International Symposium on
Room Acoustics : Design and Science 2004

A Satellite Symposium of ICA2004 Kyoto, Japan   http://rads04.iis.u-tokyo.ac.jp

Awaji Yumebutai International Conference Center, Hyogo, Japan   April 11-13, 2004

Advanced techniques for measuring and reproducing spatial sound properties of auditoria

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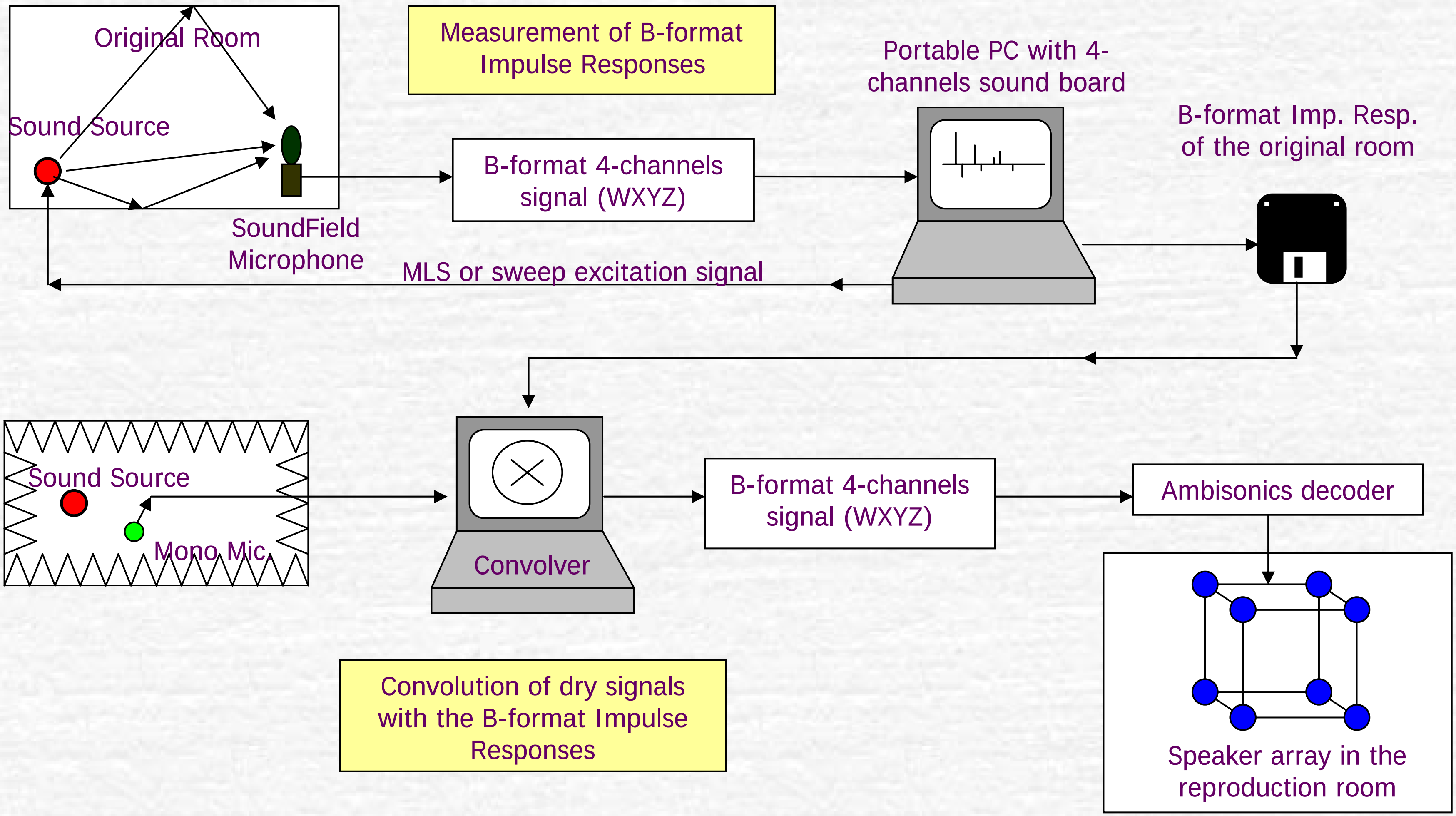
Topics

- This paper is a tribute to M. Gerzon, who had foreseen 3D impulse response measurements and 3D Auralization obtained by convolution.
- The advantages (and disadavantages) of employing measured IRs
- Comparison between Auralizations based on calculated and measured IRs (e.g. Theatre “La Fenice”, Venice)
- Different approaches to 3D Auralization

Concept (Gerzon, 1975)



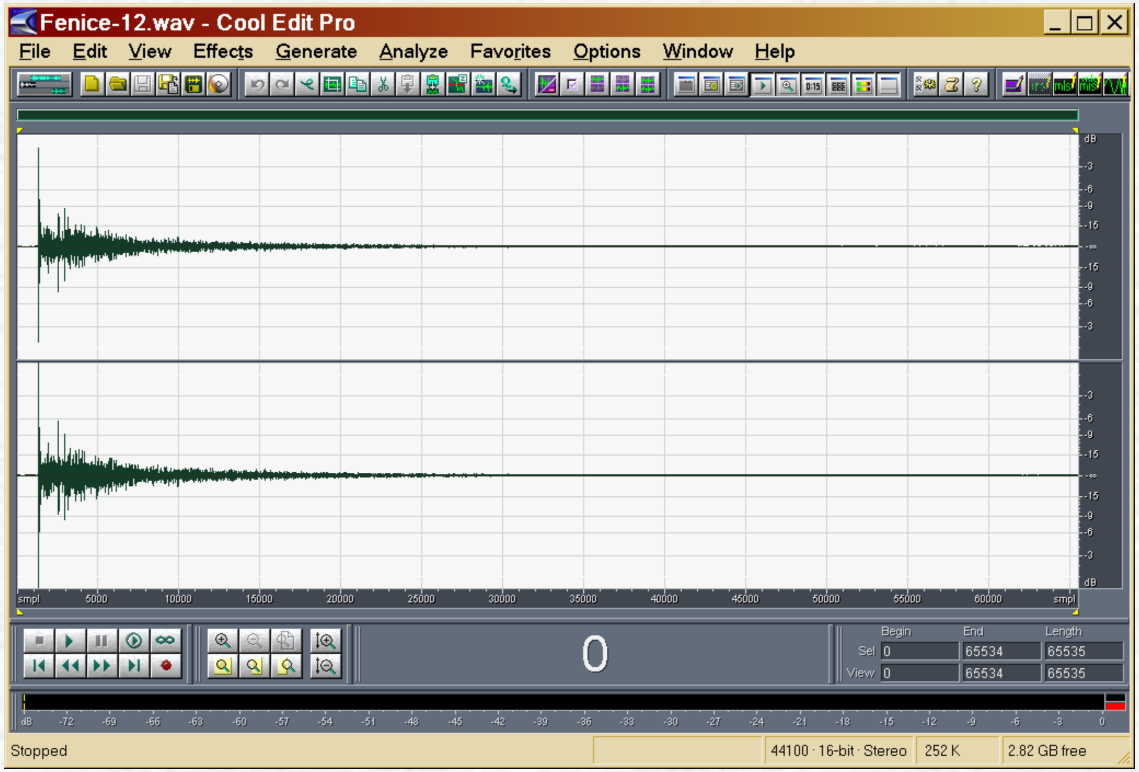
The measurements of IRs:

1. In case something happens to the original space (e.g.: La Fenice theater) they contain a detailed “acoustical photography” which is preserved for the posterity
2. They can be used for studio sound processing, as artificial reverb and surround filters for today’s and tomorrow’s musical productions
3. Several configurations of listening rooms could be developed, by means of multichannel auralization, for subjective tests

Theatre la Fenice, Venice

- The first theatre was realised in 1792 by Gian Antonio Selva, after the burning of Teatro San Benedetto
- In December 1836 the theatre burned down again and was rebuilt by G. and T. Meduna the year after
- The theatre was closed in 1995 for maintainance; it had to open again in February 1, 1996, but it burned two days before (January 29, 1996)
- A few weeks before the fire, L.Tronchin measured binaural impulse responses

Impulse Responses of La Fenice



Point n. 12

- In 27 positions a series of binaural impulse responses (with gun shots) was recorded
- Each recording is consequently a stereo file at 16 bits, 48 kHz
- During measurements the room was perfectly fitted, whilst the stage was empty (no scenery)

