Methods for Extending Room Impulse Responses Beyond Their Noise Floor

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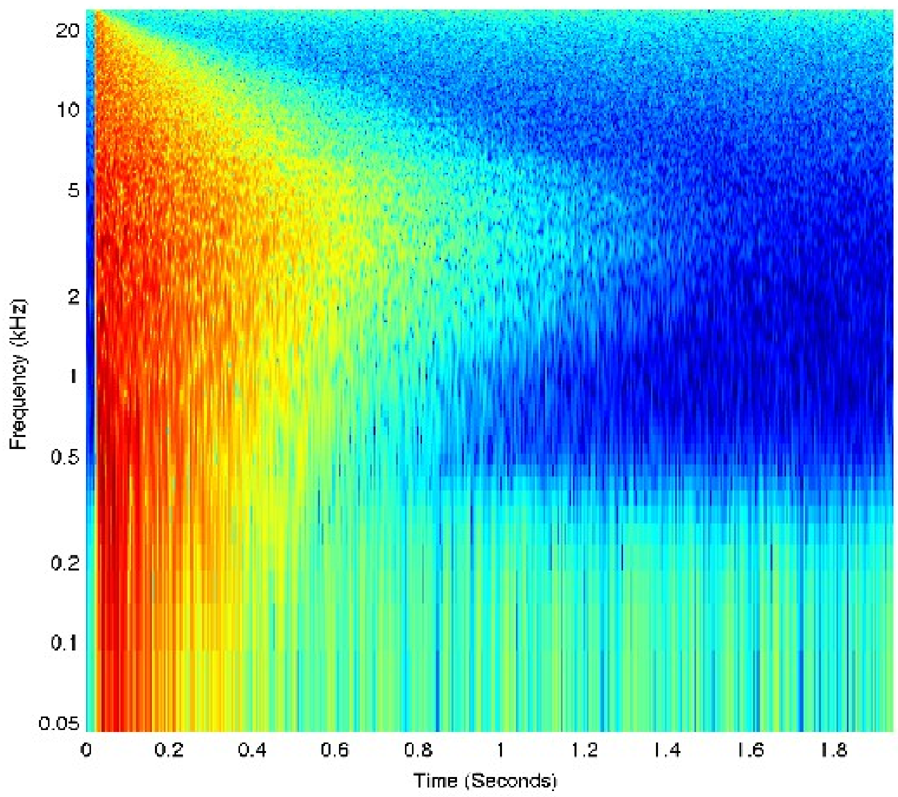
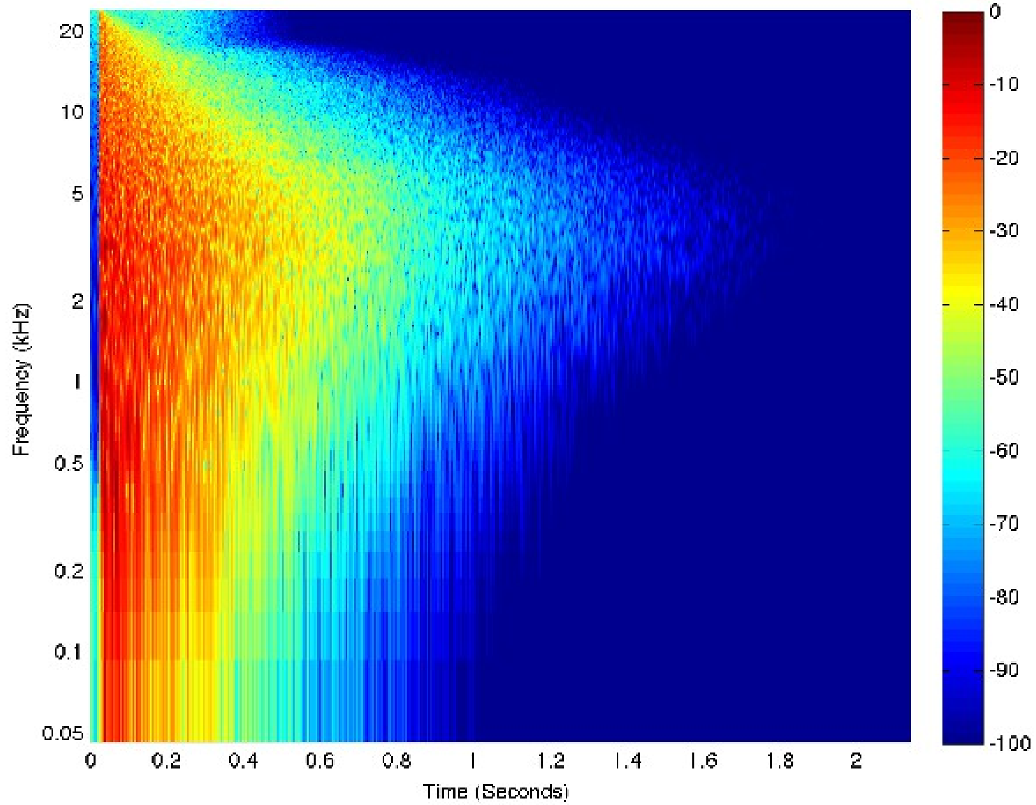
What is the problem?

