Universität Rostock Traditio et Innovatio

Detection of Constant Phase Shifts in Filters for Sound Field Synthesis

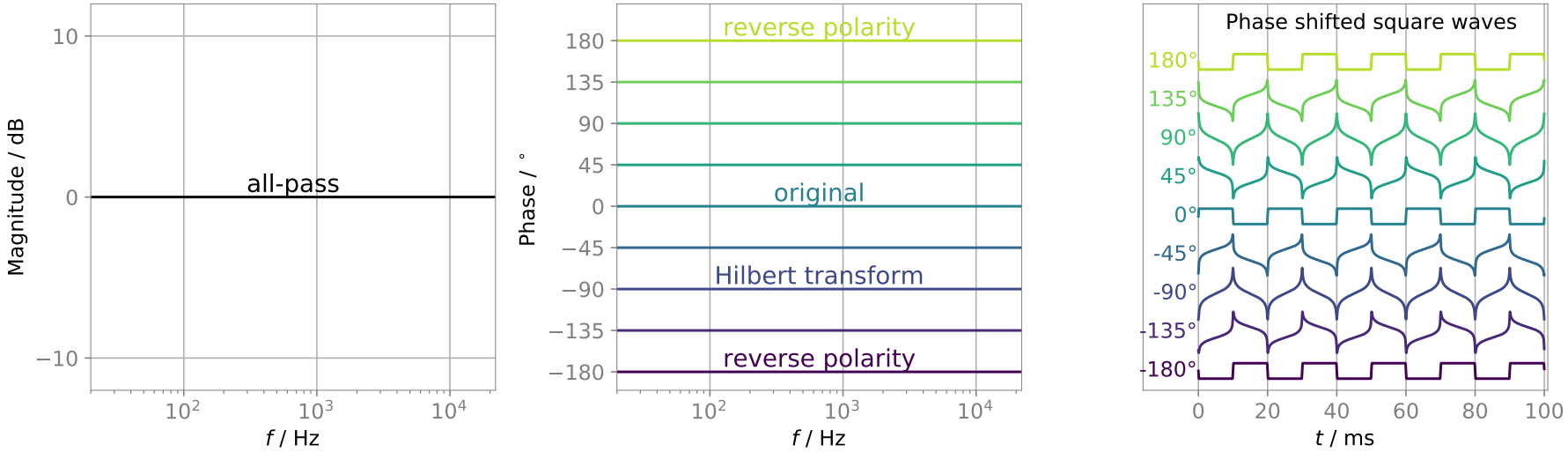
Frank Schultz, Nara Hahn, Sascha Spors

Research Group Signal Processing and Virtual Acoustics
University of Rostock

5th INTERNATIONAL CONFERENCE ON SPATIAL AUDIO, September 26th to 28th, 2019, Ilmenau, Germany

Ideal Constant Phase Shift

Audibility of constant phase shift?



Literature audibility of group delay / phase distortions:

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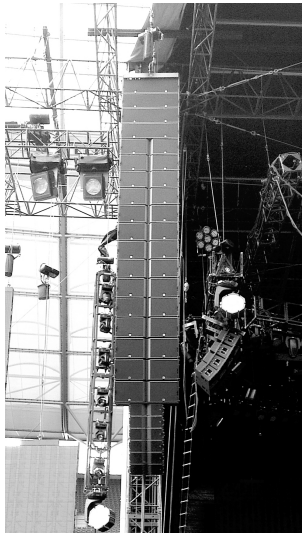
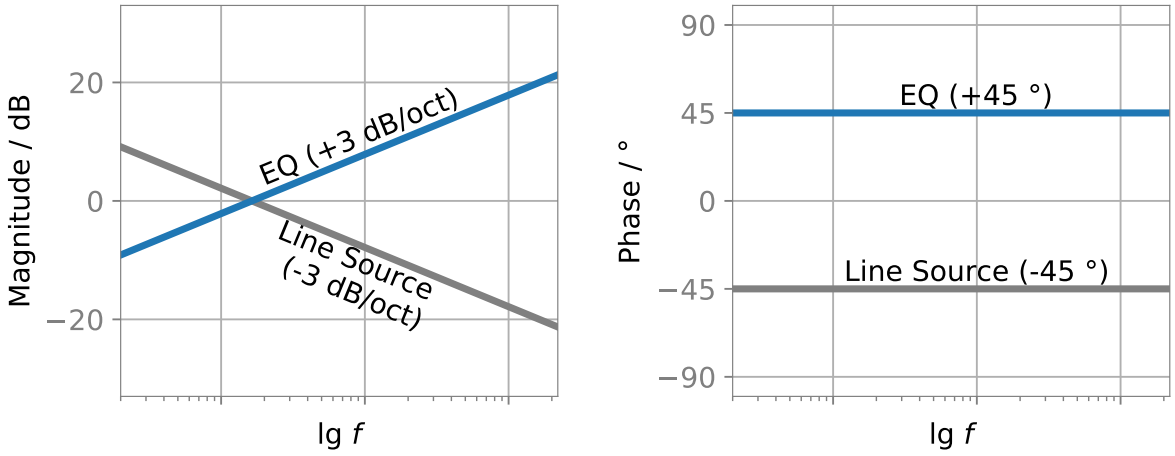
Sound Field Synthesis (SFS) with Linear / Planar Arrays

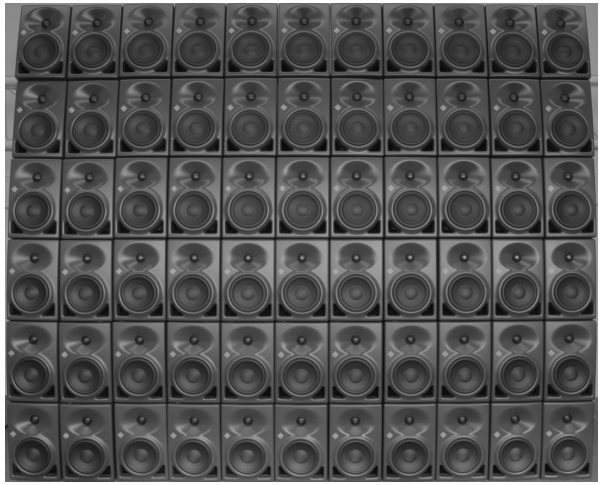
2.5-dimensional SFS



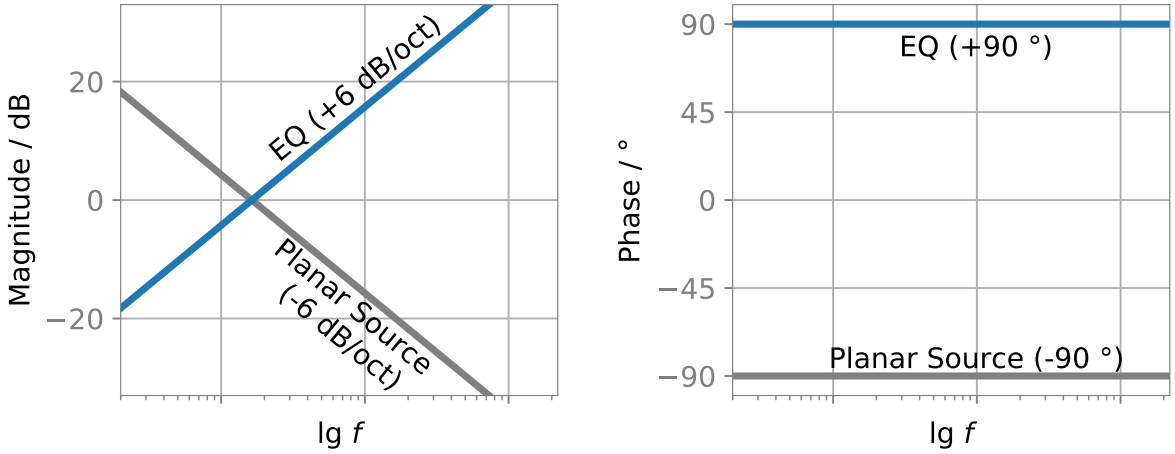
ideal half-derivative EQ for infinite linear array



3-dimensional SFS



ideal full-derivative EQ for infinite planar array



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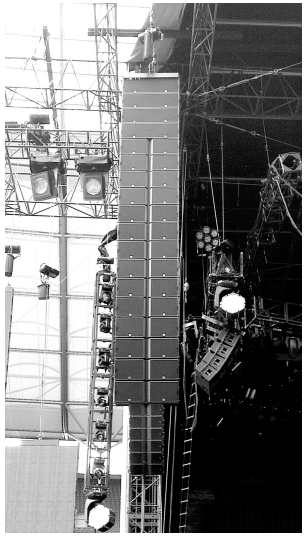

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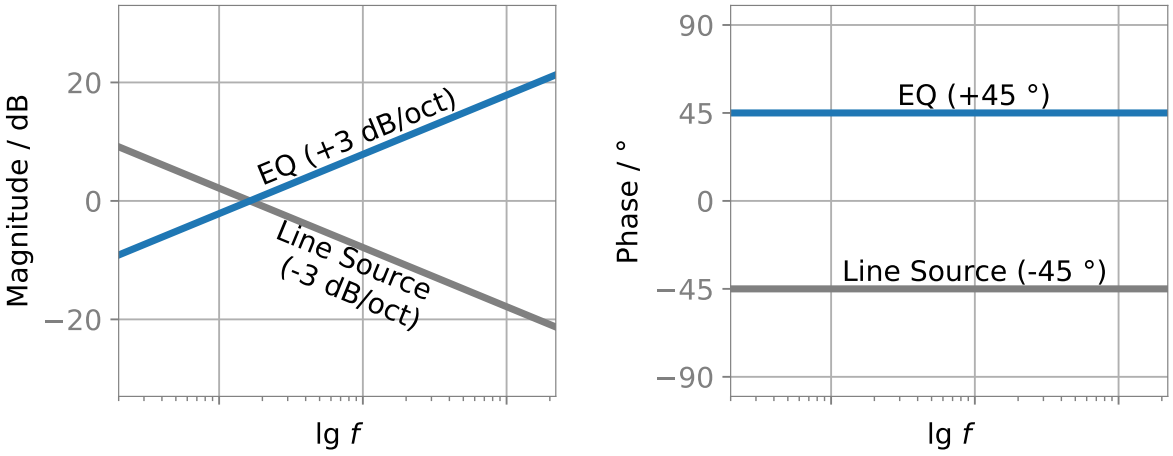
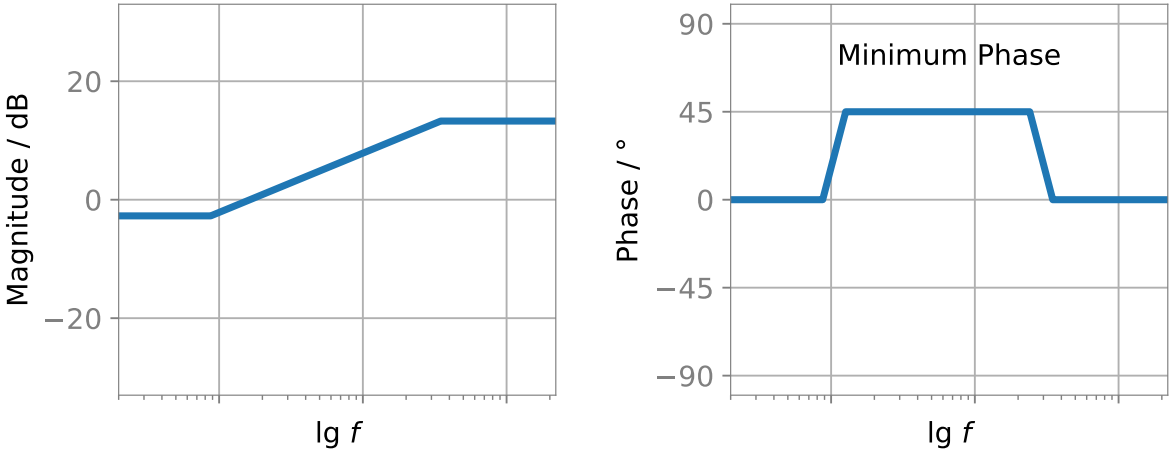


half-derivative slope for finite length array, minimum phase



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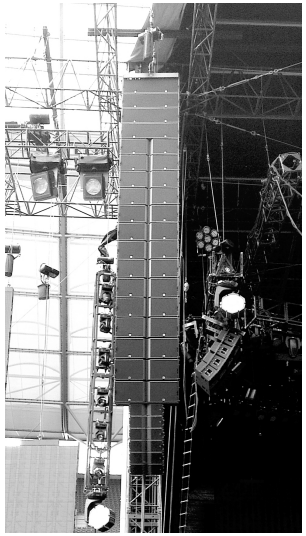

