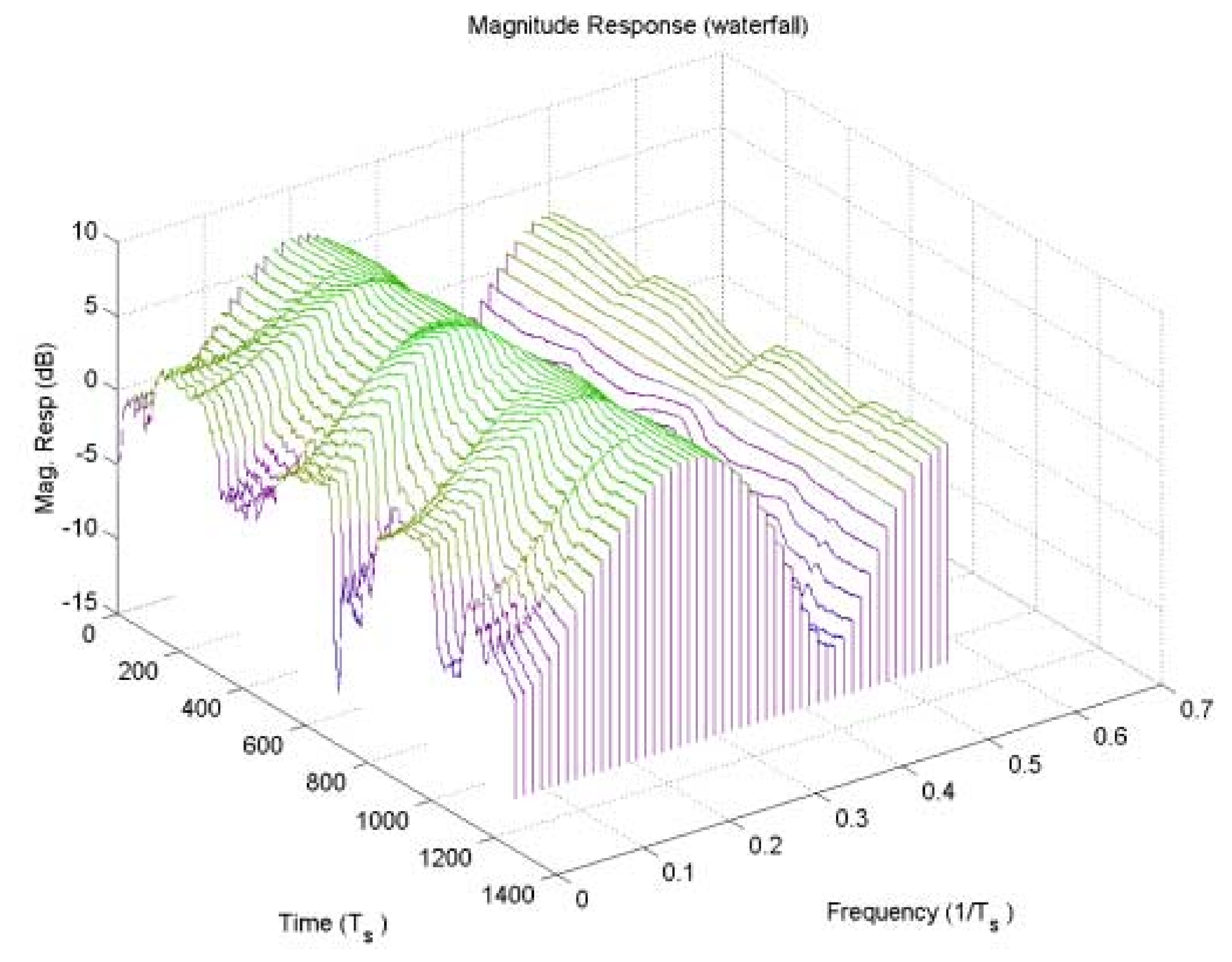
optical_511d2_swf_no_mn_nod

File Index: 6 Plotted at: 7

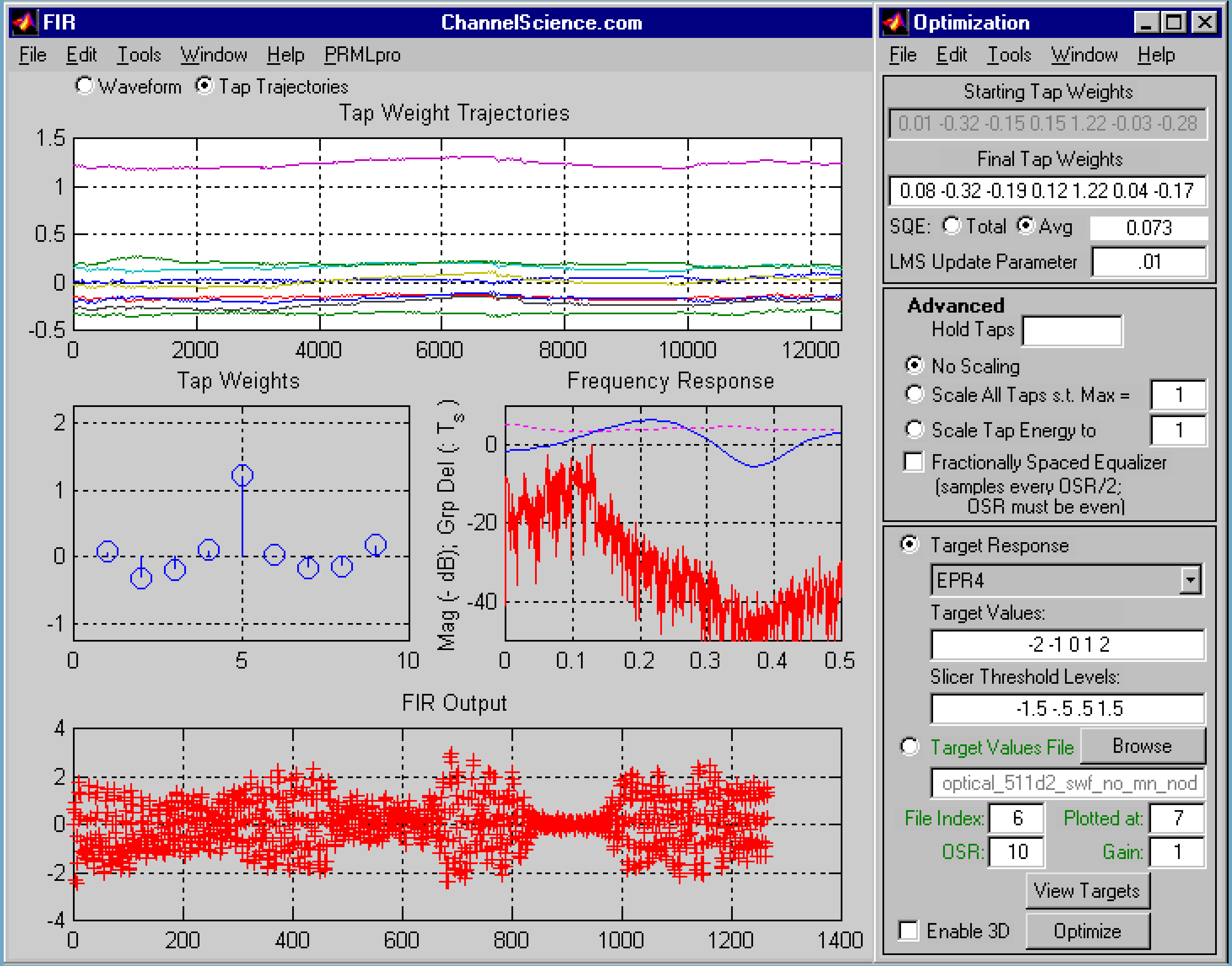
OSR: 10 Gain: 1

☑ Enable 3D

Disk Defects with Data-directed LMS



Disk Defects with Decision-directed LMS



○ Waveform ● Tap Trajectories

Starting Tap Weights: 0.01 -0.32 -0.15 0.15 1.22 -0.03 -0.28

Final Tap Weights: 0.08 -0.32 -0.19 0.12 1.22 0.04 -0.17

SQE: ○ Total ● Avg 0.073

LMS Update Parameter .01

Advanced

Hold Taps

● No Scaling

○ Scale All Taps s.t. Max = 1

○ Scale Tap Energy to 1

☐ Fractionally Spaced Equalizer (samples every OSR/2; OSR must be even)