- Frequency dependent noise floor limits the perceptual quality of reverberant impulse responses
- Unnaturally emphasized high-frequency content and low-frequency measurement noise

Impulse Response Spectrograms

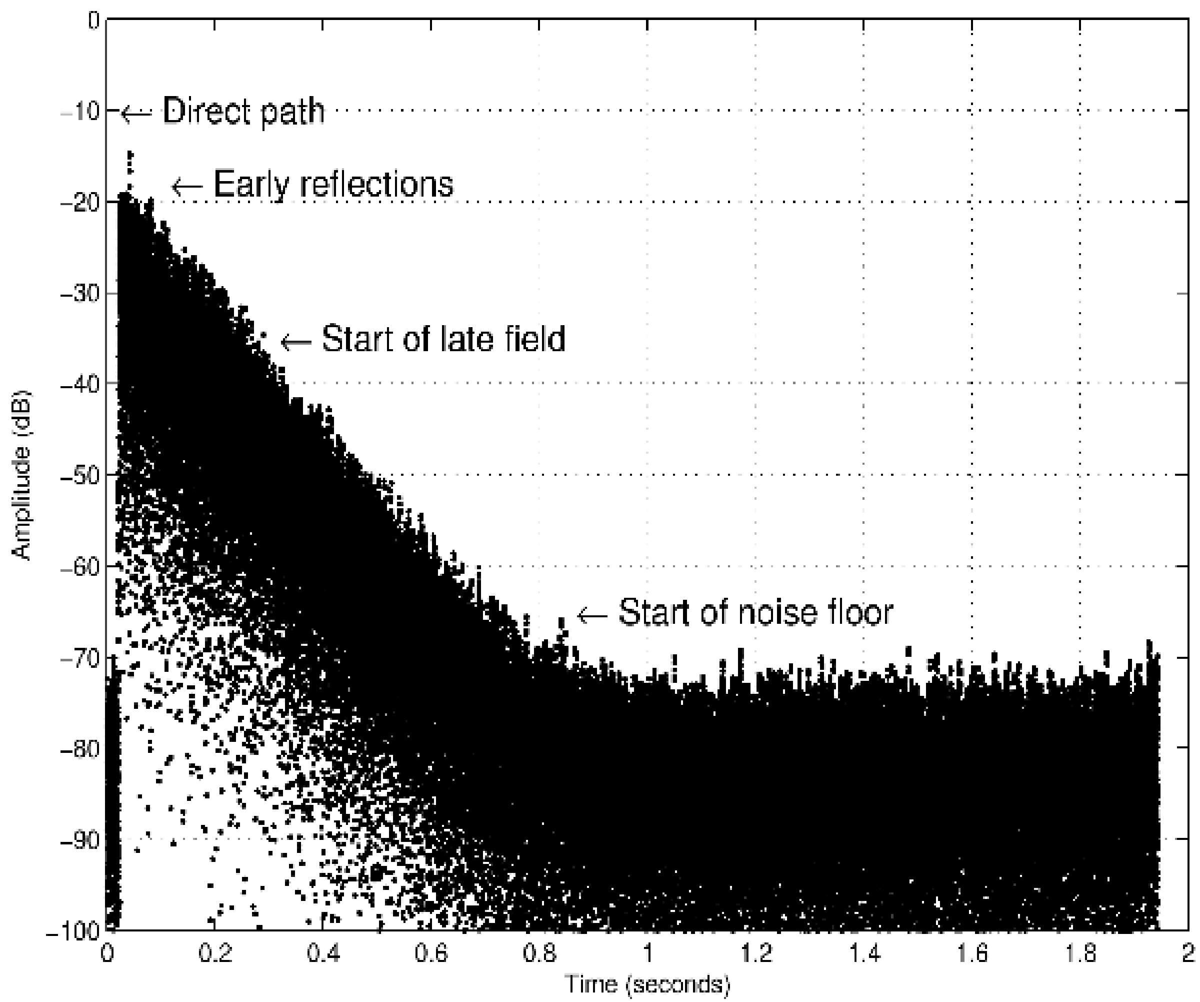


EMT 140 Measured Impulse Response Spectrogram



EMT 140 Extended Impulse Response Spectrogram

Late-field Reverberation Overview



Late-field Measurement Model

- Gaussian noise with a frequency dependent decaying exponential energy profile

$$\beta_k(t;\theta) = \sigma_k^2 + \gamma_k^2 e^{-2t/\tau_k}$$

σ^2 = Noise Floor

τ = Equalization Level

γ = Time Constant

Preprocessing + Estimation

- Two methods for estimating the frequency dependent parameters:
  - Synthetic Extension Analysis
  - Natural Extension Analysis
- Analysis methods correspond to extension methods
- Prior to estimation, preprocessing of the IR is needed