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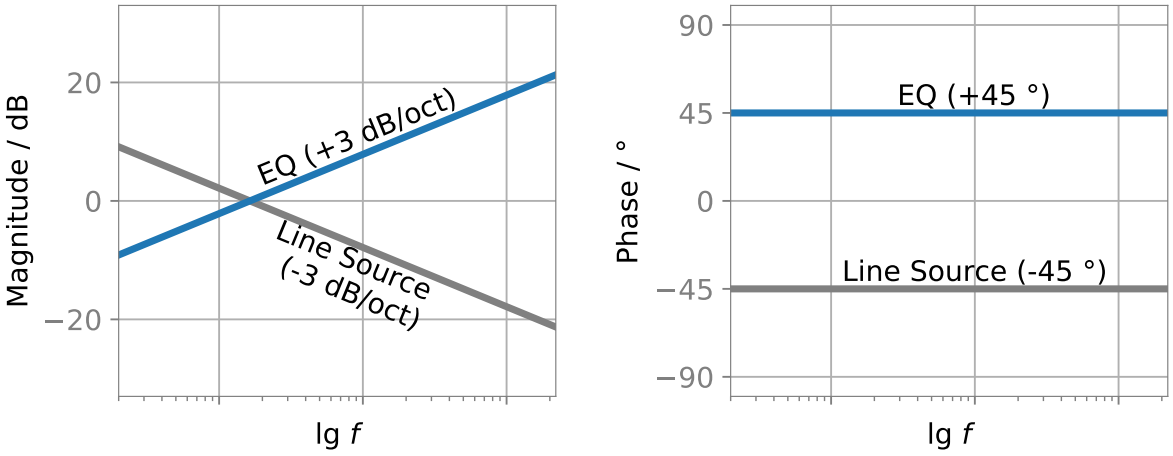
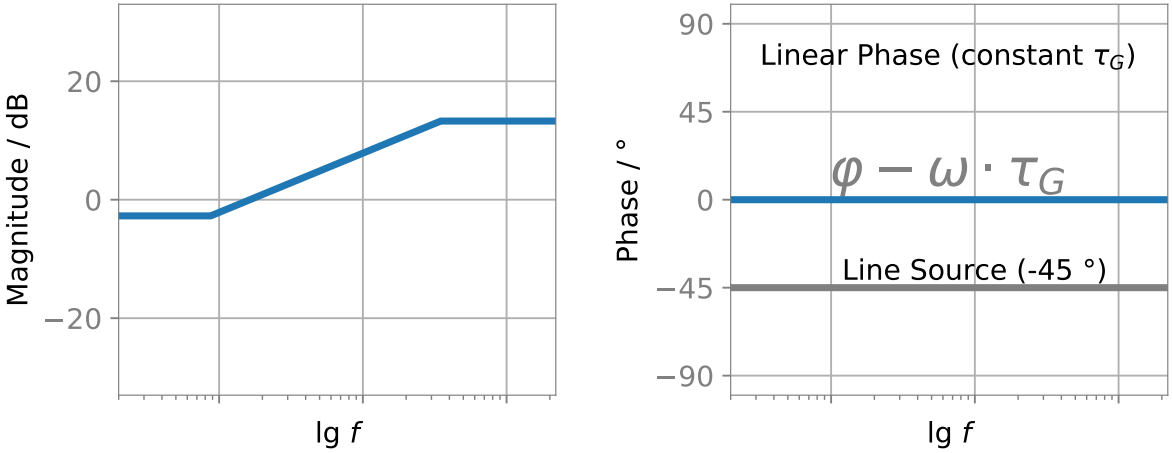


half-derivative slope for finite length array, linear phase



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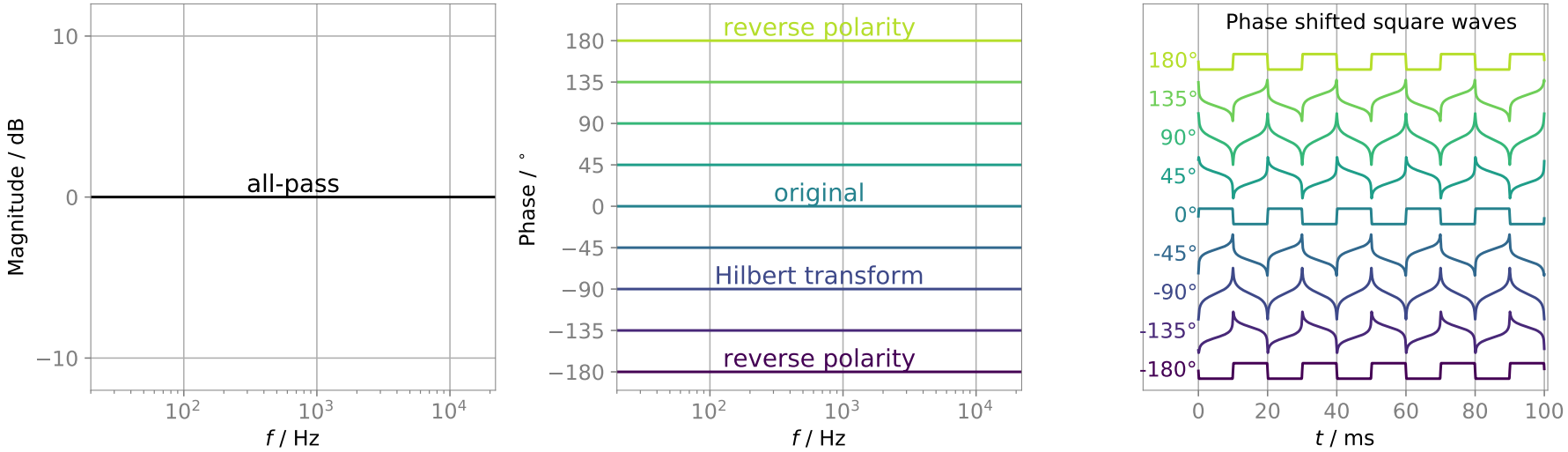

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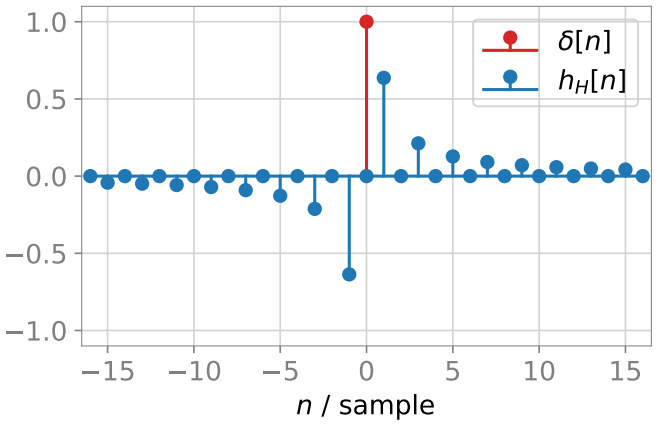
Fractional Hilbert Transform / Constant Phase Shift φ

Discrete-time <u>infinite</u> impulse response

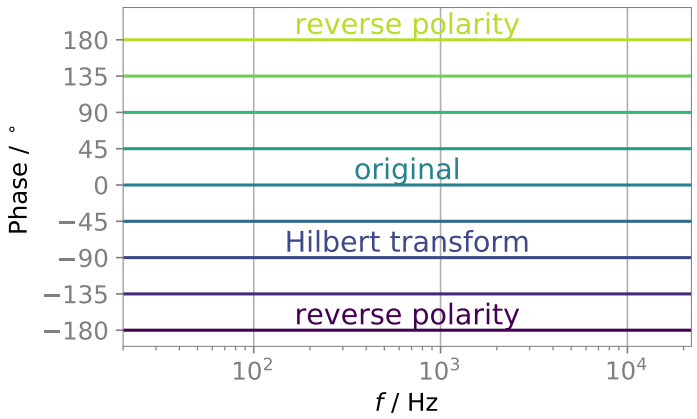
$$h[n] = \cos\varphi \cdot \delta[n] - \sin\varphi \cdot \underbrace{\begin{cases} 0, & n \text{ even} \\ \frac{2}{n\pi}, & n \text{ odd} \end{cases}}_{\text{Hilbert transform } h_{\mathrm{H}}[n]}$$



DTFT spectrum over $\Omega = 2\pi \frac{f}{f_s}$

$$H(\Omega) = \cos\varphi \cdot 1 - \sin\varphi \cdot \underbrace{(-\mathrm{j} \cdot \mathrm{sgn}(\Omega))}_{\text{Hilbert transform}}$$

$$= \begin{cases} \mathrm{e}^{+\mathrm{j}\varphi}, & 0 < \Omega < \pi \\ \mathrm{e}^{-\mathrm{j}\varphi}, & -\pi < \Omega < 0 \\ \cos\varphi, & \Omega = 0, \pi \end{cases}$$



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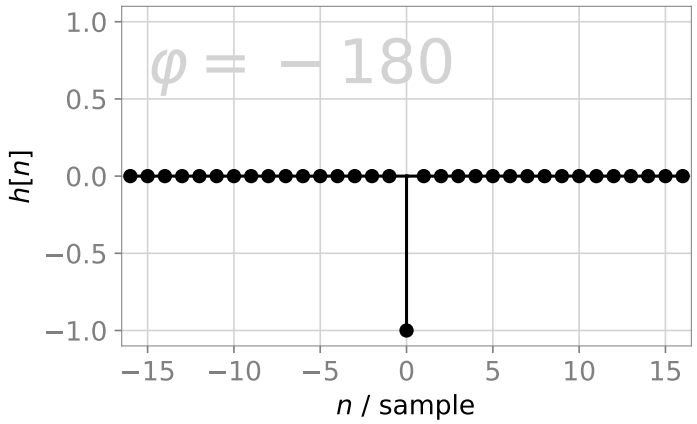

