SHARC 2000 International DSP Conference

Implementation of cross-talk canceling filters with warped structures - Subjective evaluation of the loudspeaker reproduction of stereo recordings

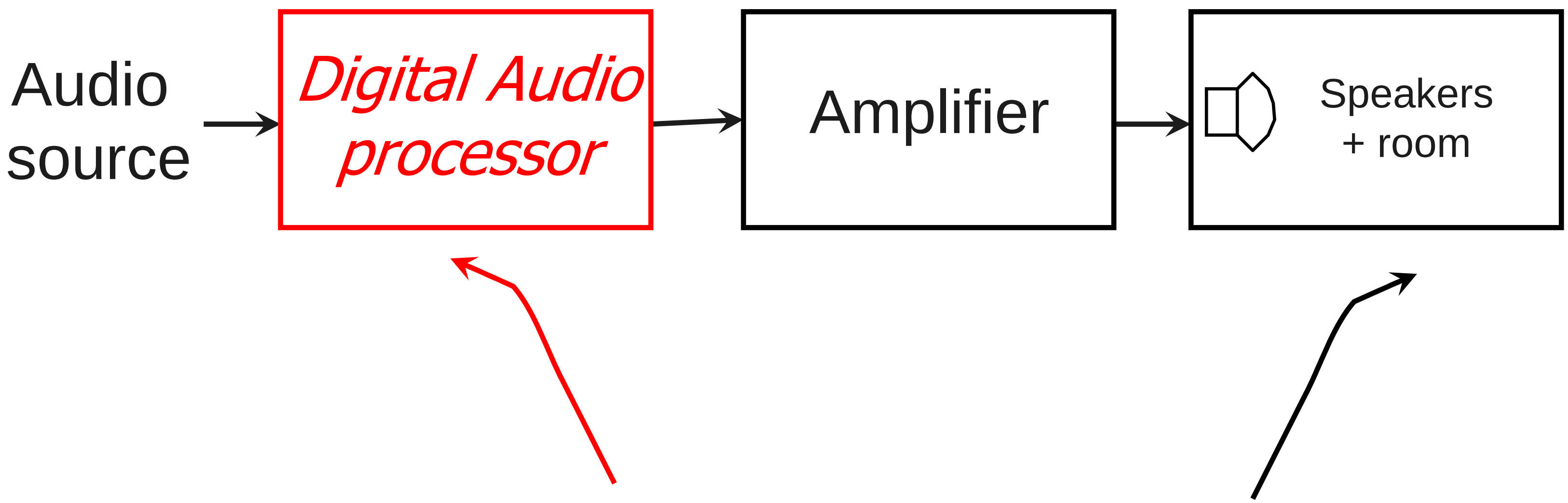
Angelo Farina, Alberto Bellini, Enrico Armelloni

farina@unipr.it
Dipartimento di Ingegneria Industriale
University of Parma
ITALY

Outline

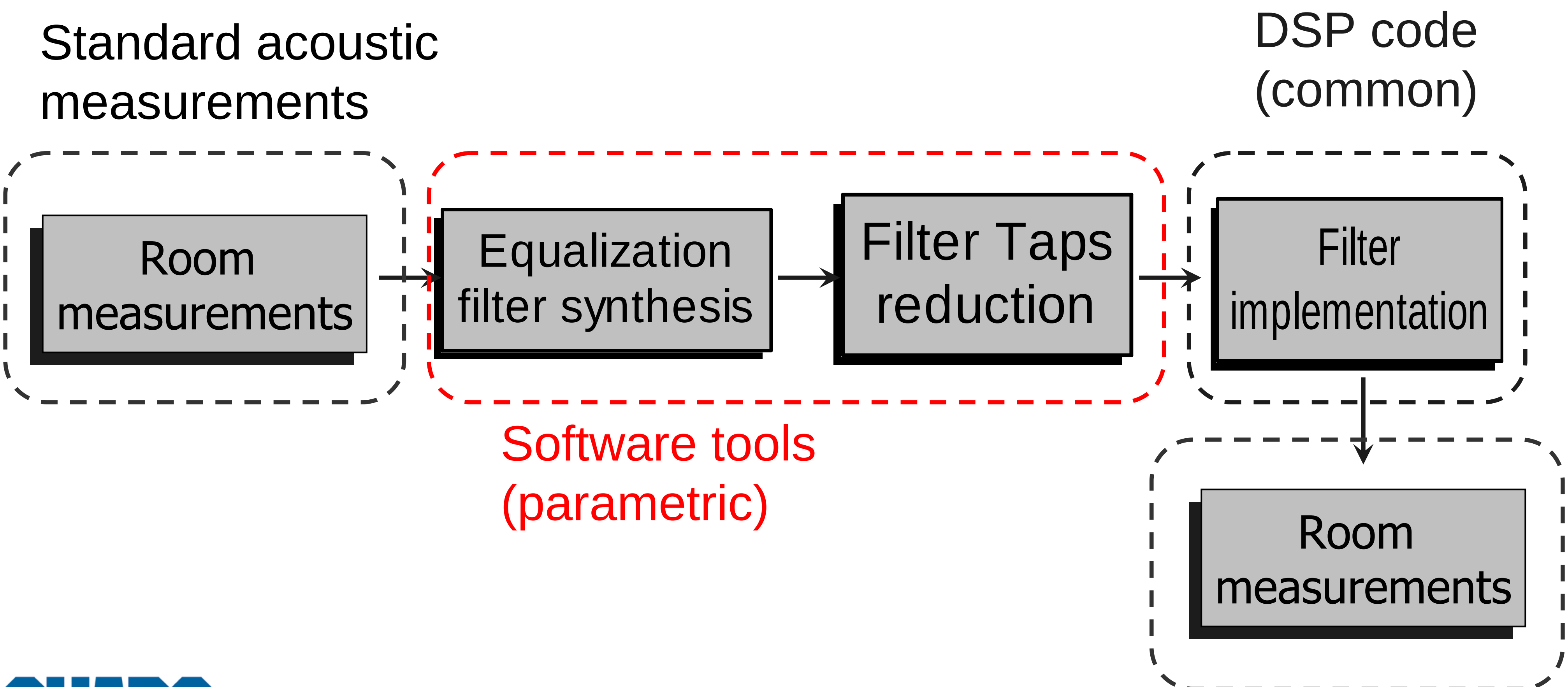
- Sound reproduction quality;
- Analysis and compensation of distortion and reduction of cross-talk paths;
- Software and hardware implementation;
- Experimental results;
- Demonstration;

Audio processor design



<u>Design a filter so that</u> *Measured SPL = Target SPL*

Equalization architecture design



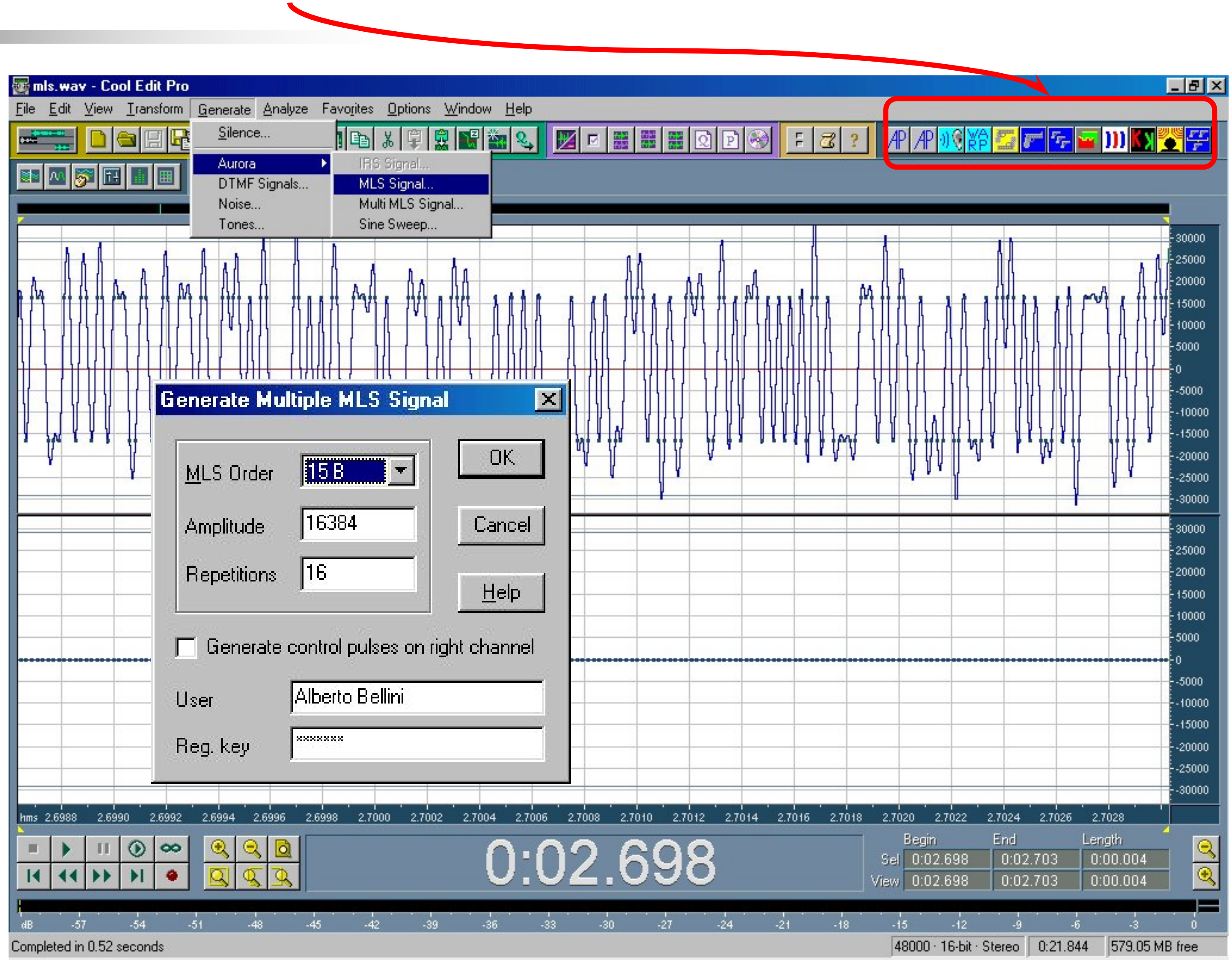
Tools

- *Hardware*:
  - Analog Devices SHARC 21061/21065 boards;
- *Software*:
  - AURORA: measurements and acoustic characterization
  - MATLAB for filters design;