Example n. 1 – La Fenice

Overture alle Nozze di Figaro di Mozart

- Dry music
- Convolution with experimental I.R. (pt. 12)
- Convolution with simulated IR

Preludio al primo atto della Traviata di G.Verdi

- Dry music
- Convolution with experimental I.R. (pt. 12)
- Convolution with simulated IR

Stop

Example n. 2 – Paris vs …la *petit Paris*

Citè de la Musique, Parigi

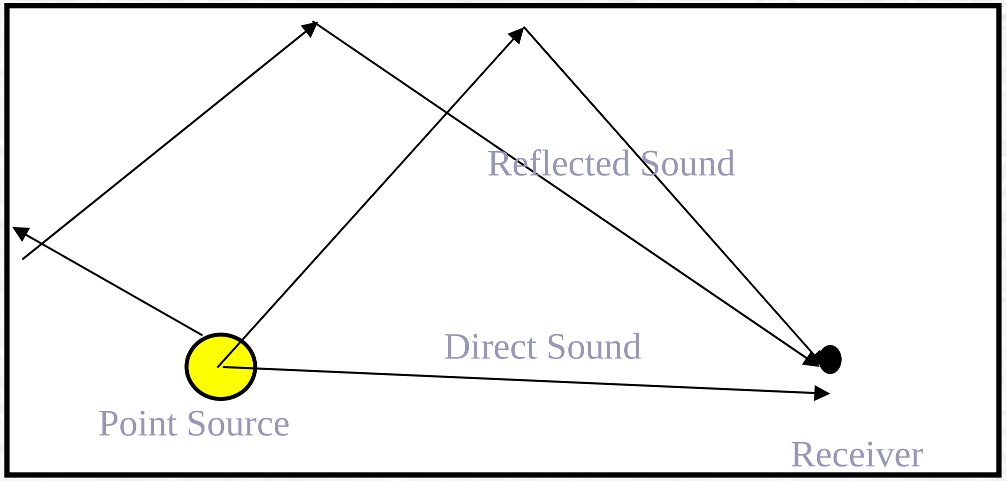
Auditorium di Parma

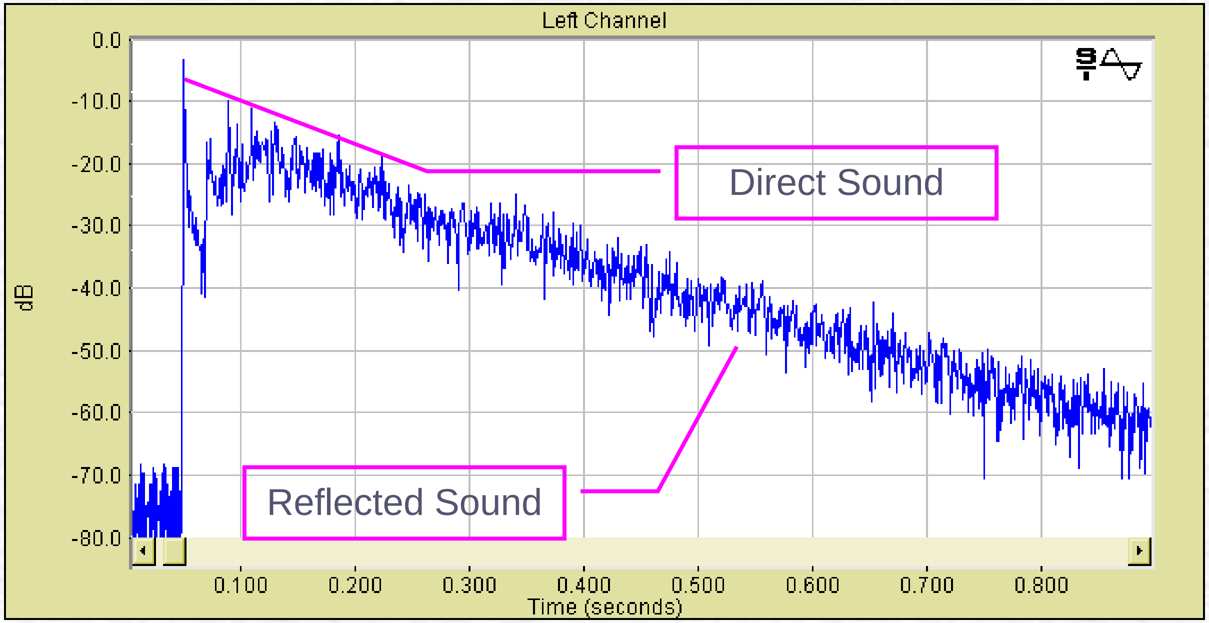
Stop

Advanced IR capture and rendering (WAVES project)

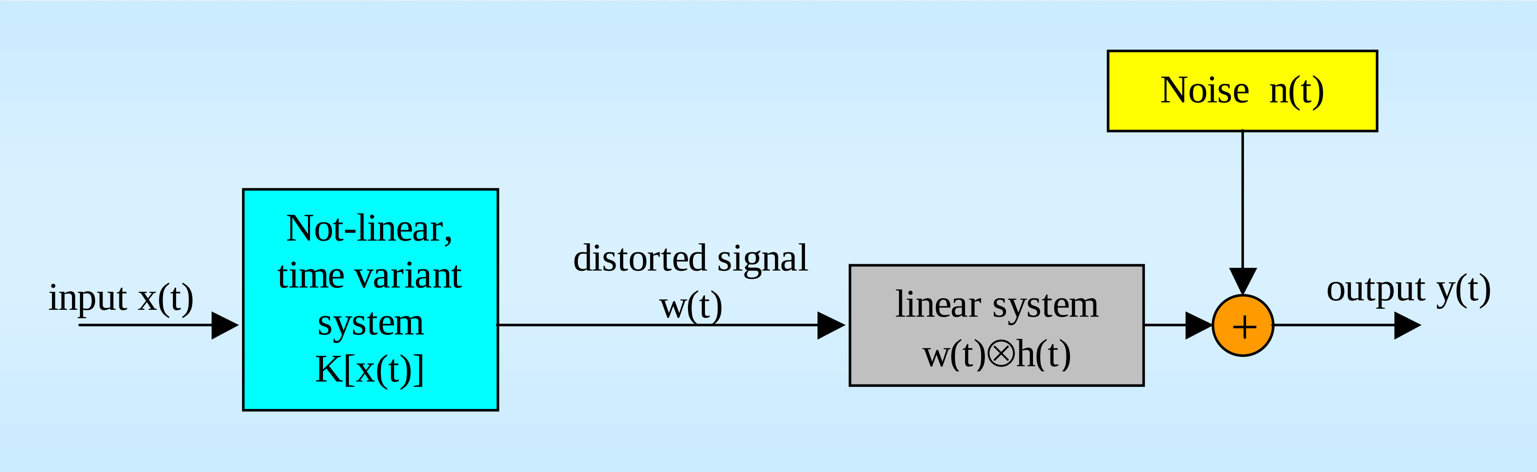
- Description of the measurement technique
- Analysis of some acoustical parameters of some theaters measured
- Description of the processing methods to be employed for transforming the measured data in audible reconstructions of the original spaces
- Description of the usage of the measured data for studio processing, musical production and for scientific Auralization tests

Sound propagation in rooms





Measurement process



- The desidered result is the linear impulse response of the acoustic propagation h(t). It can be recovered by knowing the test signal x(t) and the measured system output y(t). It is necessary to exclude the effect of the not-linear part K and of the background noise n(t).