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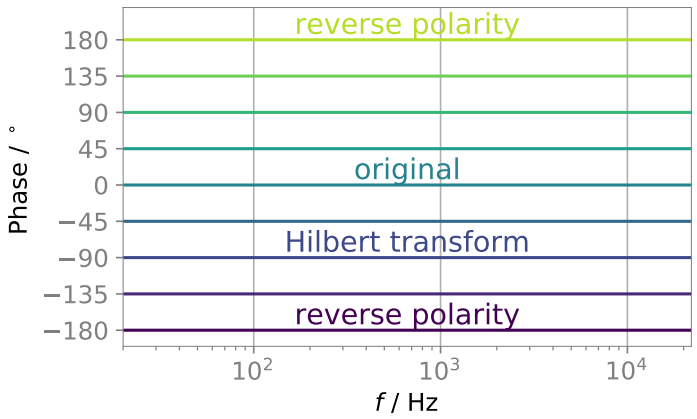

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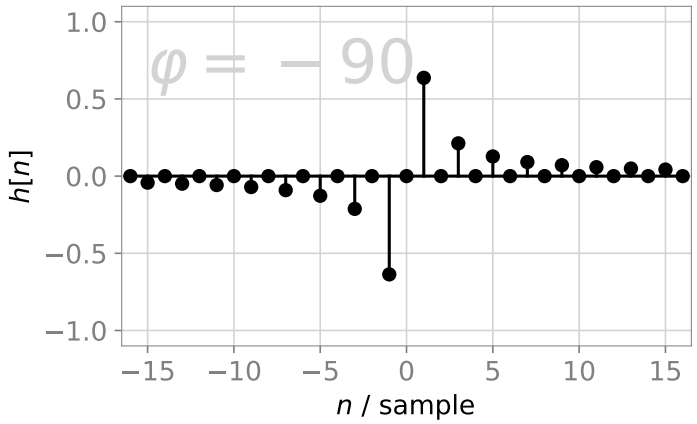

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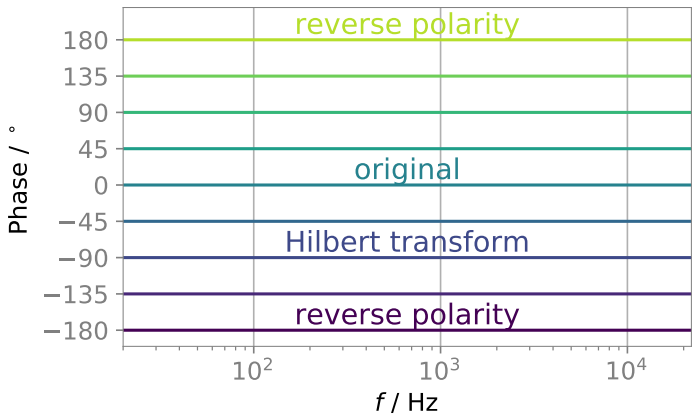

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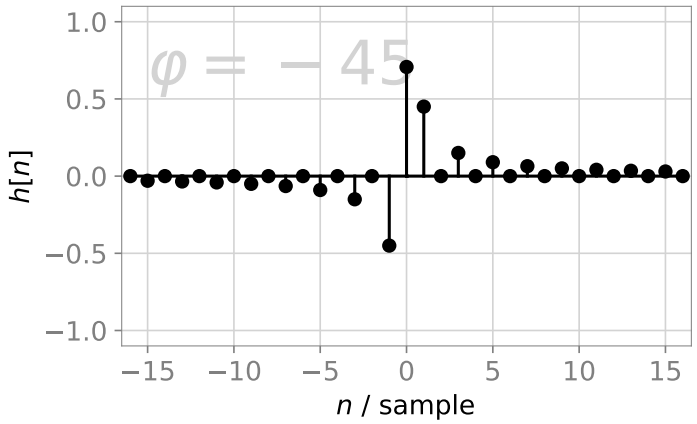

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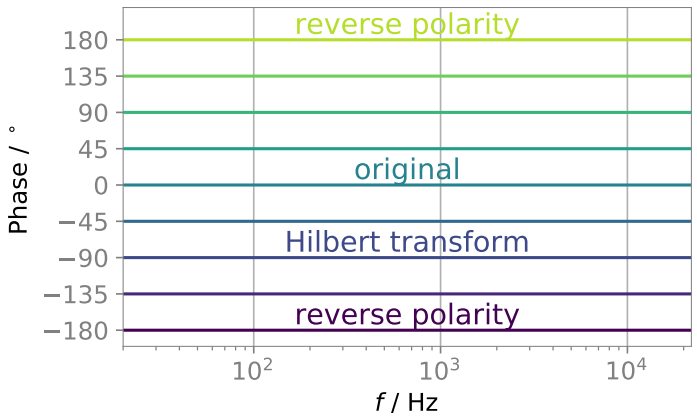

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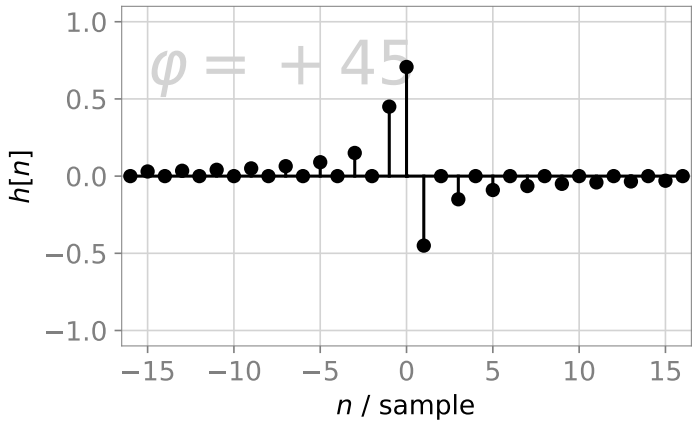

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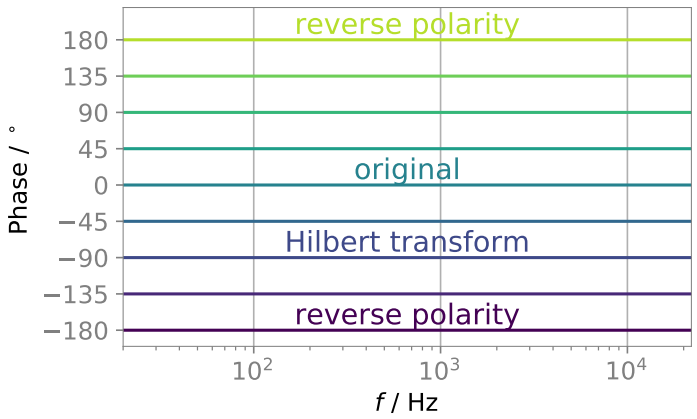
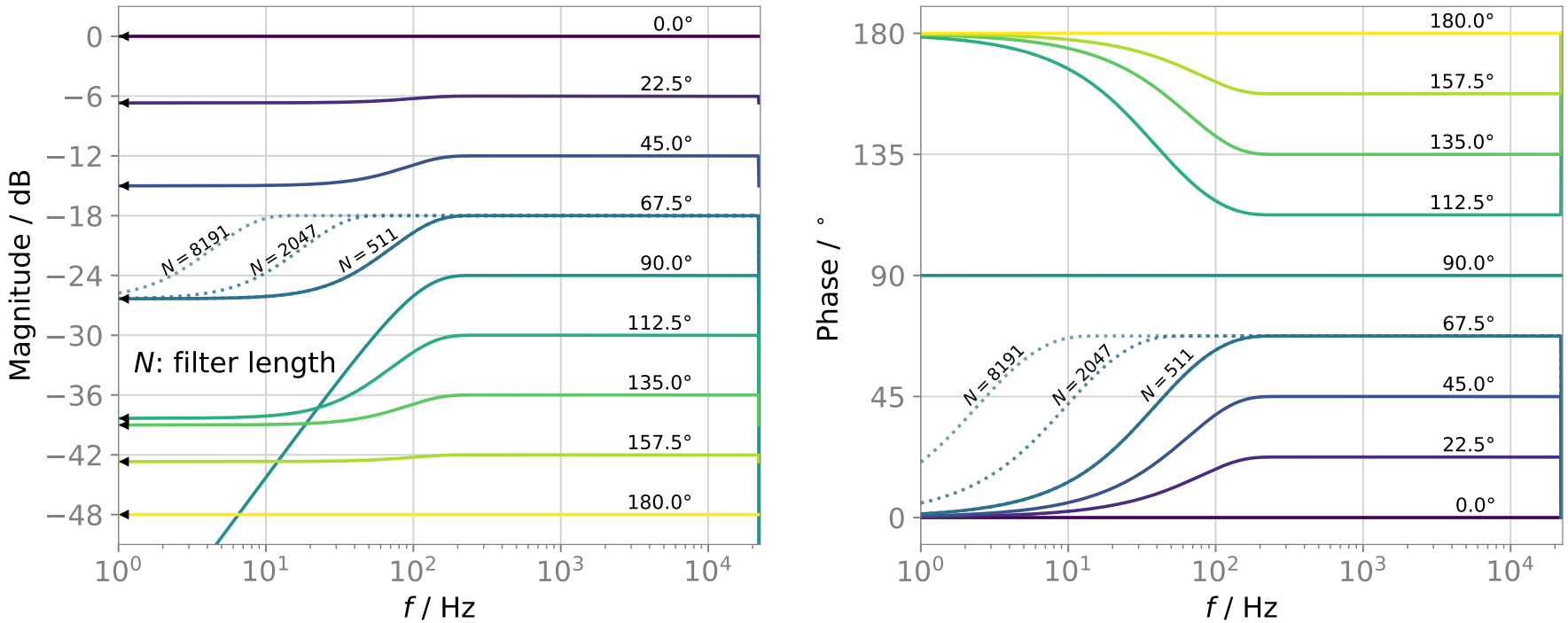