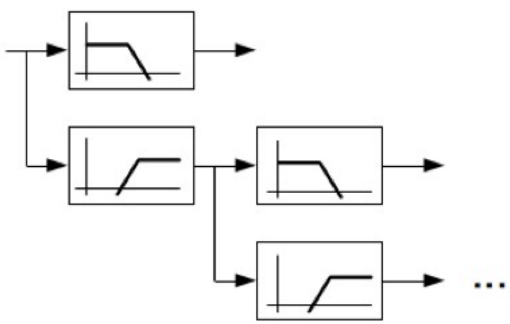
Preprocessing

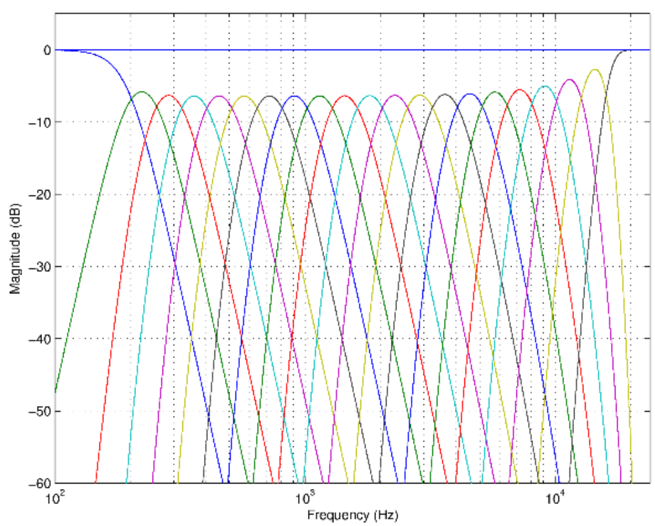
- Decompose impulse response into separate bands via a filter bank
- Apply smoothing filter resulting in frequency-dependent energy profiles

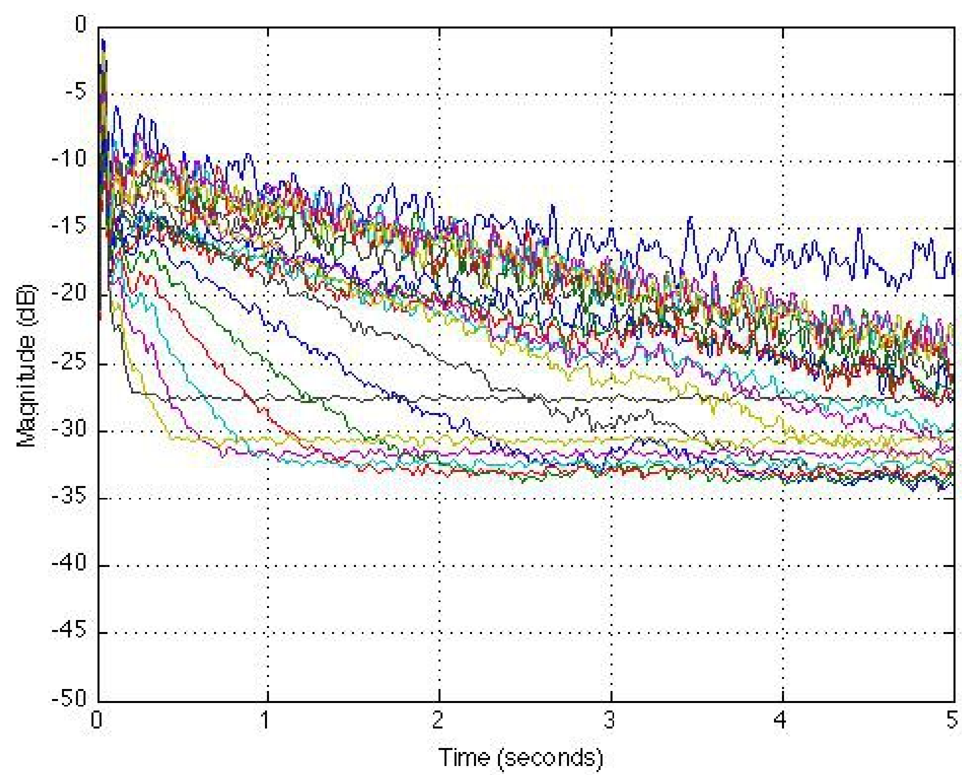
$$\tilde{\beta}_k(t) = h_k(t)^2 * w(t) \quad \sum_t w(t) = 1$$

Filter Bank

- Perfect amplitude reconstruction zero-phase filter bank via a cascade of squared Butterworth filters



