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De-Convoluting Wire Signals

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Background

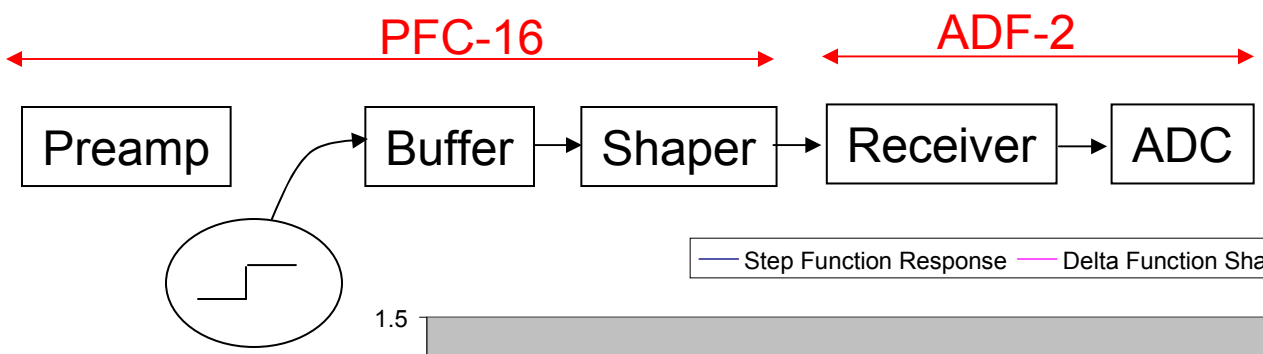
- Wire signals undergo significant modification in the DAQ
  - Preamplifier integrates and returns to baseline with a 200 μsec time constant
  - Low and high frequency filtering in the PFC-16 card → "*Shaper*"

http://www.pa.msu.edu/people/edmunds/LArTPC/T962/t962_readout_path_vs_signal_shape.txt

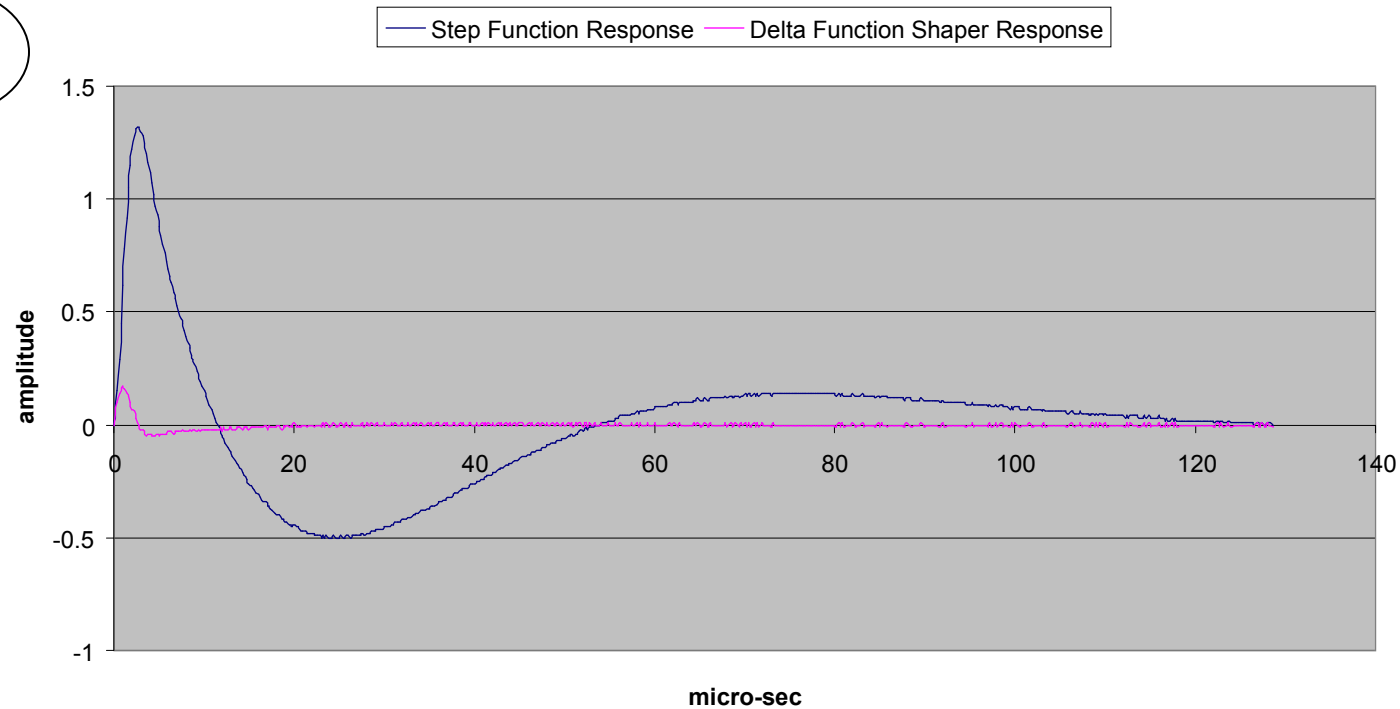
- Philosophy: Maximize S/N
  - Data size not important
- Some level of pre-processing is required off-line before hits can be identified

Shaper Response

Dan's results from 1st Production Card

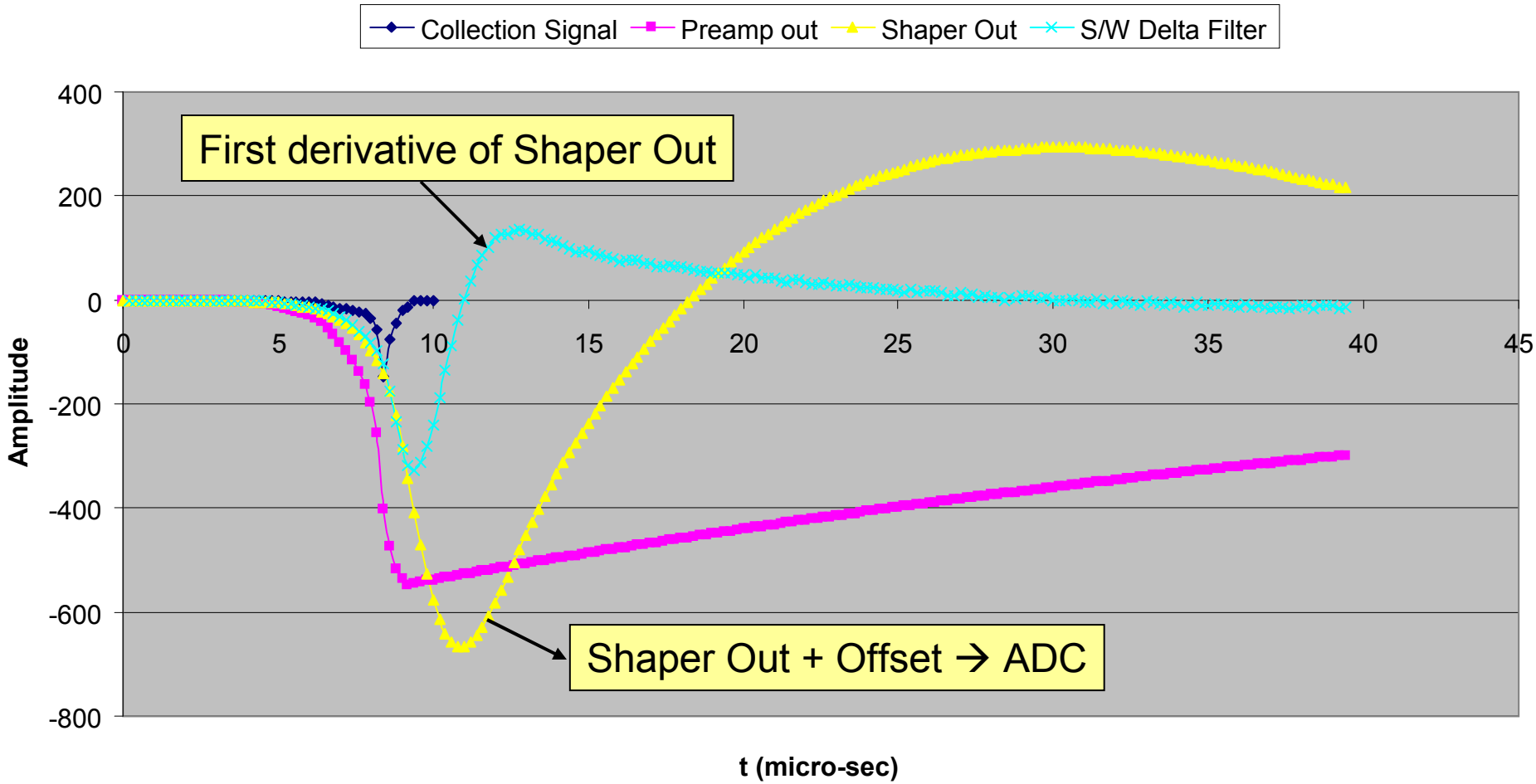


Subtracted 400 count offset



http://www.pa.msu.edu/~edmunds/LArTPC/T962/Preamp_Filter_Card/Testing/

Garfield Collection Plane Signal



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Problem & Resolution

- Simple minded software filter is inadequate
  - Significant baseline shift

- Propose FFT de-convolution of the ADC's to "restore" the wire signals
  - Significant computation
  - \+ Remove coherent and incoherent noise offline
  - \+ Consider different induction plane & collection plane de-convolution schemes
    - Make wire signals look alike in both planes

Convolution & De-convolution

Convolution

$$\text{ADC} = \text{Shaper Out} = \text{Signal} \otimes \text{Preamp} \otimes \text{Shaper}$$