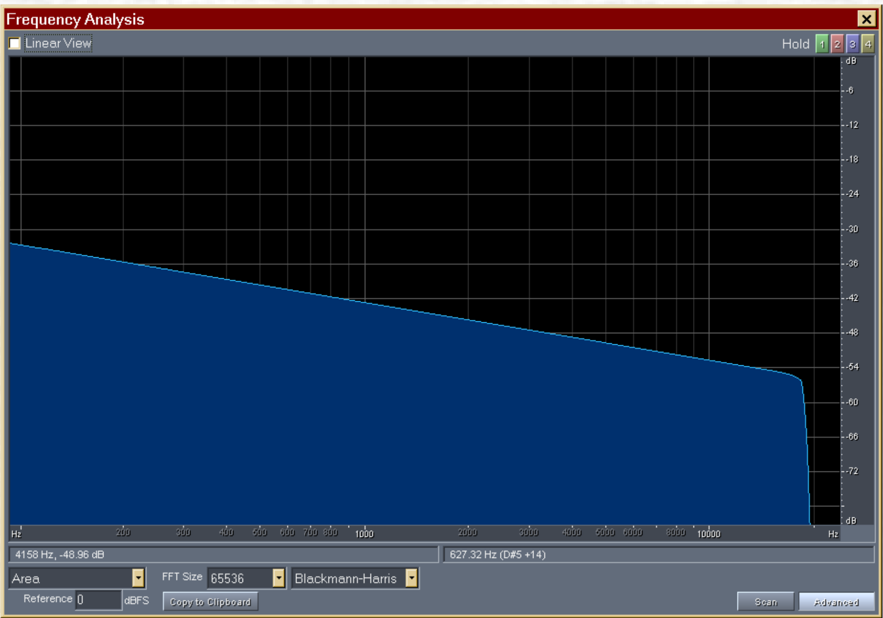
Test signal: Log Sine Sweep

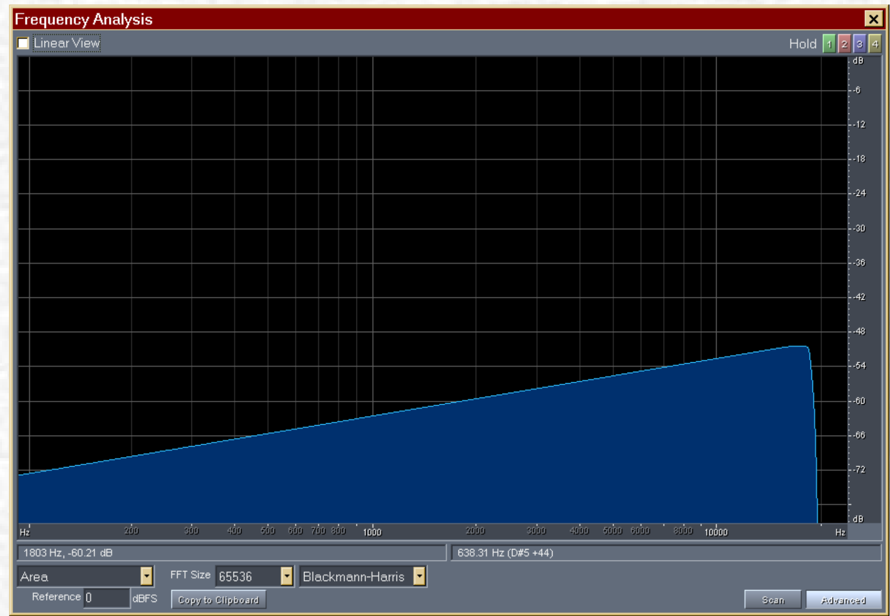
x(t) is a sine signal, which frequency is varied exponentially with time, starting at f_1 and ending at f_2.

$$x(t) = \sin\left[\frac{2\cdot\pi\cdot f_1\cdot T}{\ln\left(\frac{f_2}{f_1}\right)}\cdot\left(e^{\frac{t}{T}\cdot\ln\left(\frac{f_2}{f_1}\right)} - 1\right)\right]$$

Deconvolution of Log Sine Sweep

The “time reversal mirror” technique is emplyed: the system’s impulse response is obtained by convolving the measured signal y(t) with the time-reversal of the test signal x(-t). As the log sine sweep does not have a “white” spectrum, proper equalization is required

