Estimating Room Impulse Responses from Recorded Balloon Pop

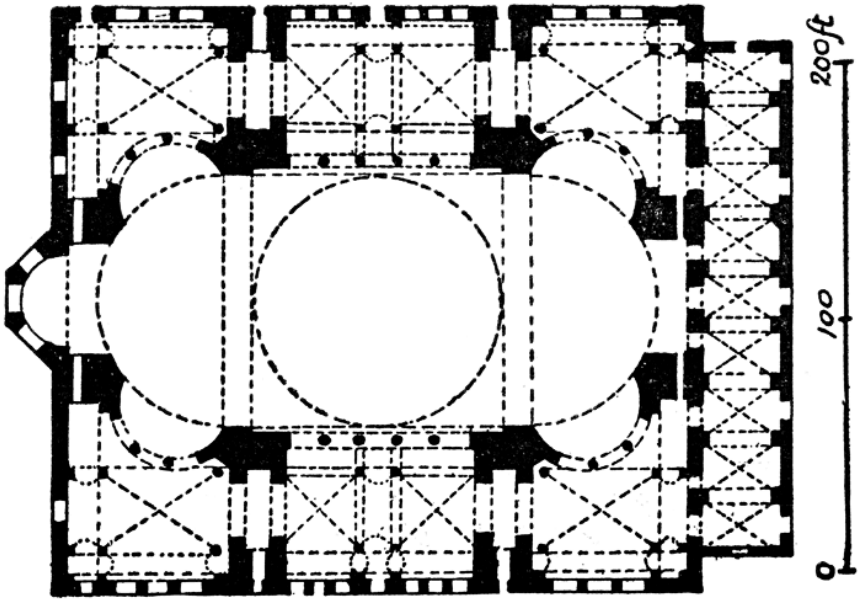
Jonathan S. Abel, Nicholas J. Bryan, Patty P. Huang, Miriam A. Kolar, Bissera V. Pentcheva

CCRMA, Art & Art History, Stanford University

Icons of Sound

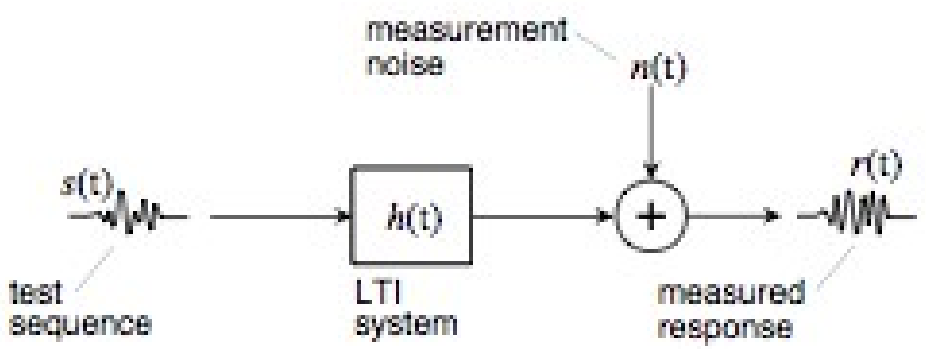
- Icons of Sound: Architectural Psychoacoustics in Byzantium explores the sensory experience of Hagia Sophia
- Interdisciplinary research with SU Art & Art History, CCRMA; funded via grant from SU Presidential Fund, SiCa
- Virtual acoustic reconstruction; f lmic exploration
- Auralization using music created for HS, “Cherubikon”

Hagia Sophia



- Justinian-era religious center
  - Built in 532; mosque in 1453; museum since 1934
- Unprecedented scale and expansive domed design
  - 70m long by 50m high; 11-second reverberation time
  - Grey-veined marble, gold tile, green-blue glass
  - Visual, acoustic interplay evokes water imagery

•RIR Measurement Approaches

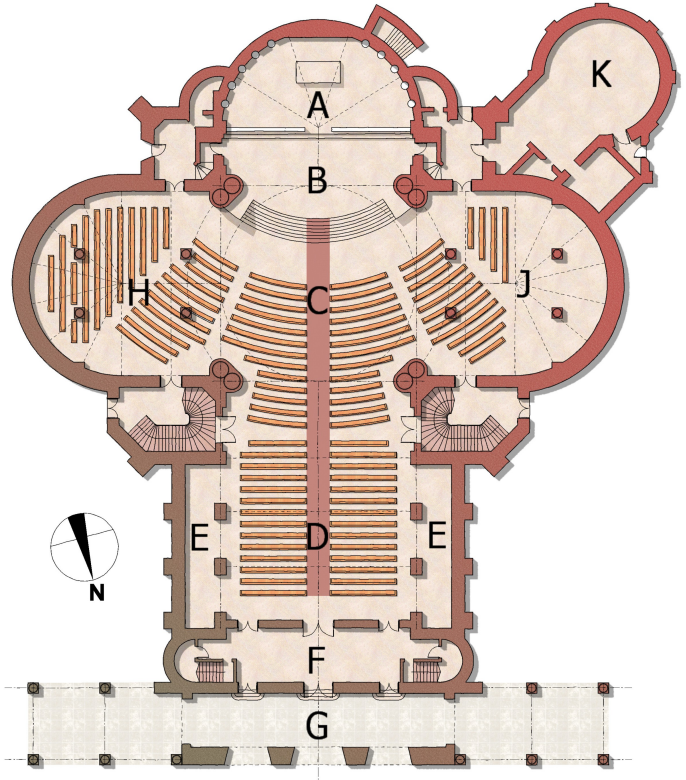


$$\sum_k s_k(t) * s_k(-t) = \gamma \cdot \delta(t)$$

$$\hat{h}(t) = \frac{1}{\gamma} \cdot \sum_k s_k(t) * r_k(t)$$

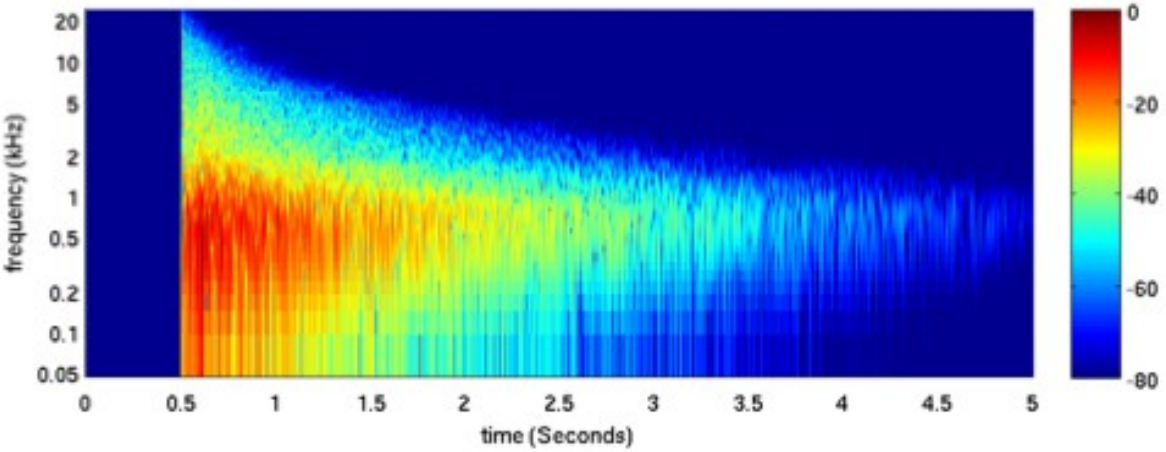
- Loudspeaker/sine sweep, MLS
  - Precise, controlled measurement; logistically diff cult
- Impulsive sound source
  - Balloon pop, orchestral whip, starter pistol
- Balloon pop logistically simple, remotely triggerable, uniform radiation pattern, consistent N-wave waveform