Aurora

- Plug-ins of Syntrillium CoolEdit™, http://www.sytrillium.com
- AURORA™: http://www.ramsete.com/aurora
  - TIM filter
  - Convolve with Clipboard
  - Generate MLS Signal
  - Generate IRS Signal
  - Deconvolve MLS Signal
  - Deconvolve IRS Signal
  - Acoustical Paramenters
  - Inverse Filter
  - Flatten Spectrum
  - Subtract Convolved;

Aurora GUI


mls.wav - Cool Edit Pro
File Edit View Transform Generate Analyze Favorites Options Window Help
Silence...
Aurora
DTMF Signals...
Noise...
Tones...
IRS Signal...
MLS Signal...
Multi MLS Signal...
Sine Sweep...
Generate Multiple MLS Signal
MLS Order 15 B
Amplitude 16384
Repetitions 16
OK
Cancel
Help
Generate control pulses on right channel
User Alberto Bellini
Reg. key
0:02.698
Begin End Length
Sel 0:02.698 0:02.703 0:00.004
View 0:02.698 0:02.703 0:00.004
Completed in 0.52 seconds
48000 · 16-bit · Stereo
0:21.844
579.05 MB free

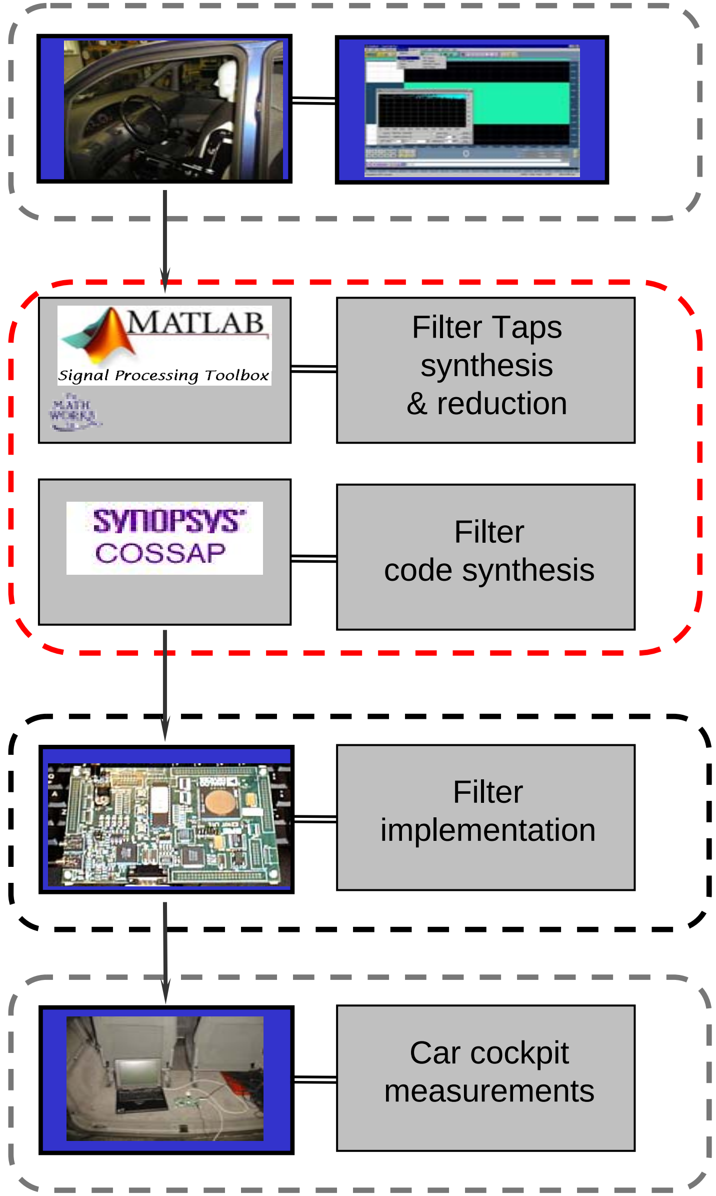
Design-flow

Standard acoustic measurements

Software tools (parametric)

DSP code (common)

Acoustic validation (common)



Warped FIR

- Warped FIR algorithm. You can get more info on this specific algorithm looking at:

  http://www.acoustics.hut.fi/publications/papers.html
  http://www.acoustics.hut.fi/software/warp
  http://www.ludd.luth.se/~torger/filter.html

Warping: Frequency mapping

- Applying the following bilinear transformation to the z-plane

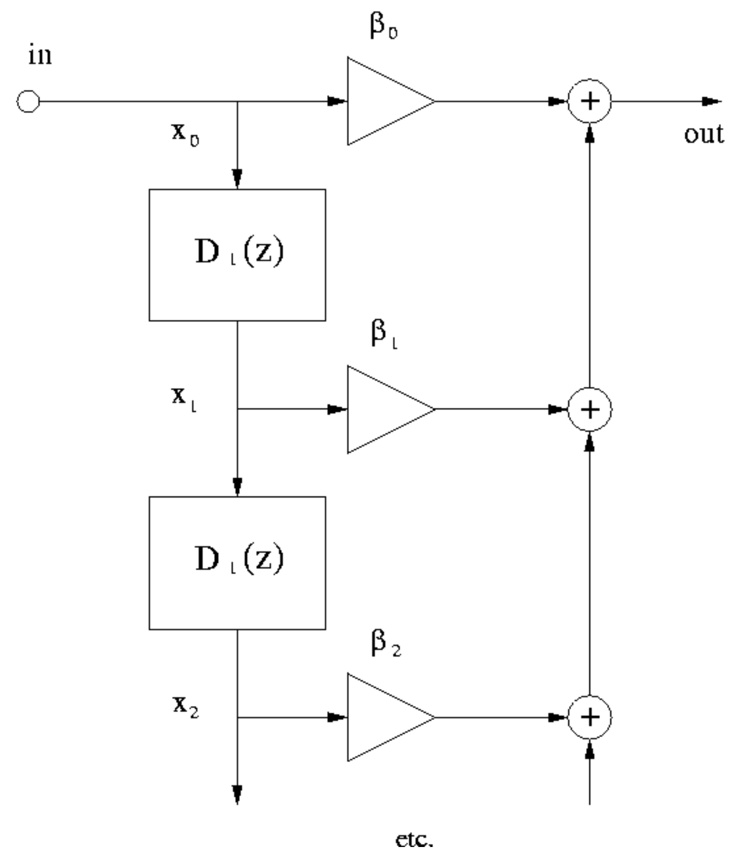
$$z = A_{\lambda}(\zeta) = \frac{\zeta + \lambda}{1 + \zeta \cdot \lambda}$$

- Sampling-rate is not constant
- Consistent with psychoacoustics representations

Warping FIR

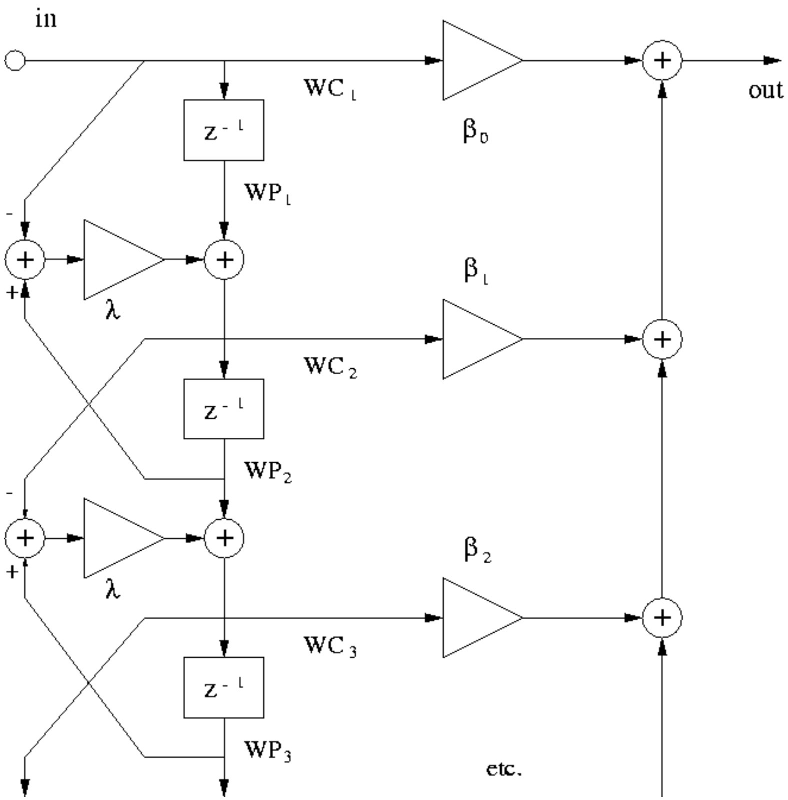
- Same structure as FIR, the delay unit is replaced by

$$D_1(z) = \frac{z^{-1} - \lambda}{1 - \lambda \cdot z^{-1}}$$



- The FIR features:
  - ↓ Poor resolution at low frequencies
  - ↓ Properties well defined on a linear frequency scale
  - ↑ Linear phase
  - ↑ Short execution time (0.5 clock cycles / tap)
  - ↑ No added quantization noise

Warping FIR



LCNTR=Wfilter_taps-1 , DO wmac_rr UNTIL LCE;

*F12=F2*F4, F9=dm(I5,M7), F4=pm(I9,M8);*

*F10=F2*F5, F8=F8+F12, F9=dm(I5,M6);*

F1=F9-F10, F9=dm(I5,0);