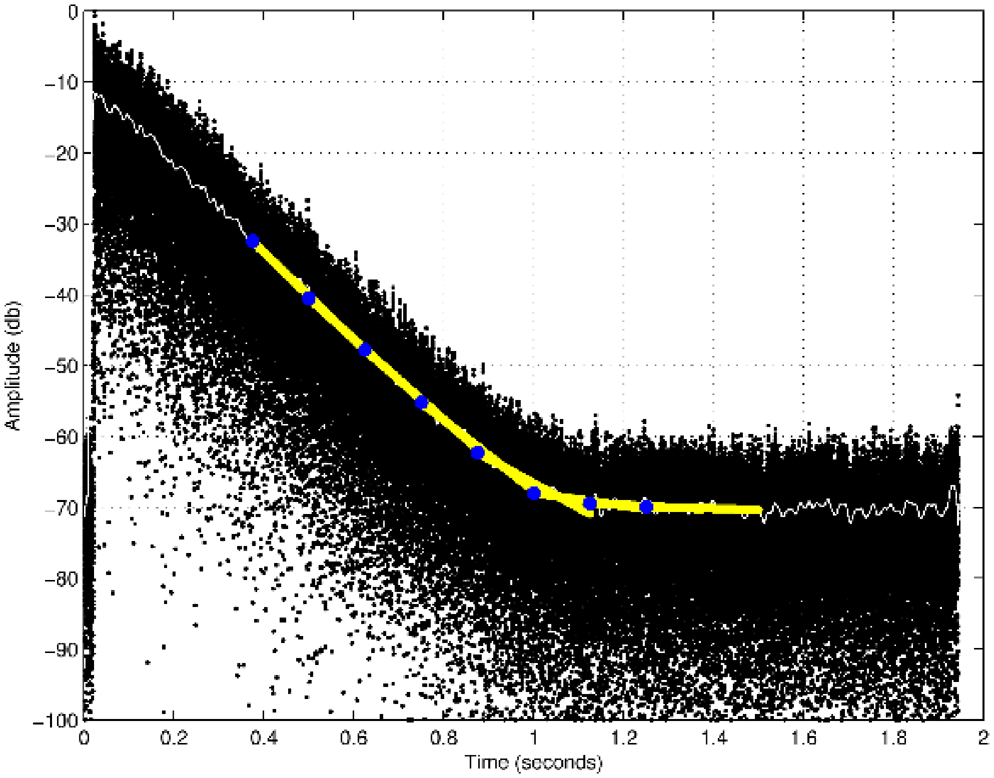




Frequency dependent energy profiles

Synthetic Extension Analysis

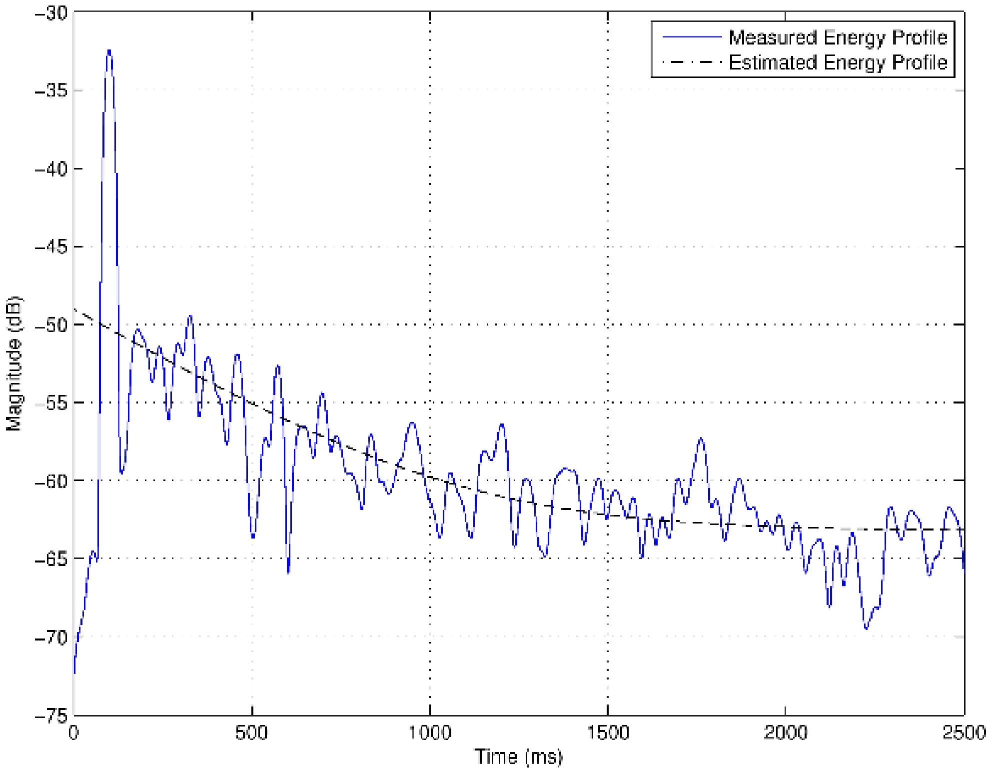
- First estimate noise floor arrival time
- Estimate the decay rate and equalization level prior to the noise floor arrival



$$\underset{\theta}{\operatorname{argmin}} \parallel 20\log_{10}(\beta(\mathbf{t};\theta)-\sigma^2) - 20\log_{10}\tilde{\beta}(\mathbf{t};\theta) \parallel_2^2$$

Natural Extension Analysis

- Simultaneously estimate the noise floor level, decay time, and equalization level
- No assumption of above the noise floor



$$\underset{\theta}{\operatorname{argmin}} \| \, 20 \log_{10} \beta(\mathbf{t}_m;\theta) - 20 \log_{10} \tilde{\beta}(\mathbf{t}_m;\theta) \, \|_2^2$$