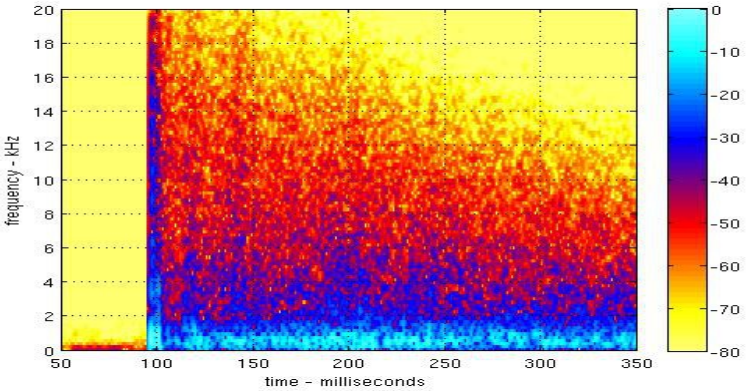
Example Balloon Pop Recording



SU Memorial Church

Mem Chu Response Spectrogram

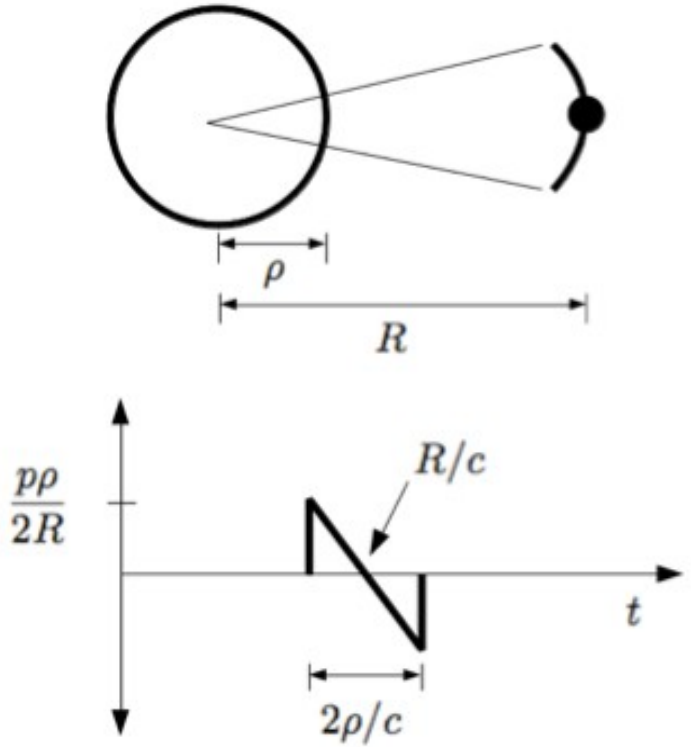




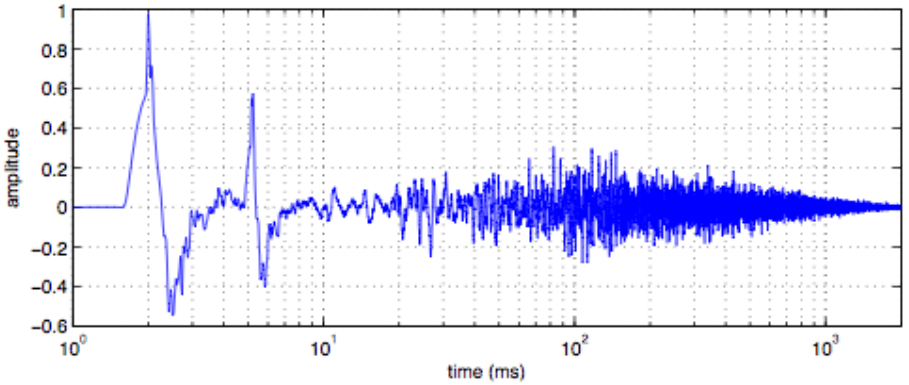
(original)

(8x)

Balloon Pop Acoustics



Mem Chu Balloon Pop Response

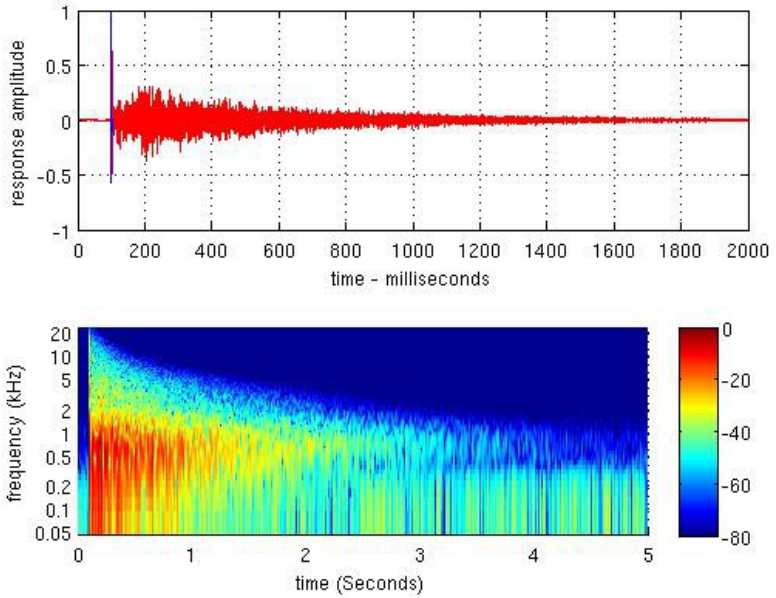


- Consistent N-wave waveform; uniform radiation pattern

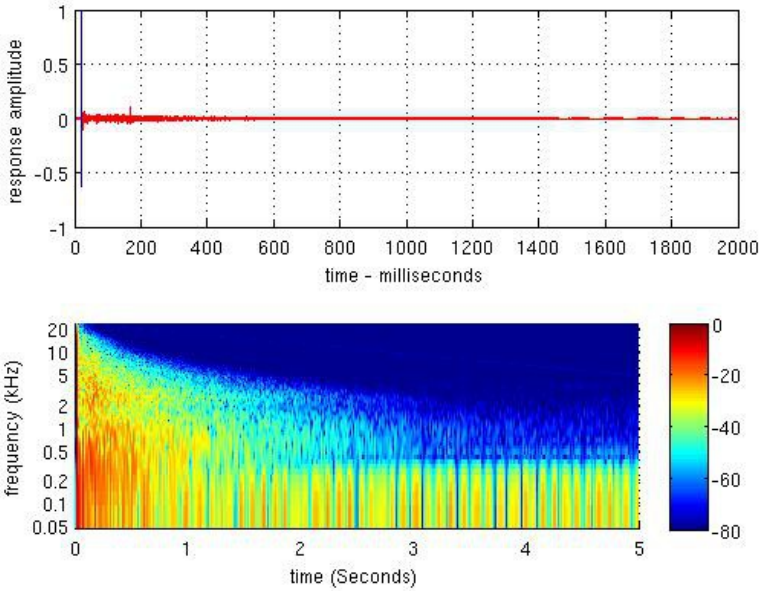
  (D. T. Deihl and F. R. Carlson Jr., Am. J. Physics, 1968)

Auralization with Balloon Pop Recording

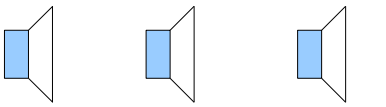
Measured Impulse Response



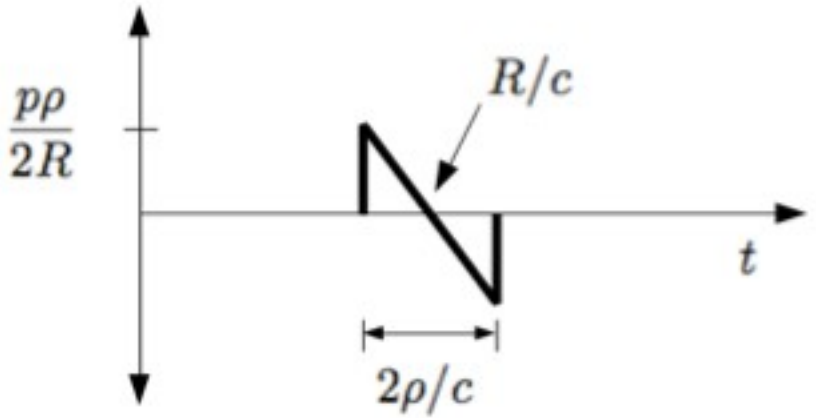
Recorded Balloon Pop



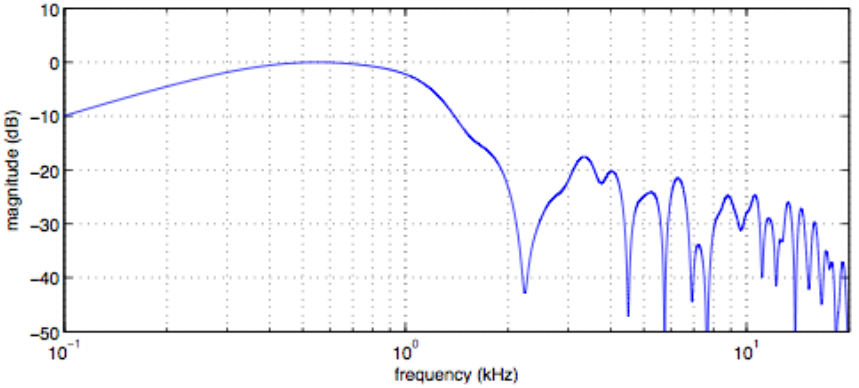
- Balloon pop response reveals room acoustic parameters; e.g. reverberation time
- Can sound “comby” when applied to audio



Balloon Pop Spectrogram



Measured N-wave spectrogram



$$n(t) = \begin{cases} \frac{p}{2R}(R - ct), & ct \in [R-\rho, R+\rho] \\ 0, & \text{otherwise,} \end{cases}$$

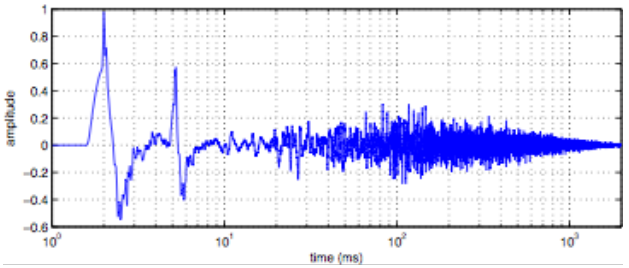
$$N(\omega) = \frac{pc}{2R}\,\frac{\nu\sin(\nu) - \cos(\nu)}{j\nu^2}$$

$$\nu = \omega c/\rho$$

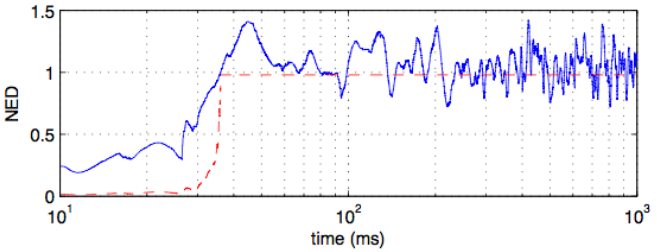
- N-waves have spectral nulls DC and frequencies proportional to multiples of the inverse balloon diameter