*F10=F1*F7, dm(I5,M7)=F2;*

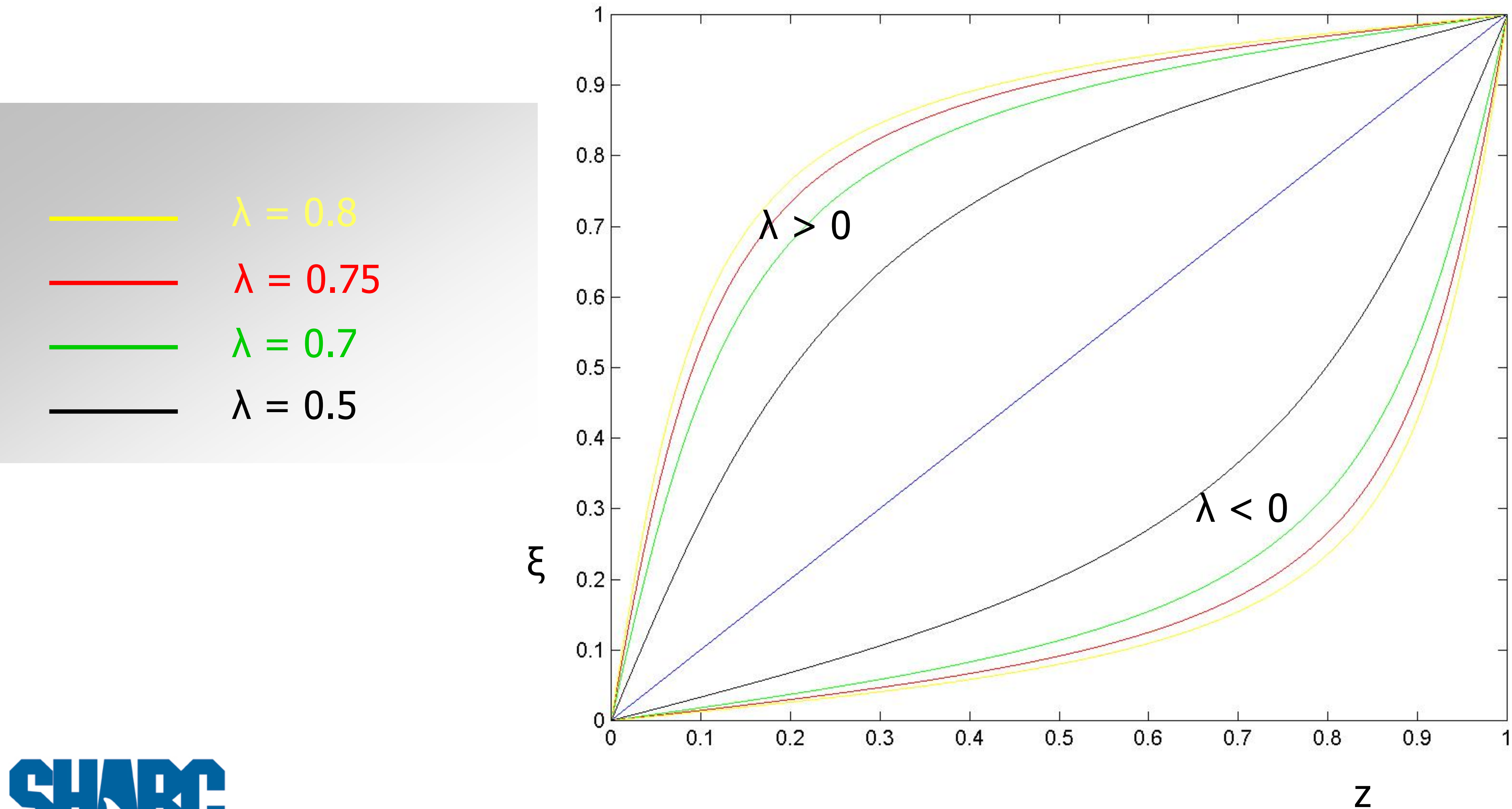
wmac_rr: F2=F9+F10;

/* convolution */

LCNTR = Ff_taps-1, DO lpf_filter_rr UNTIL LCE;

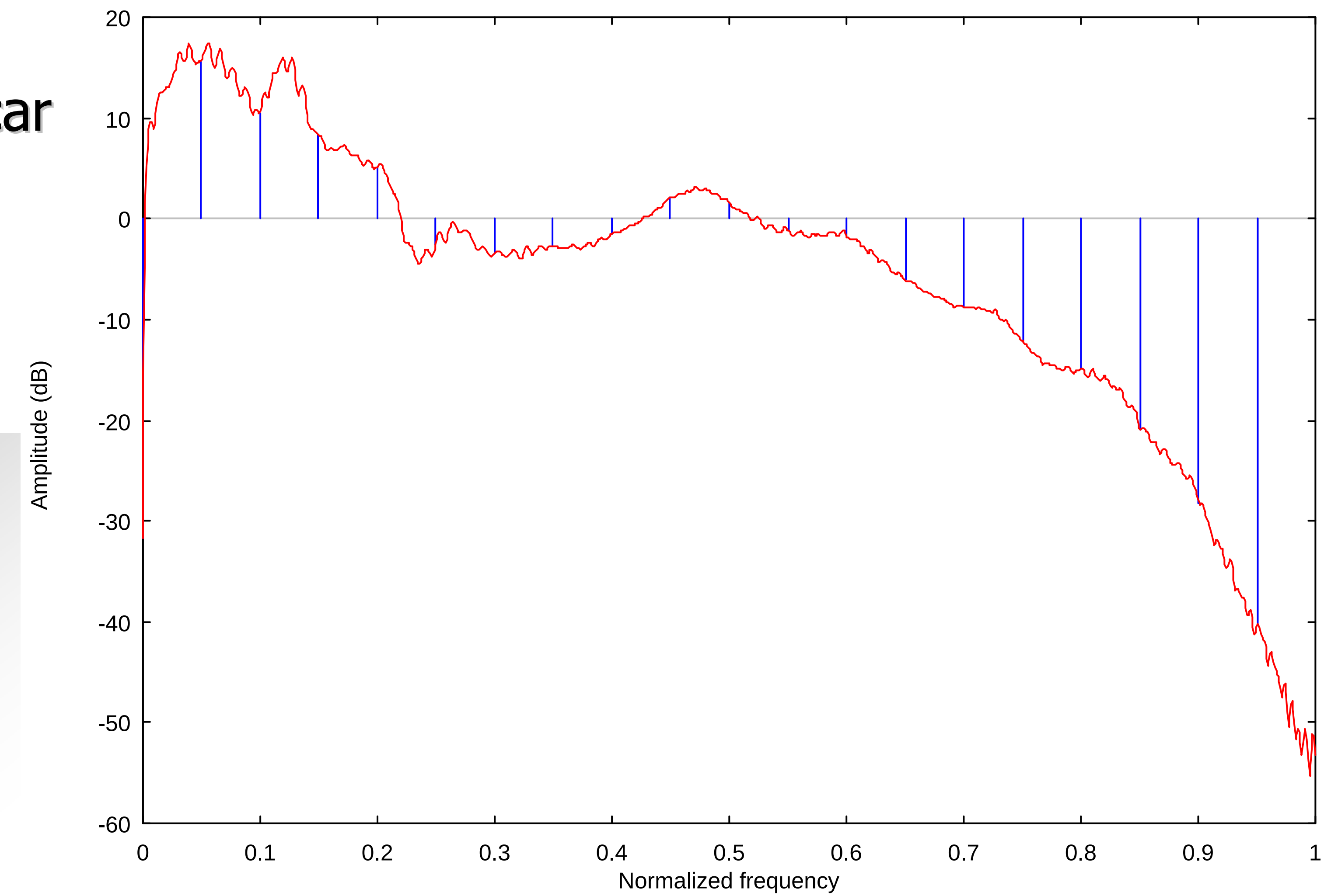
lpf_filter_rr: F8=F2*F4, F12=F8+F12, F2=dm(I5,M5), F4=pm(I9,M9);