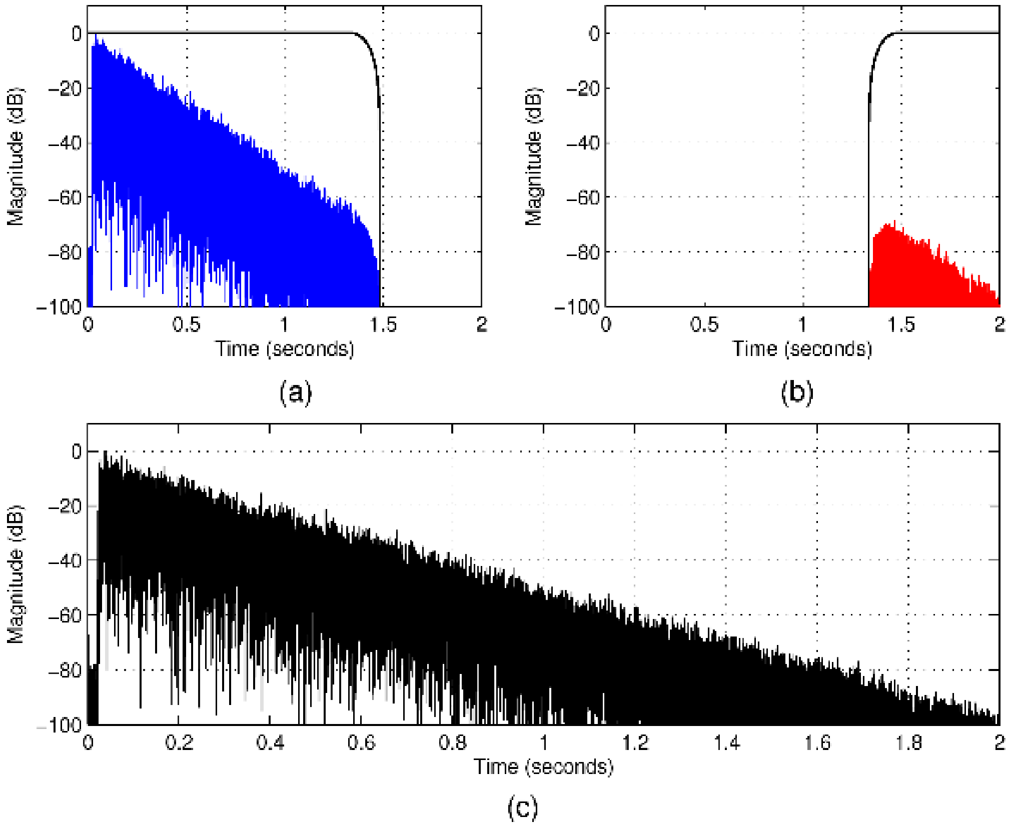
Extension Methods

- Synthetic Extension Synthesis
  - Crossfade synthesized measured impulse response bands with synthesized bands prior to the noise floor arrival
- Natural Extension Synthesis
  - Window the noise floor found within the measured IR and leverage the measured, natural signal statistics

Synthetic Extension

- Cross fade synthetically generated Gaussian noise bands
- Window bands according to the estimated parameters

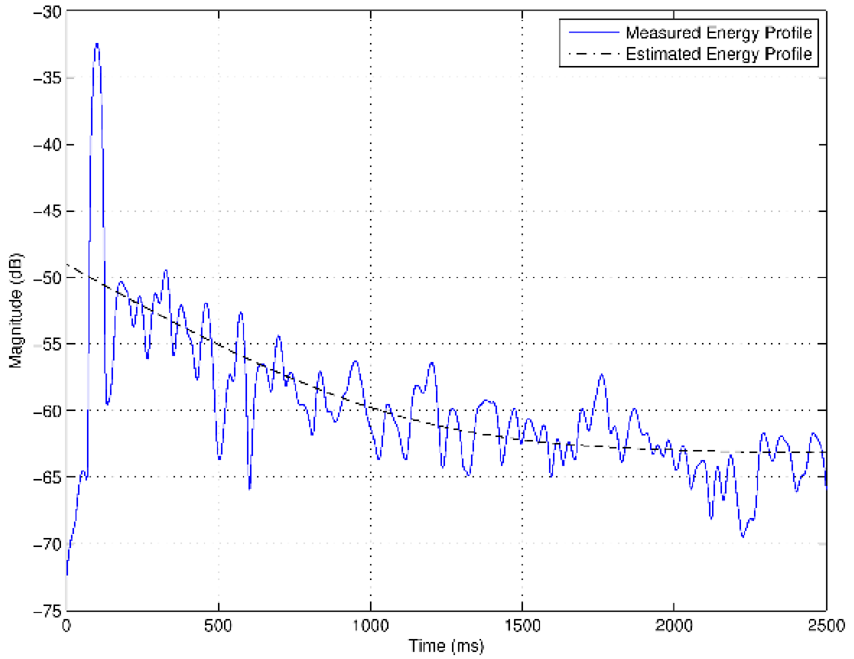
$$\lambda_k(t) = \hat{\gamma}_k e^{-t/\hat{\tau}_k}$$



Crossfade Between Measured and Synthesized Noise Bands

Natural Extension Synthesis

- Window the measure noise bands to effectively “bend down” the undesirable noise floor