RIR Estimation Approach

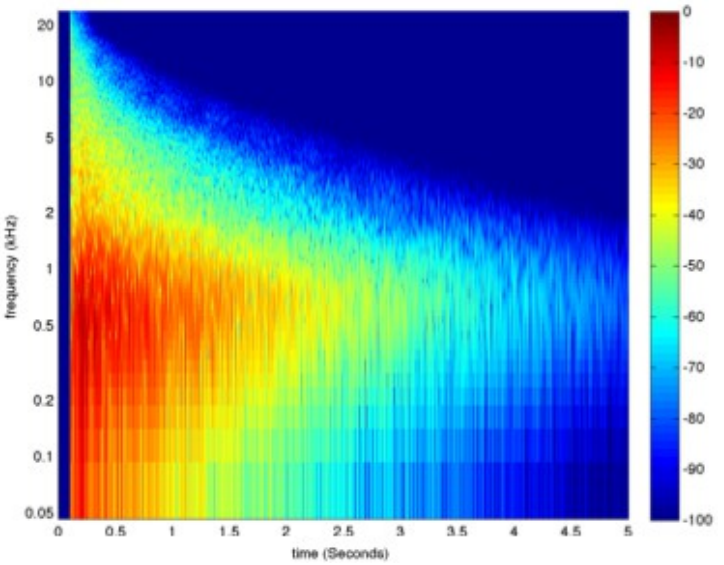
Recorded Balloon Pop



Echo Density Profile

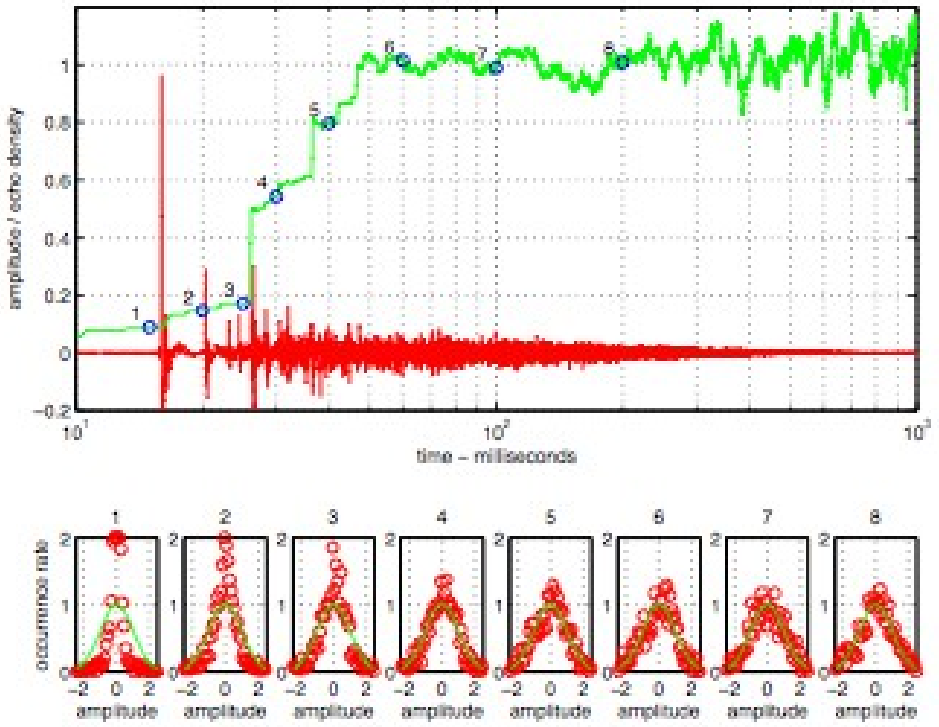


Normalized Spectrogram



- Measure balloon pop response $b(t)$
- Estimate arrival density $e(t)$ along $b(t)$
- Synthesize echo pattern accordingly
- Imprint measured/normalized energy profiles

Normalized Echo Density (NED)



$$\eta(t) = \frac{1/\mathrm{erfc}(1/\sqrt{2})}{2\Delta + 1} \sum_{\tau=t-\Delta}^{t+\Delta} 1\{h^2(\tau) > \sigma^2(t)\}$$

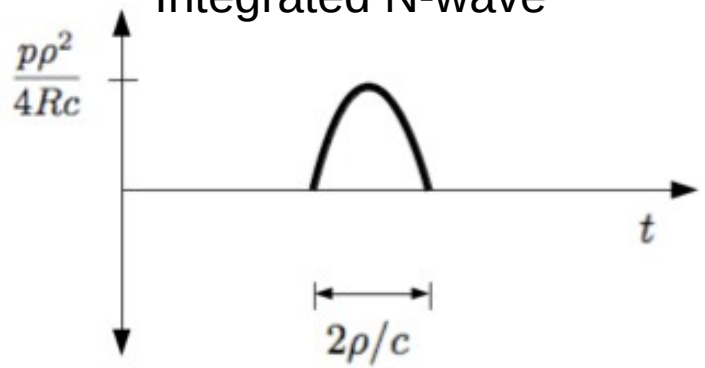
$$\sigma^2(t) = \frac{1}{2\Delta + 1} \sum_{\tau=t-\Delta}^{t+\Delta} h^2(\tau)$$

(echo sequences)

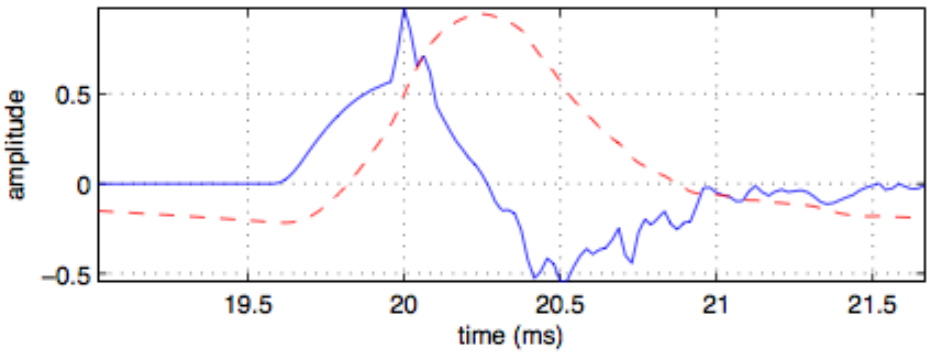
- The NED indicates closeness to Gaussian statistics
- NED is predictive of perceptual differences among echo patterns

Recorded Balloon Pop NED

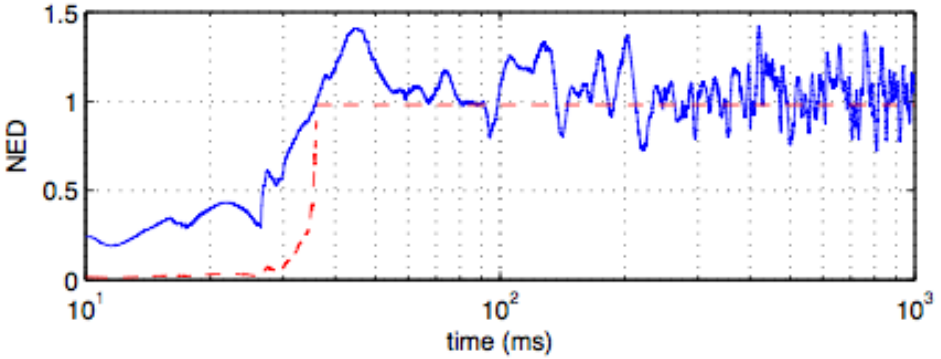
Integrated N-wave



Measured, Integrated N-wave



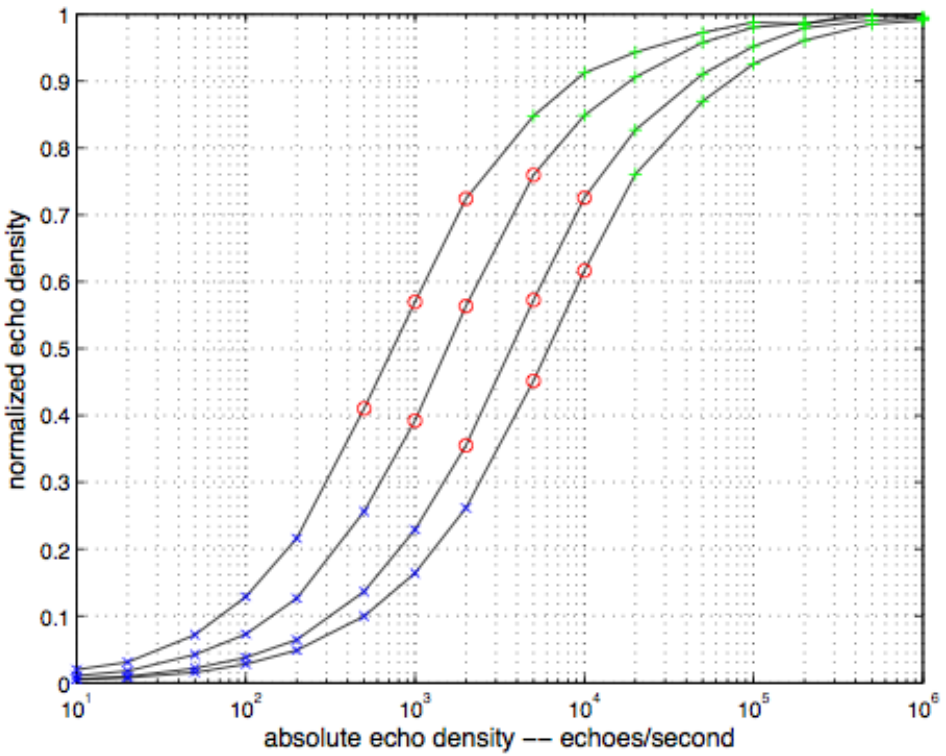
Memorial Church b(t) NED



- To find the recorded balloon pop b(t) NED, b(t) is first integrated to convert the N-wave into pulses