Warping Frequency mapping



Warping Frequency mapping

- Frequency response of a car cockpit
- FIR

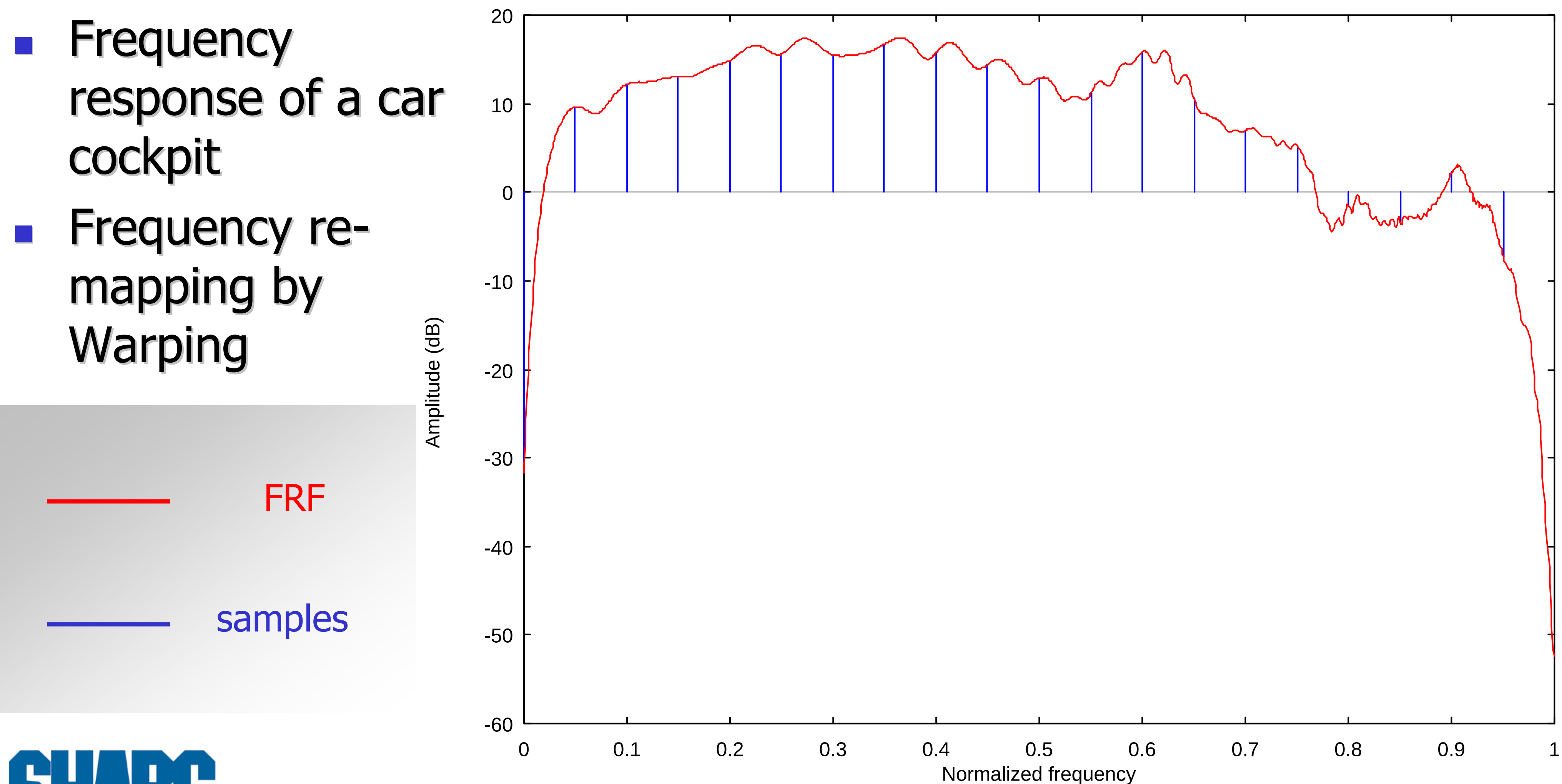


FRF

samples

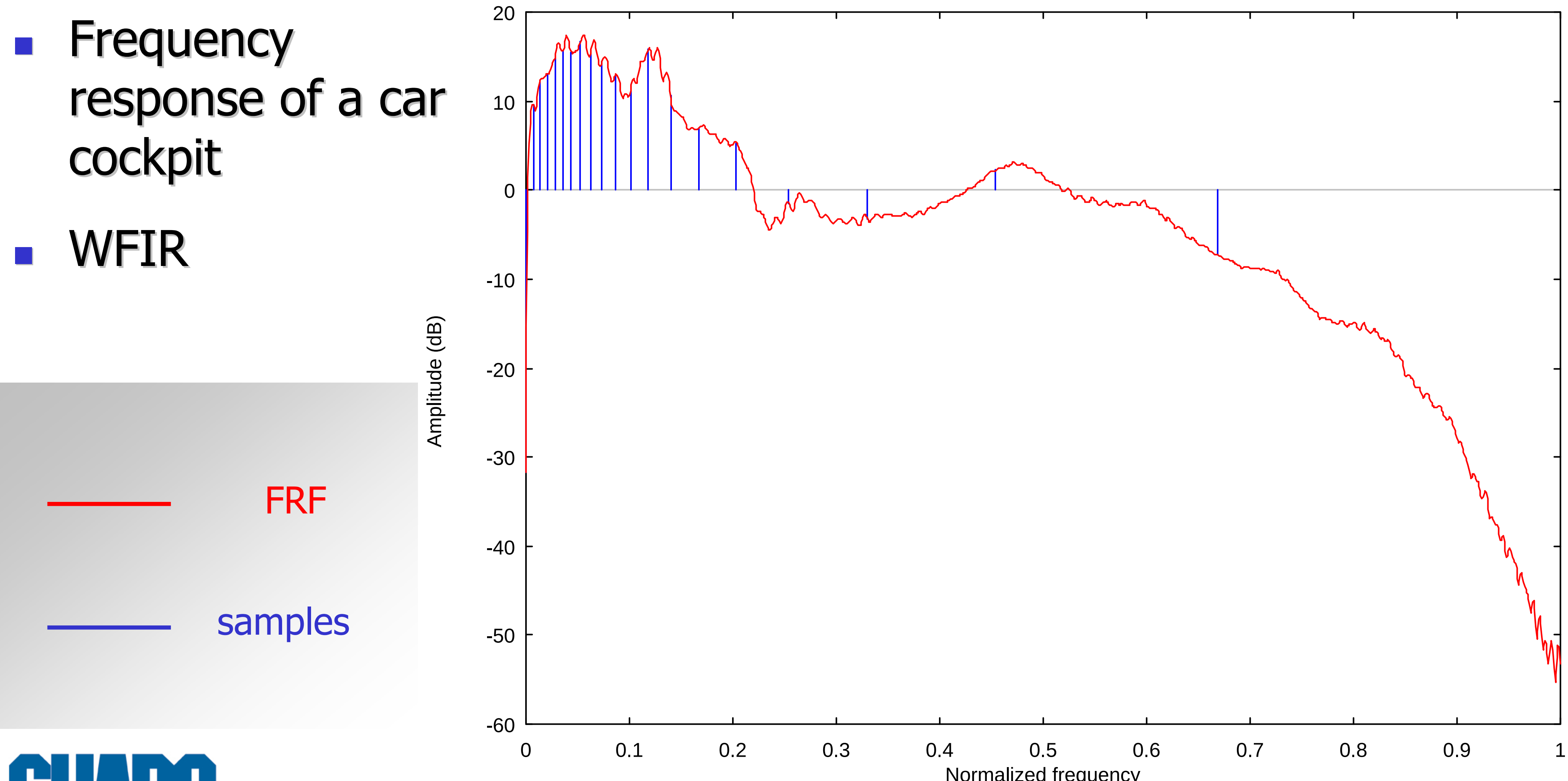
Warping Frequency mapping

- Frequency response of a car cockpit
- Frequency re-mapping by Warping



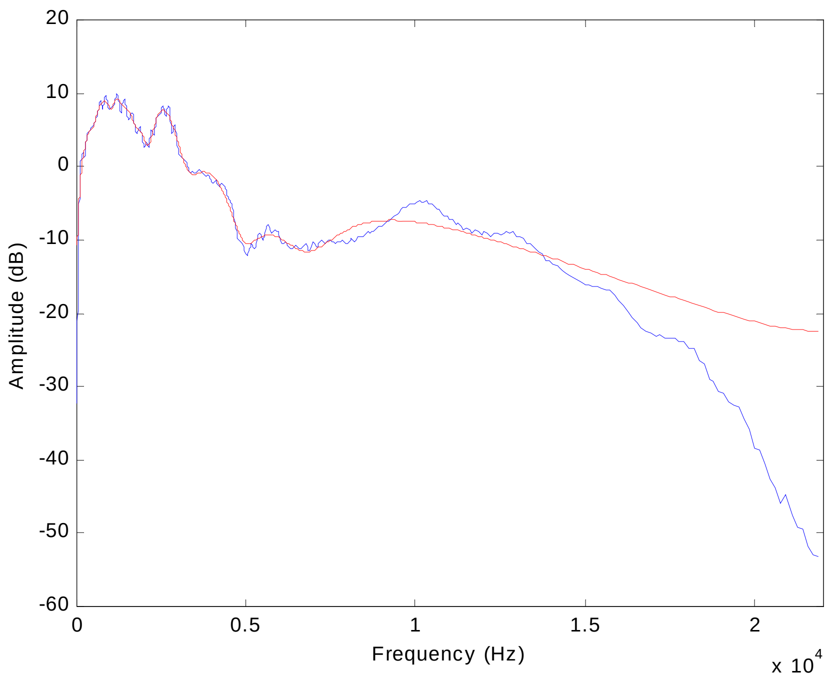
Warping Frequency mapping

- Frequency response of a car cockpit
- WFIR

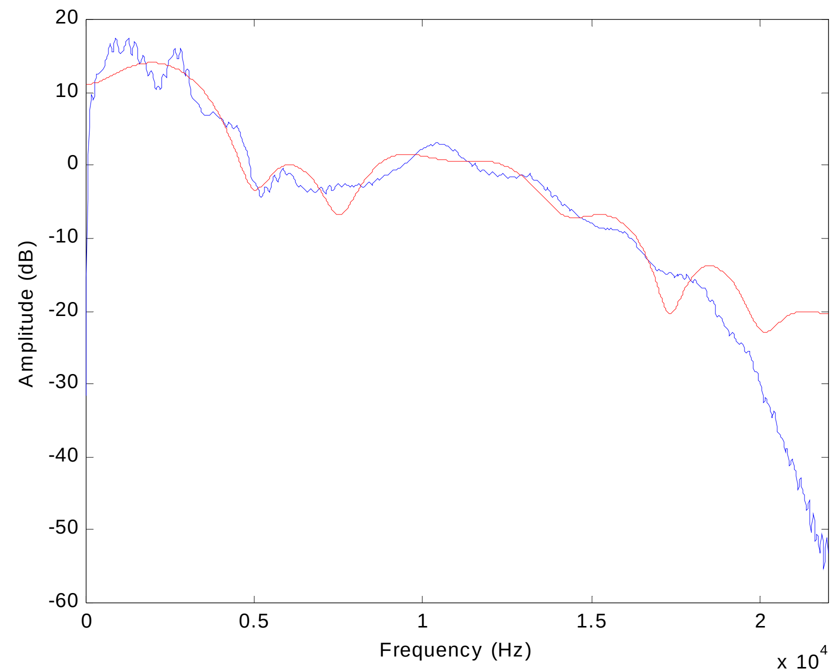


FIR synthesis vs WFIR synthesis

- 30 taps WFIR



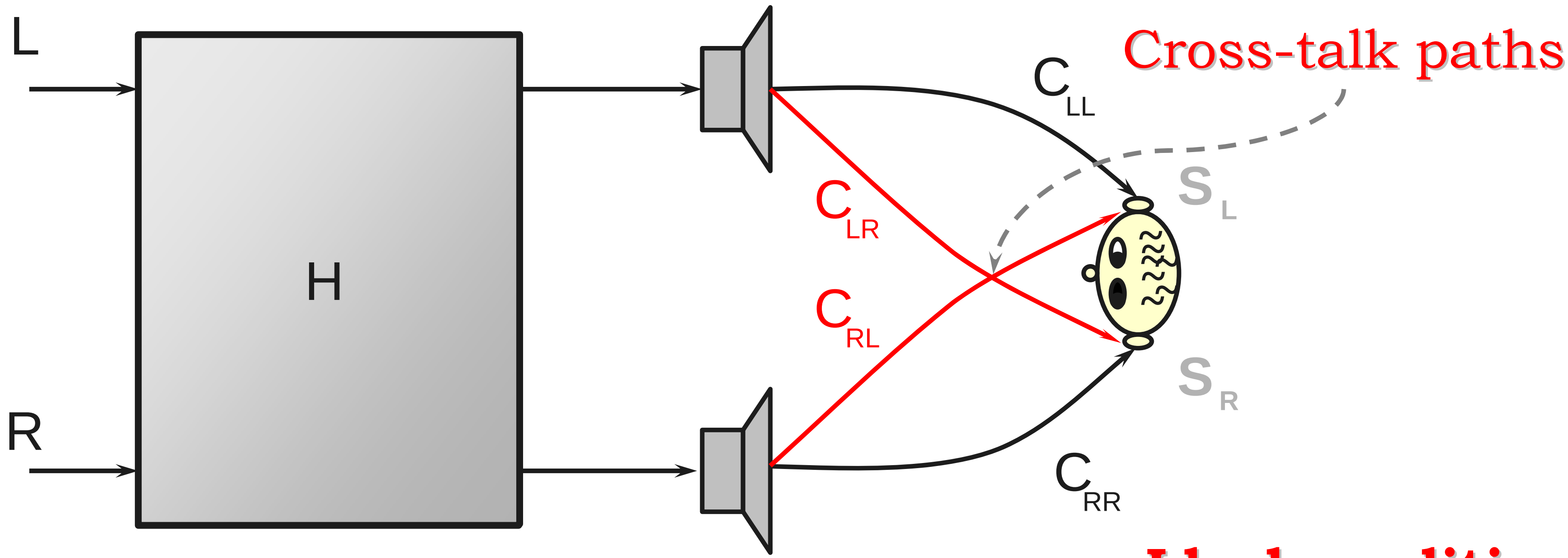
- 30 taps FIR



Sound harmonization

- Equalization is not sufficient to achieve a global increase of sound comfort;
- Harmonization of sound image achieves a subjective improvement of binaural sound quality;
  - *Stereo-dipole systems*