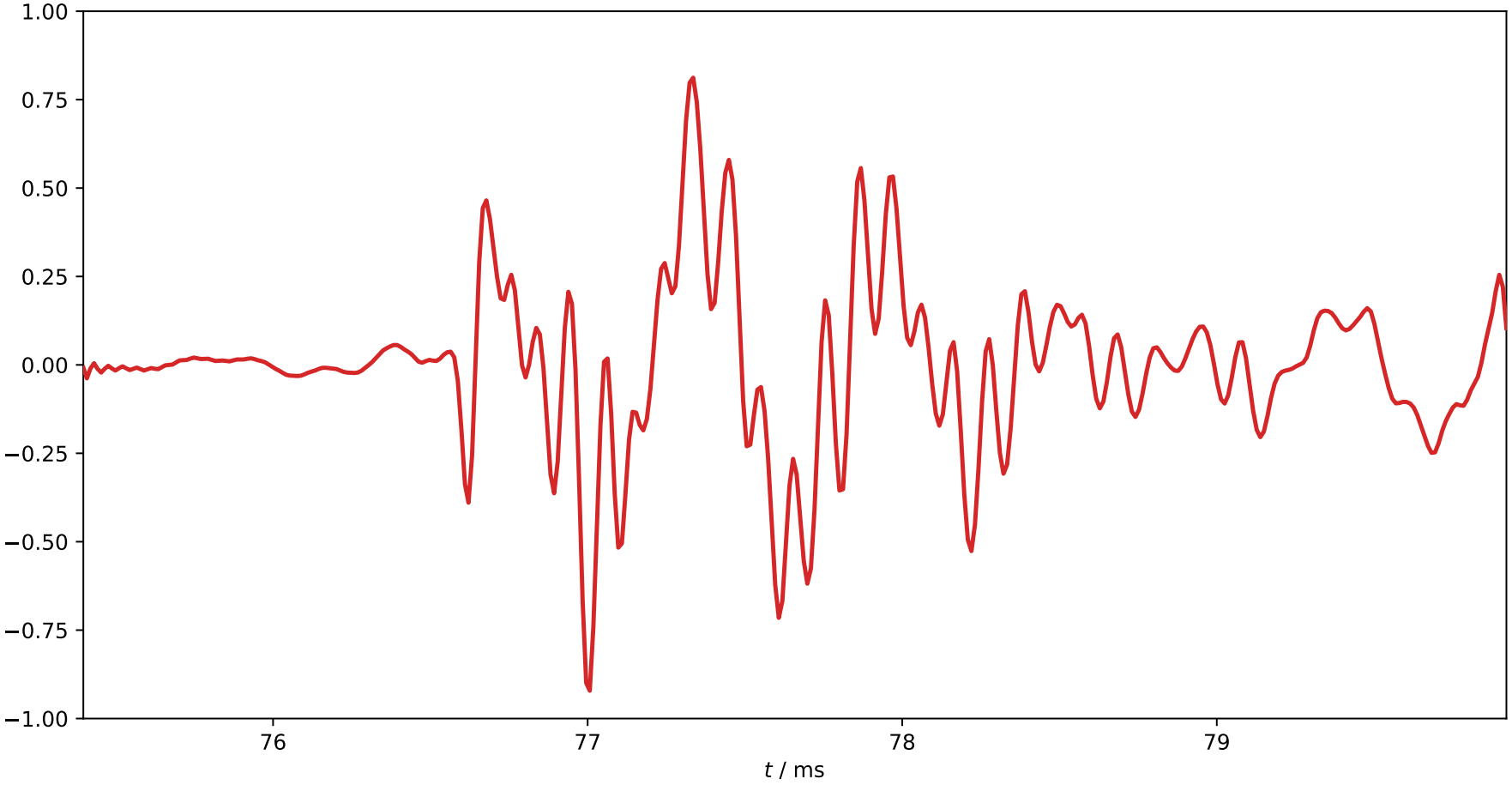
Finite Length Filter of Fractional Hilbert Transform



- for $\varphi = \pm 180°$: perfect phase and perfect magnitude, i.e. inverted Dirac impulse
- for $\varphi = \pm 90°$: perfect phase, largest magnitude deviation
- for all other φ at lowest / highest frequencies:
  magnitude convergence to $\cos\varphi$ and phase convergence to $0°$ or $180°$

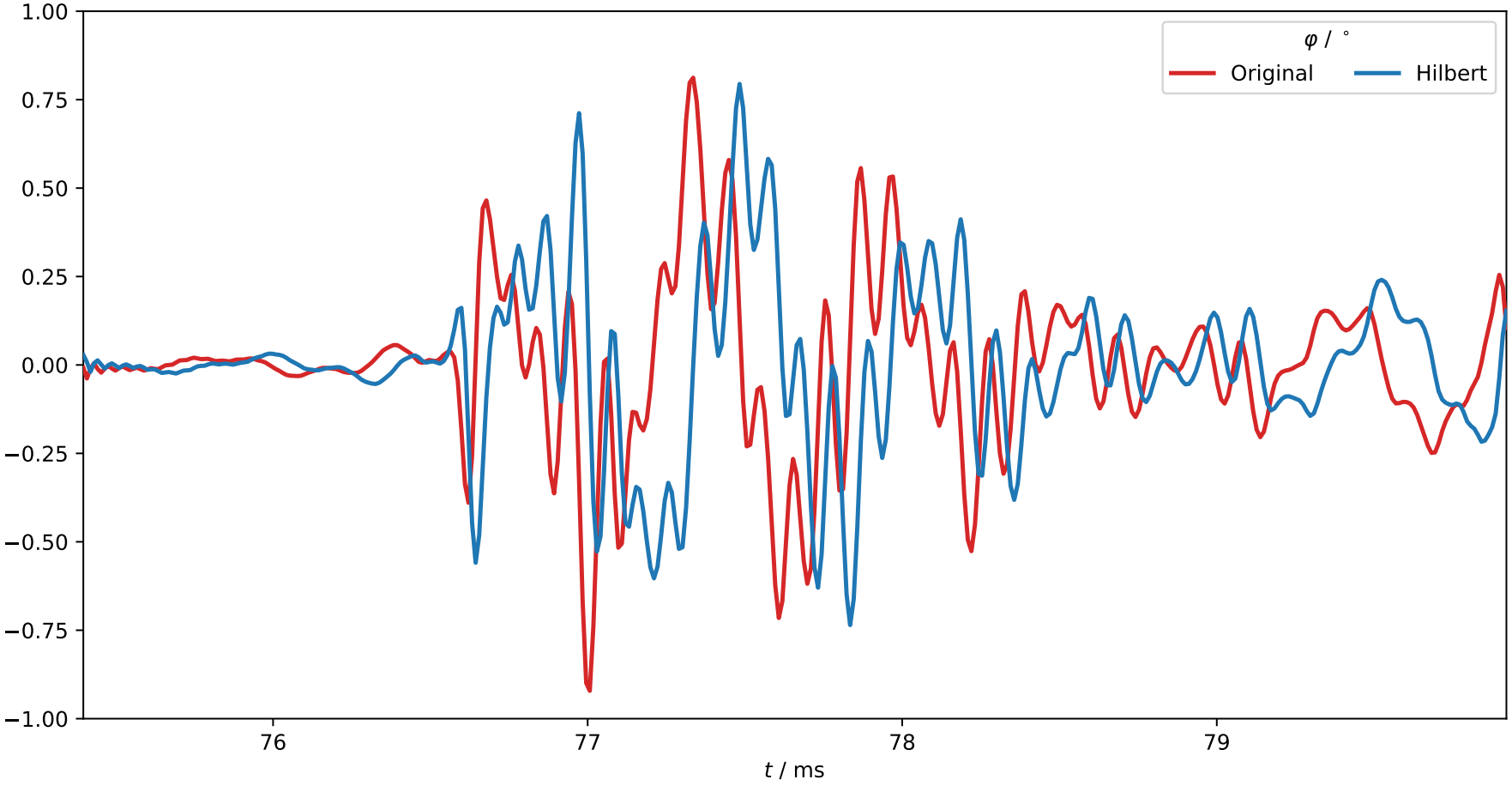
Example: Constant Phase Shift for Transient Signal

Original signal $x[n]$



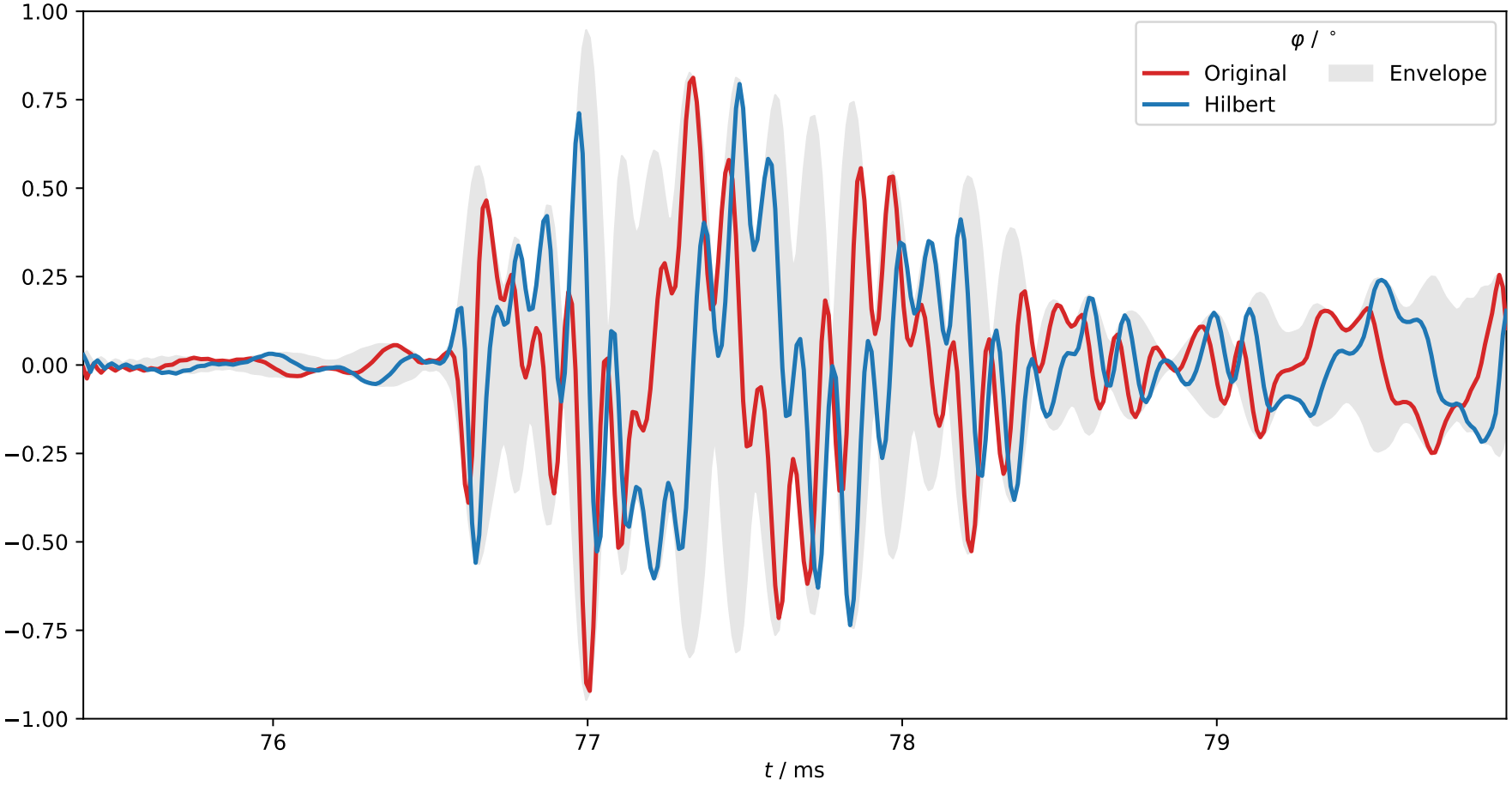
Example: Constant Phase Shift for Transient Signal

