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Room Acoustics Measurements with an Approximately Spherical Source of 120 Drivers

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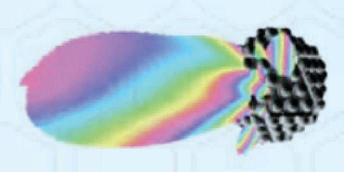
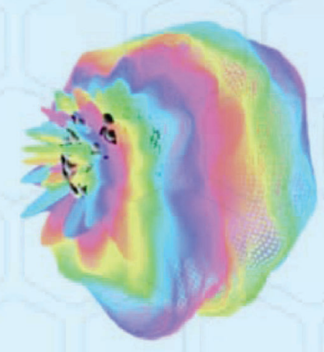
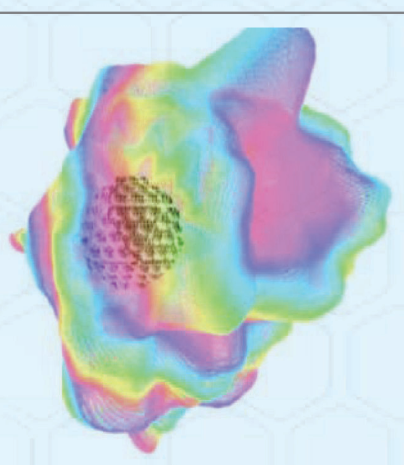
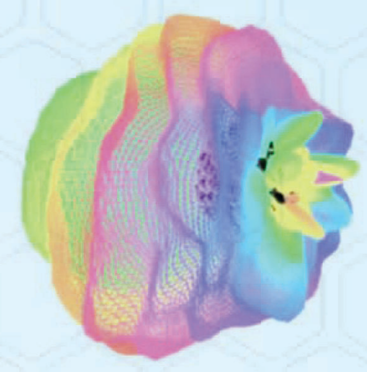








The Spherical Harmonics Transform Let $g(\boldsymbol{\Omega})$ represent an angular radiation pattern in amplitude vs spherical angle $\boldsymbol{\Omega} = (\phi, \theta)$. The spherical harmonics transform of g yields the expansion coefficients g_{nm} by integration with spherical harmonics of order n, degree m, Y_n^m.

$$g_{nm} = \mathcal{SHT}\left\{g(\boldsymbol{\Omega})\right\}_n^m, \quad (1)$$
$$\mathcal{SHT}(g(\boldsymbol{\Omega}))_n^m := \iint_{\mathbb{S}^2} g(\boldsymbol{\Omega}) \cdot Y_n^m(\boldsymbol{\Omega})\,\mathrm{d}\boldsymbol{\Omega}, \quad (2)$$
$$n = 0 \ldots \infty, m = -n \ldots n \quad (3)$$

The inverse transform is:

$$\mathcal{SHT}^{-1}(\boldsymbol{g}) = \sum_{n=0}^{\infty} \sum_{m=-1}^{n} g_{nm} \cdot Y_n^m(\boldsymbol{\Omega})^* \quad (4)$$

Loudspeaker Patterns For a discrete array of L elements with angular positions $\boldsymbol{\Omega}_l$, $l = 1 \ldots$ L, the bandwidth of an angular pattern is limited to spherical harmonics less than order N proportional to $\sqrt{L}$, assuming the angular positions are near-uniformly distributed over the surface of the sphere. In this situtation, a discrete approximation to $\mathcal{SHT}$ is used to control angular patterns over the given arrangement of loudspeakers. In order to address these coefficients by a single index, let $p = n^2 + n + m + 1$ and $Y_n^m = Y_p$. Note that $1 \leq p \leq (N+1)^2$