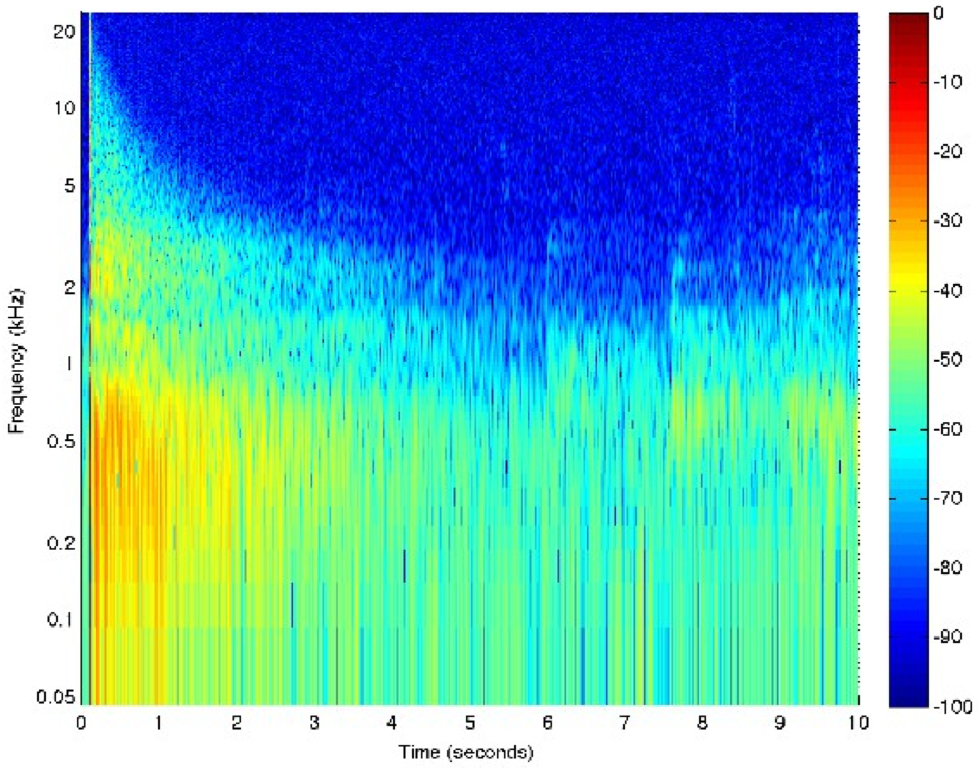


Numerator bends the energy profile back down

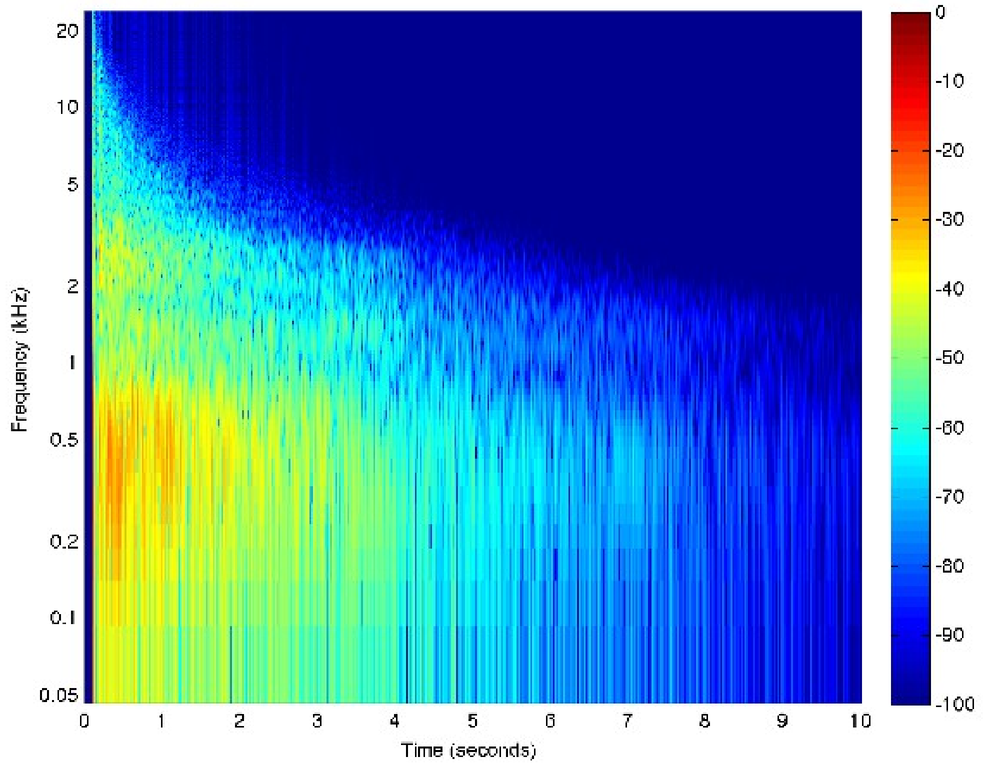
$$\lambda_k(t) = \frac{\hat{\gamma}_k e^{-t/\hat{\tau}_k}}{\left[\hat{\gamma}_k^2 e^{-2t/\hat{\tau}_k} + \hat{\sigma}_k^2\right]^{1/2}}$$