Complex Multiplication

Fourier Transform

$$\text{ADC} = \mathcal{F}^{-1}\{ (\mathcal{F}(\text{Signal}) * \mathcal{F}(\text{Preamp}) * \mathcal{F}(\text{Shaper}) \}$$

De-convolution

$$\text{Signal} = \mathcal{F}^{-1}\{ (\mathcal{F}(\text{ADC}) / (\mathcal{F}(\text{Preamp}) * \mathcal{F}(\text{Shaper})) \}$$

De-convolution & Filter

$$\text{Signal} = \mathcal{F}^{-1}\{ \text{Filter} * \mathcal{F}(\text{ADC}) / (\mathcal{F}(\text{Preamp}) * \mathcal{F}(\text{Shaper})) \}$$

De-Convolution to Arbitrary Form

ADC for single hit
e.g. induction plane

Response
Function

Desired Output
Shape - Gaussian

Calculate R

$$\mathcal{F}(R) = \mathcal{F}(G_1) \,/\, \mathcal{F}(ADC_1)$$

De-convolute n hits
in the ADC channel
to a Gaussian form

$$G_n = \mathcal{F}^{-1} \{ (\mathcal{F}(ADC) \,/\, \mathcal{F}(R) \}$$

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Excel FFT Test Bed

- Created FFT.xls to test these concepts
  - Multiple Garfield simulated wire signals
  - Excel formula preamp simulation
  - Dan's step function response measurements
  - User selectable coherent or random noise
  - 1024 "ADC" bins @ 0.2 μsec/bin
  - Simulate 10 bit round-off error
  - User selectable filtering
  - Visual Basic macro convolutes wire signals, applies the filter and de-convolutes
    - Compare rms difference between original wire signal and de-convoluted wire signal

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Convolution Section

Noise	Amp	Freq (kHz)	omega	Preamp RC
	0	1500	9.42	0.999

Pick Noise

Do FFT

Time (micro-sec)	Wire Signal 1	Wire Signal 2	Signal 1 + Signal 2	Noise	Signal + Noise	Preamp Kernel	Preamp out	Shaper Kernel
0	0	0	0	0.71	1	1.00	0	0.00
0.2	0	0	0	0.53	0	1.00	0	0.05
0.4	0	0	0	0.58	0	1.00	0	0.10
0.6	0	0	0	0.29	0	1.00	0	0.13
0.8	0	0	0	0.30	0	1.00	0	0.16
1	0	0	0	0.77	1	1.00	0	0.16
1.2	0	0	0	0.01	0	0.99	-1	0.16
1.4	0	0	0	0.76	1	0.99	-1	0.14
1.6	0	0	0	0.81	1	0.99	-1	0.12
1.8	0	0	0	0.71	0	0.99	-1	0.10
2	0	0	0	0.05	0	0.99	-1	0.08
2.2	0	0	0	0.41	0	0.99	-1	0.06
2.4	0	0	0	0.86	1	0.99	-1	0.03
2.6	0	0	0	0.79	1	0.99	-2	0.01
2.8	0	0	0	0.37	0	0.99	-2	0.00
3	0	0	0	0.96	1	0.99	-2	-0.02
3.2	0	0	0	0.87	1	0.98	-2	-0.02
3.4	0	0	0	0.06	0	0.98	-2	-0.03
3.6	0	0	0	0.95	1	0.98	-3	-0.04
3.8	0	0	0	0.36	0	0.98	-3	-0.05
4	0	0	-1	0.52	0	0.98	-3	-0.05
4.2	-1	0	-1	0.77	0	0.98	-4	-0.05

Signal Convolution

FFT_F	FFT_G	FFT_I			InvFFT_O	-109
FFT Wire Signal + Noise	FFT Preamp Kernel	FFT Shaper Kernel	FFT Preamp * FFT Shaper	FFT Signal * FFT Preamp * FFT Shaper	Inv FFT (Col O)	Shaper Out
-614.67162	641.16503	-0.496833	-318.55237	195805.10	86.315363	-23
-1077.6520	16.901380	-0.416658	36.649754	-54153.322	85.978314	-23
-952.64658	4.5477324	-0.190061	140.476410	-46296.870	85.642952	-23
-765.47992	2.2061668	0.1444184	36.872047	-26052.632	85.309279	-24
-524.32290	1.3825442	0.5324589	31.254051	-4443.5387	84.966991	-24
-252.69720	1.0006053	0.9160168	24.889105	13130.335	84.602698	-24
31.554631	0.7929411	1.2454377	18.559415	23578.436	84.226331	-25
315.30971	0.6676610	1.4885818	12.831543	26486.271	83.820681	-25
577.36988	0.5863232	1.6349035	8.0641846	23872.474	83.394815	-26
798.10228	0.5305463	1.6939362	4.4053167	17669.307	82.959455	-26
945.68555	0.4906435	1.6891936	1.8163388	10347.990	82.520727	-26
1031.0972	0.4611167	1.6496522	0.1227897	3337.5671	82.066830	-27
1031.7130	0.4386574	1.6014046	-0.9205744	-1998.6785	81.589531	-27
959.46206	0.4211776	1.5617111	-1.5656788	-5807.0036	81.102984	-28
823.70016	0.4073073	1.5366963	-2.0212656	-8420.5078	80.616593	-28
630.04329	0.3961170	1.5227096	-2.4251842	-9847.1838	80.124141	-29
394.29915	0.3869582	1.5102843	-2.8401517	-10131.728	79.638317	-29
133.54164	0.3793675	1.4890153	-3.2683947	-9438.1790	79.165830	-30
-143.93793	0.3730063	1.4516653	-3.6768548	-7675.6413	78.692063	-30
-373.47926	0.3676226	1.3963321	-4.0237426	-5429.7692	78.216649	-31
-577.86327	0.3630261	1.3263288	-4.2789455	-2678.3391	77.728275	-31
-739.87633	0.3590704	1.2482405	-4.4342134	-130.72308	77.219143	-32

Garfield wire signals

From Dan's measurements

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Deconvolution Section

User inserted values

Signal Deconvolution

FFT_Q	Filter		InvFFT_U	rms err=	12
FFT Shaper Out	Filter	(FFT Shaper Out * Filter) / (FFT Preamp * FFT Shaper)	Inv FFT (Col S)	Deconv Signal	Deconv Error
84198	1.02	-269.35994	2.7726384	2.77	4.27
-54147.984	1.02	-1098.15410	0.2984827	0.30	0.04
-46296.352	1.02	-970.73685	-0.208151	-0.21	0.49
-26049.937	1.02	-779.90598	1.3524401	1.35	1.33
-4446.5683	1.02	-534.33464	-0.1702481	-0.17	0.14
13126.125	1.02	-257.41681	0.3485106	0.35	0.10
23577.250	1.02	32.179126	2.3658046	2.37	6.26
26488.223	1.02	321.25119	0.7004677	0.70	0.02
23878.681	1.02	588.05410	1.5147465	1.51	0.83
17665.826	1.02	813.08817	0.1223159	0.12	0.13
10346.115	1.02	963.42946	-1.2617847	-1.26	1.14
3341.7930	1.02	1049.98599	1.7990449	1.80	2.69
-1997.5532	1.02	1050.7996	-0.6638133	-0.66	1.58
-5802.8033	1.02	976.56136	2.3761649	2.38	3.52
-8412.0588	1.02	839.13505	-3.8132053	-0.04	0.01
-9843.1050	1.02	642.16972	1.5616379	1.56	0.87
-10125.997	1.02	401.75028	-0.4706260	-0.47	0.97
-9437.1218	1.02	136.33957	1.6064576	1.61	3.76
-7674.9280	1.02	-146.19784	6.7170588	0.07	0.21
-5437.3400	1.02	-379.28488	0.9071590	0.91	1.04
-2683.8635	1.02	-587.85761	-0.8570306	-0.86	0.68
-135.34588	1.02	-752.21508	0.5206912	0.52	0.25

Spectral Power

4.8828

f (kHz)	Wire Signal & Noise Power	Preamp * Shaper Kernel Power	Shaper Out Power	Deconv Signal Power
0	615	319	195805	269
5	1117	62	68953	1139
10	1112	43	47446	1133
15	1113	37	41139	1134
20	1106	34	37142	1127
24	1110	31	34078	1131
29	1103	28	30789	1123
34	1083	25	27263	1103
39	1082	23	24342	1102
44	1079	20	21558	1099
49	1065	18	18836	1085
54	1051	16	16488	1071
59	1034	14	14524	1054
63	1018	13	12981	1036
68	1009	12	11878	1027
73	997	11	11003	1015
78	979	10	10230	996
83	969	10	9625	987
88	956	9	9013	972
93	947	9	8452	964
98	916	8	7710	932
103	905	8	7158	920