Original signal $x[n]$ and treatment Hilbert transform $x_{\mathrm{H}}[n]$



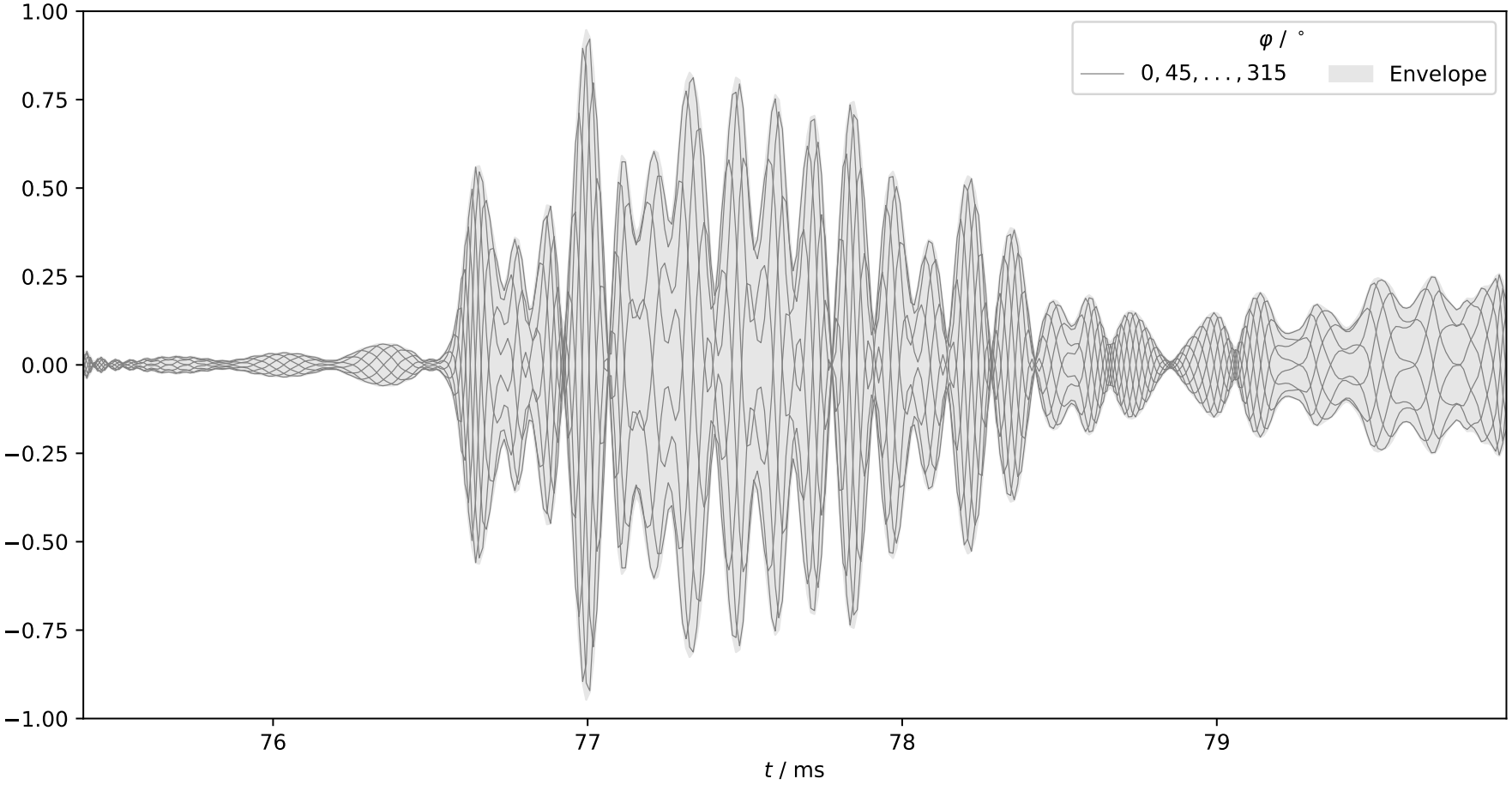
Example: Constant Phase Shift for Transient Signal

Original $x[n]$, treatment Hilbert transform $x_{\mathrm{H}}[n]$ and envelope $\pm\sqrt{x[n]^2 + x_{\mathrm{H}}[n]^2}$



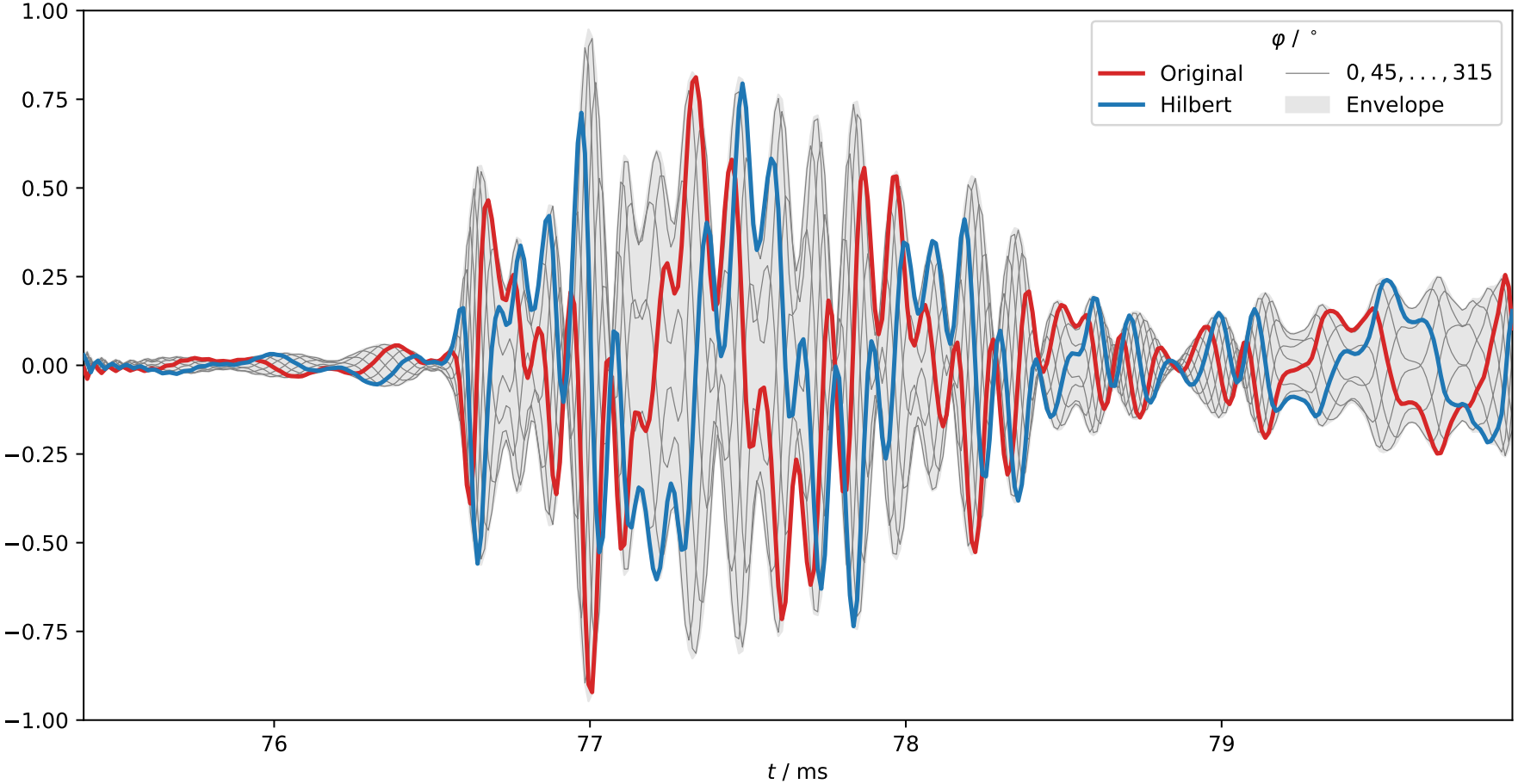
Example: Constant Phase Shift for Transient Signal

Treatment $x[n] * h[n]$ for different constant phase shifts φ



Example: Constant Phase Shift for Transient Signal

Audibility of the treatment Hilbert transform ($\varphi = -90°$) against original ?!



Listening Experiment: Audio Material & Conditions

4x Audio

- square wave bursts 50 Hz, 200 ms on, 300ms off, $\sin^2$ fades
- 300 Hz-lowpass filtered pink noise
- castanets (anechoic by Matthias Frank)
- music excerpt with percussion, drums (Eagles, Hotel California, Hell freezes over, 1994)

5x Treatment: Constant Phase Shift vs. Original ($\varphi = 0°$)

I square wave bursts with $\varphi = -90°$

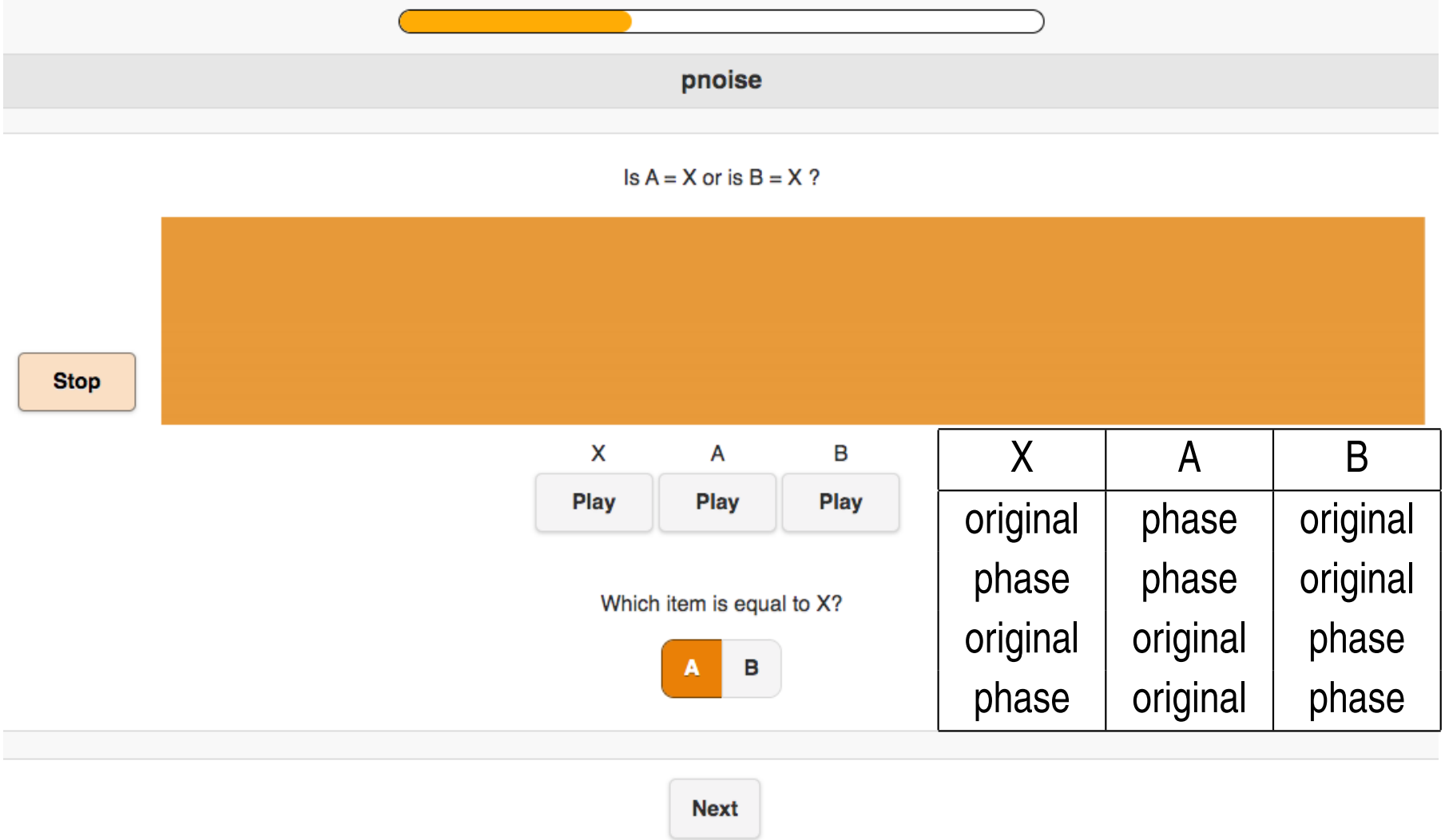
II square wave bursts with $\varphi = -45°$