NED, AED Relationship

NED (AED), $1/\delta$ = 1, 2, 5, 10 kHz



absolute echo density

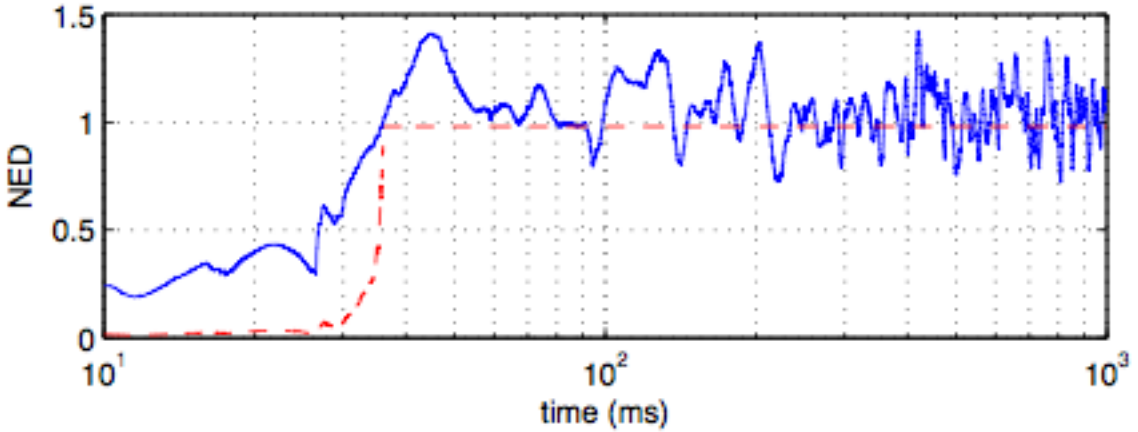
$$\eta(t) = \frac{e(t)}{e(t) + 1/\delta}$$

normalized echo density

echo duration

- NED, AED are related via the echo duration/bandwidth

Memorial Church NED



Mem Chu b(t) NED,
Estimated Full-Bandwidth NED

full bandwidth NED

balloon response NED

$$\eta_h = \frac{\eta_b}{(1-\eta_b)\cdot 2\rho/\delta c + \eta_b}$$

bandwidth ratio

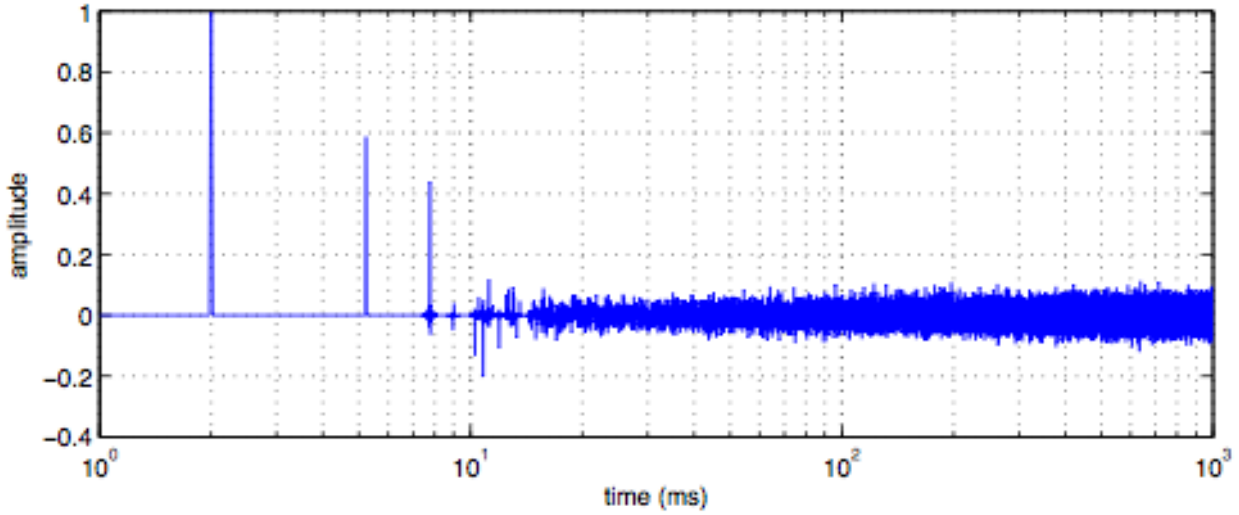
$$e(t) = \frac{\eta_b(t)\ c/2\rho}{1-\eta_b(t)}$$

absolute echo density

- Given the balloon radius, the full bandwidth NED may be estimated from the recorded balloon pop NED

Echo Pattern Synthesis

Synthesized Echo Pattern p(t)



successive echo time interval

$$\wp(\tau; t) = \exp\{-\tau / e(t)\}$$

estimated echo density

$$\alpha(t) \sim N(0, 1/e(t))$$

echo amplitude

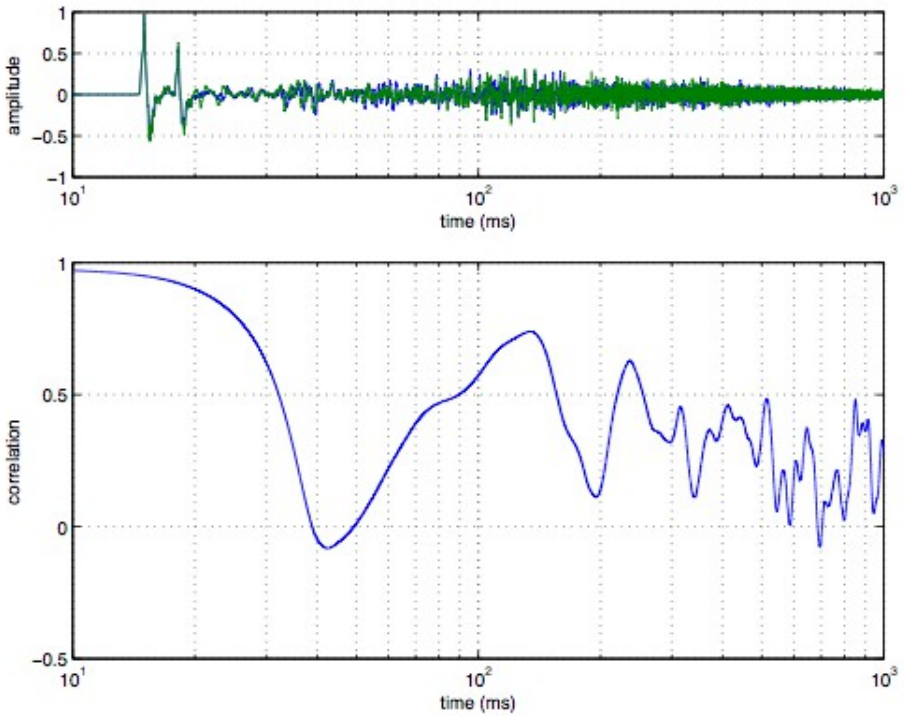
- Echo patterns are synthesized (i.i.d. per channel) according to Poisson-distributed arrival times with Gaussian-distributed amplitudes
- Initial clear arrivals in b(t) may be placed by hand

(memorial church)

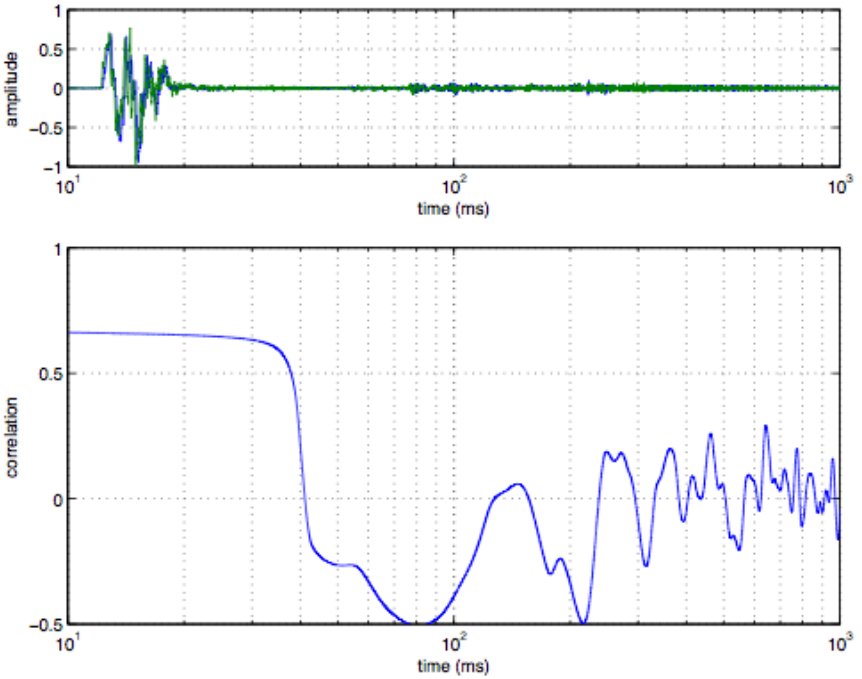
(echo sequences)