Suppose that the velocity pattern at the surface of the array for each element is is well approximated by bandlimited Dirac delta distributions at the angular positions $\boldsymbol{\Omega}_l$, $l = 1$...L of the elements. In spherical harmonics these deltas can be gathered into the *loudspeaker encoding* matrix $\boldsymbol{C}$

$$\boldsymbol{C} = [\mathbf{c}_1, \ldots, \mathbf{c}_L], \quad (5)$$
$$\boldsymbol{c}_l = [\mathcal{SHT}(\delta(\boldsymbol{\Omega} - \boldsymbol{\Omega}_l))] = [Y_p(\boldsymbol{\Omega}_l)]. \quad (6)$$

Optimal Angular Reproduction An optimal decoder matrix $\boldsymbol{D}$ for the reproduction of angular patterns on the array surface is given by the pseudo-inverse of $\boldsymbol{C}$

$$\boldsymbol{D} = \boldsymbol{C}^t\left(\boldsymbol{C}\boldsymbol{C}^t\right)^{-1}. \quad (1)$$

It contains a set of real-valued weights for reproduction of $g(\boldsymbol{\Omega})$ using the transducer signals $\boldsymbol{y}$ and the input signal x.

$$\boldsymbol{y} = \boldsymbol{D}\,\boldsymbol{g}\,x. \quad (2)$$

Optimal Radial Reproduction For non-omnidirectional patterns, the dispersion of acoustic energy is dependent on wavelength, giving rise to the near-field and far-field effects. Compensation for this effect requires an equalization filter per-order $\boldsymbol{H}_n(r)$ at every frequency to ensure the desired spectral balance is achieved at the target radius r. It is convenient to notate the radially-equalized transducer signals and the input x in the frequency domain

$$\tilde{\boldsymbol{y}} = \boldsymbol{D}\,\boldsymbol{H}(r)\;\boldsymbol{g}\,x. \quad (3)$$

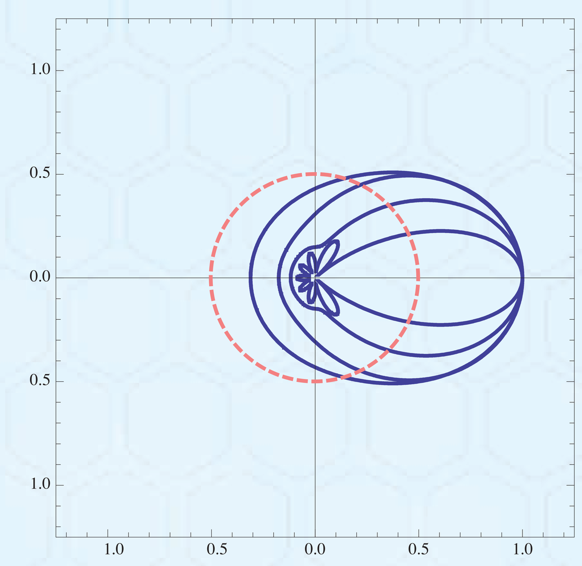
Note, however, that $\boldsymbol{H}_n(r)$ is efficiently and accurately implemented with an IIR filter.

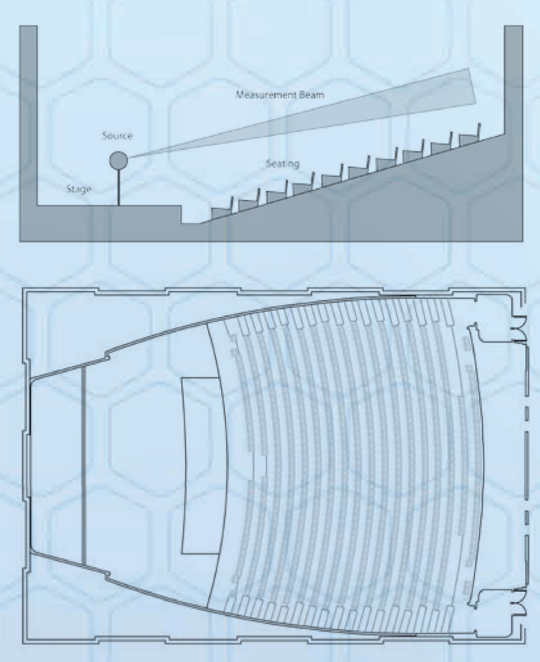
Angular Aliasing The finite realization of $\mathcal{SHT}$ requires a low-pass filter to prevent aliasing of patterns that exceed the reproduction capability of the array. The design of windowing function $\boldsymbol{W}_N$ with coefficients $w(n)$ attenuates terms of increasing order n and influences the tradeoff between ripple and main-lobe width in the spatial domain. Reconstruction on the array is then given by