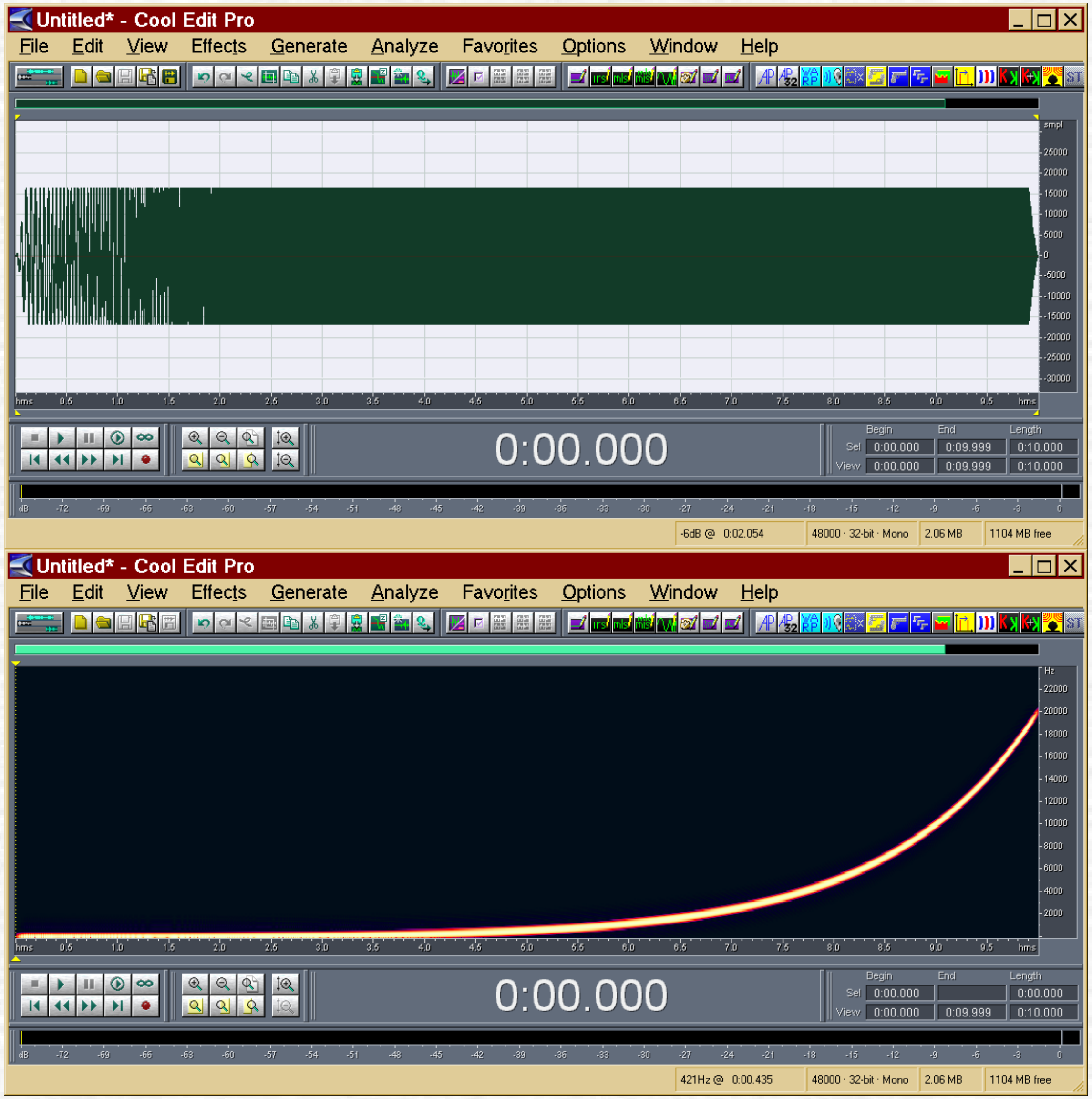




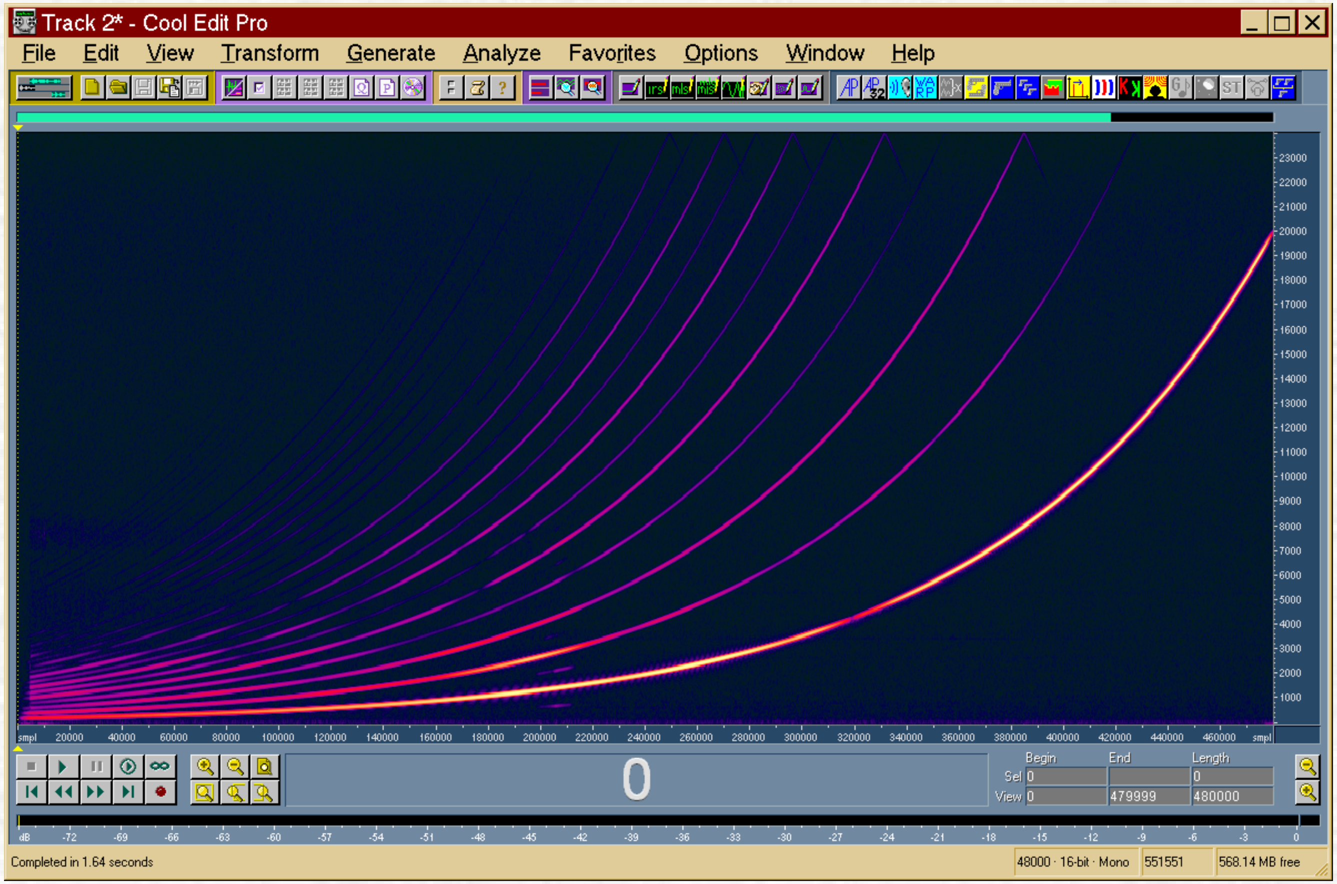
Test Signal x(t)

Inverse Filter z(t)

Test Signal – x(t)

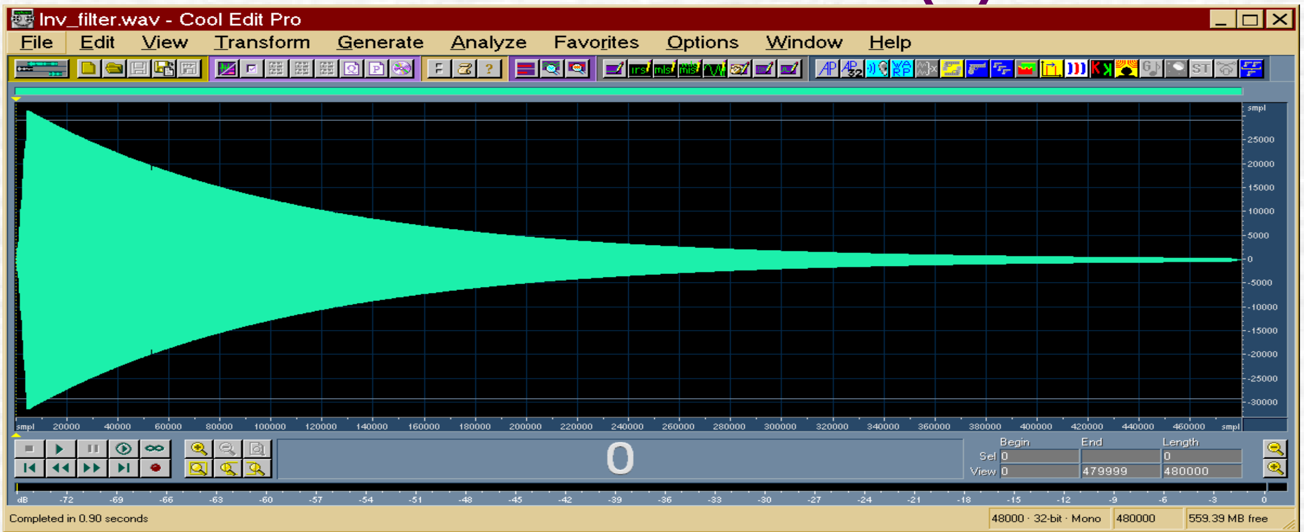


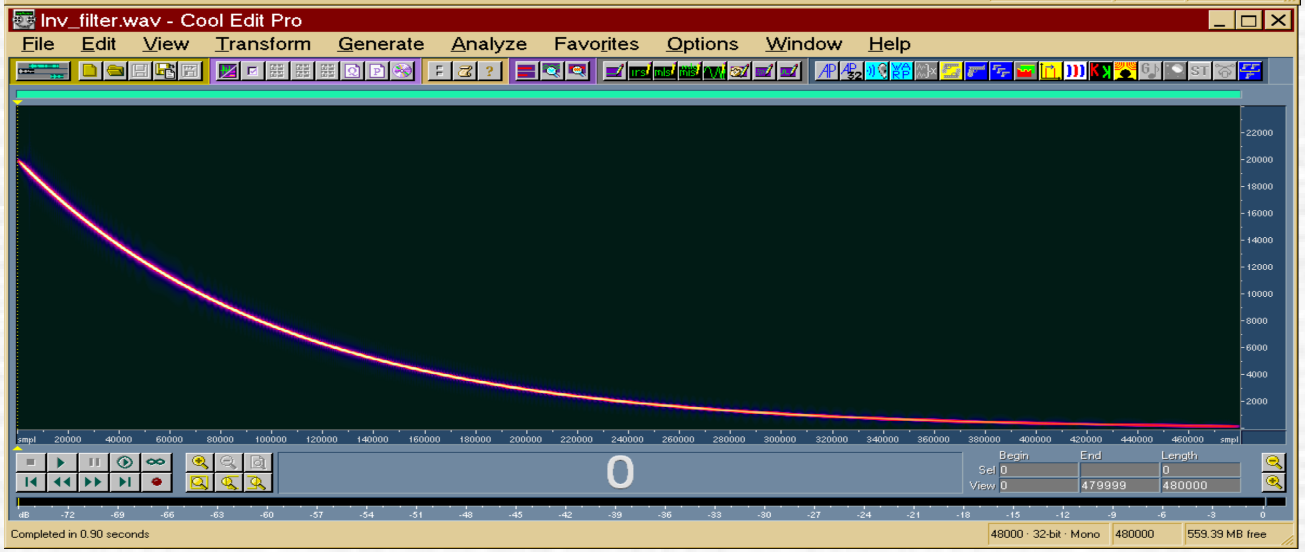
Measured signal - y(t)