Denominator bends the energy profile up

Results

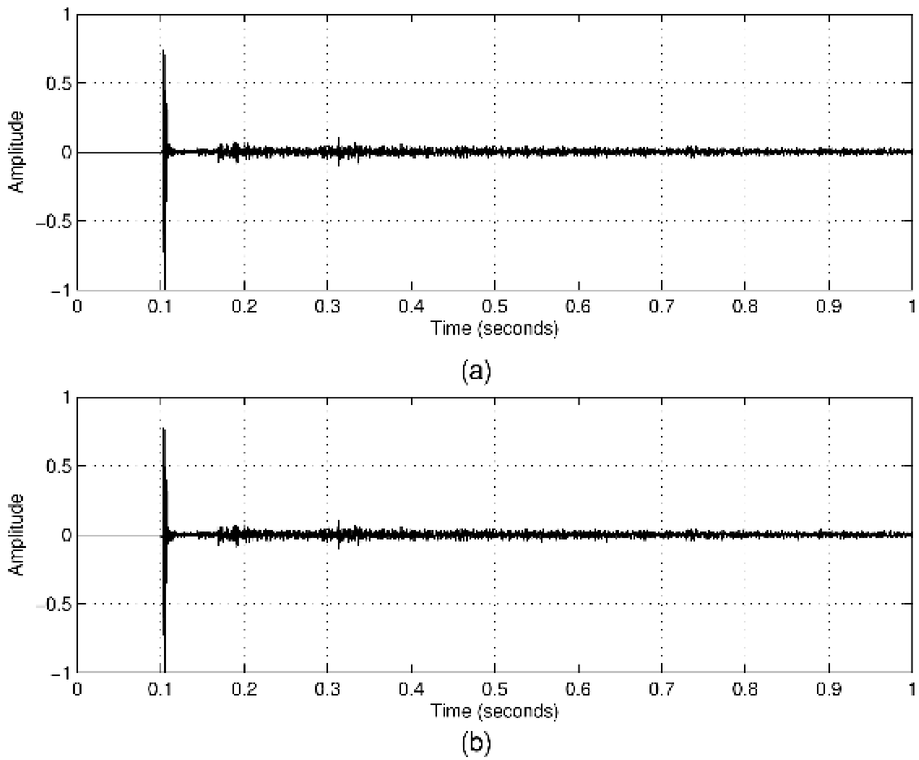


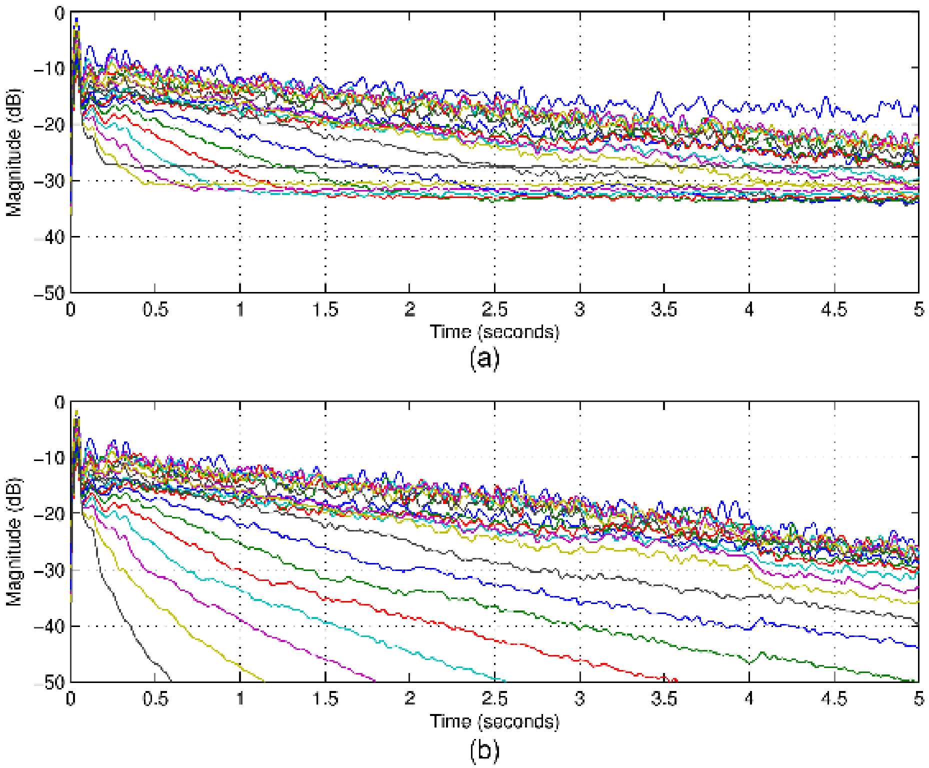
Measured Hagia Sophia Balloon Pop Spectrogram