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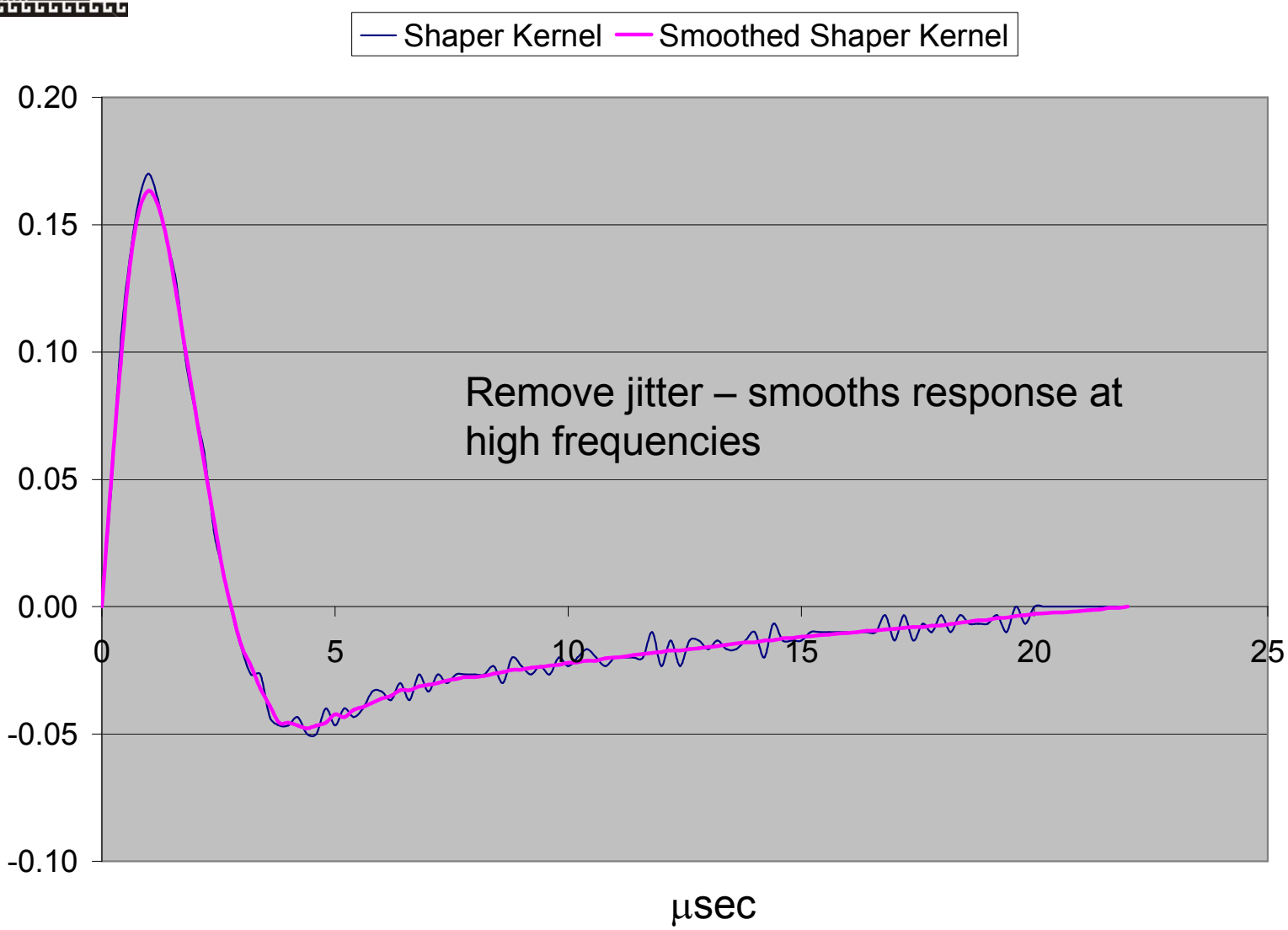
Shaper Kernel Smoothing



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Reality Check

- Define a wire signal
- Set ADC round-off error to 10 digits
- Include 1.5 MHz coherent noise
- Set filter array = 1's

Expect de-convoluted signal + noise = original signal + noise

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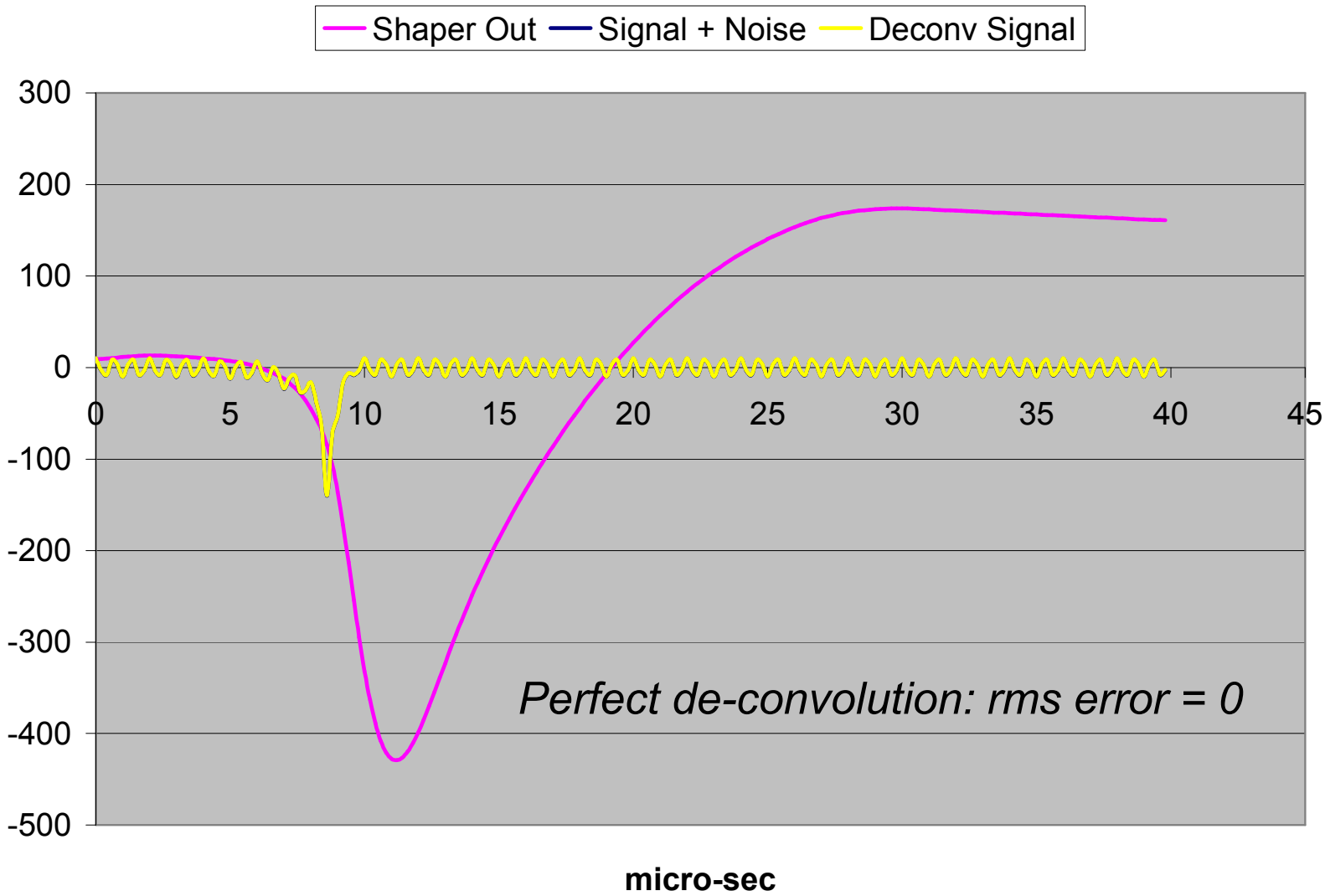
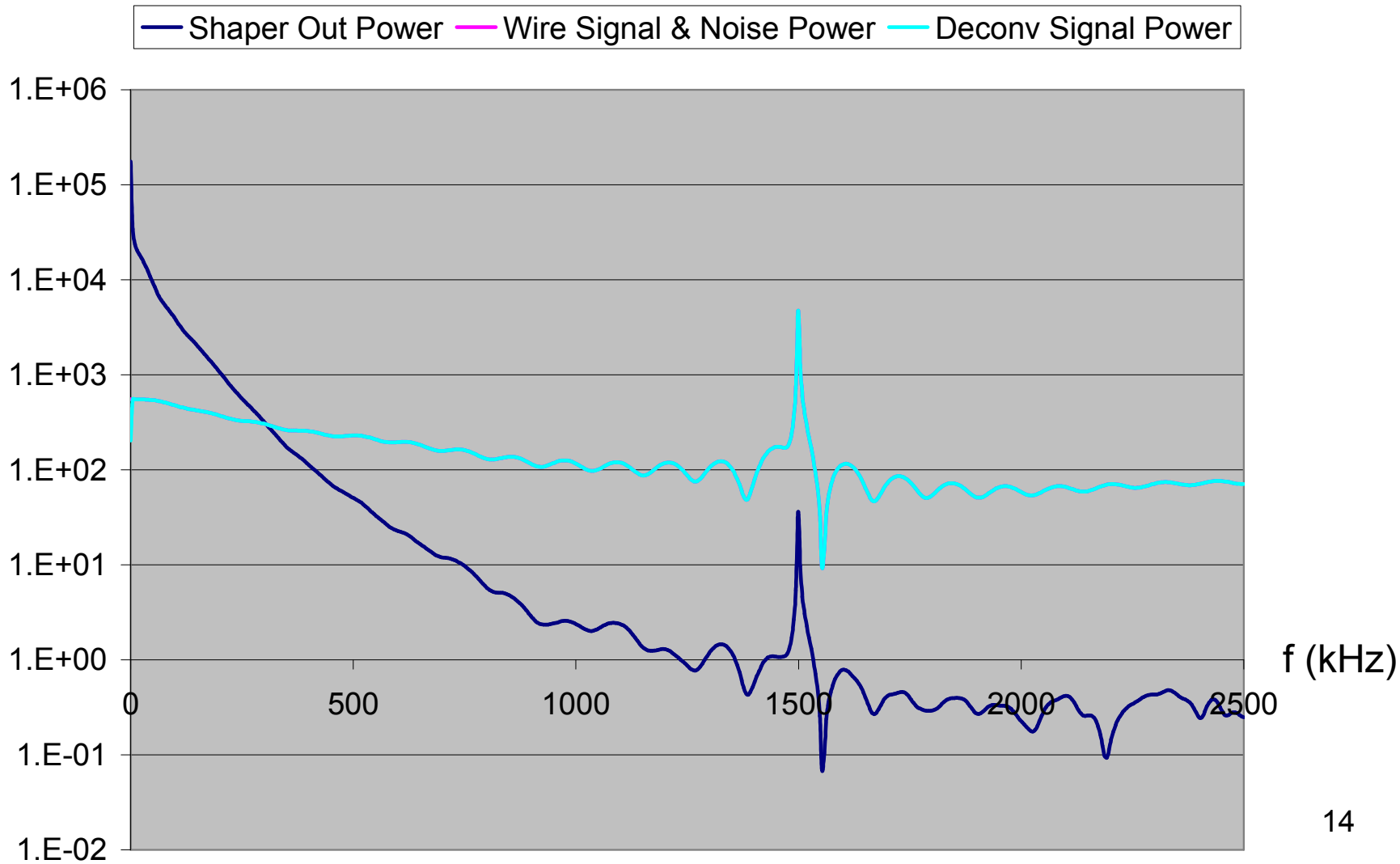
Reality Check Signals