III lowpass filtered pink noise with $\varphi = -90°$

IV castanets with $\varphi = -90°$

V Hotel California with $\varphi = -90°$

Listening Experiment: ABX Test with webMUSHRA



X	A	B
original	phase	original
phase	phase	original
original	original	phase
phase	original	phase

https://www.audiolabs-erlangen.de/resources/webMUSHRA

ABX / χ^2 Test Statistic Considerations

Pre hoc for individual participants:

- null hypothesis $\mathcal{H}_0(p_{\text{detect}} = 0.5)$, i.e. pure guessing
- target rejection level $\alpha = 0.05$, target test power $1 - \beta = 0.95$
- assumed $p_{\text{detect}} = 0.9$ (effect size $g = 0.4$)
- per audio content for $\frac{\geq 19 \text{ correct trials}}{25 \text{ total trials}} \rightarrow p_{\text{Binomial PDF}} < \frac{\alpha}{5} \rightarrow \mathcal{H}_0$ can be rejected

Post hoc for tested population (cumulated frequencies):

- per audio content: comparison against 50:50 answering
- 10 pairwise comparisons over all audio contents: same rating for different content?

using $p_{\chi^2\text{PDF}}$ for small / medium effect size

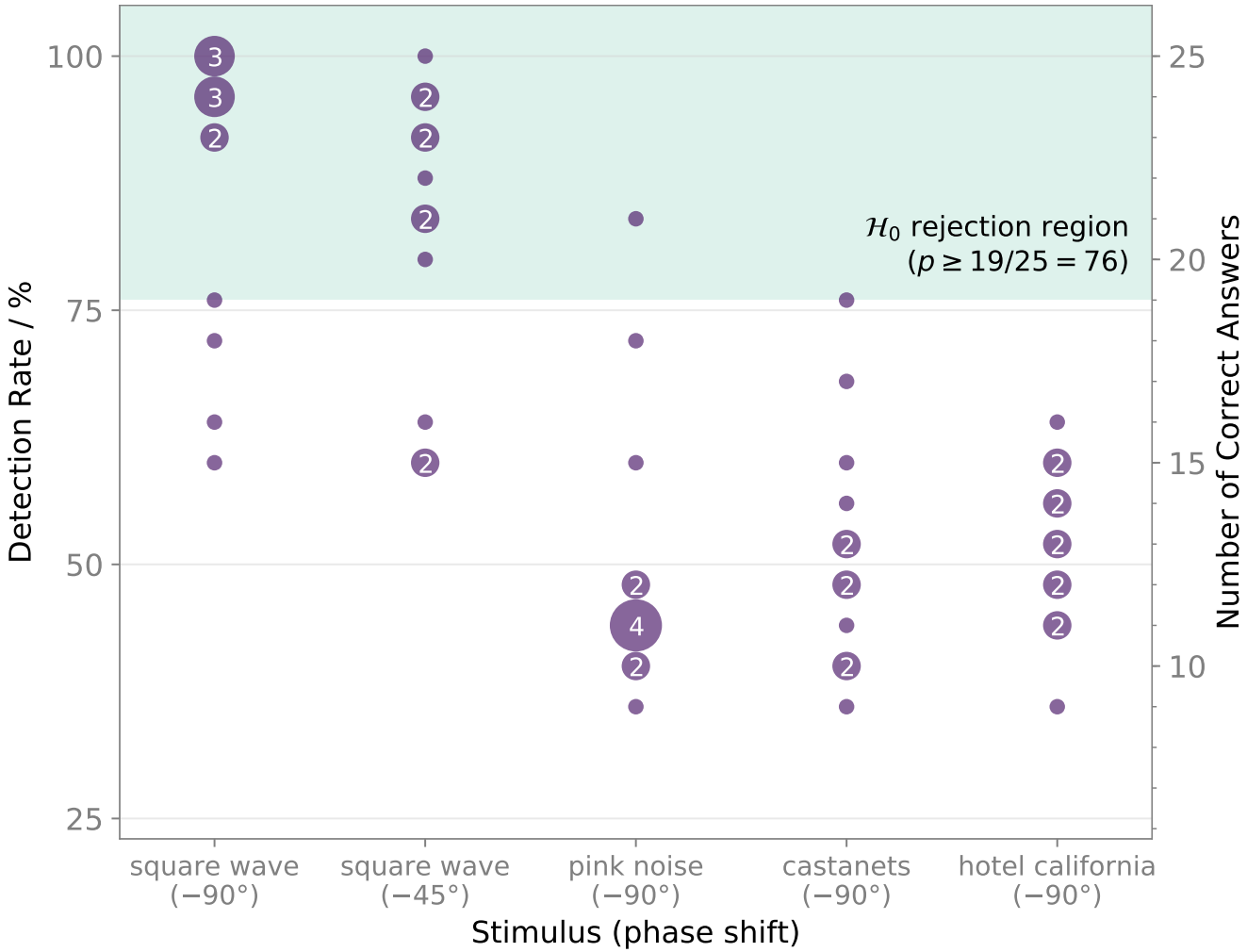
Listening Experiment: Procedure

- experiments conducted in our audio lab
- diotic playback via headphone Sennheiser HD 800 (dynamic, open)
- stimuli ITU-R BS.1770-4 loudness matched (except castanets)
- playback at 73 $dB(A)_{Leq}$ / 88 $dB(C)_{Peak}$ for fullband pink noise

- ratings: 5 treatments x 25 trials per treatment x 12 participants (4 female, 8 male)
- fully randomized stimuli sequence