Extended Hagia Sophia Balloon Pop Spectrogram

Results

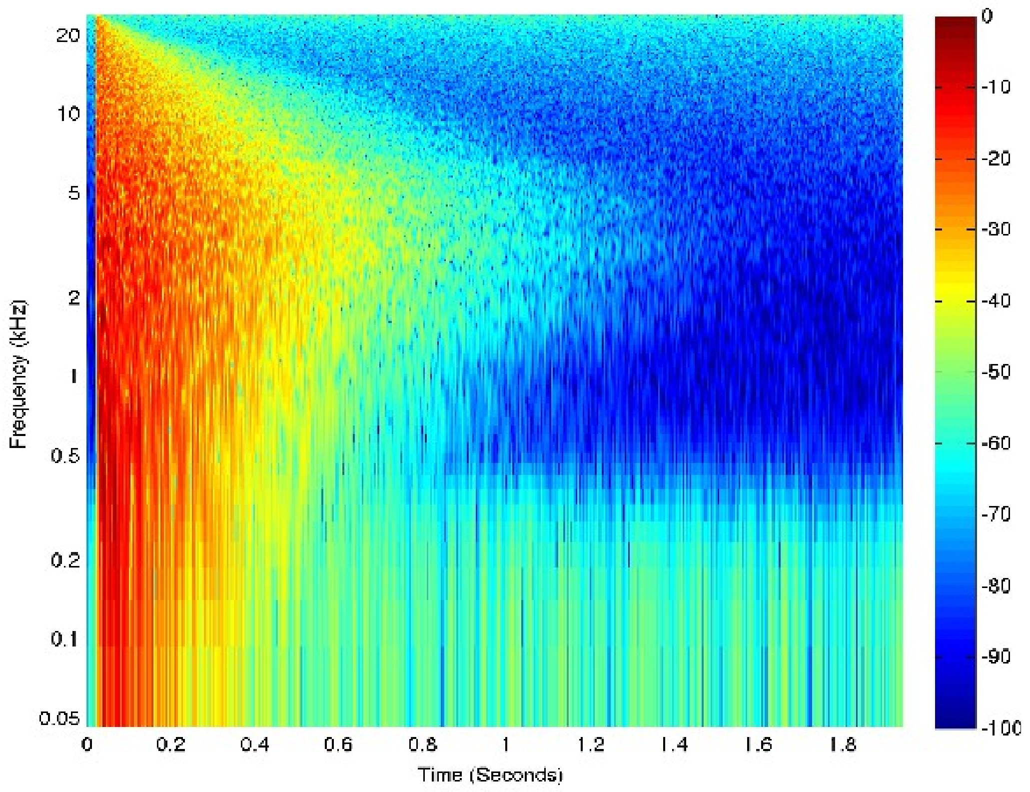




Measured and Extended Hagia Sophia Balloon Pop Response

Measured and extended Hagia Sophia Energy Profiles

Results



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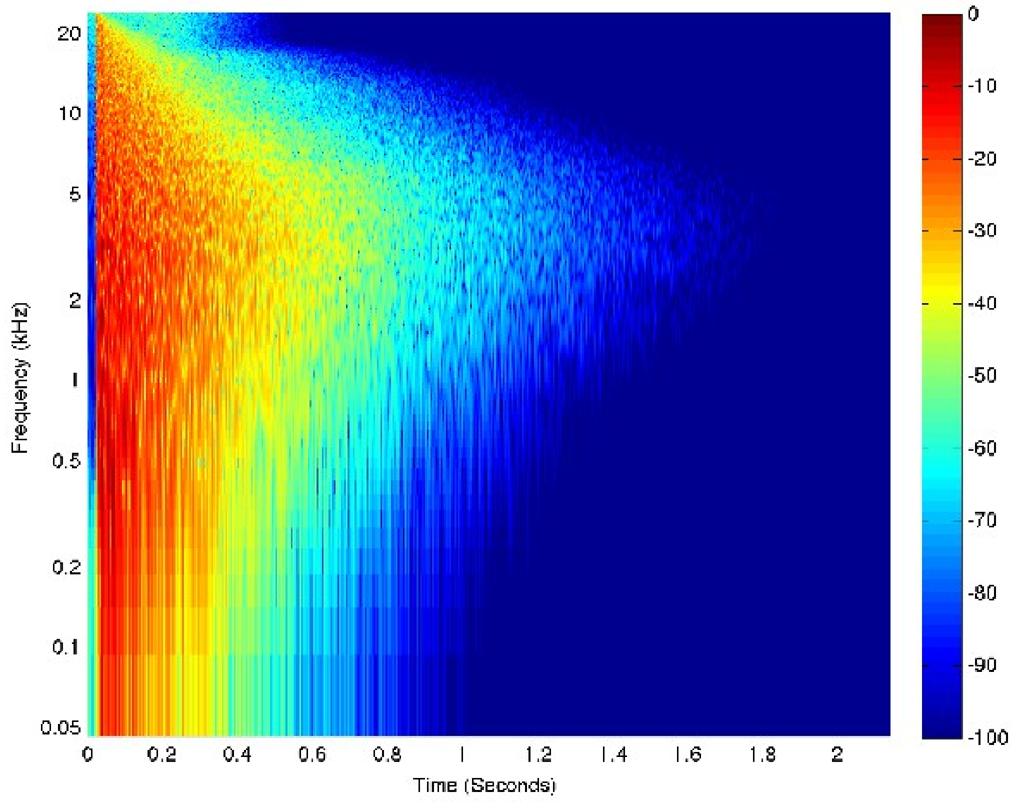

EMT 140 Extended Impulse Response Spectrogram

Sound Examples

EMT140 long (cutoff ending)

EMT140 long extended

EMT140 short (late-field hiss)

EMT140 short extended

Hagia Sophia (late-field hiss + talking)

Hagia Sophia extended

Conclusions

- Two methods for extended room impulse responses beyond their measured noise floor
  - The first method crossfades synthetically generated noise with the measured IR
  - The second method windows the naturally found late-field noise
- Both methods maintain an identical impulse response prior to the noise floor arrival and impose a natural sounding decay afterward

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