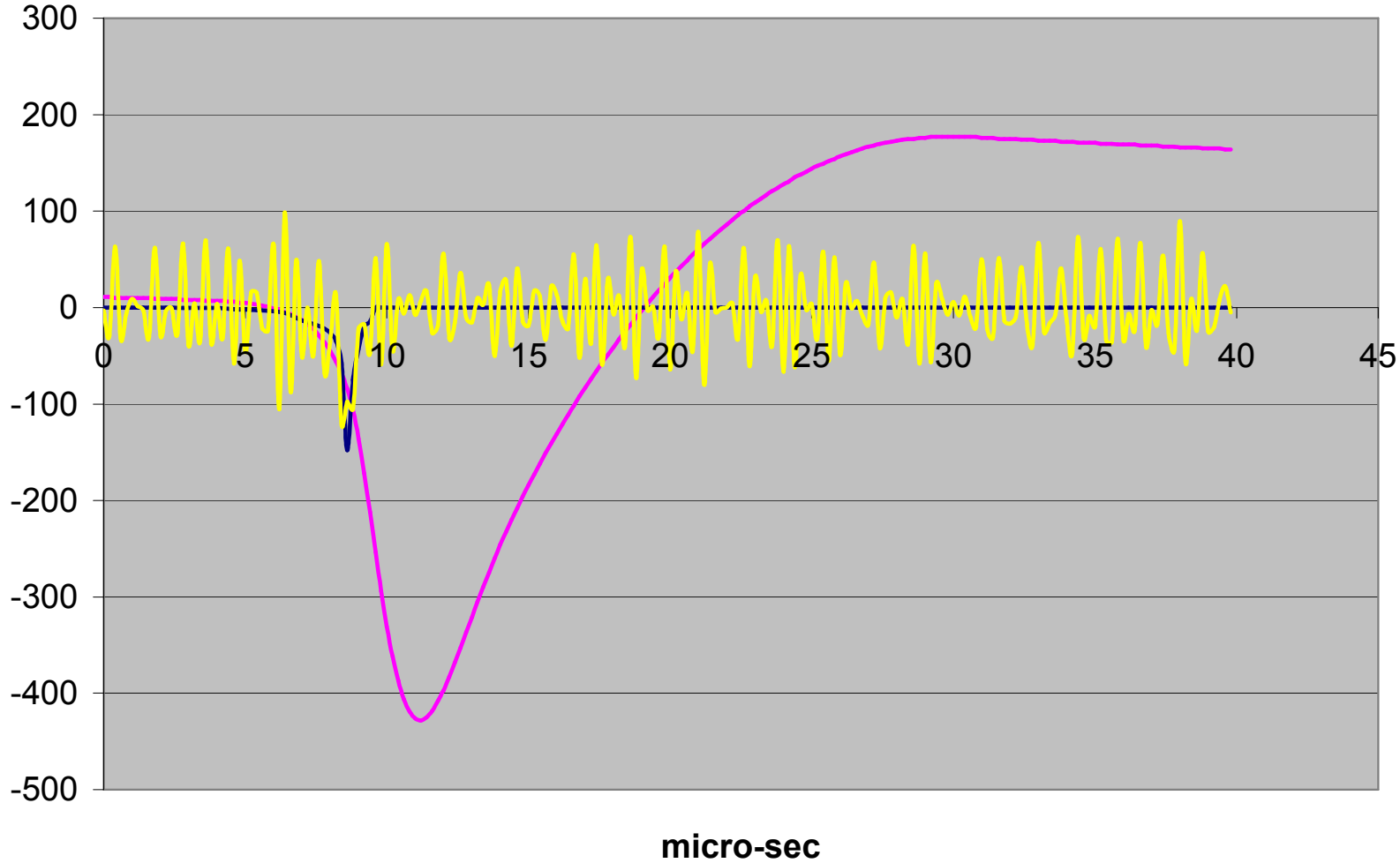


Reality Check
Spectral Power

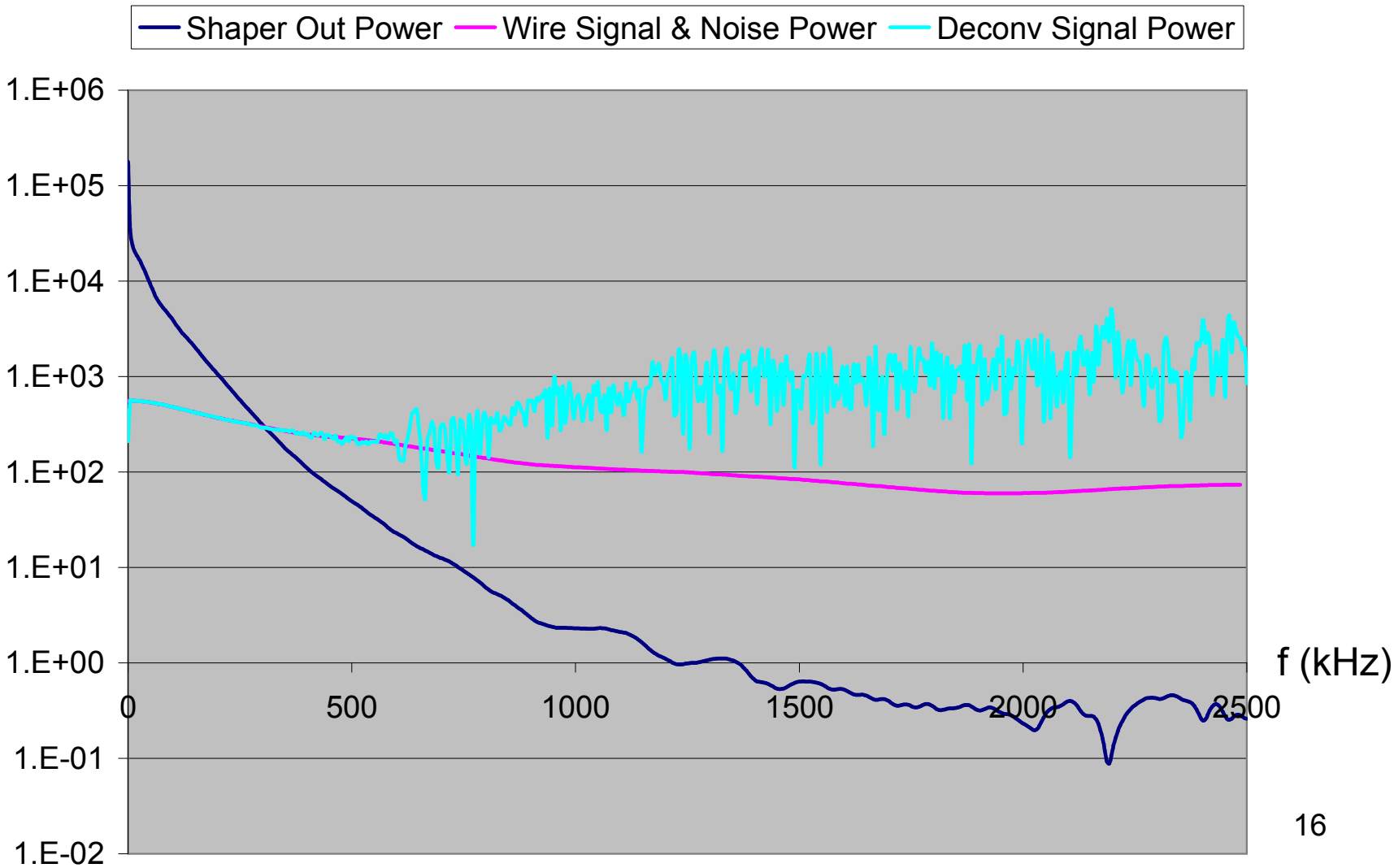


Check #2
Signals

Remove coherent noise, set round-off error = 0 digits



Check #2
Spectral Power



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Explanation

- Round-off error ~ high frequency noise
- This noise is reduced by ~10^4 by the shaper band pass filter
- This “noise” is next restored *unfaithfully* by de-convoluting with the shaper kernel containing the band pass filter