Stereo dipole system



Digital audio processor

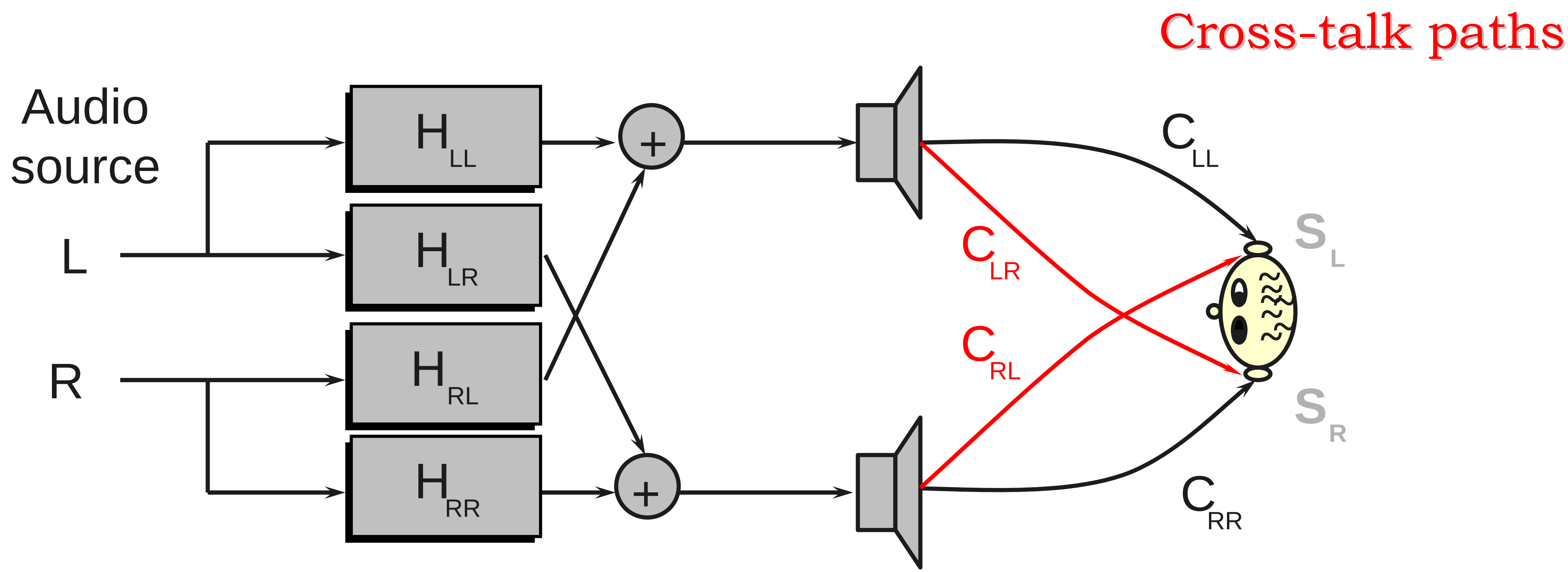
Ideal condition:

Design H so that:

$$S_L = L \cdot C_{LL}$$

$$S_R = R \cdot C_{RR}$$

Stereo dipole system



Stereo dipole structure

Target:

$$S_L = L \cdot C_{LL}$$

$$S_R = R \cdot C_{RR}$$

$$\Rightarrow \begin{cases} f_{ll} = (h_{rr}) \otimes \mathrm{InvDen} \\ f_{lr} = (-h_{lr}) \otimes \mathrm{InvDen} \\ f_{rl} = (-h_{rl}) \otimes \mathrm{InvDen} \\ f_{rr} = (h_{ll}) \otimes \mathrm{InvDen} \\ \mathrm{InvDen} = \mathrm{InvFilter}(h_{ll} \otimes h_{rr} - h_{lr} \otimes h_{rl}) \end{cases}$$

In the frequency domain:

$$C(\omega) = FT(h_{ll}) \cdot FT(h_{rr}) - FT(h_{lr}) \cdot FT(h_{rl})$$

Hence:

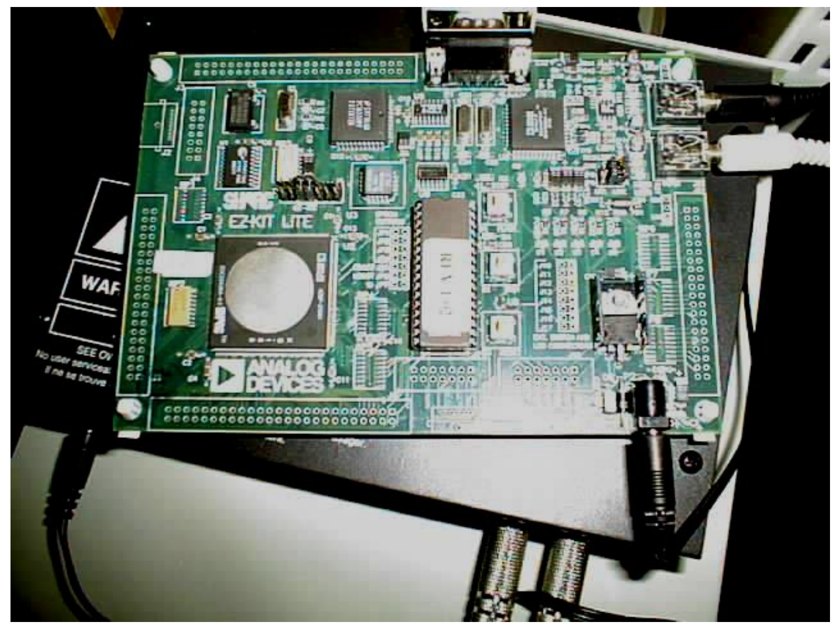
$$\mathrm{InvDen}(\omega) = \frac{\mathrm{Conj}[C(\omega)]}{\mathrm{Conj}[C(\omega)] \cdot C(\omega) + \varepsilon(\omega)}$$