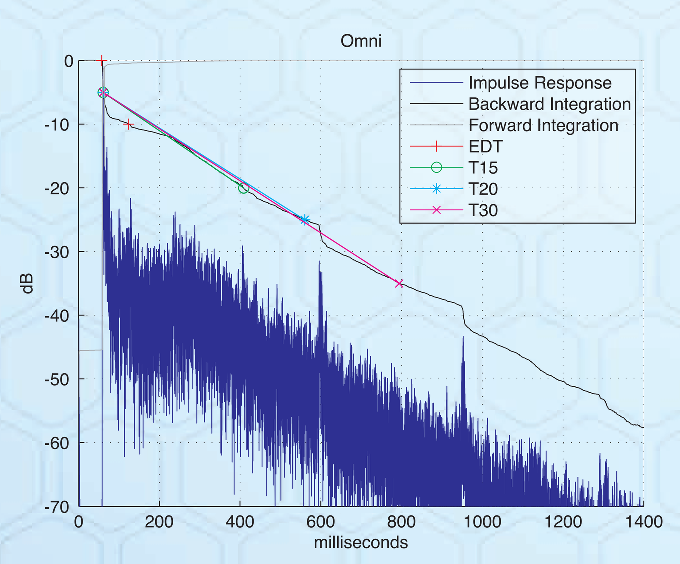
$$\tilde{\boldsymbol{y}} = \boldsymbol{D}\,\mathbf{W}_N\;\boldsymbol{H}(r)\;\boldsymbol{g}\,x \quad (4)$$

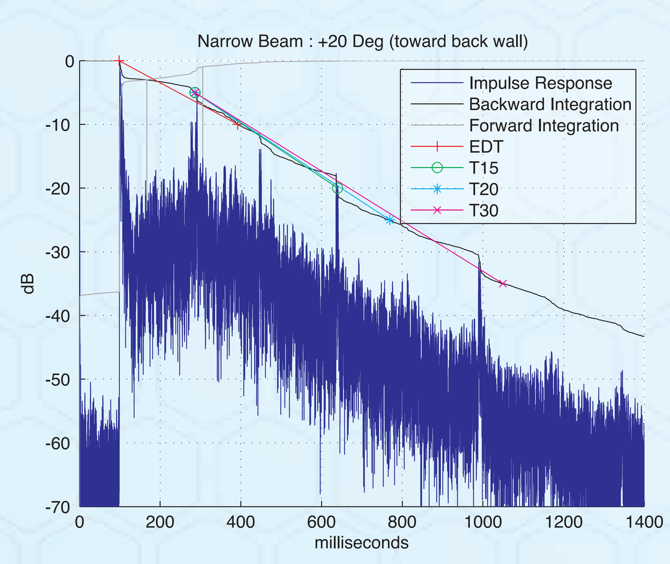
The Steerable Beam Given a 1-dimensional signal x, a beam having the maximum possible angular selectivity transmitting x in the direction $\boldsymbol{\Omega}_d$ can be constructed using the order-N-limited spherical harmonics expansion of a spherical dirac-delta function, $\delta(\phi - \phi_d, \theta - \theta_d)$.