- Solution
  - Apply a low pass software filter

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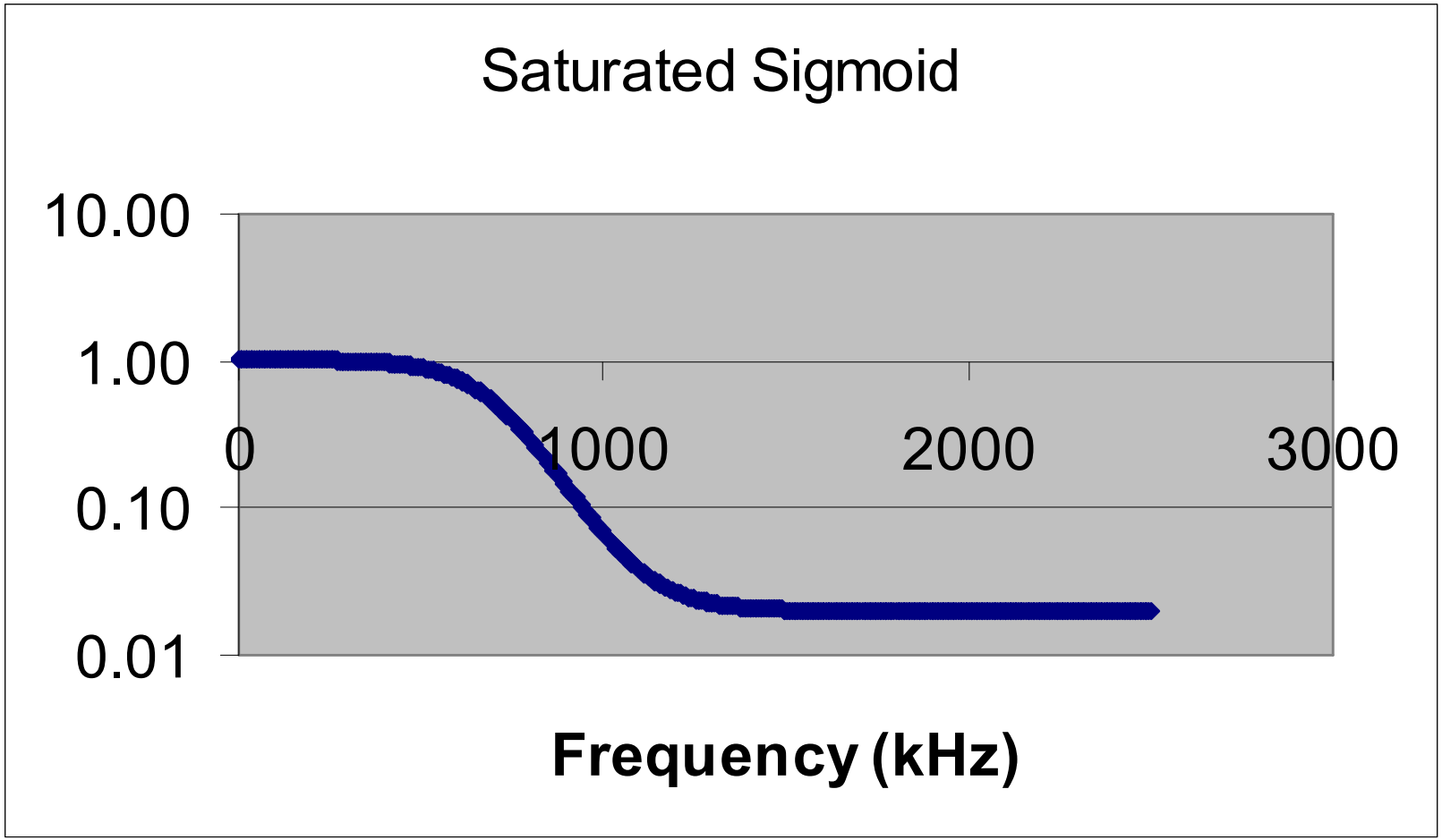
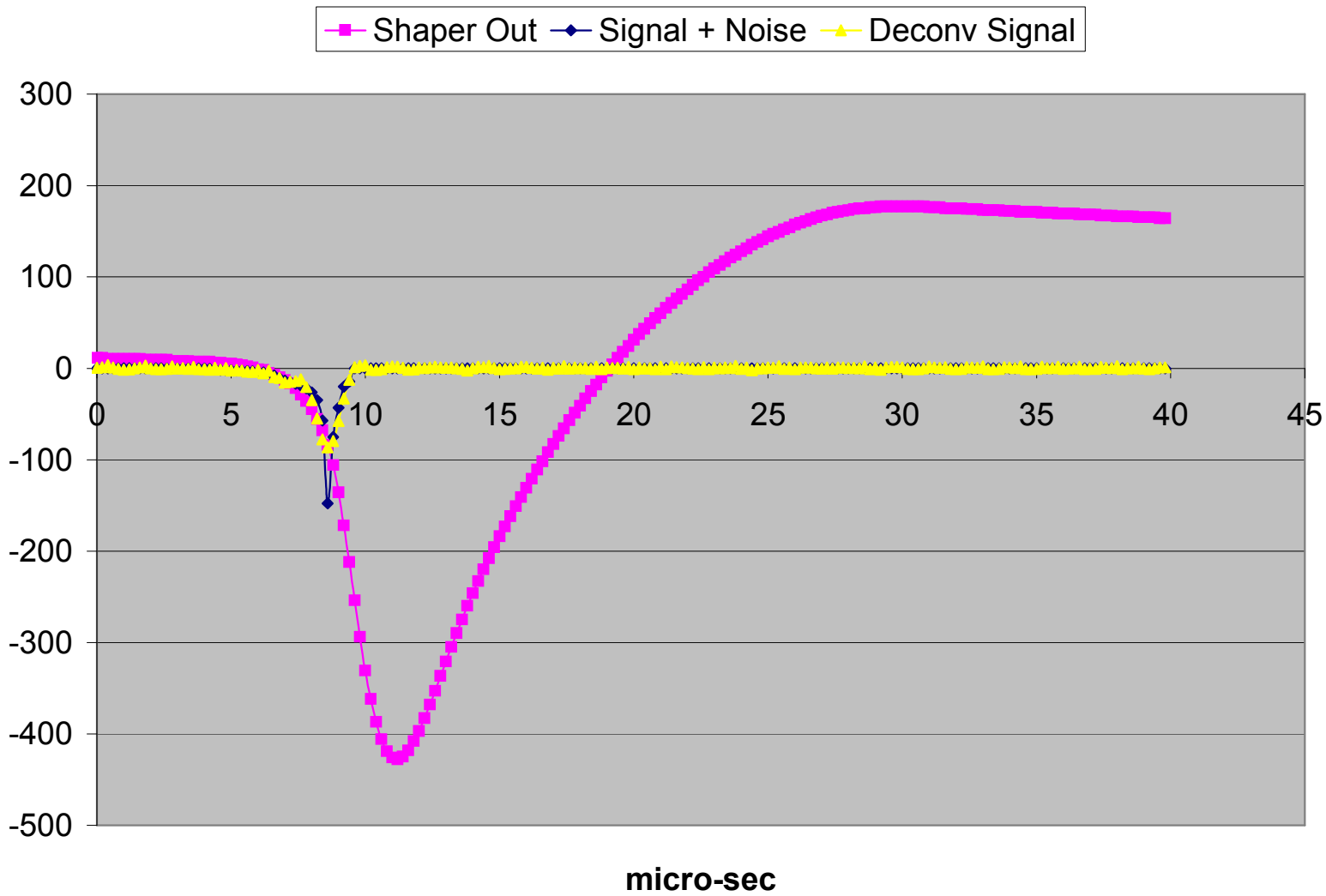
Low Pass Filter



User selectable breakpoint, rolloff and saturation level (FFT.xls!Sheet1)