● Target Response: EPR4

Target Values: -2 -1 0 1 2

Slicer Threshold Levels: -1.5 -.5 .5 1.5

○ Target Values File: optical_511d2_swf_no_mn_nod

File Index: 6

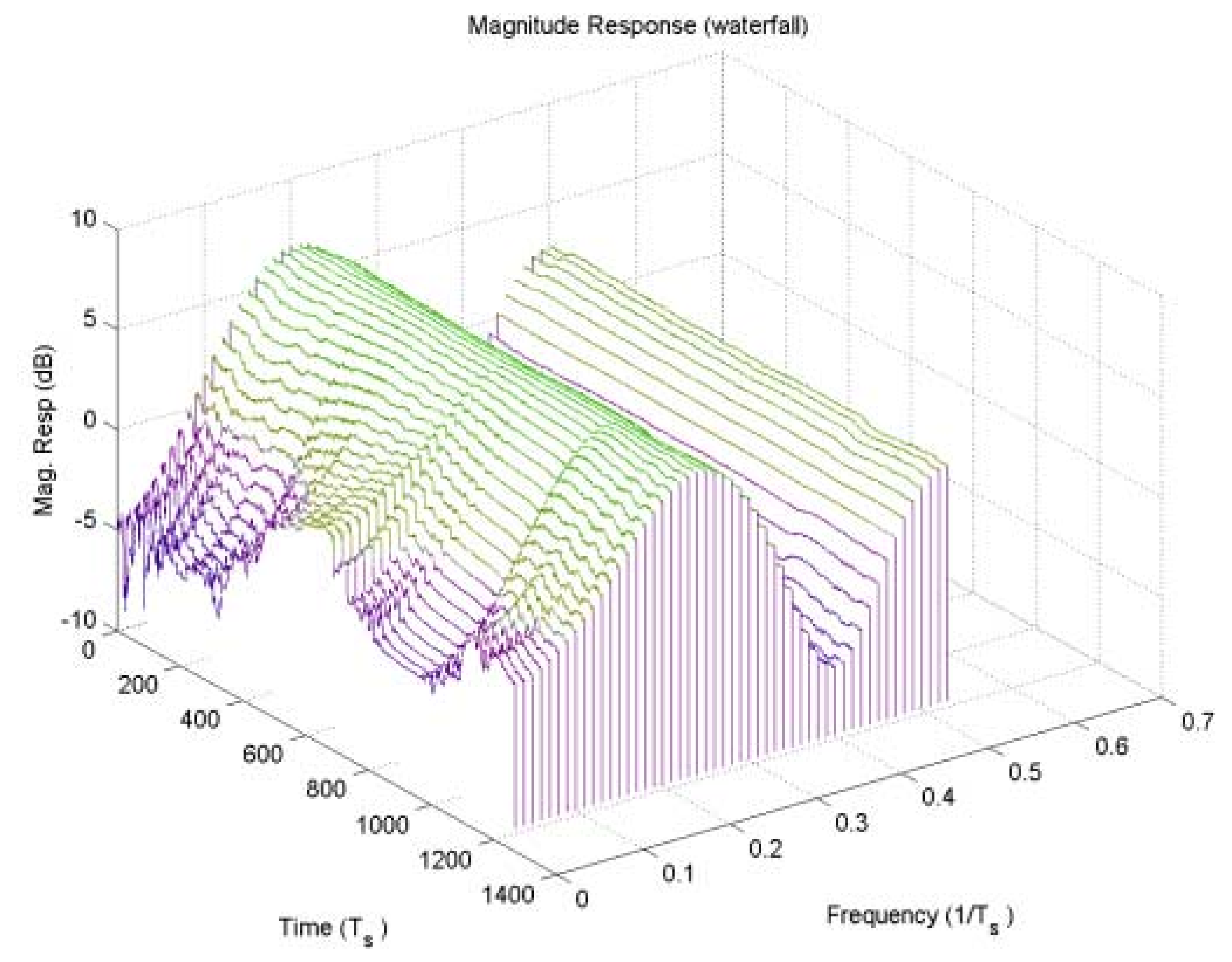
Plotted at: 7

OSR: 10

Gain: 1

☐ Enable 3D

Disk Defects with Decision-directed LMS



Observations: Disk Defects

- There is Not Sufficient Signal Energy to Properly Drive Adaptation at Higher Frequencies
- Data-directed Adaptation Increases the Amplitude of the Signal more Successfully during Smaller Attenuation Defects. This is Because the Adjustment is Weighted by the Input Samples.
- LMS has a Tendency to “Overshoot” the Gain Needed, When Coming Out of a Defect - This can be Improved by Decreasing the LMS Bandwidth, but the Performance Going Into a Defect will be Impaired
- LMS Responds to Disk Defects by Increasing the Low Frequency Gain of the FIR Magnitude Response - There is Little Change at the Higher Frequencies
- Defects that Attenuate the Signal to a Level Just ABOVE the Inner Targets cause Decision-directed LMS to Further DECREASE the Signal Amplitude

Summary of Results: MSE

Distortion	**Adaptation**	**MSE**	**MSE w.r.t. No Adaptation, No Distortion**
Nominal Case (Noise and Jitter)	None	0.093	1
Nominal Case	Data-Directed	0.072	0.77
Nominal Case	Decision-Directed	0.063	0.68 (errors)
Modulation	None	0.152	1.63
Modulation	Data-Directed	0.072	0.77
Modulation	Decision-Directed	0.074	0.80 (errors)
Defocusing (no jitter)	None	0.226	2.43
Defocusing (no jitter)	Data-Directed	0.116	1.25