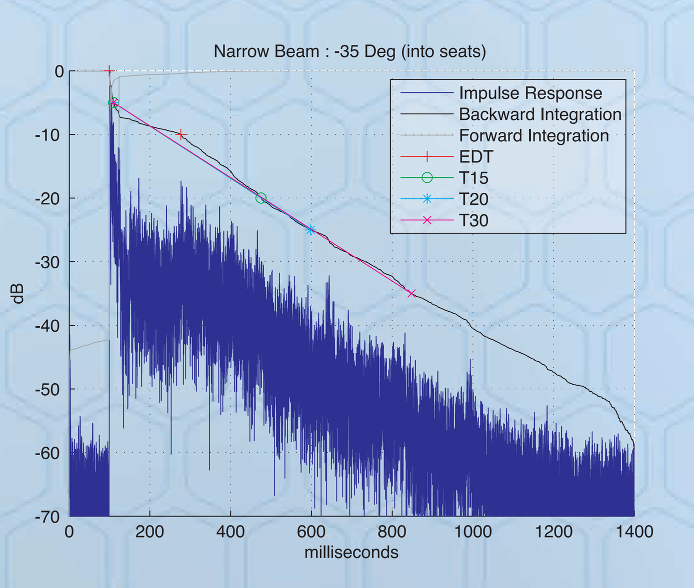
$$\tilde{y}_{\mathrm{beam}} = \boldsymbol{D}\,\boldsymbol{H}(r)\;\mathbf{W}_N\;\mathcal{SHT}(\delta(\boldsymbol{\Omega} - \boldsymbol{\Omega}_d)) \cdot x \quad (5)$$

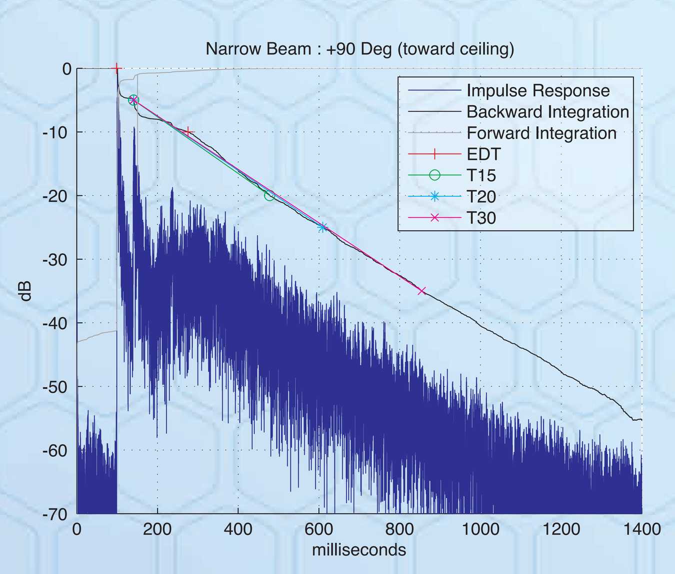


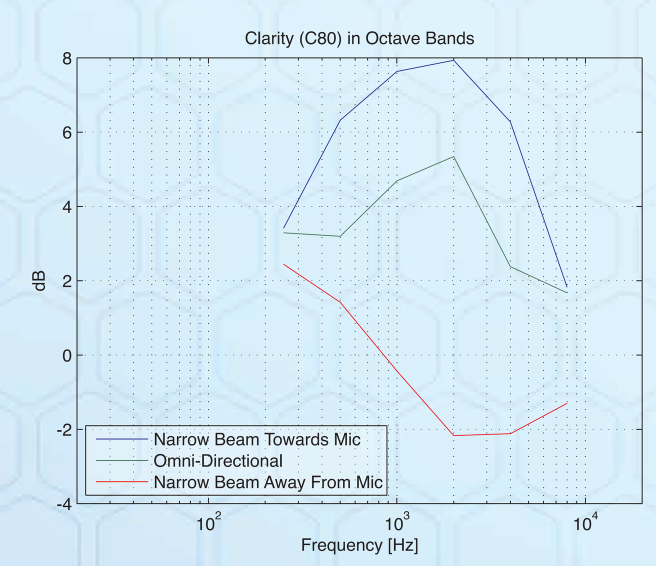












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