Filtering Signals



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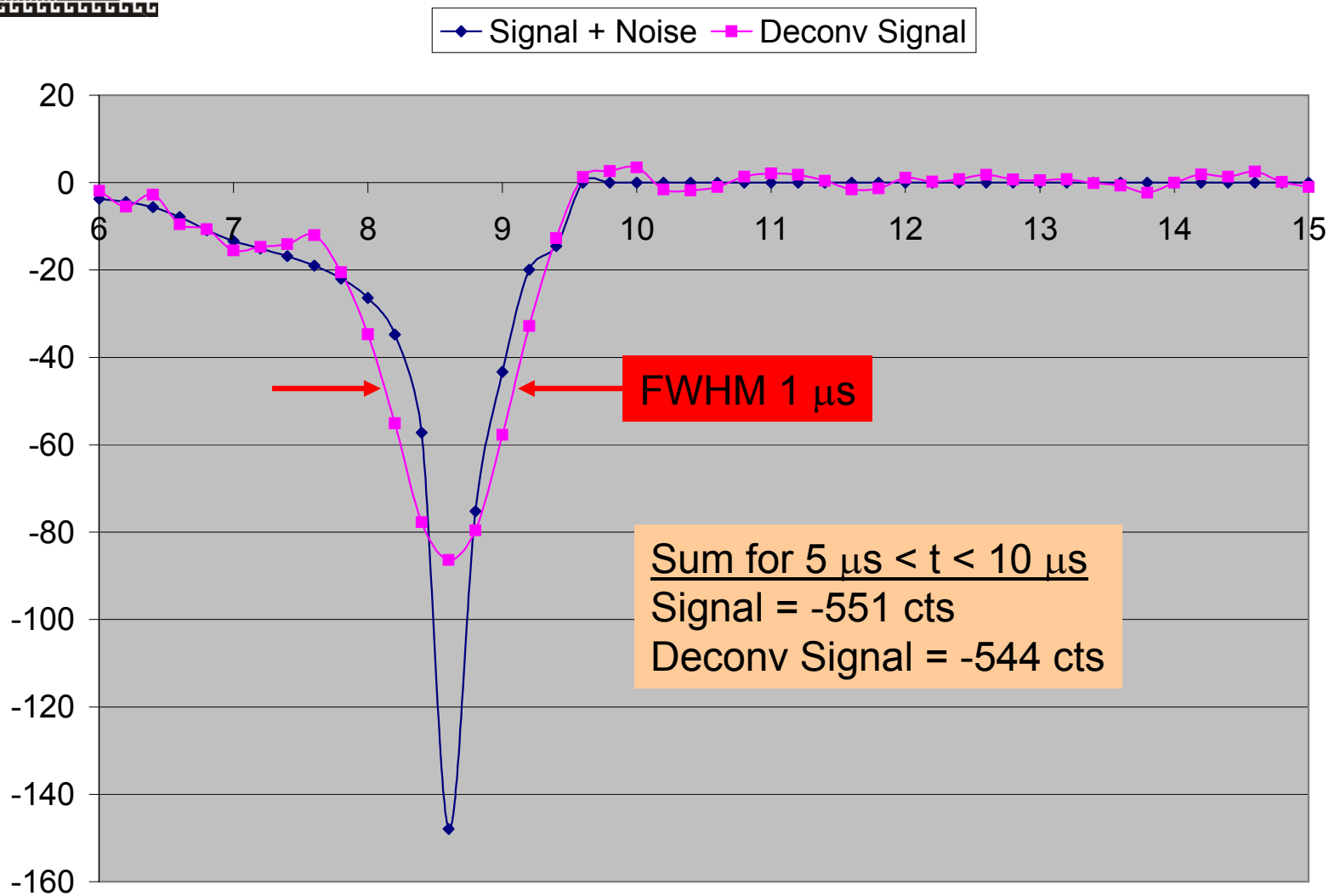
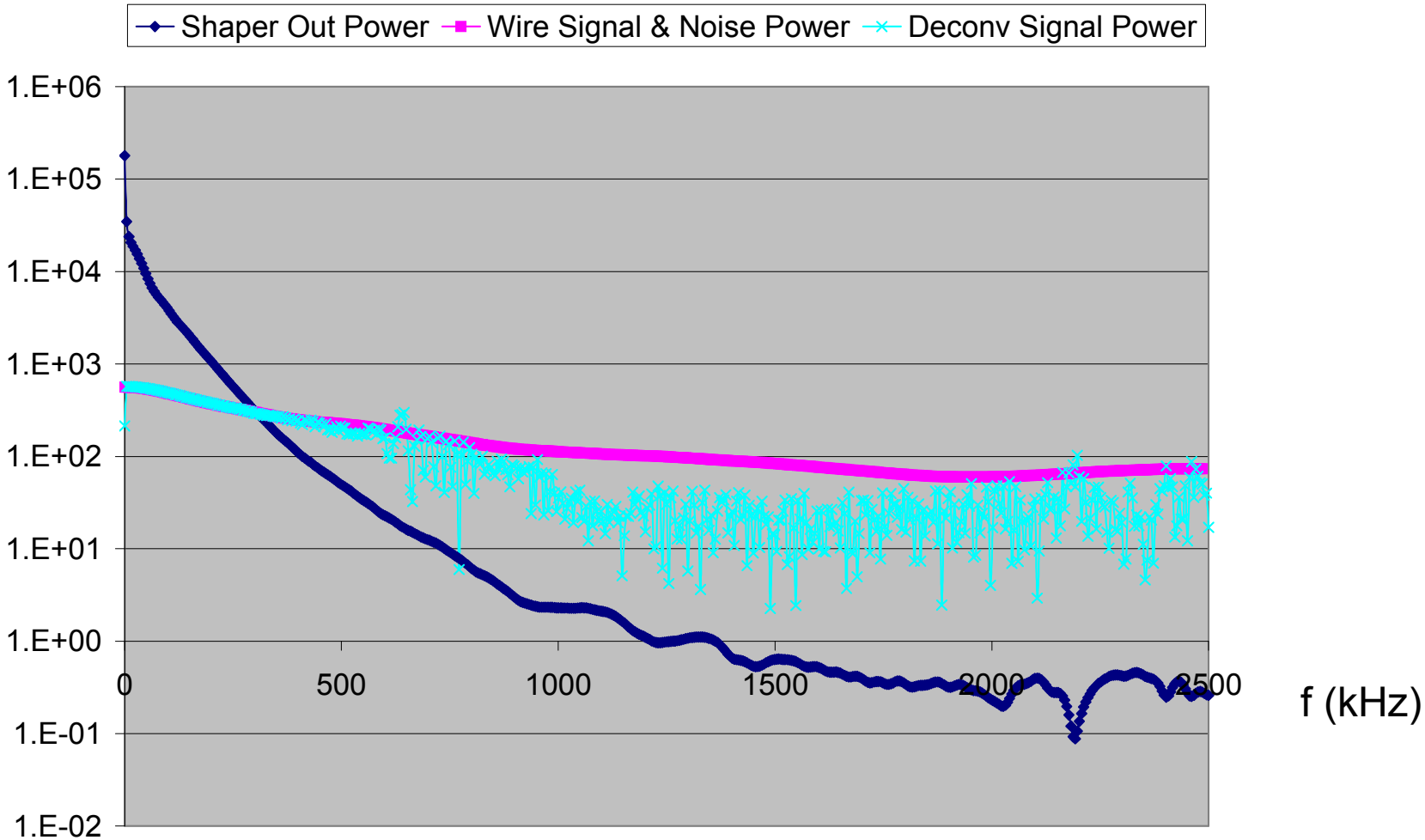
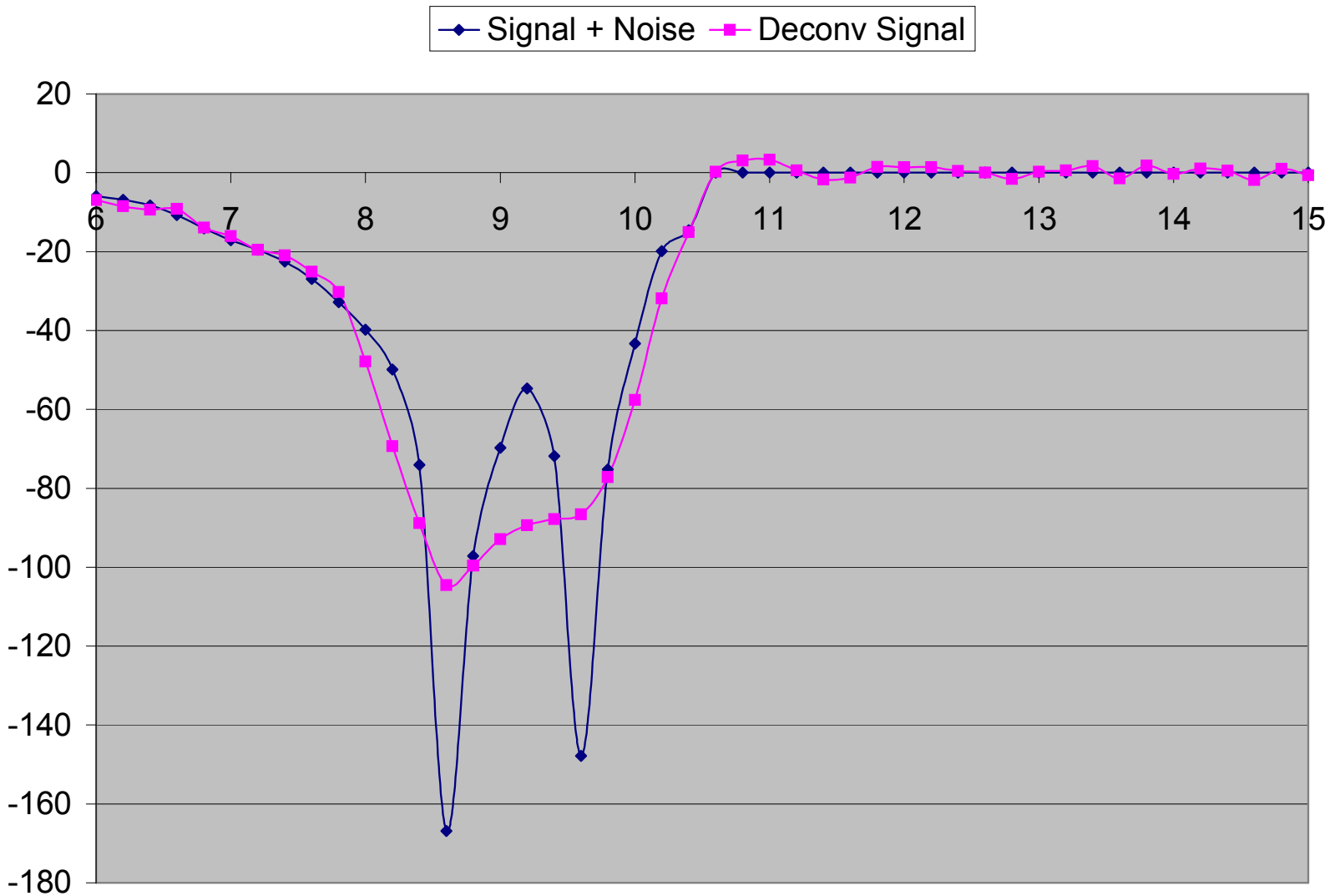
A Closer Look