Balloon Pop Response Spatial Character

Memorial Church Response



Hagia Sophia Response



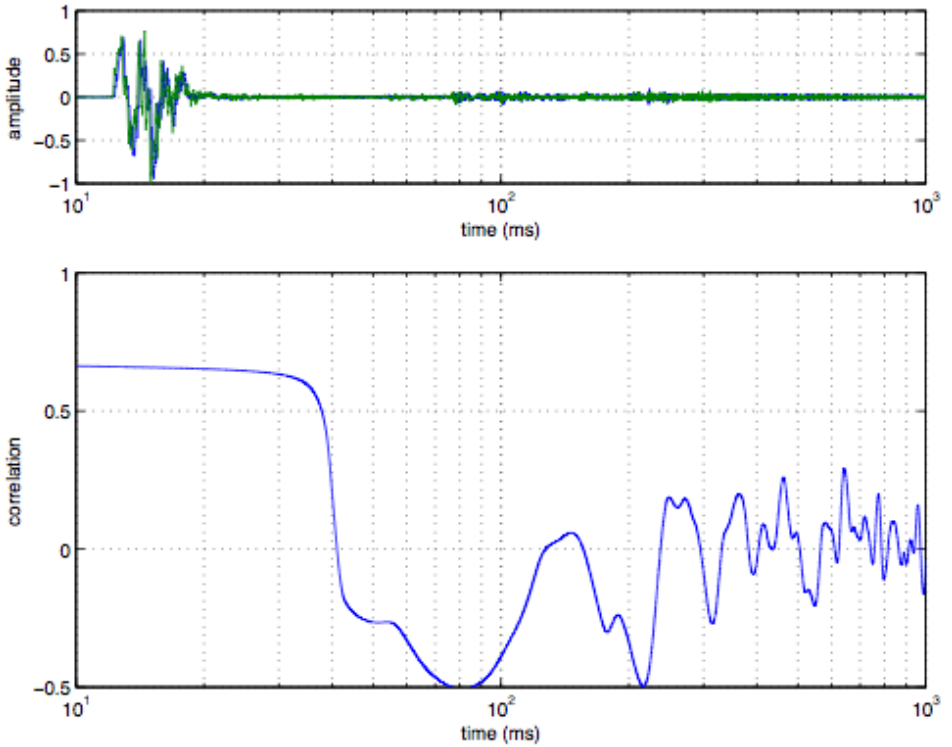
- The Spatial character of the recorded balloon response is indicated by the inter-channel correlation coeff cient

Measurement Correlation Synthesis

$$y(t) = \mathbf{M} \cdot x(t)$$

$$\mathbf{M} = \begin{bmatrix} \cos\theta & \sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$

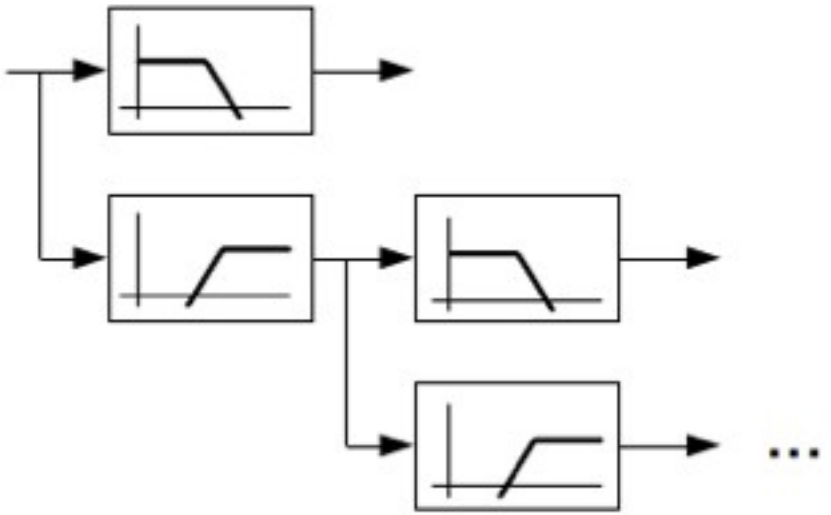
$$\theta(t) = \frac{\arcsin C(t)}{2}$$



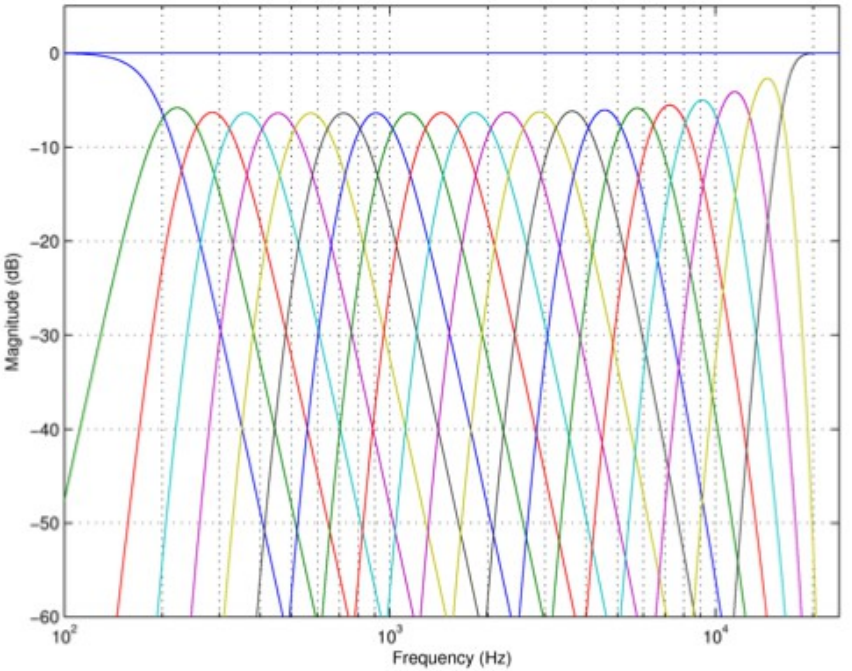
- A stereo pair of echo patterns having a perceived correlation coeff cient $C(t)$ may be generated from a pair of statistically independent sequences

Band Energy Analysis

Filter Bank Architecture

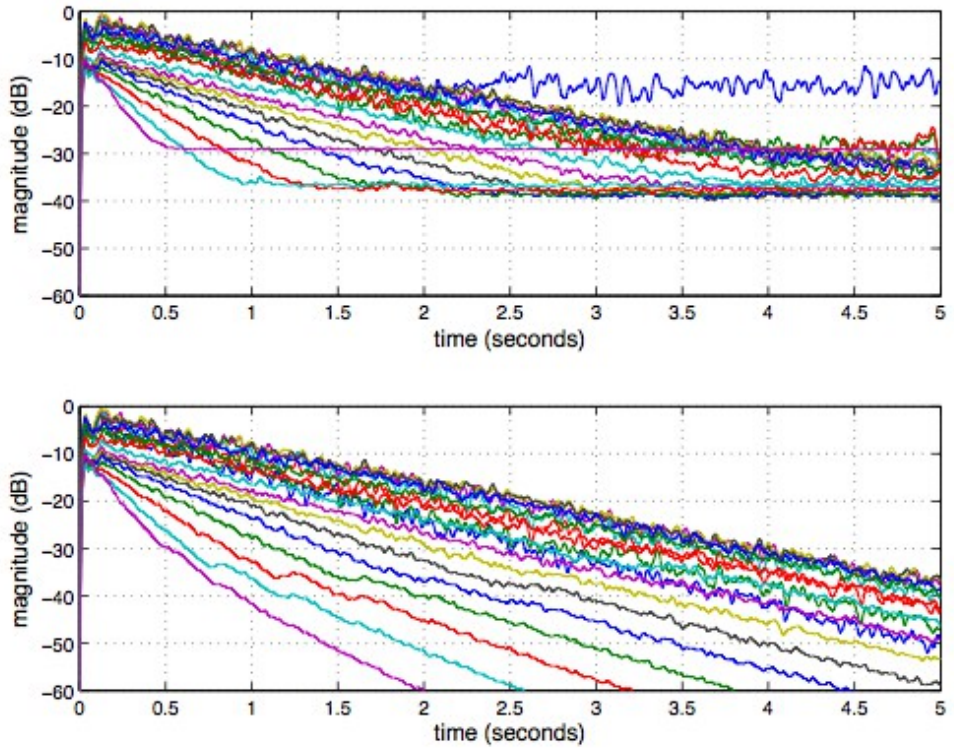


Filter Bank Band Transfer Functions



- Band energies are found by smoothing squared zero-phase Butterworth filter band outputs
- Estimated band energies are then applied to p(t)