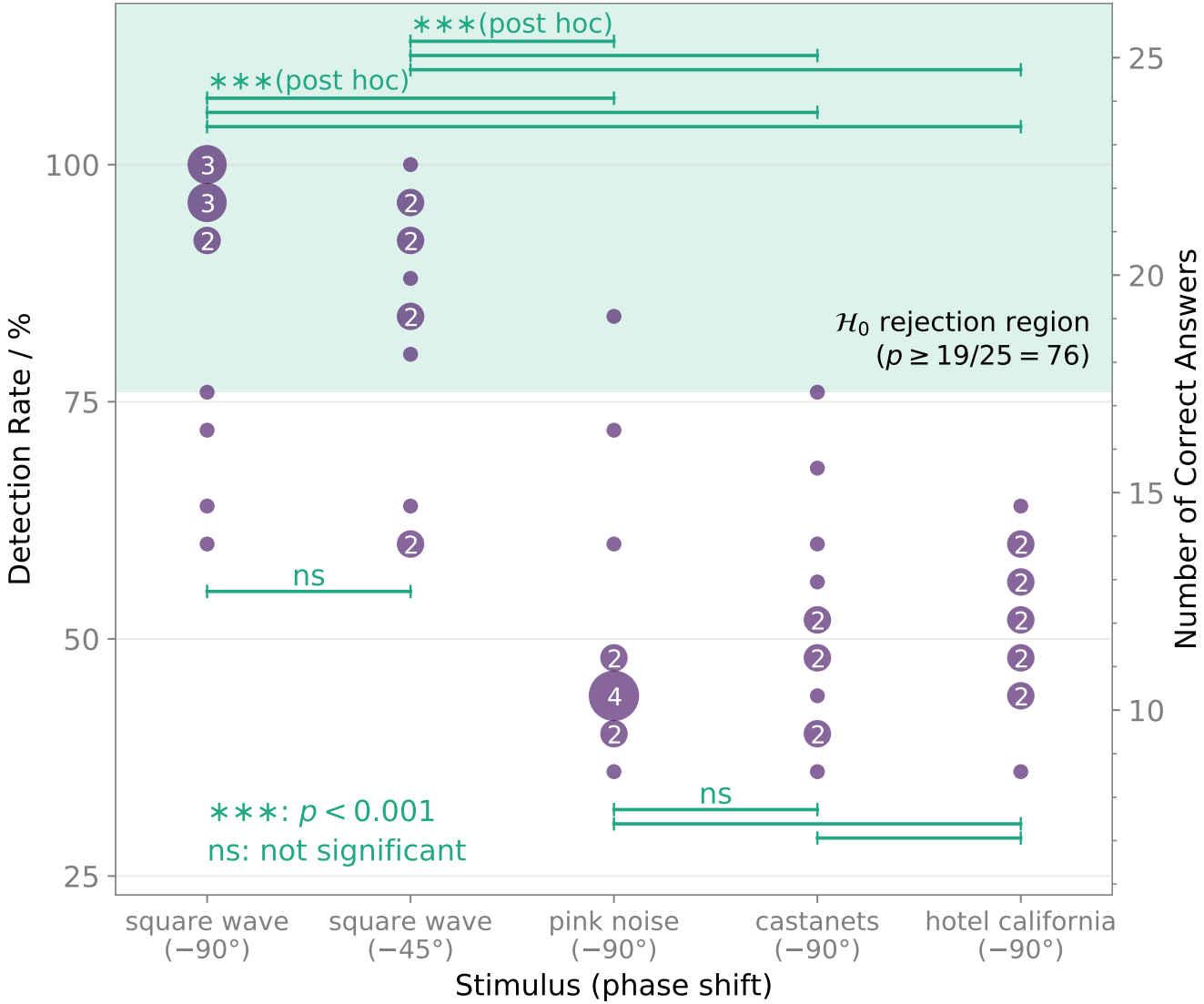
Listening Experiment: Results

ABX / Binomial



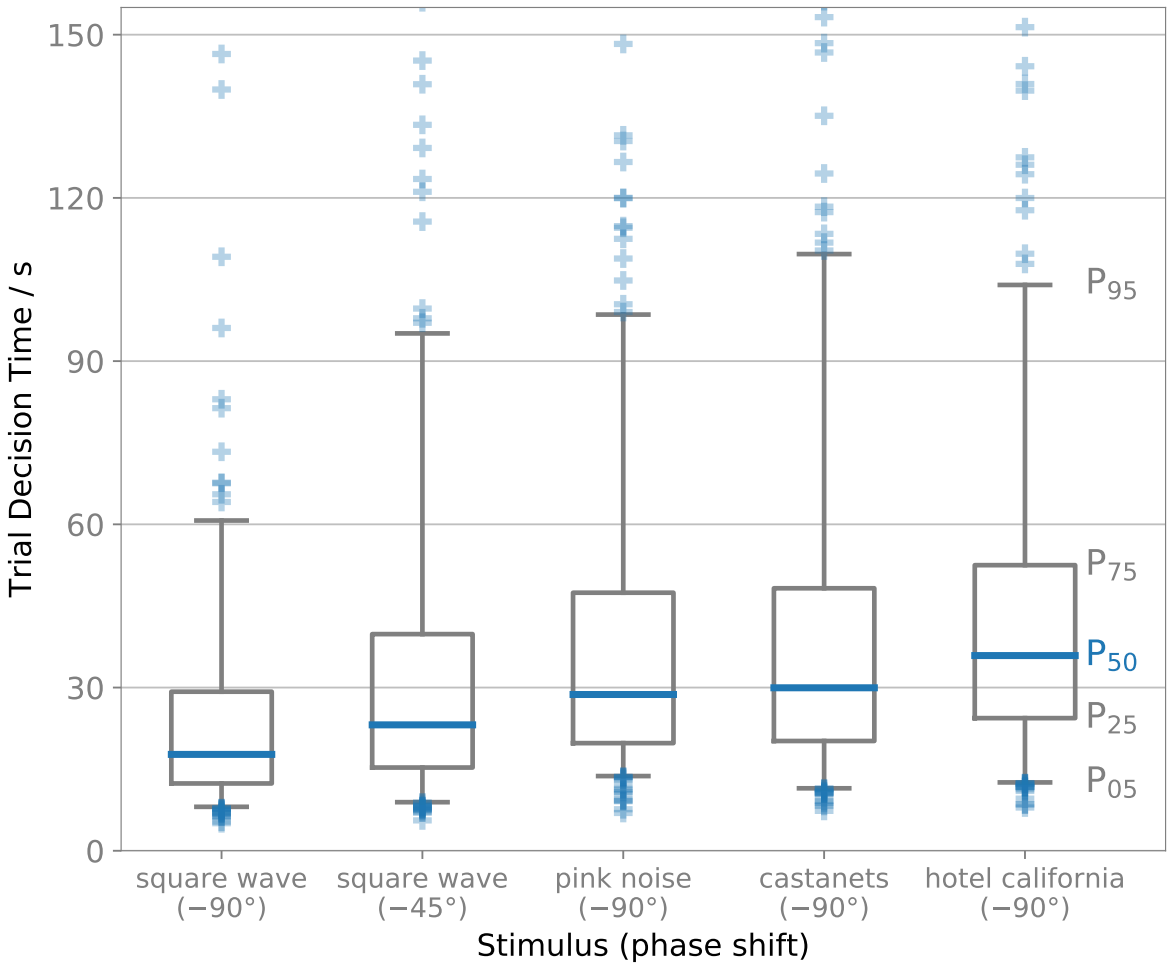
Listening Experiment: Results

Contingency Tables / χ^2



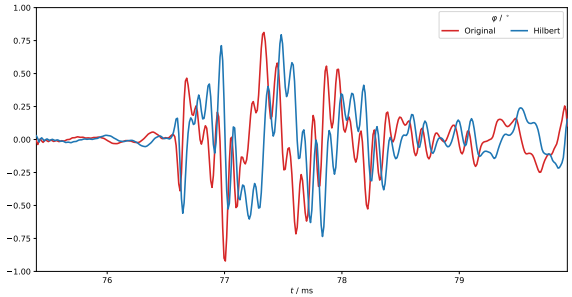
Listening Experiment: Results

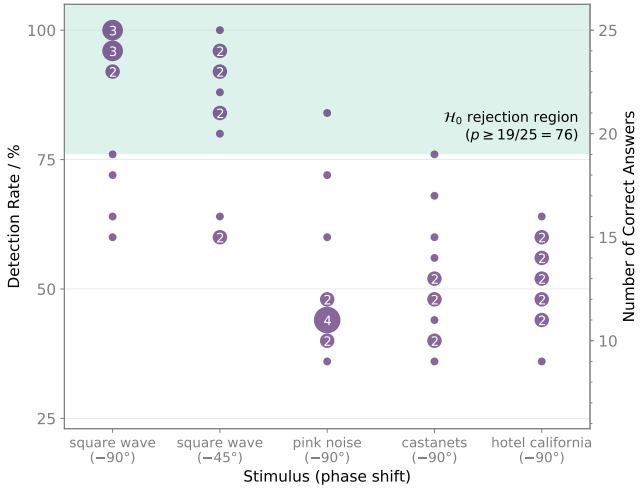
Trial Decision Time



Conclusion

Audibility constant phase shift$\longrightarrow$ yes





Discrimination of phase shift against original

- very sensitive to square wave bursts
- likely sensitive for transient signals and lowpass filtered noise
- audibility for musical content not yet shown
- training improves sensitivity...

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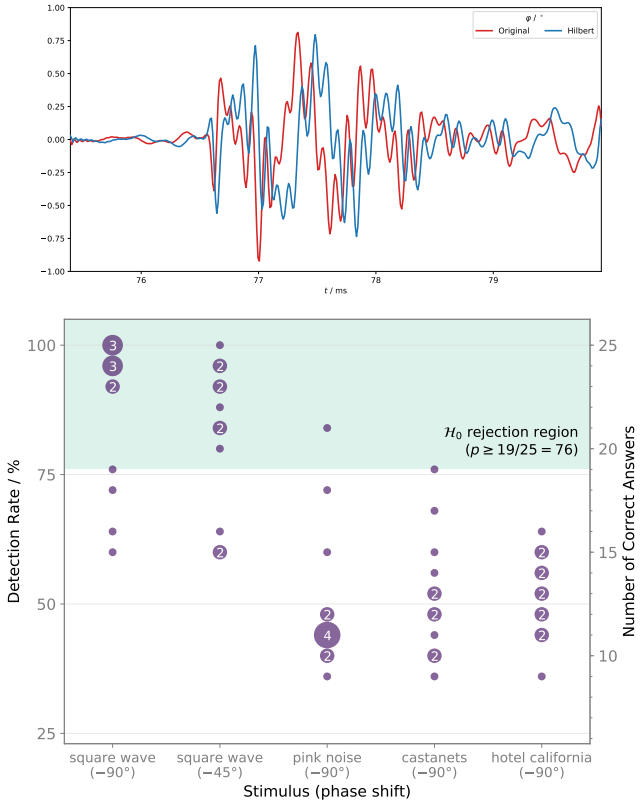

Outlook

trained experts achieve

pink noise $\varphi = -90°$: 95% (***)

castanets $\varphi = -90°$: 92% (***)

ABX test design with assumed effect size $g = 0.25$, $\alpha = 0.05$, power

$1 - \beta = 0.95 \rightarrow \frac{\geq 27 \text{ correct trials}}{42 \text{ total trials}}$

psychometric function detection over φ

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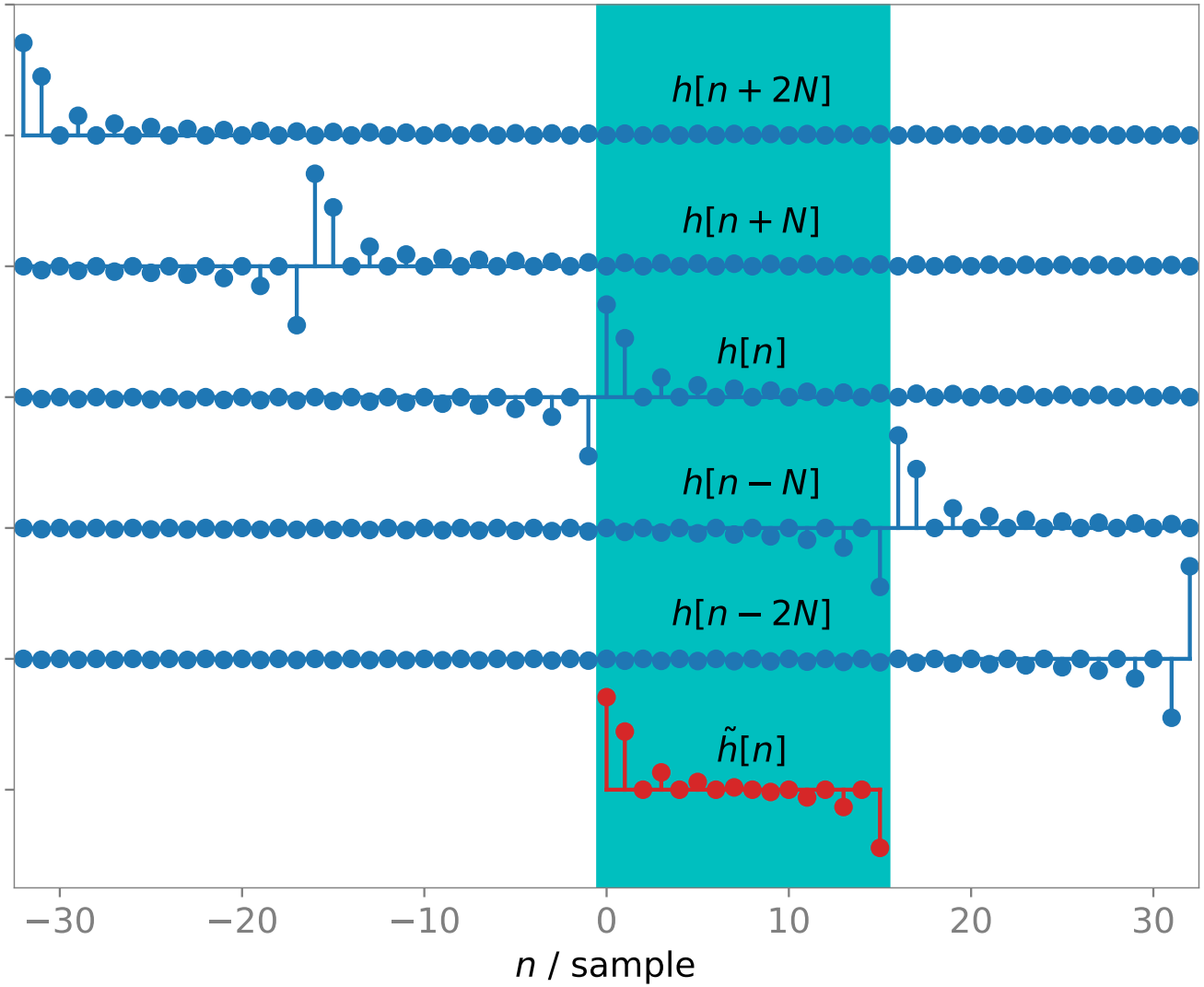
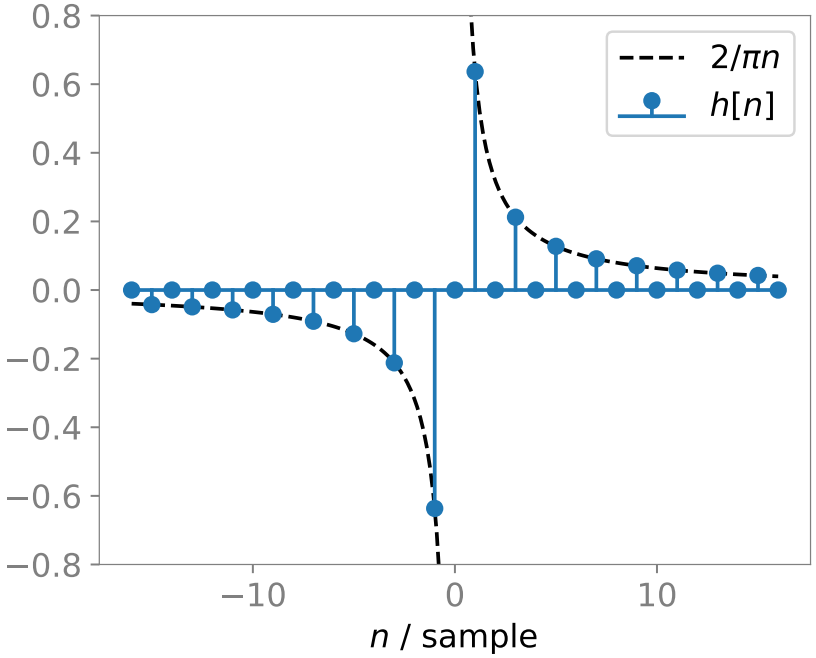
This project supports open science:
https://doi.org/10.5281/zenodo.3383286