- The not-linear behaviour of the loudspeaker causes many harmonics to appear

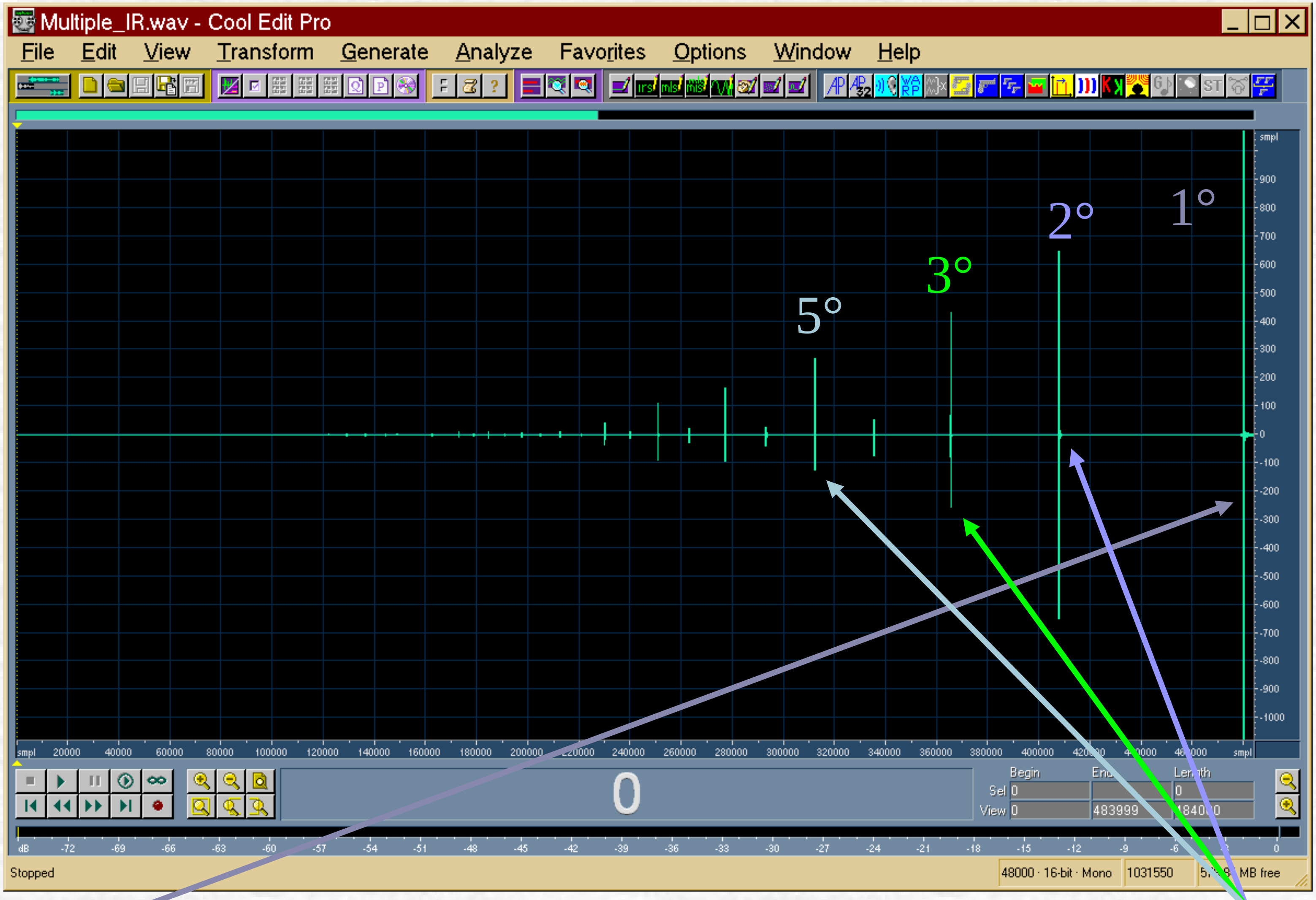
Inverse Filter – z(t)





The deconvolution of the IR is obtained convolving the measured signal y(t) with the inverse filter z(t) [equalized, time-reversed x(t)]

Result of the deconvolution



The last impulse response is the linear one, the preceding are the harmonics distortion products of various orders

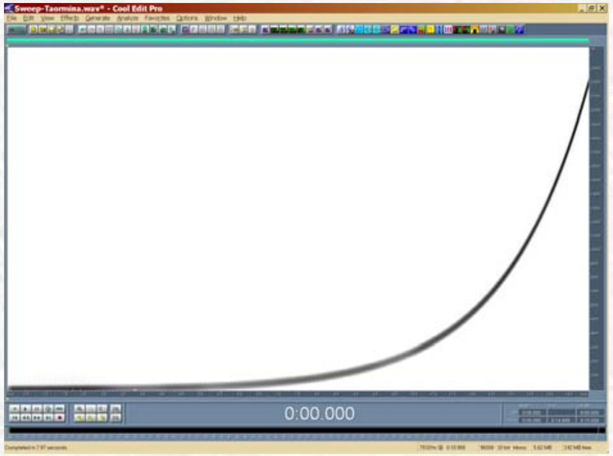
Measurement Setup

- The measurement method incorporates all the known techniques:
  - Binaural
  - B-format (1st order Ambisonics)
  - WFS (Wave Field Synthesis, circular array)
  - ITU 5.1 surround (Williams MMA, OCT, INA, etc.)
  - Binaural Room Scanning
  - M. Poletti high-order virtual microphones
- Any multichannel auralization systems nowadays available is supported

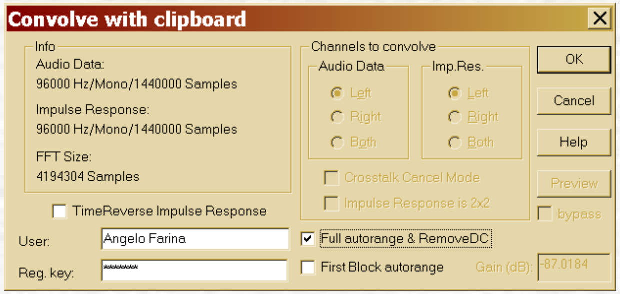
Measurement Parameters

- Test Signal: pre-equalized sweep

Start Frequency	**22 Hz**
End Frequency	**22 kHz**
Sweep length	**15 s**
Silence between sweeps	**10 s**
Type of sweep	**LOG**

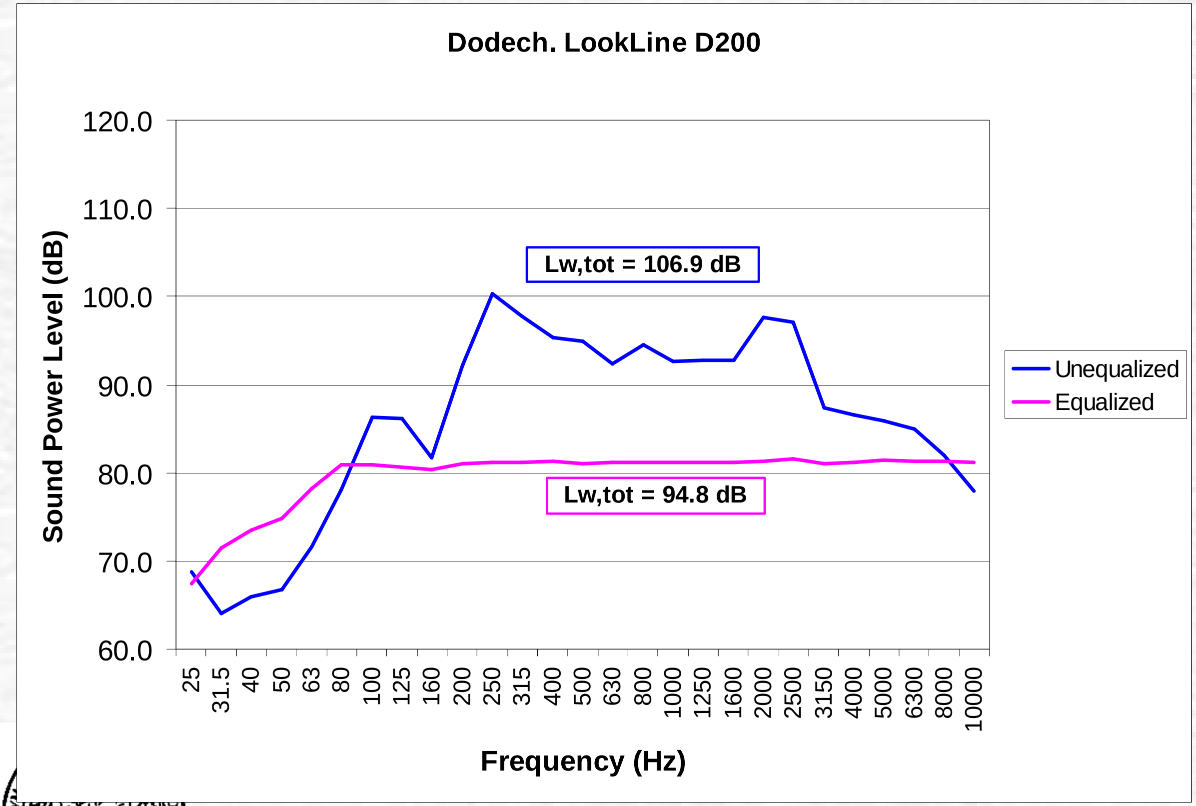


- Deconvolution:



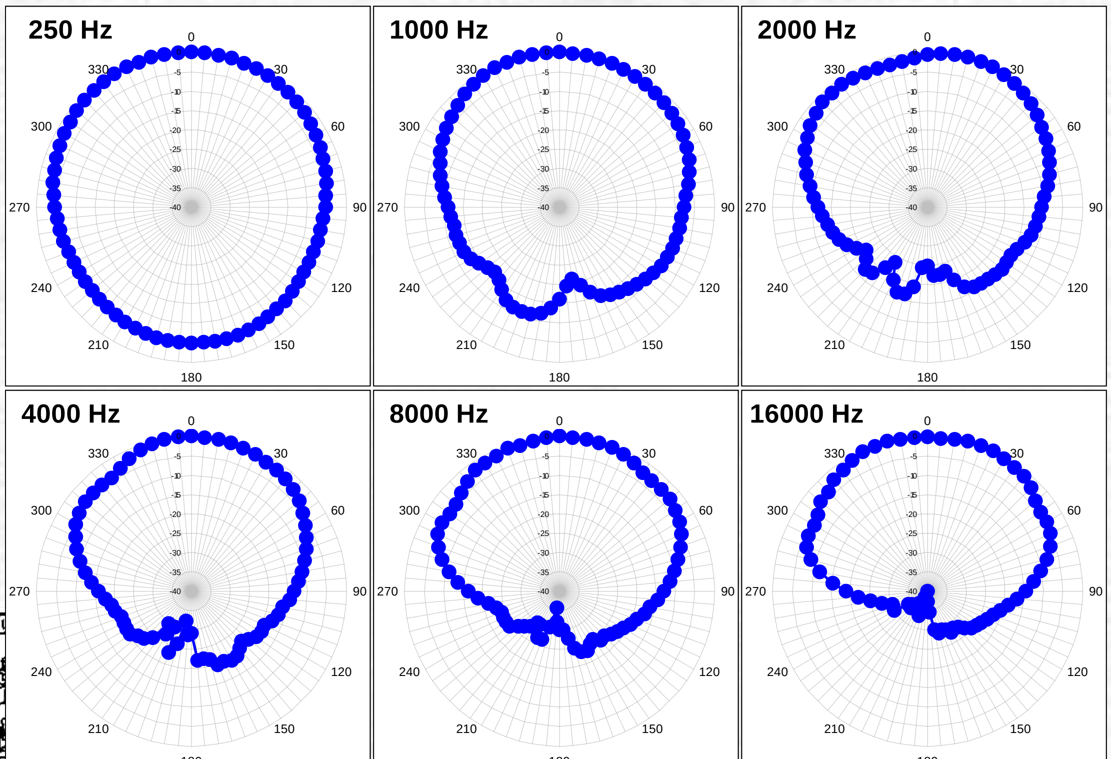
Transducers (sound source #1)

- Equalized, omnidirectional sound source:
  - Dodechaedron for mid-high frequencies
  - One-way Subwoofer (<120 Hz)



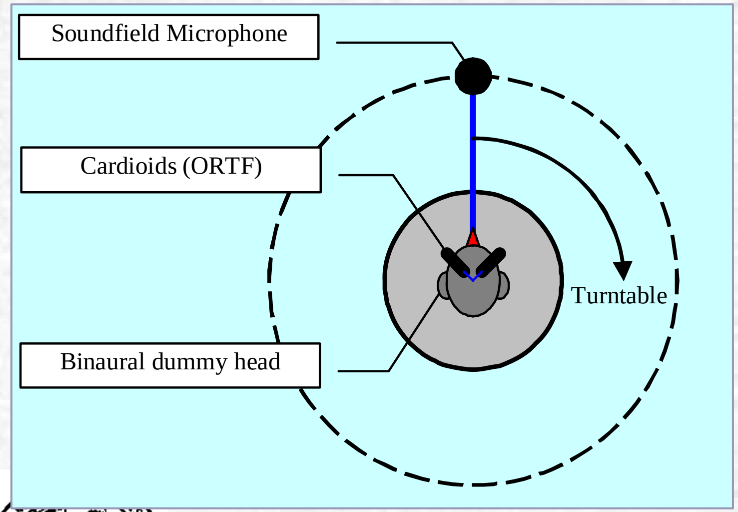
Transducers (sound source #2)

- Genelec S30D reference studio monitor:
  - Three-ways, active multi-amped, AES/EBU
  - Frequency range 37 Hz – 44 kHz (+/- 3 dB)



Transducers (microphones)

- 3 types of microphones:
  - Binaural dummy head (Neumann KU-100)
  - 2 Cardioids in ORTF placement (Neumann K-140)
  - B-Format 4 channels (Soundfield ST-250)