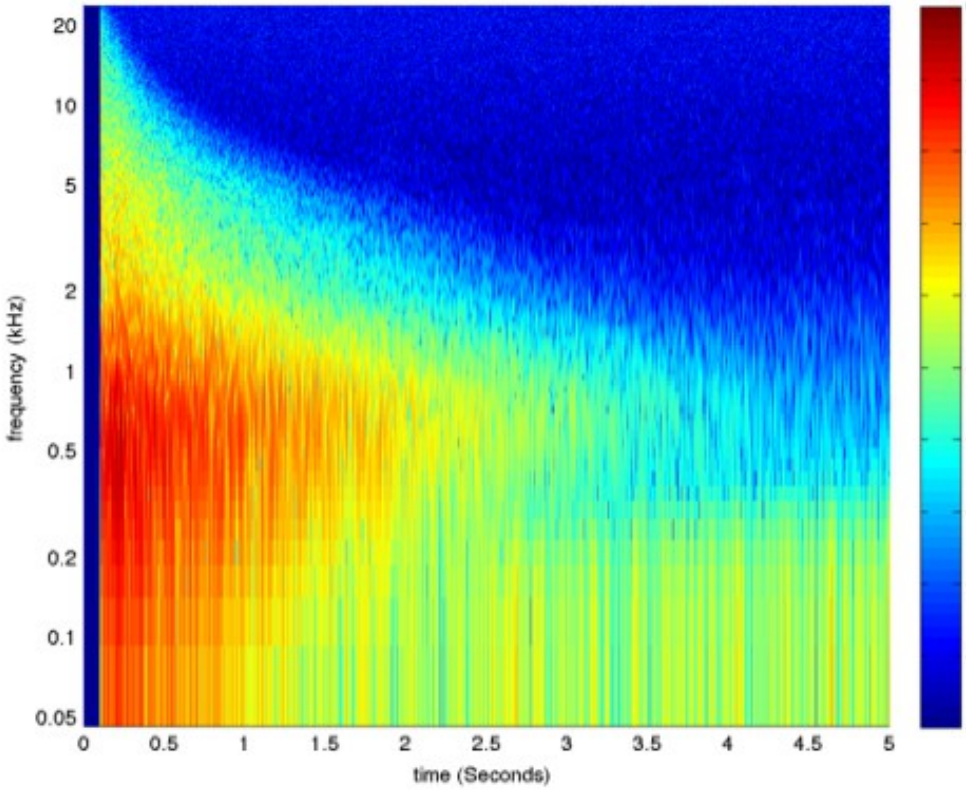
Measured, Extrapolated Band Energies



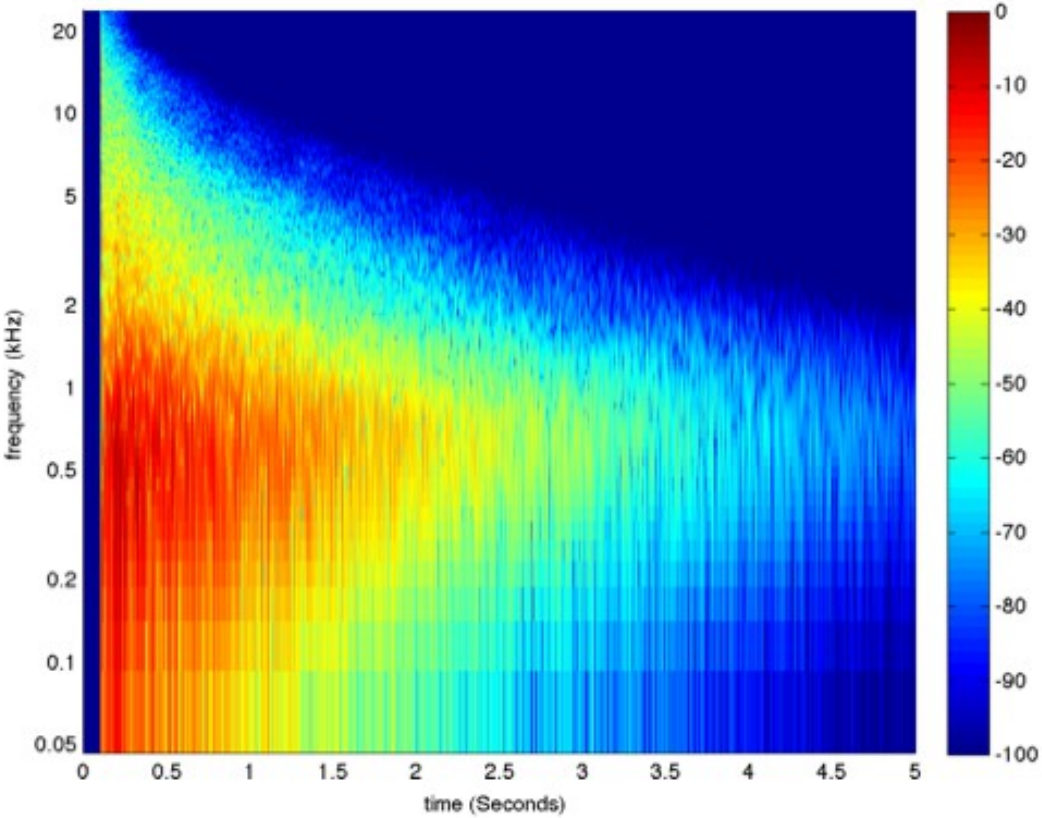
- Measured band energies may be extrapolated as they approach the noise floor or recording end