$\varepsilon(\omega)$ is a function of frequency

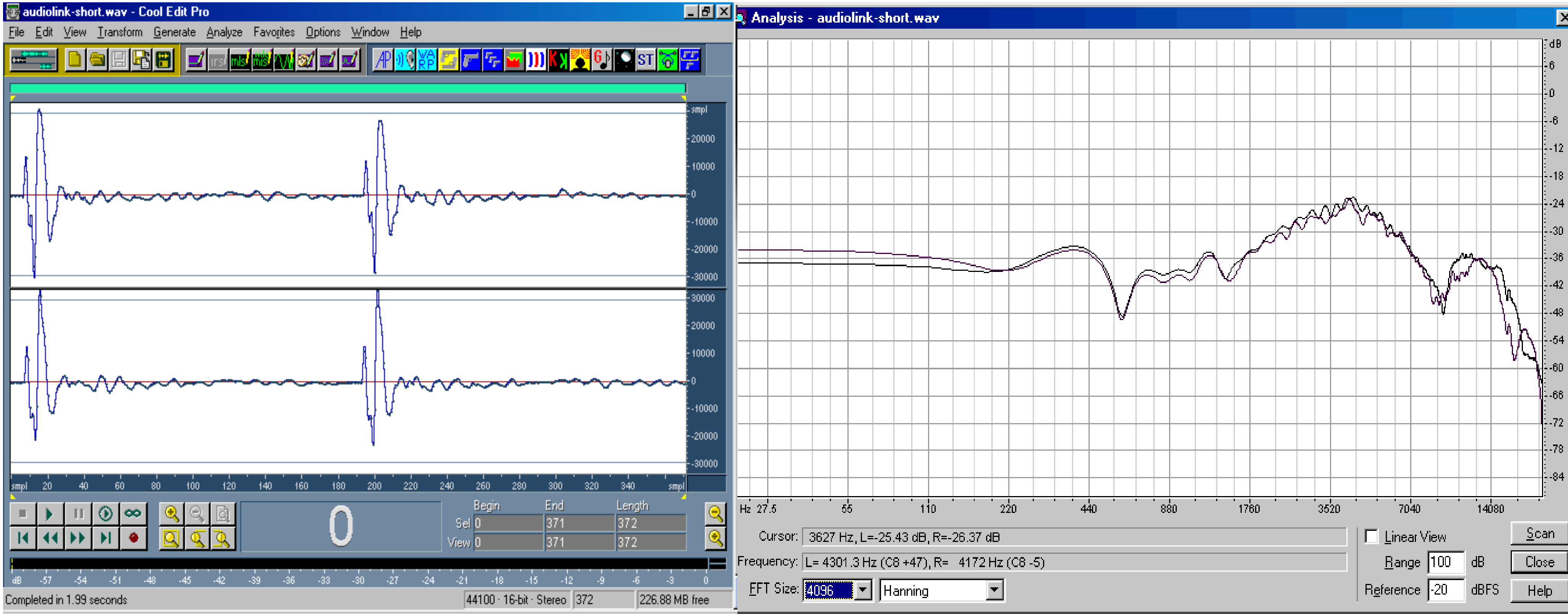
ASK listening room

Digital implementation

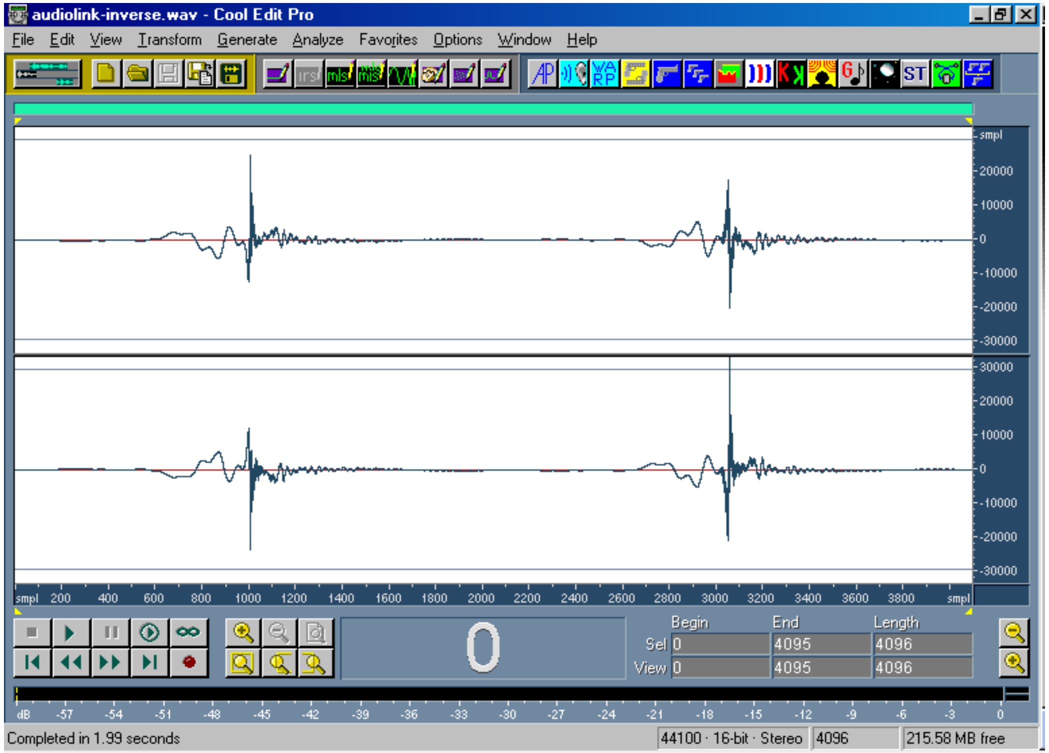
- DSP SHARC 21061 EZ-LITE:
  - 40 Mips, with which 880 Taps can be computed for each sample @ 44100 Hz
- DSP SHARC 21065L
- AD 1847 @ 44100/48000;



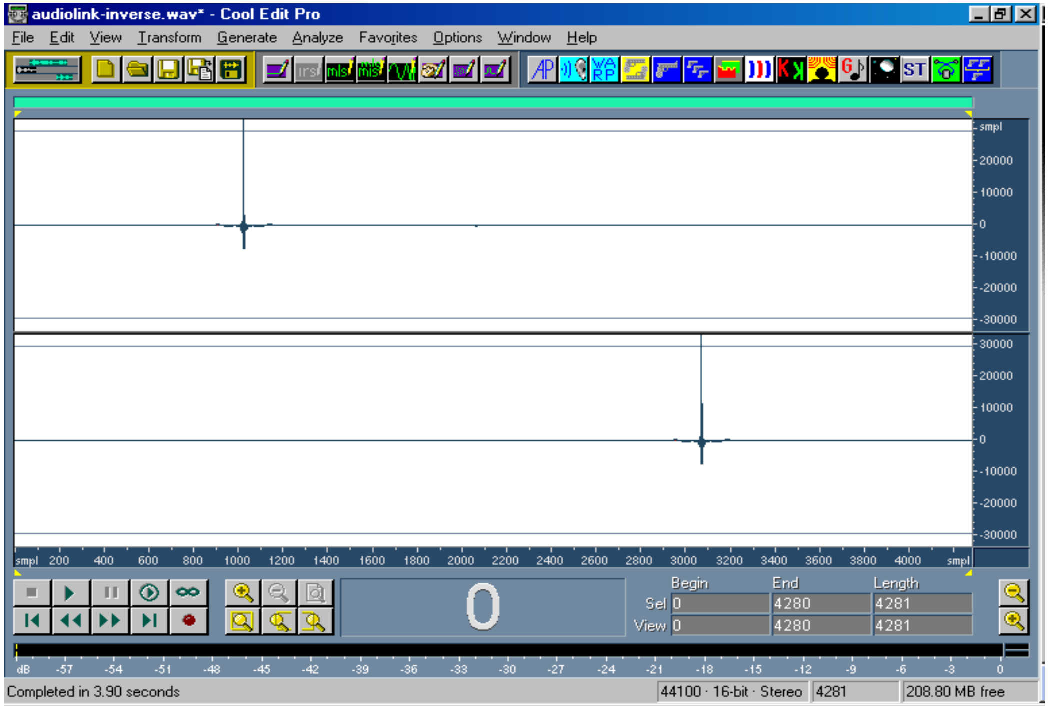
Experimental results
(Measured binaural response of the room)

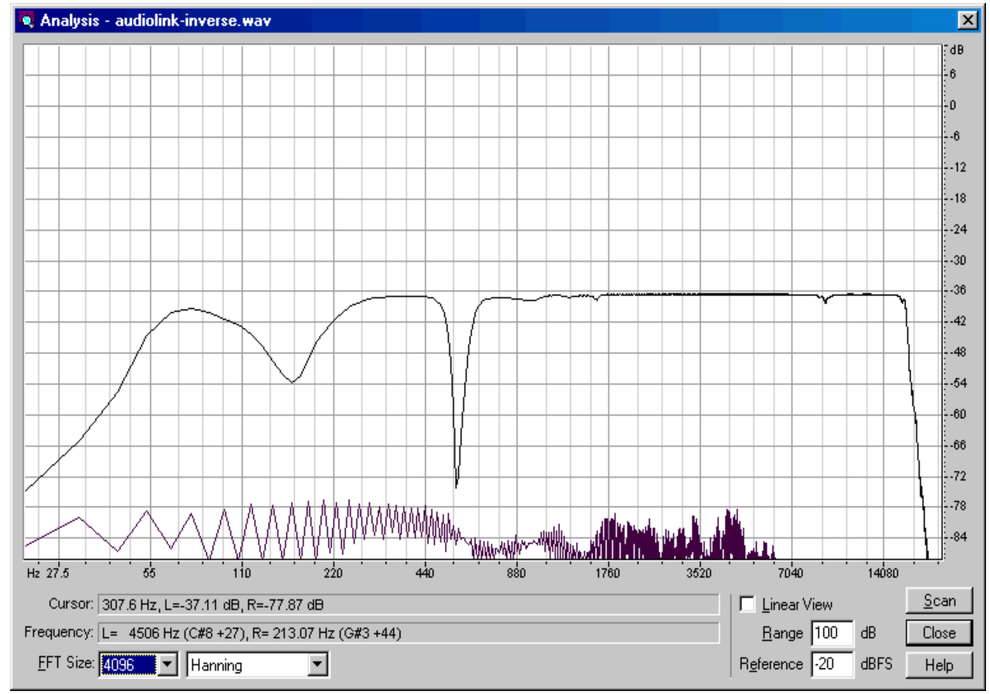


Experimental results
(2048 FIR cross-talk cancelling filters)