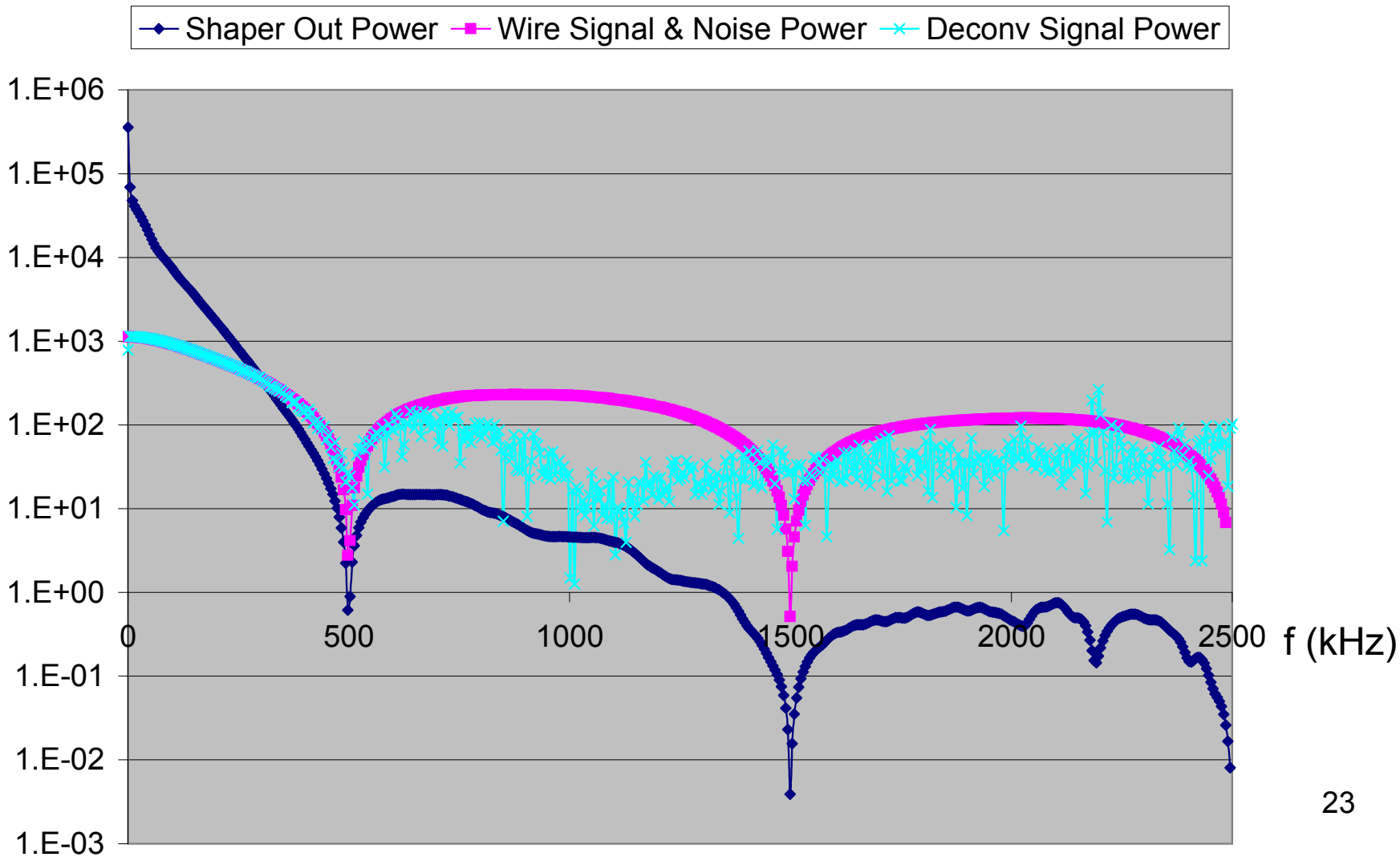
Filtering
Spectral Power



Double Hit
600 μm separation



Double Hit Spectral Power



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Optimal Filter

- Best filter for removing noise inside and outside of the signal region
- Step 1 – Determine noise spectral power
  - Use an ADC channel with no signal → N(f)
- Step 2 – Wire signal power → S(f)
  - Use Garfield signal

$$OF(f) = \frac{|S(f)|^2}{|S(f)|^2 + |N(f)|^2}$$

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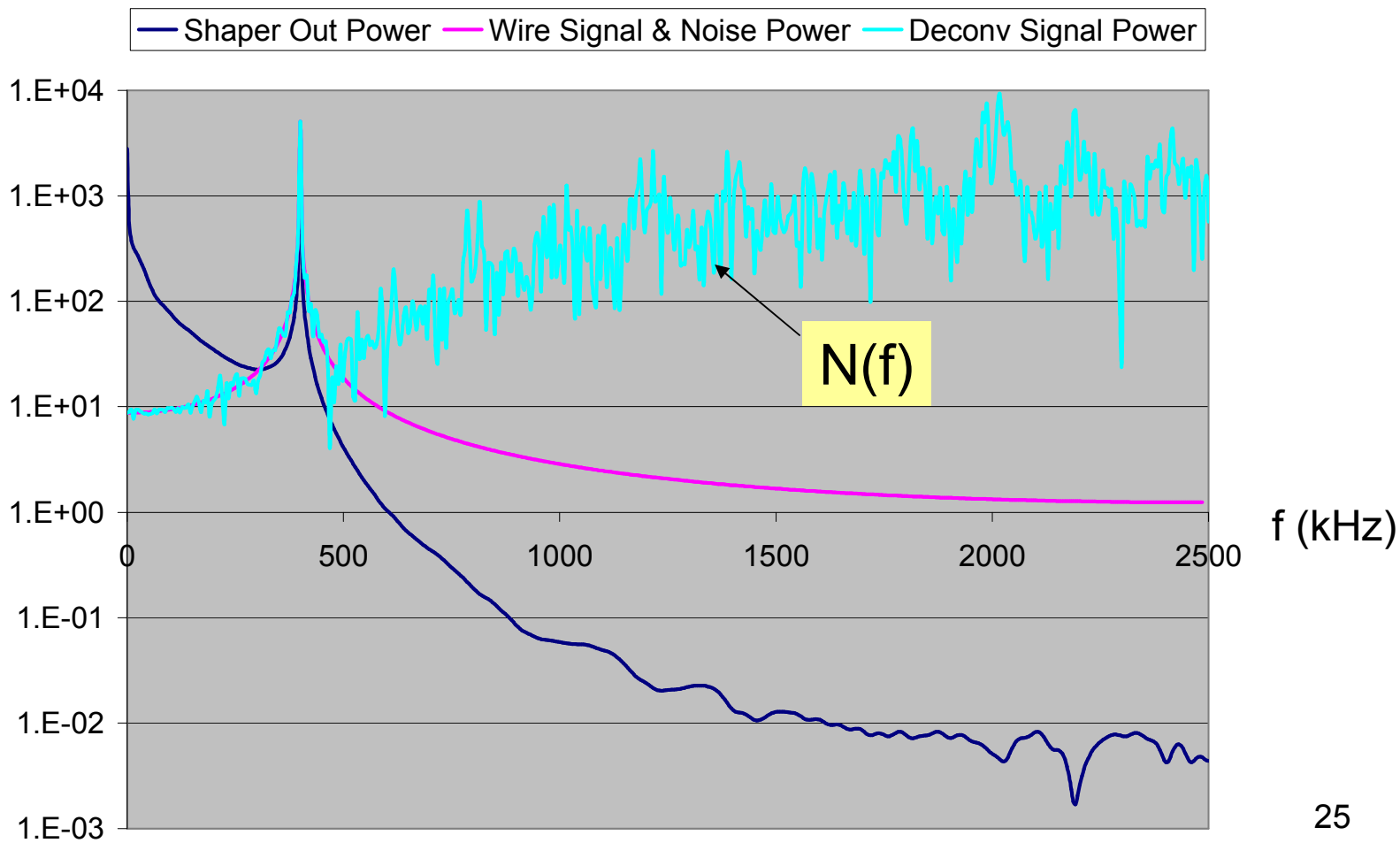
Noise Spectral Power

Generate 400 kHz noise. No wire signal



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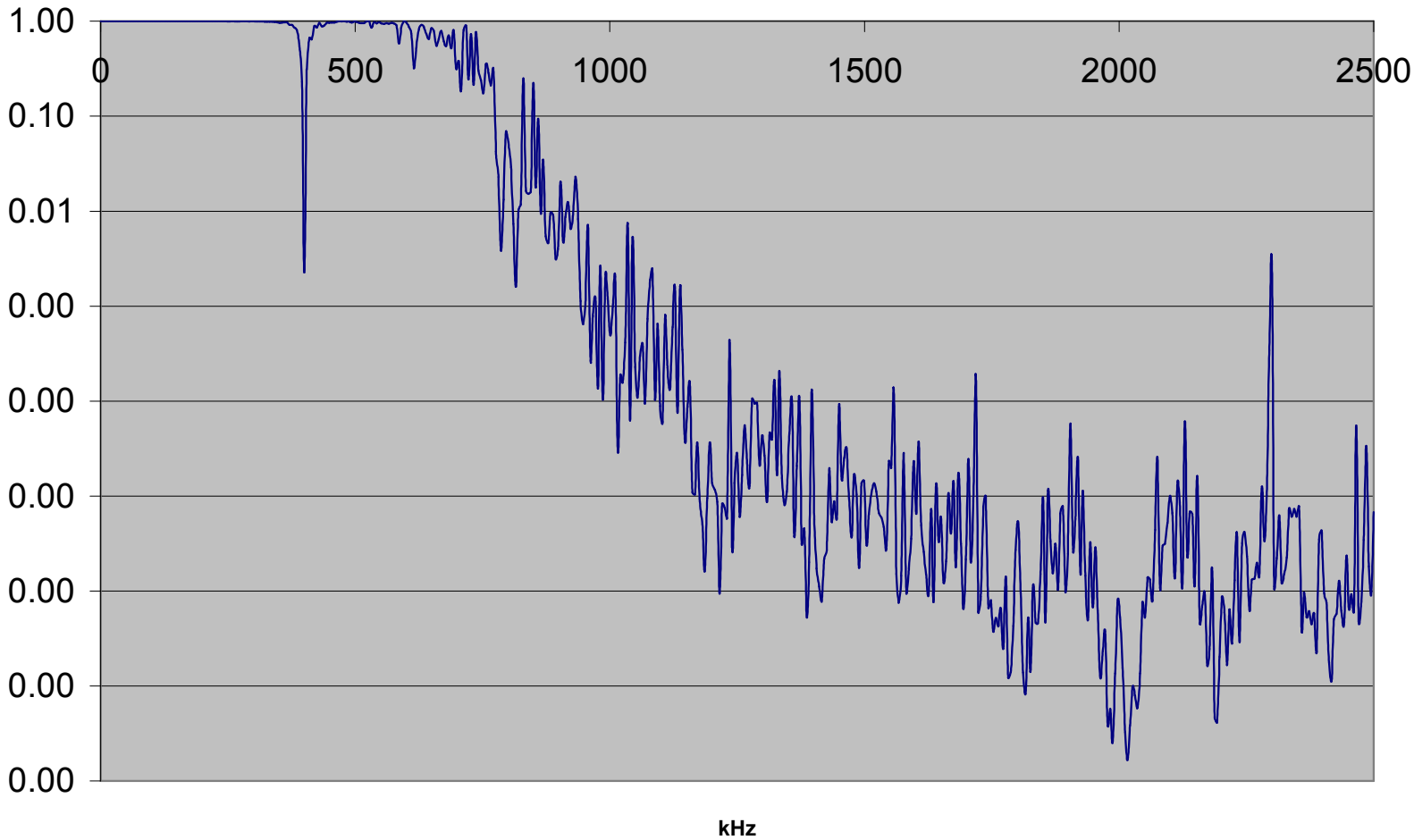
Optimal Filter