Measured, Extended Balloon Pop Spectrograms

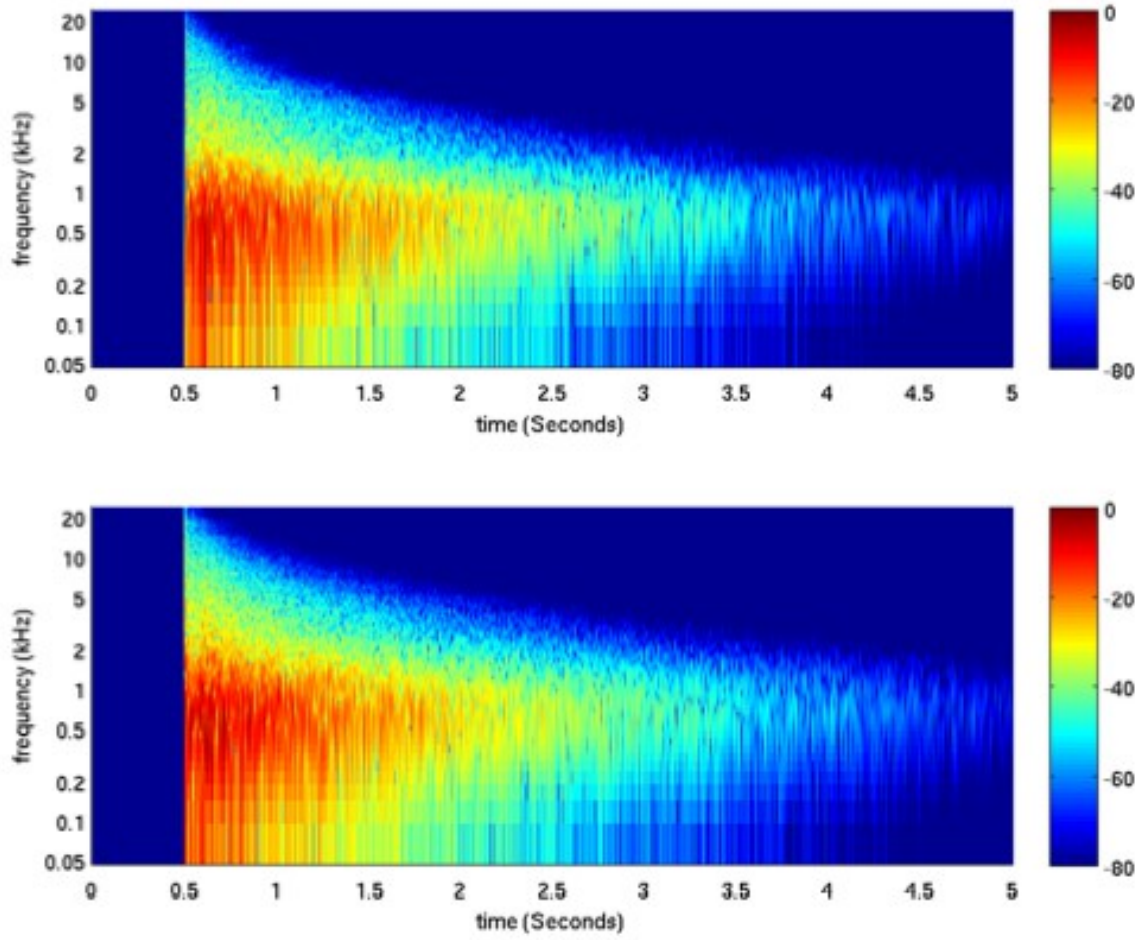
Measured BR Spectrogram



Extended BR Spectrogram

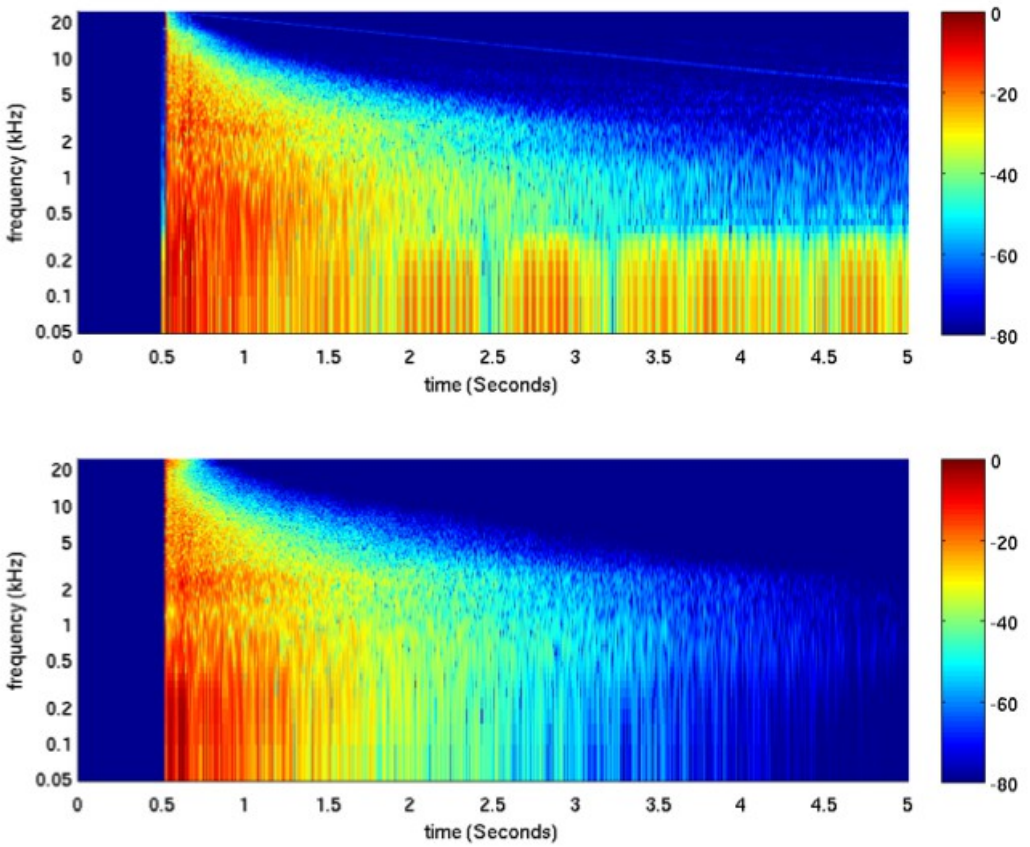


Measured, Estimated BR Spectrograms



- The measured (upper) and estimated (lower) BR spectrograms are similar

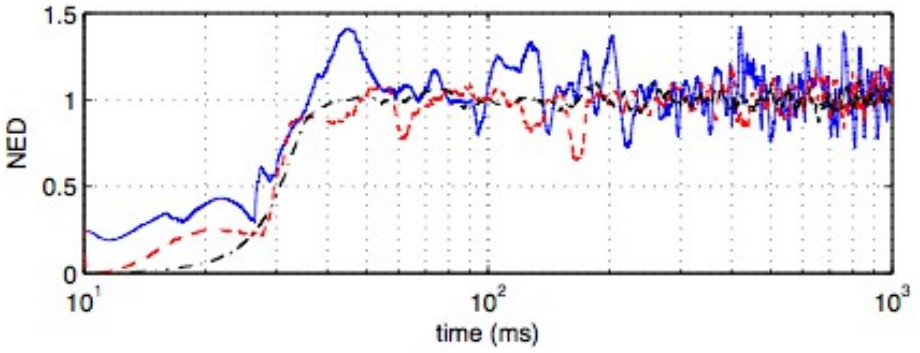
Measured Estimated Impulse Response Spectrograms



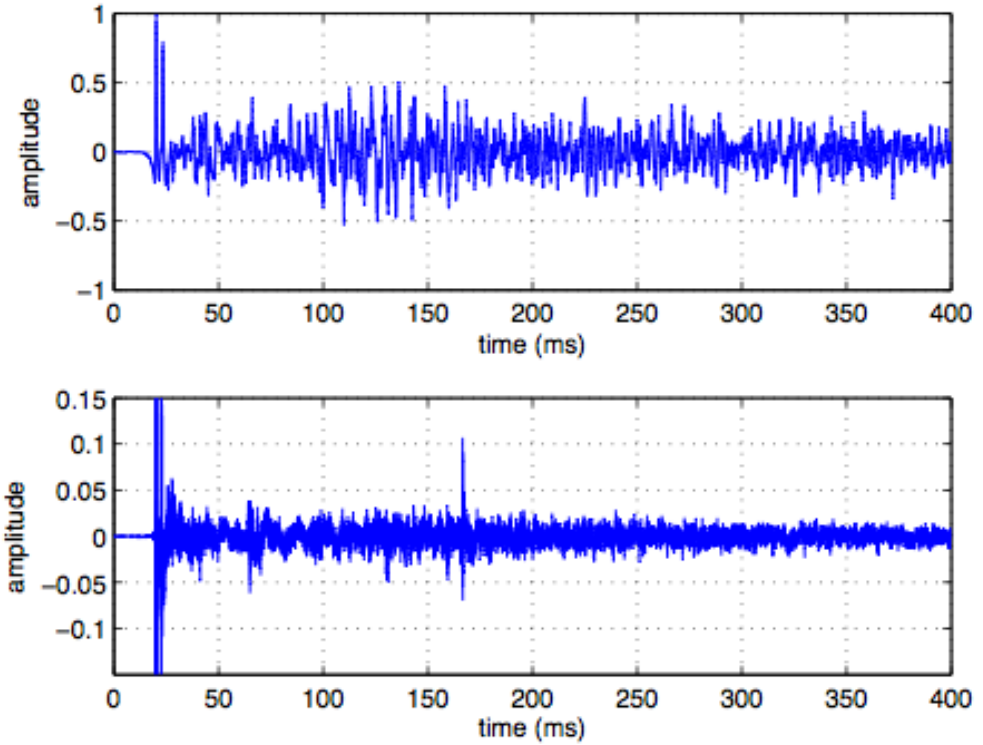
- The measured (upper) and estimated (lower) impulse response spectrograms are similar

Estimated, Measured RIR NED

BR (-), Estimated (-.), Measured (–) NED



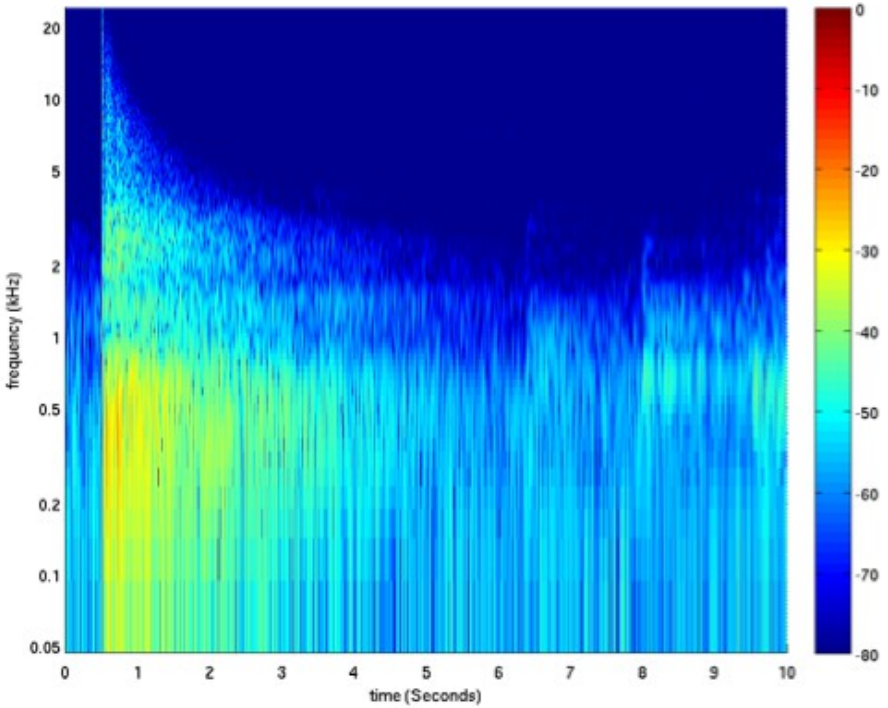
BR onset (upper), IR onset (lower)



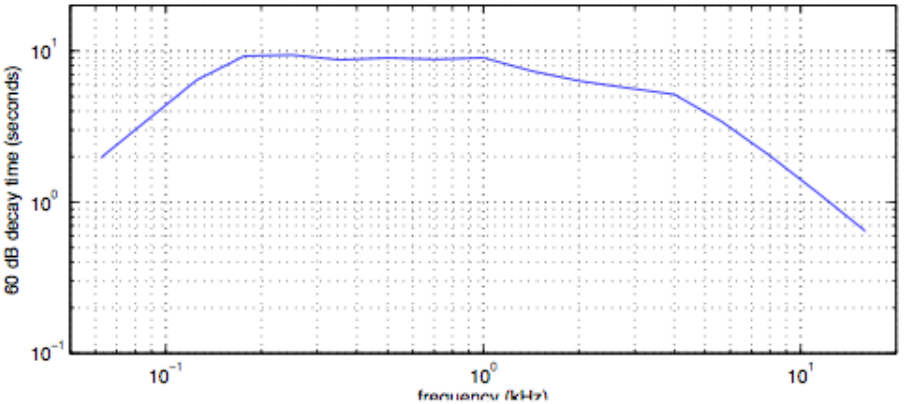
- The estimated and measured NED prof les indicate a good perceptual match over the duration of the impulse response