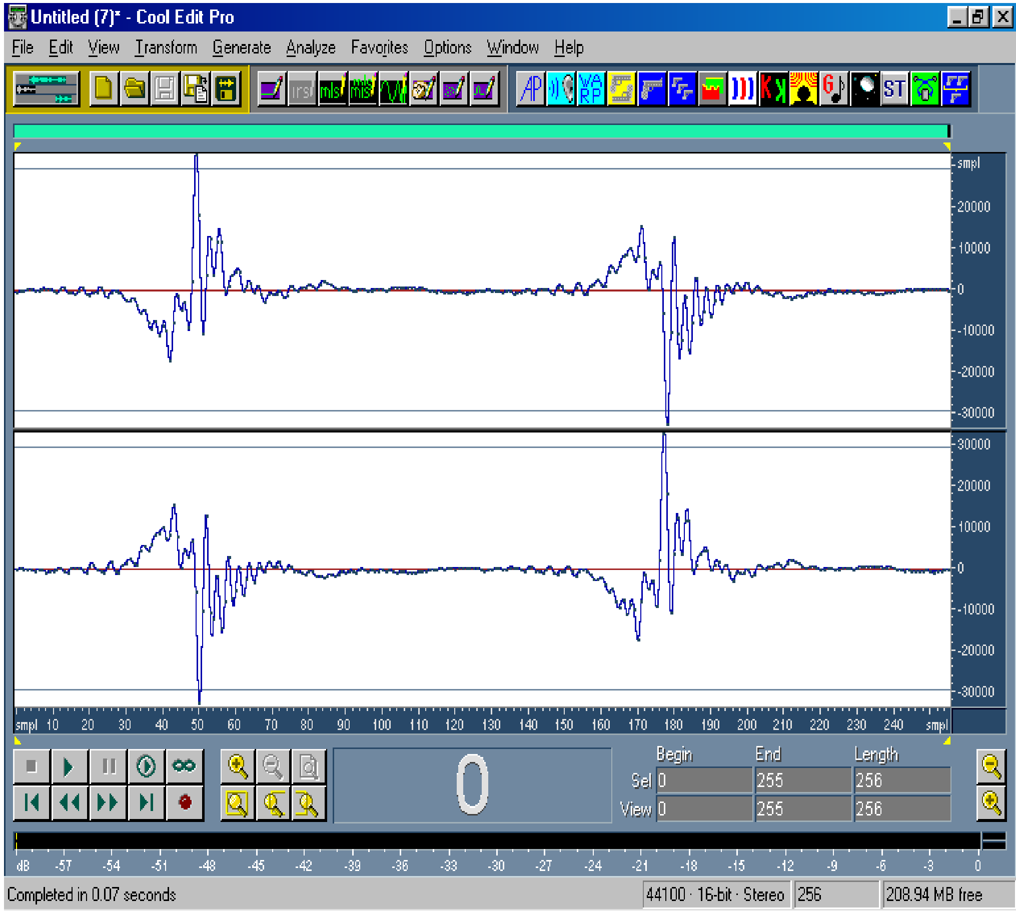


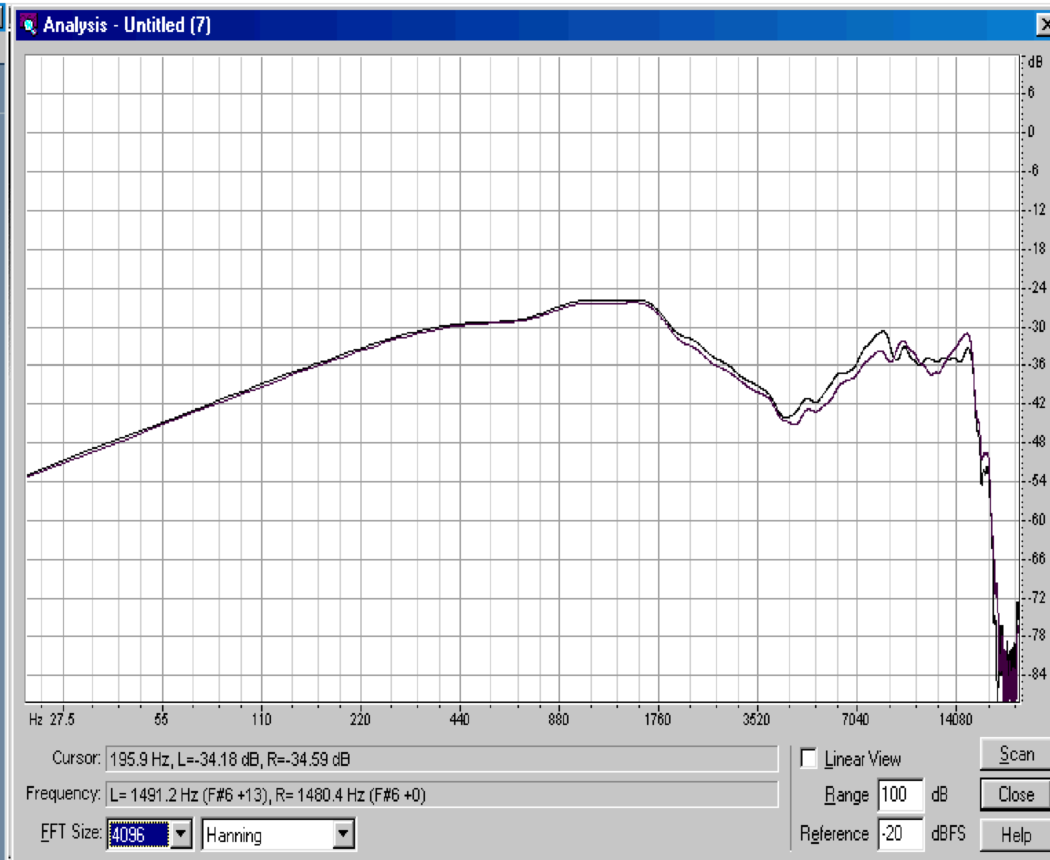
Experimental results (Measured response with 2048 FIR)



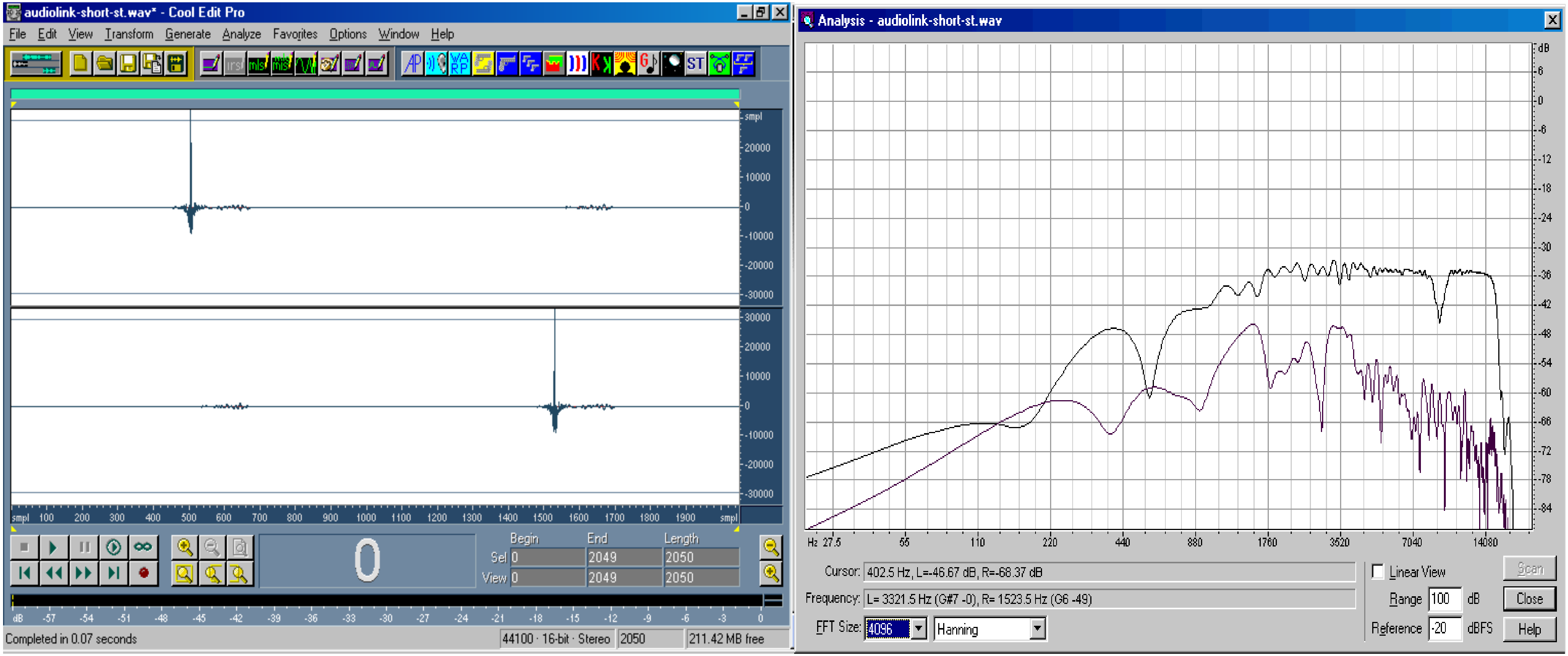


Experimental results (220 FIR cross-talk cancelling filters)

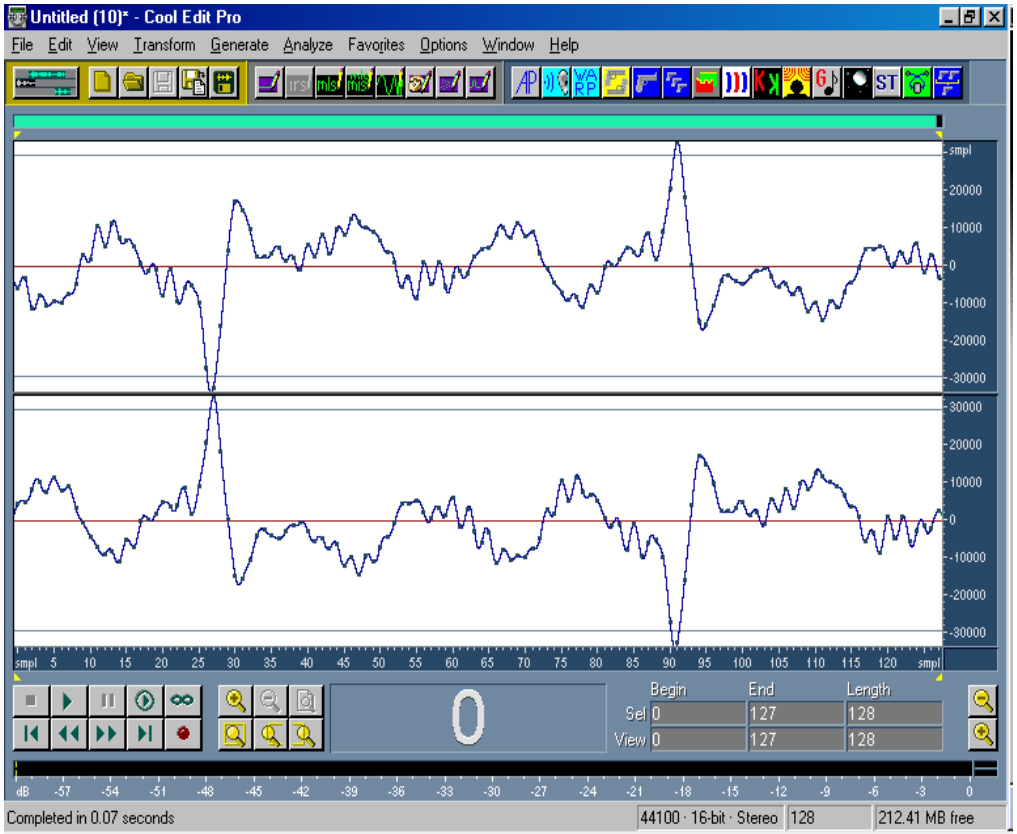


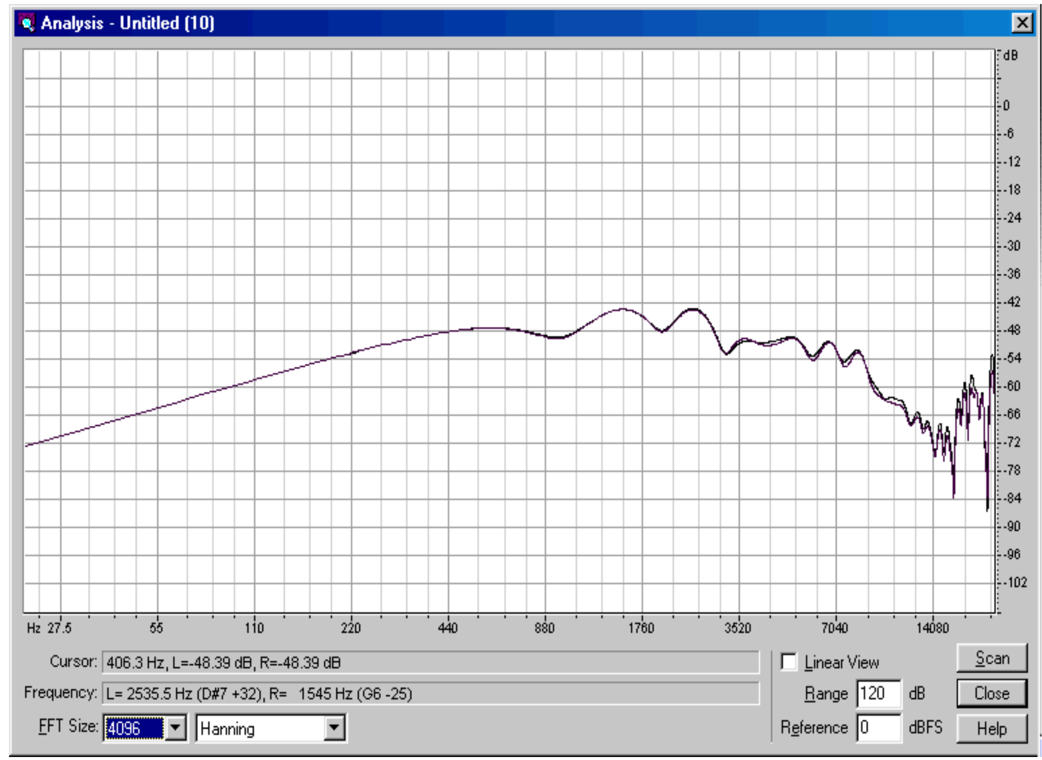


Experimental results
(Measured response with 220 FIR)