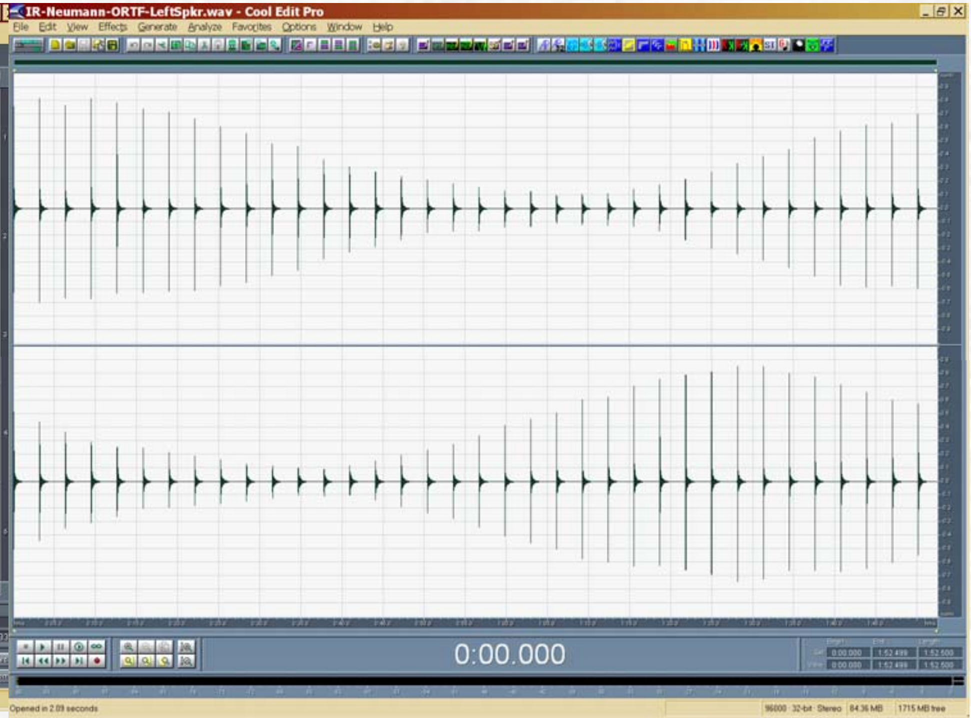
Other hardware equipment

- Rotating Table:
  - Outline ET-1

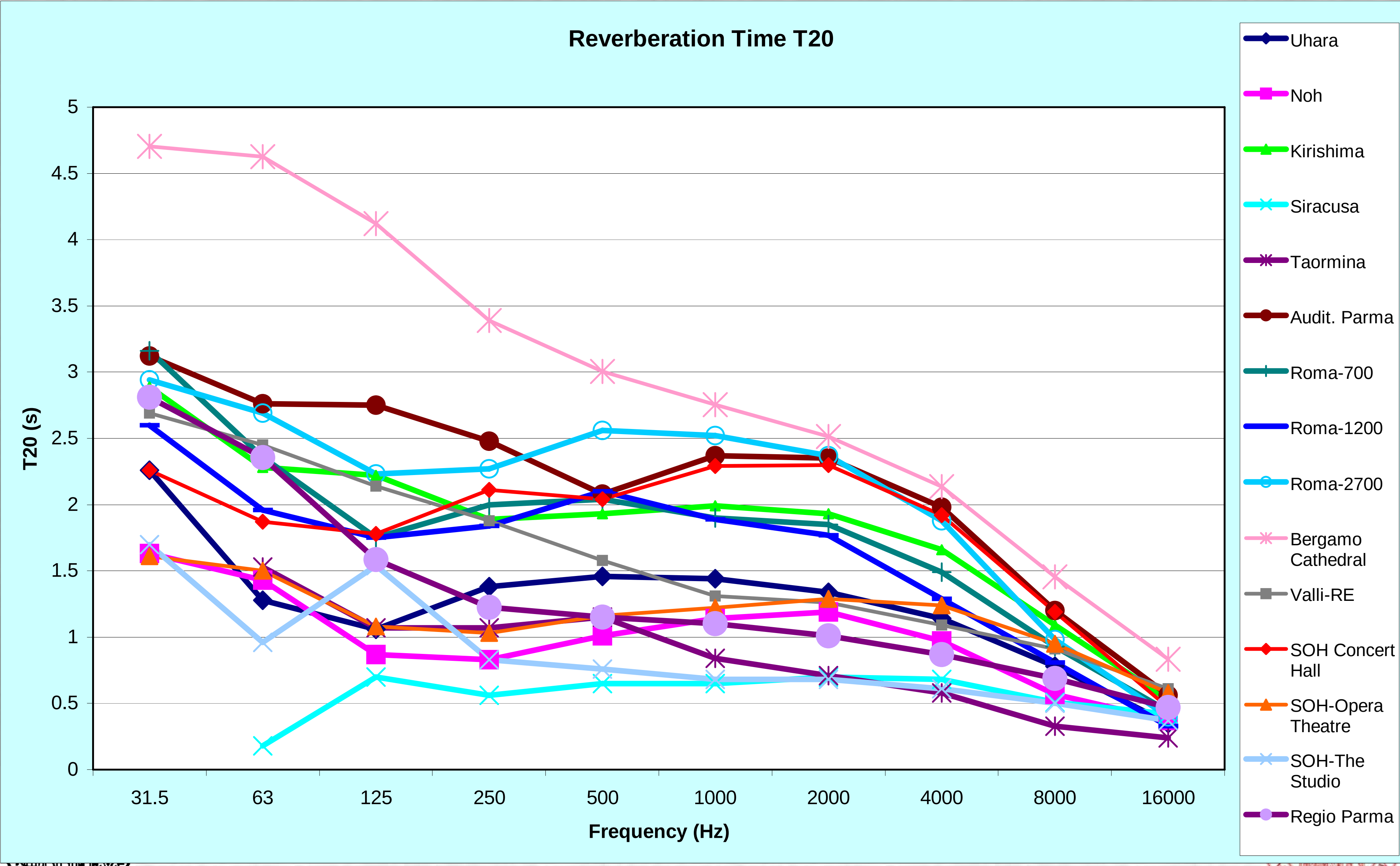
- Computer and sound card:
  - Signum Data Futureclient P-IV 1.8 GHz
  - Aardvark Pro Q-10 (8 ch., 96 kHz, 24 bits)

Measurement procedure

- A single measurement session play backs 36 times the test signal, and simultaneusly record the 8 microphonic channels

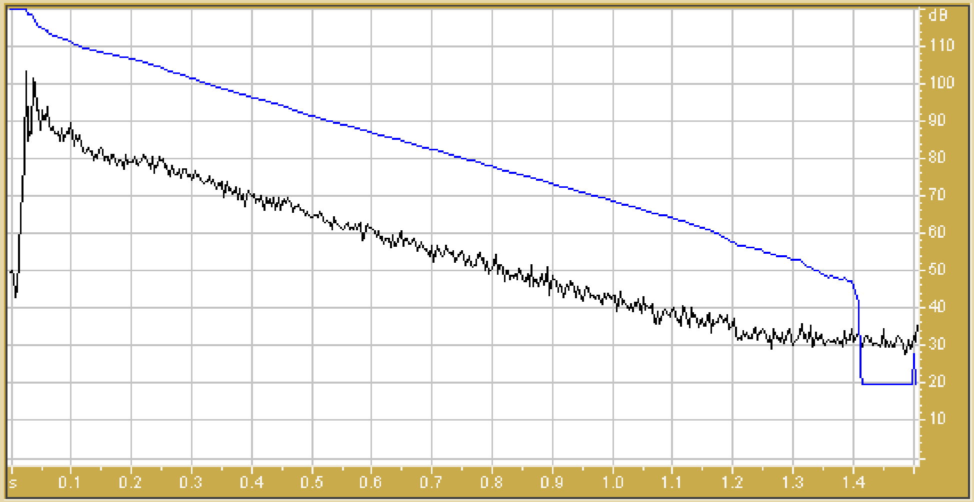


Theatres measured



Uhara Hall, Kobe, Japan

Acoustical Parameters according to ISO3382



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Tuser limits: (-5. dB, -15. dB)

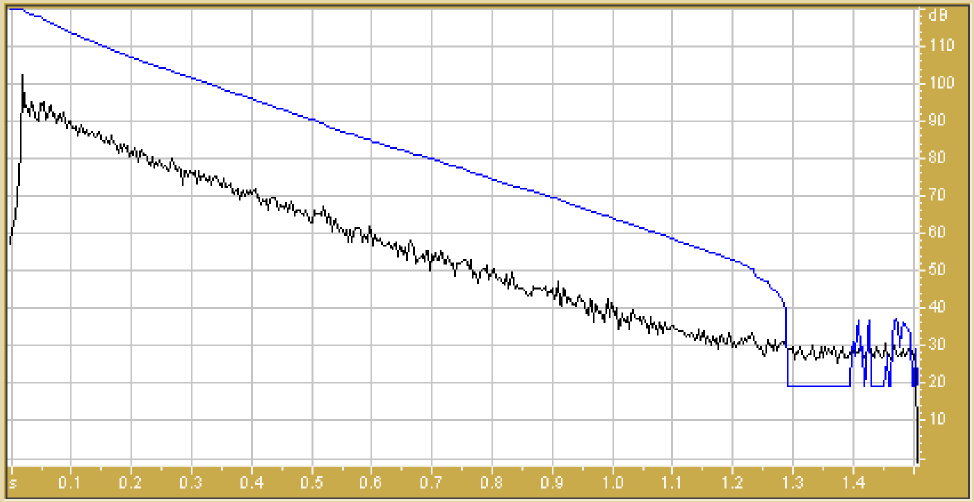
Left Channel

Freq. (Hz)	31.5	63	125	250	500	1k	2k	4k	8k	16k	Lin	A
Signal (dB)	38.62	63.15	70.39	65.09	69.61	71.06	73.56	76.88	76.40	78.76	82.91	82.44
Noise (dB)	17.37	24.72	25.25	16.20	15.28	18.54	19.71	17.71	20.31	29.34	32.80	28.99
strenGth(dB)	-30.38	-5.85	1.39	-3.91	0.61	2.06	4.56	7.88	7.40	9.76	3.91	5.44
C50 (dB)	3.39	7.02	0.54	2.16	5.01	4.77	4.02	6.51	8.64	13.60	6.24	6.30
C80 (dB)	4.91	8.67	4.69	4.83	7.83	6.37	5.73	9.11	11.64	17.92	8.68	8.58
D50 (%)	68.59	83.45	53.11	62.19	76.02	75.01	71.60	81.74	87.97	95.82	80.80	81.02
Ts (ms)	102.03	56.49	82.94	74.39	45.93	51.61	53.52	33.91	23.70	15.08	36.27	36.17
EDT (s)	1.36	--	0.88	1.35	0.86	1.26	1.30	0.63	0.38	0.20	0.64	0.67
T20 (s)	2.26	1.28	1.06	1.38	1.46	1.44	1.34	1.14	0.78	0.35	1.22	1.24
r T20	0.97	0.98	0.96	1.00	0.98	0.99	1.00	0.99	0.99	0.98	1.00	1.00
T30 (s)	2.13	1.40	1.17	1.33	1.34	1.43	1.34	1.08	0.73	0.42	1.23	1.23
r T30	0.96	0.99	0.98	1.00	0.99	1.00	1.00	1.00	0.99	0.98	1.00	1.00
Tuser (s)	1.61	1.21	1.18	1.42	1.74	1.72	1.51	1.22	0.61	0.27	1.26	1.31
r Tuser	0.97	0.94	0.96	0.98	0.96	0.99	0.99	0.98	0.98	0.94	0.98	0.98

T_{20} = 1.44 s

Noh theater, Kobe, Japan

Acoustical Parameters according to ISO3382



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Store Reference Signal

Switch to Right Channel

Tuser limits:
(-5. dB, -15. dB)