Hagia Sophia Balloon Pop Spectrogram

Hagia Sophia BR spectrogram



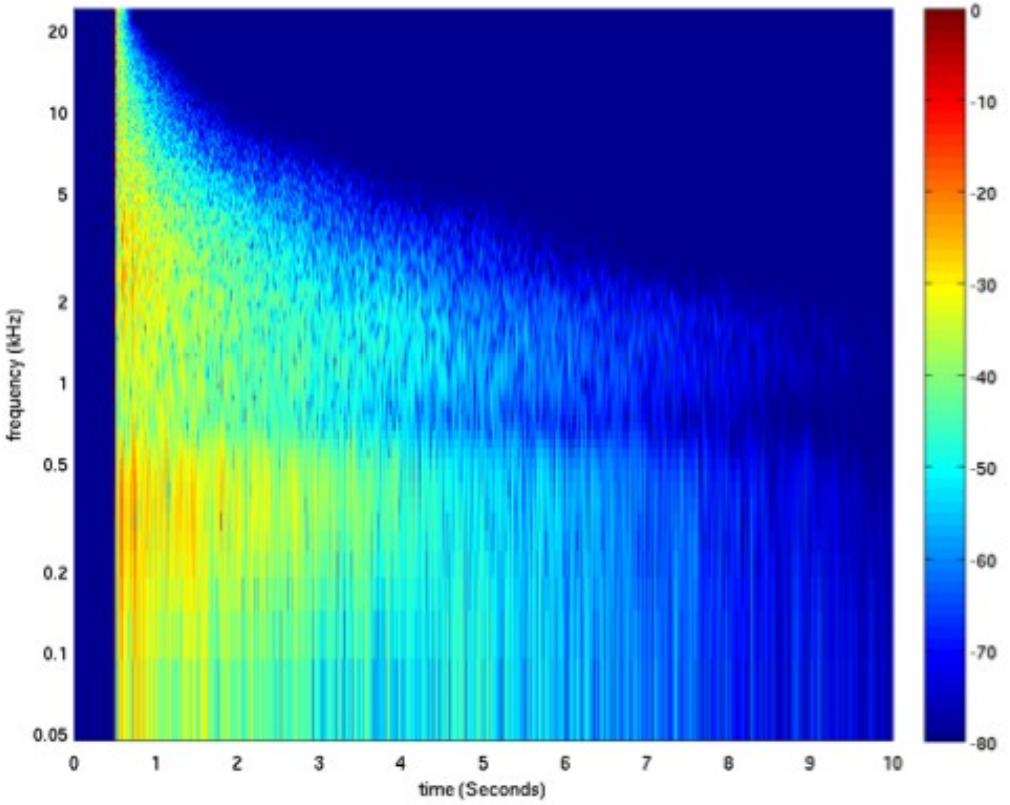
Hagia Sophia estimated T30



- The Hagia Sophia BR contains unwanted noise, starting around 2.7 seconds after the direct path arrival
- The measured T30 is in agreement with published results
  (C. A. Weitze, J. H. Rindel, C. L. Christensen, A. C. Gade 2009)

Hagia Sophia Estimated Impulse RIR

Hagia Sophia estimated RIR spectrogram



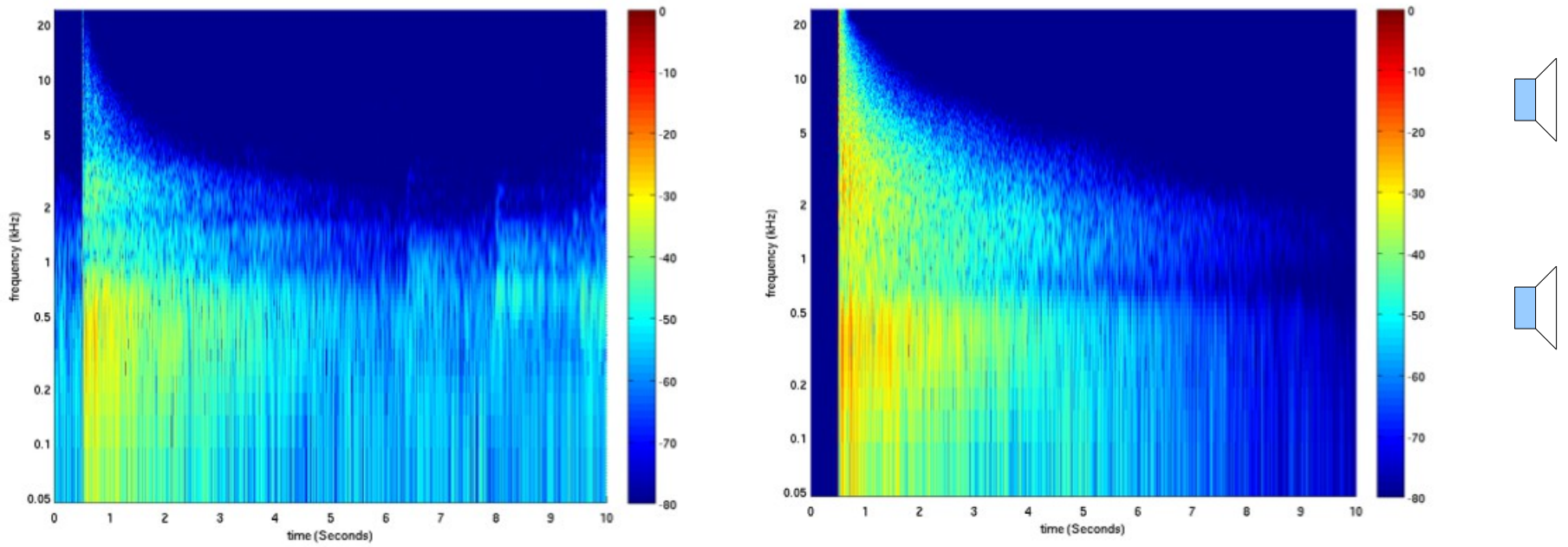
(balloon response extended wet)

(balloon response hat wet)

(impulse response hat wet)

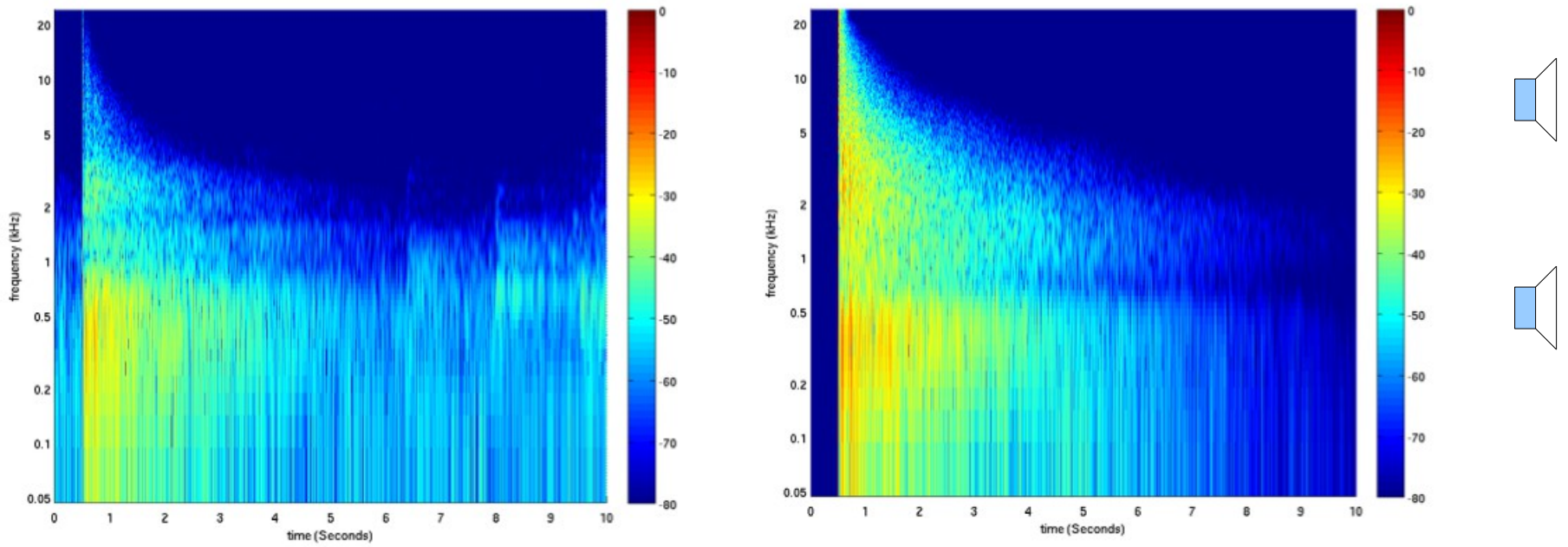
(impulse response hat)

Summary, Future Work



- Balloon pops provide an inexpensive, convenient way to measure room acoustics
- RIRs estimated from balloon pop recordings seem to match loudspeaker measured RIRs
- Cherubikon auralization; “correction” impulse response development, dodecahedron measured, estimated RIR using a loudspeaker

Summary, Future Work



- Balloon pops provide an inexpensive, convenient way to measure room acoustics
- RIRs estimated from balloon pop recordings seem to match loudspeaker measured RIRs
- Cherubikon auralization; “correction” impulse response development, dodecahedron measured, estimated RIR using a loudspeaker