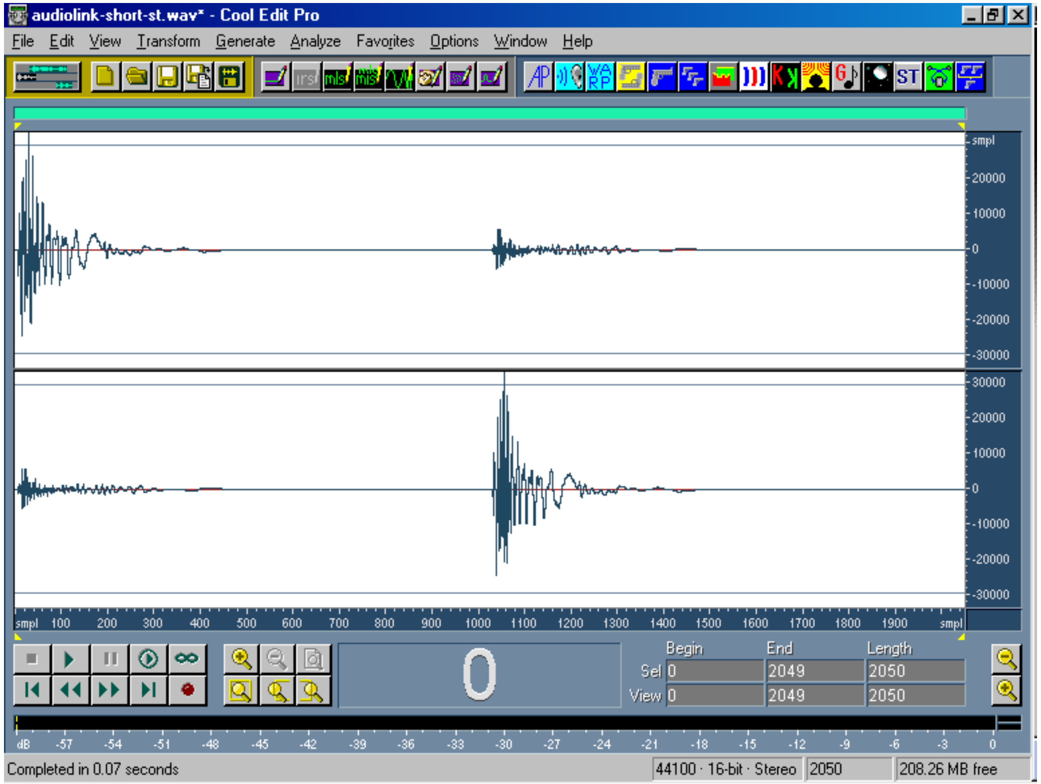


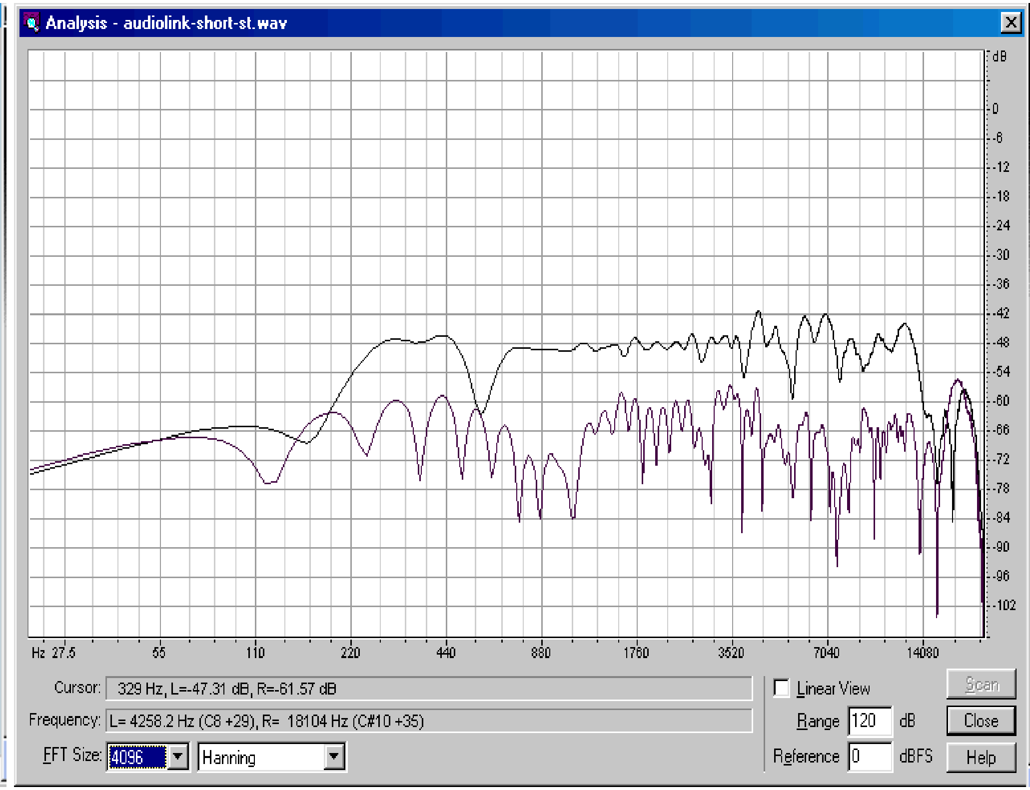
Experimental results
(42 WFIR cross-talk cancelling filters)





Experimental results (Measured response with 42 WFIR)





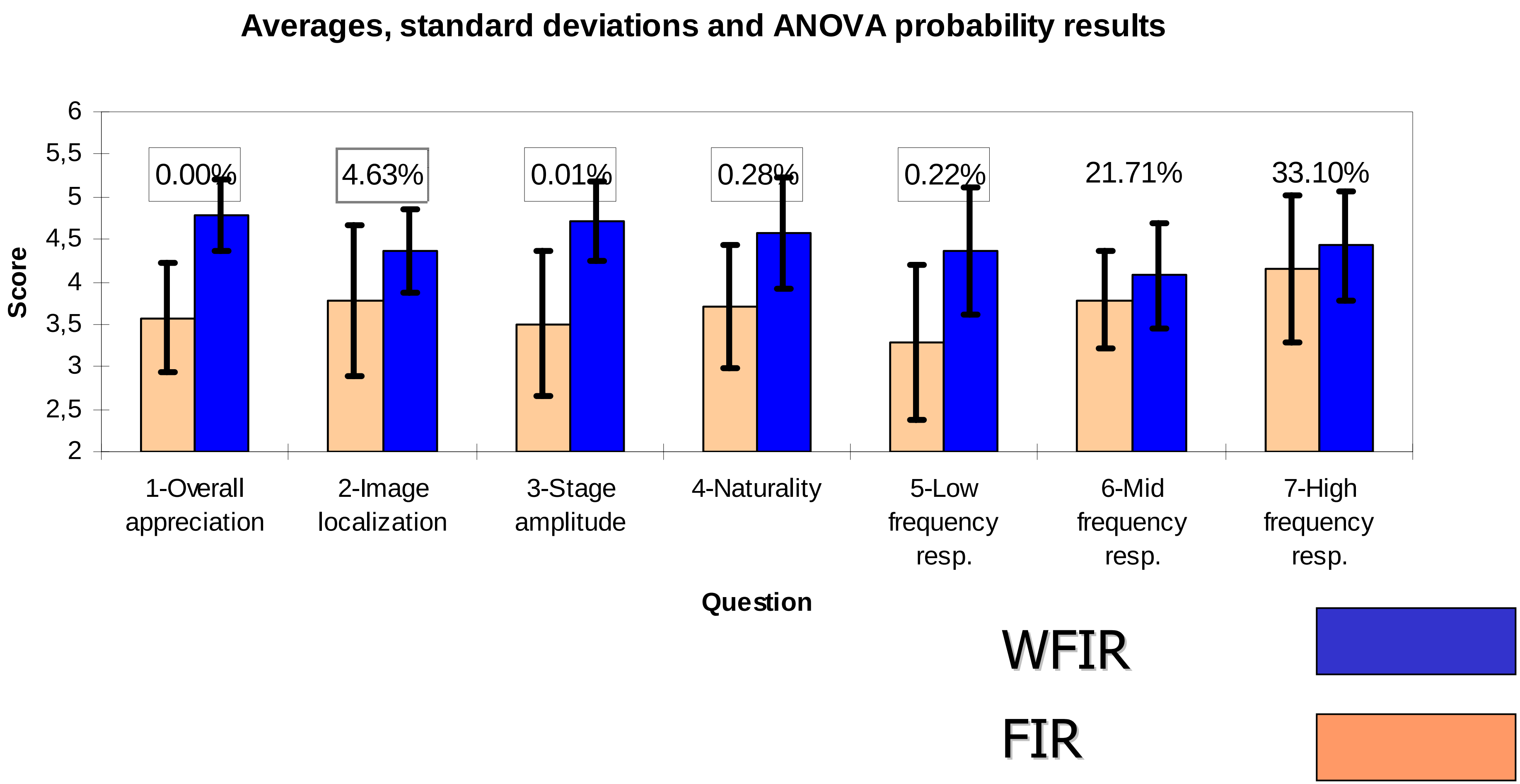
Subjective tests

- Subjective tests have been performed by trained people, no time-limit, several choices of music available;
- Blind Evaluation for each of the four systems (the listener can switch between them at any time):
  - WFIR
  - FIR
- 7 question with a 0-5 score.
- ANOVA statistical post-processing analysis

Subjective tests

Question	Avg. FIR	Avg.WFIR	Anova's F factor	Prob.
Overall appreciation	3.57	4.79	**34.47**	0.00%
Image localization	3.79	4.36	**4.38**	4.63%
Stage amplitude	3.50	4.71	**21.72**	0.01%
Naturality	3.71	4.57	**10.88**	0.28%
Low frequency resp.	3.29	4.36	**11.56**	0.22%
Mid frequency resp.	3.79	4.07	1.60	21.71%
Hi frequency resp.	4.14	4.43	0.98	33.10%

Subjective tests



Conclusions

- Multi-channel Warped filter equalization and harmonization;
- Automatic design of audio processors with standard acoustic measurements (AURORA);
- Implementation on DSP systems;
- Experimental results and listening tests;