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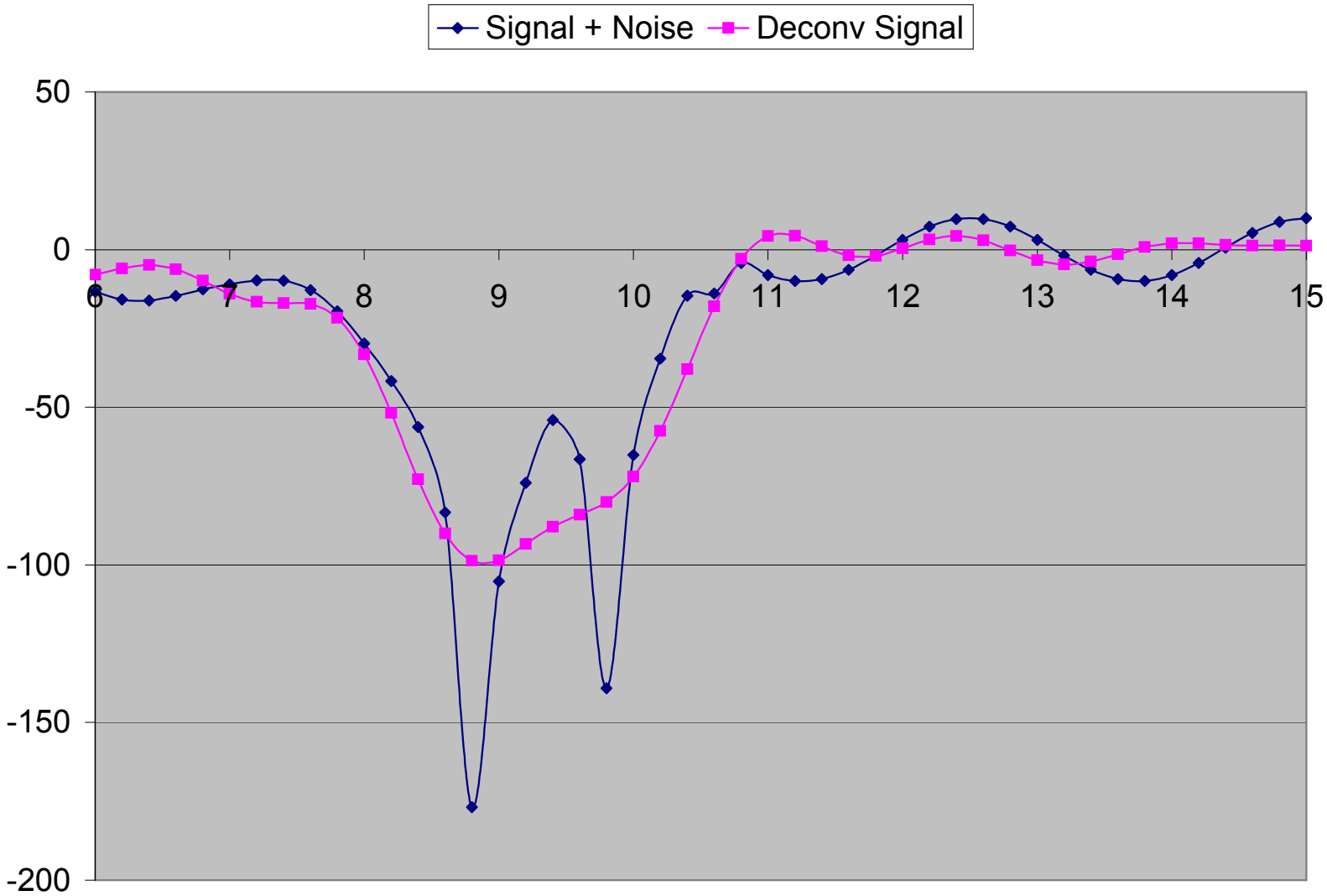
Test the Filter

- Move the 1st wire signal by 1 time bin
- Add a 2nd wire signal 1 μsec later
- Include the coherent noise
- Use the optimal filter in the de-convolution

Optimal Filter Signals



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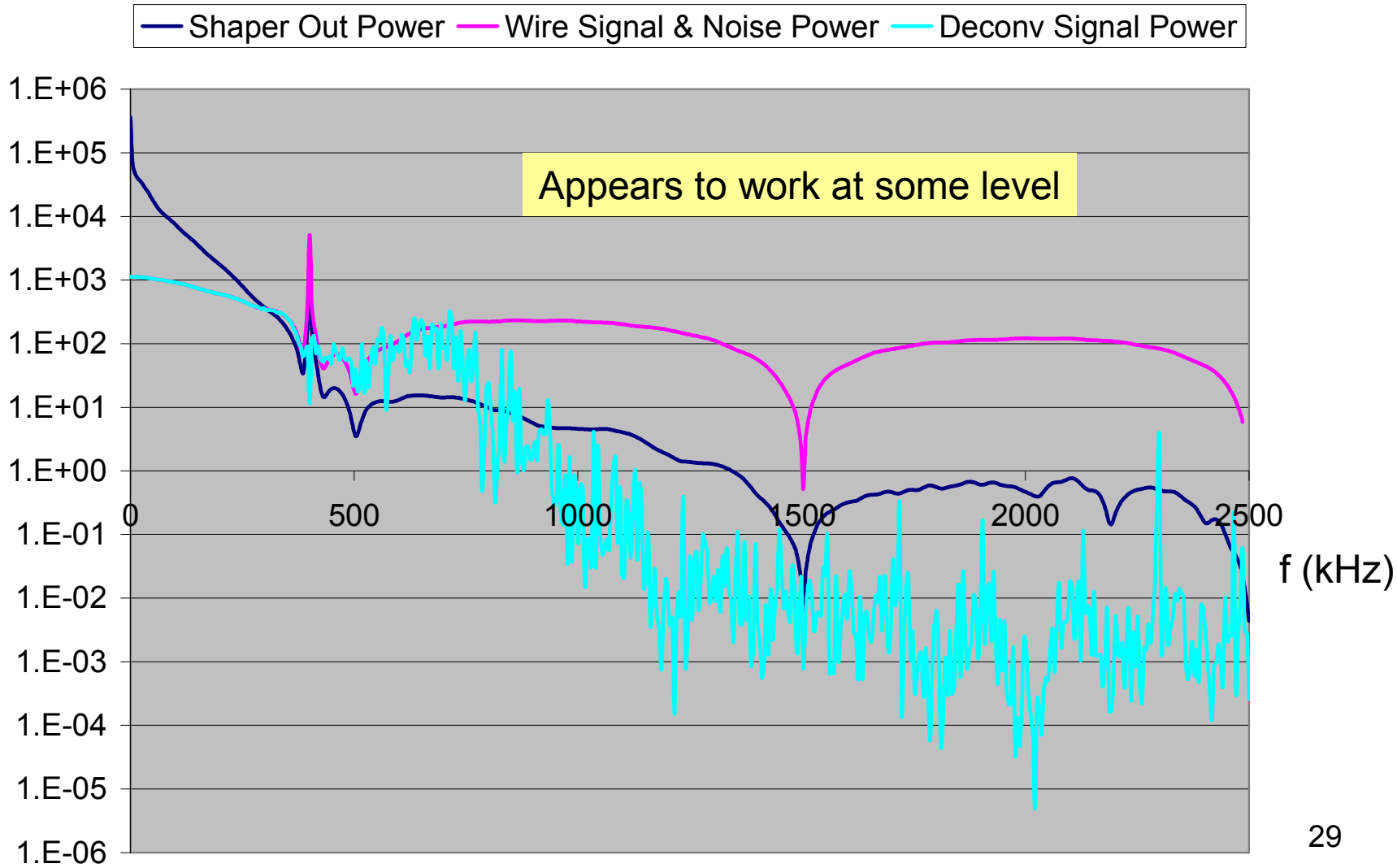
Optimum Filter Spectral Power



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Summary

- FFT de-convolution is attractive
- Early in the learning curve
  - Results shown are
    - Maybe believable
    - Probably not optimal