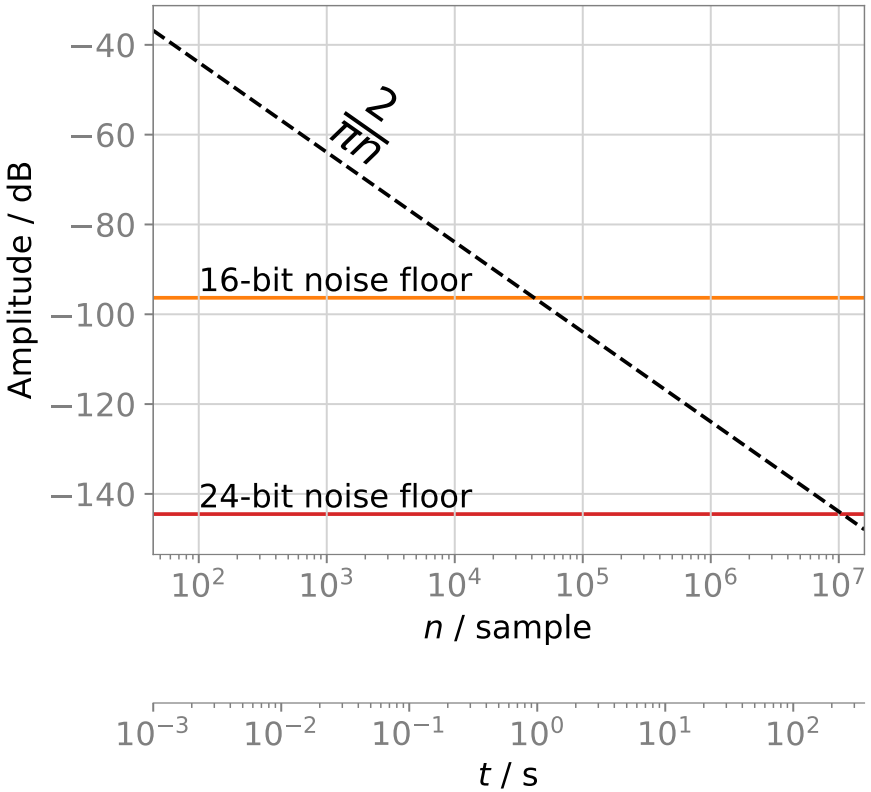
Periodic Convolution

Impulse response for $\varphi = -\frac{\pi}{4}$

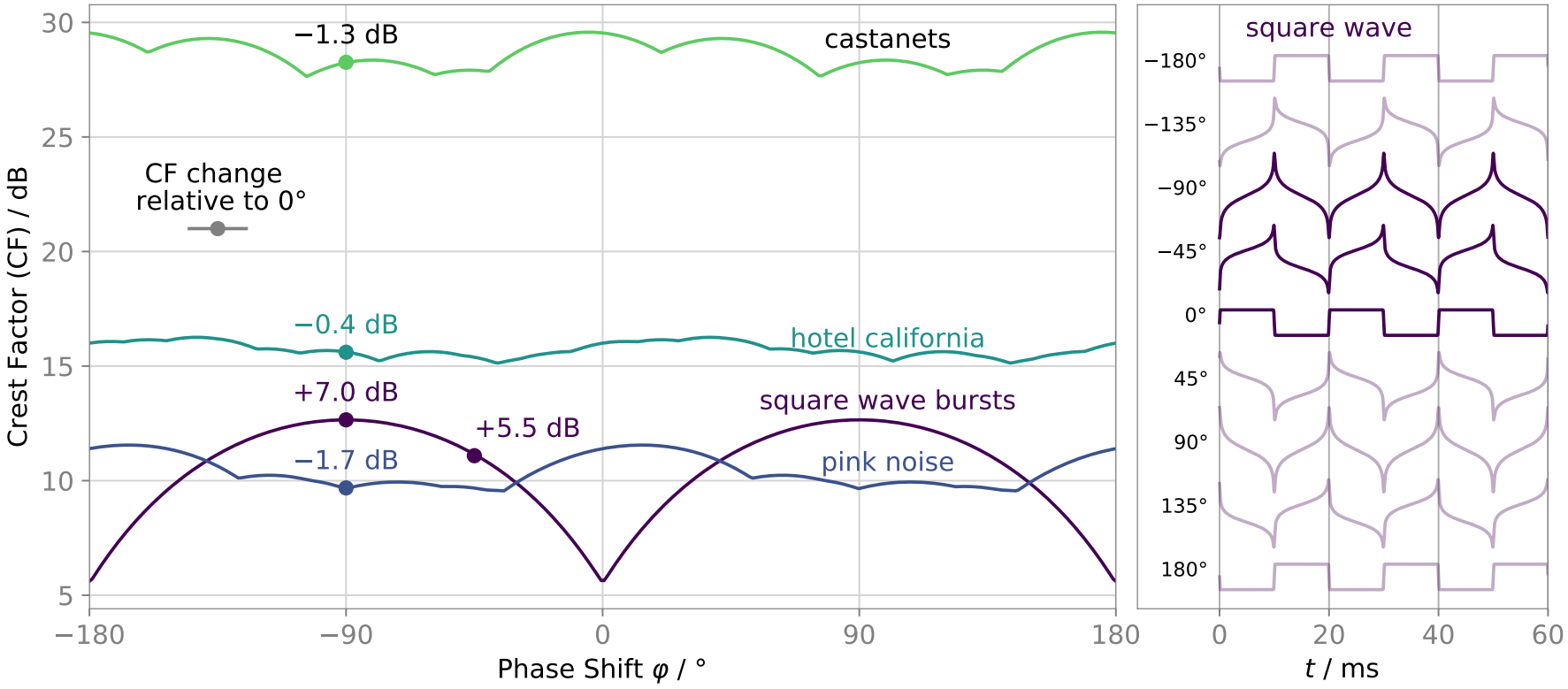


Quantization Filter Coefficients

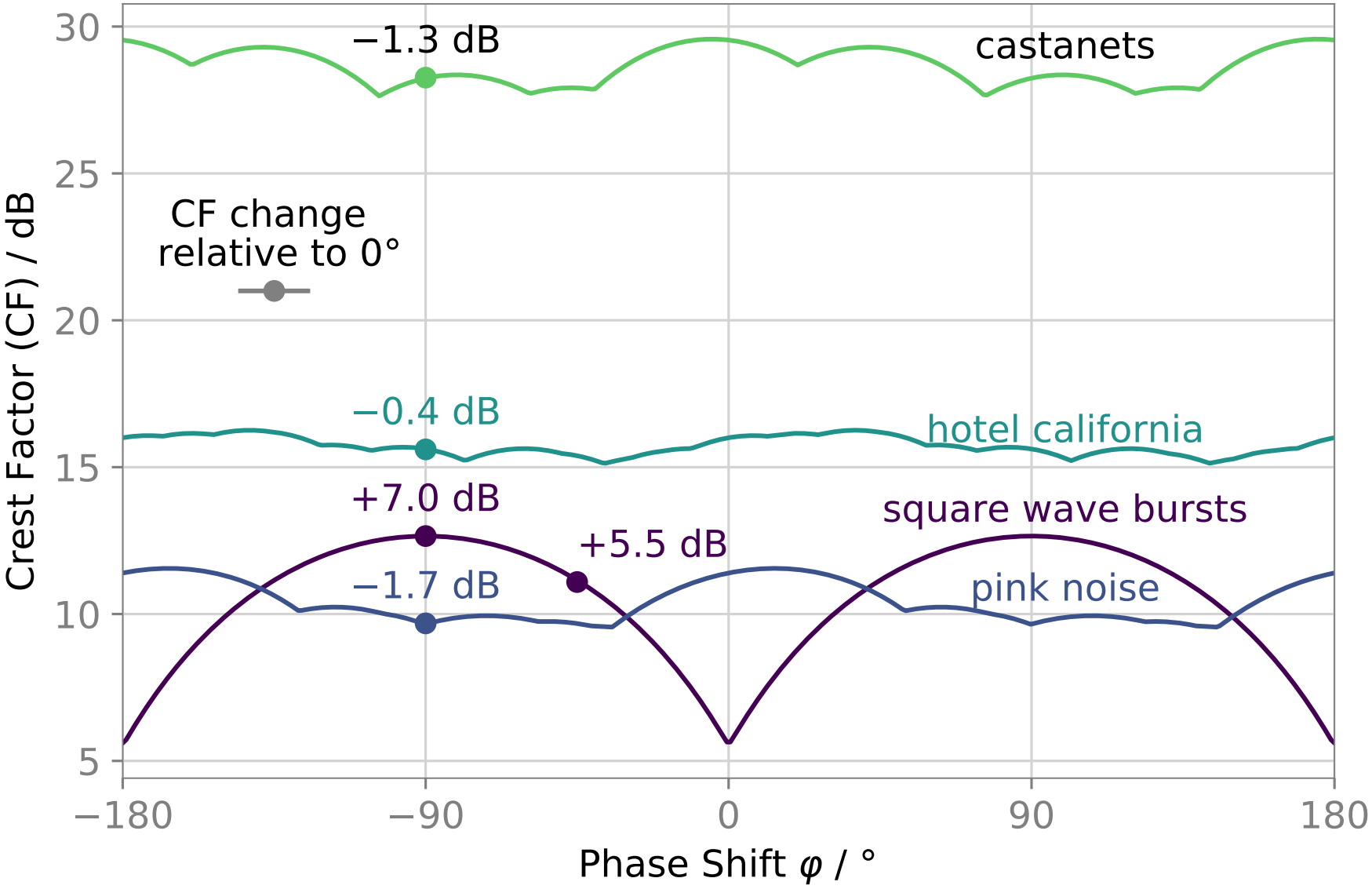




Crest Factor



Crest Factor



Audio Content Spectra