Defocusing (no jitter)	Decision-Directed	0.072	0.77 (errors)
Disk Defects	None	0.421	4.53
Disk Defects	Data-Directed	0.273	2.94
Disk Defects	Decision-Directed	0.073	0.78 (errors)

Conclusions

- RLL d=2 Constraint does not Provide Sufficient Signal Energy for LMS to Properly Control the Filter at Higher Frequencies
- Decision-directed LMS Adaptation Sometimes gives Erroneously Low MSE Values due to Incorrect Decisions
- For the Distortions Studied, LMS Mostly Adapts the Lower Frequency Portion of the FIR Magnitude Response
- For the Conditions as Modeled, LMS Respond Very Little to PW50/T Variation
- High LMS Step-size Parameter Values during Disk Defects can cause Overshoot, and Even Ringing, in FIR Magnitude Response
- Deep Disk Defects Cause LESS of a Disruption to LMS Adaptation than Defects that Attenuate Largest Signal Down to Intermediate Levels

References

- Christopher Painter, “A Maximum Likelihood Sequence Detector for DVD,” 1998, contact Chis Painter chrisp@colorado.cirrus.com.

- Inci Ozgunes, *et al*, “Effect of Transition Noise on the Signal-to-Noise Ratio of Magneto-optic Read Channels,” *IEEE Trans. Magn.*, Vol. 32, No.4; July 1996; pp. 3291-3304.

- PRML*pro*$^{\text{TM}}$ is available for download at www.ChannelScience.com

- Chun-Sup Kim, *et al*, “A CMOS 4X Speed DVD Read Channel IC,” *IEEE Journal of Solid-State Circuits*, Vol. 33, No. 8; August, 1998; pp. 1168-1178.

- Jan W.M. Bergmans, “Digital Baseband Transmission and Recording,” Kluwer Academic Publishers, ISBN 0-7923-9775-4, 1996