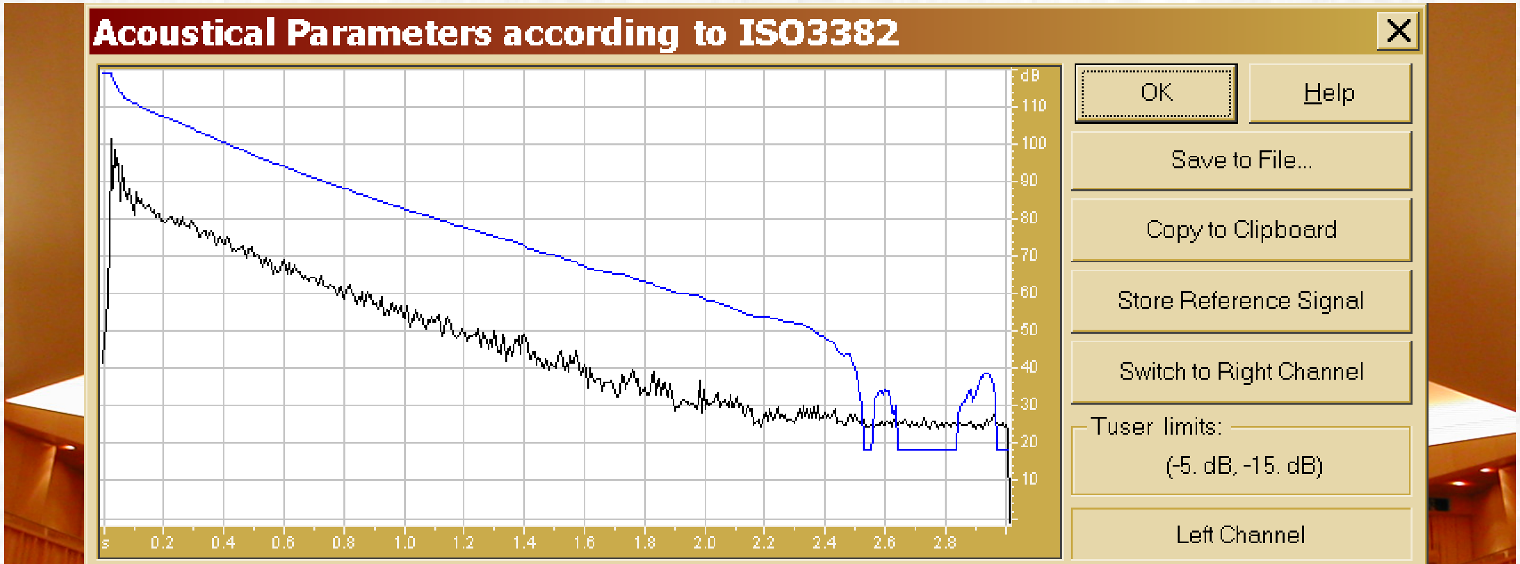
Left Channel

Freq. (Hz)	31.5	63	125	250	500	1k	2k	4k	8k	16k	Lin	A
Signal (dB)	41.61	61.05	70.09	66.51	68.33	71.62	75.65	76.58	77.81	80.23	83.62	83.28
Noise (dB)	15.45	20.46	19.40	11.83	15.17	17.23	23.32	18.80	20.99	26.39	30.14	28.54
strenGth(dB)	-27.39	-7.95	1.09	-2.49	-0.67	2.62	6.65	7.58	8.81	11.23	4.62	6.28
C50 (dB)	-2.00	5.19	3.00	2.32	1.23	-0.16	0.36	0.29	3.54	8.69	2.40	1.67
C80 (dB)	1.57	10.58	7.83	6.17	3.63	2.07	3.04	3.69	8.31	13.99	5.62	4.83
D50 (%)	38.69	76.77	66.61	63.07	57.06	49.08	52.07	51.68	69.30	88.09	63.48	59.51
Ts (ms)	143.48	63.84	49.94	54.27	73.70	79.21	74.89	69.56	38.04	17.51	52.26	58.60
EDT (s)	1.59	0.49	0.70	0.79	1.16	1.17	1.09	0.93	0.59	0.54	0.83	0.89
T20 (s)	1.63	1.43	0.87	0.83	1.01	1.14	1.19	0.97	0.57	0.37	1.03	1.05
r T20	0.94	0.93	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T30 (s)	2.34	1.68	0.82	0.86	0.99	1.12	1.17	0.95	0.59	0.37	1.05	1.06
r T30	0.94	0.97	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Tuser (s)	1.07	--	0.48	0.79	1.08	1.17	1.17	0.93	0.53	0.36	0.92	0.97
r Tuser	0.97	--	0.95	0.99	0.99	0.99	1.00	1.00	0.99	0.98	1.00	1.00

$T_{20} = 1.14$ s

Kirishima Concert Hall, Japan

Kirishima Concert Hall, Japan

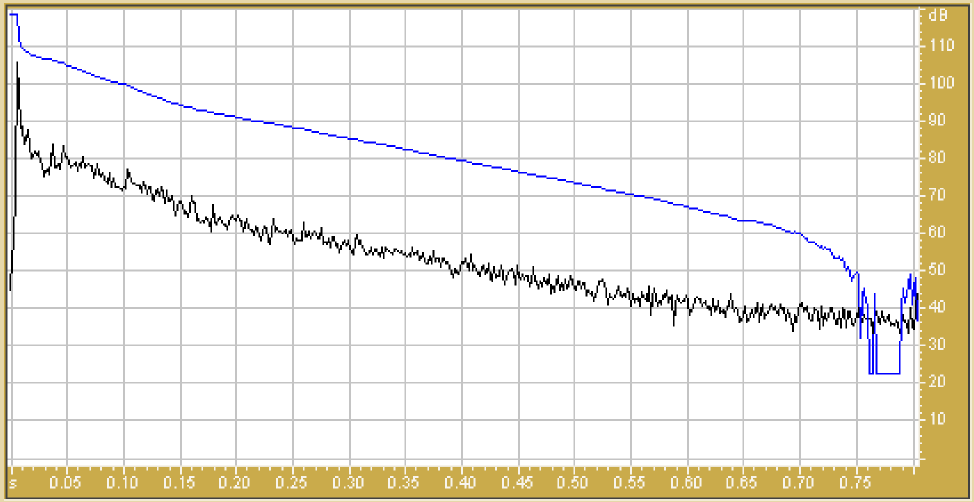


Freq. (Hz)	31.5	63	125	250	500	1k	2k	4k	8k	16k	Lin	A
Signal (dB)	41.00	61.66	67.66	63.99	65.79	68.49	74.16	76.06	78.93	81.19	83.37	83.00
Noise (dB)	10.48	20.70	14.89	12.06	12.97	14.80	18.12	19.52	22.64	28.87	30.09	27.92
strenGth(dB)	-28.00	-7.34	-1.34	-5.01	-3.21	-0.51	5.16	7.06	9.93	12.19	4.37	6.00
C50 (dB)	5.66	2.88	-4.28	-0.76	0.67	1.46	3.82	4.62	8.10	14.02	5.92	5.92
C80 (dB)	7.70	3.51	0.57	0.26	3.45	2.81	4.70	5.81	9.89	15.62	7.31	7.13
D50 (%)	78.63	66.00	27.18	45.63	53.87	58.31	70.65	74.33	86.60	96.19	79.62	79.64
Ts (ms)	109.92	101.24	163.59	136.38	89.78	94.58	62.37	53.25	27.46	14.07	44.01	43.36
EDT (s)	1.07	1.69	2.42	2.39	1.81	1.92	1.39	1.20	0.48	--	0.96	0.95
T20 (s)	2.89	2.28	2.22	1.89	1.93	1.99	1.93	1.66	1.09	0.53	1.73	1.67
r T20	0.97	0.97	0.99	0.99	1.00	1.00	1.00	1.00	0.99	0.96	1.00	1.00
T30 (s)	4.38	2.63	2.54	2.09	1.92	1.99	1.97	1.69	1.13	0.58	1.87	1.78
r T30	0.93	0.98	0.99	0.99	1.00	1.00	1.00	1.00	1.00	0.99	1.00	1.00
Tuser (s)	4.09	1.99	1.94	1.61	1.95	2.04	1.80	1.67	0.95	0.29	1.66	1.56
r Tuser	0.93	0.97	0.98	0.99	1.00	1.00	1.00	1.00	0.96	0.86	0.99	0.99

T_{20} = 1.93 s

Greek Theater in Siracusa

Acoustical Parameters according to ISO3382



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Store Reference Signal

Switch to Right Channel

Tuser limits:

(-5. dB, -15. dB)

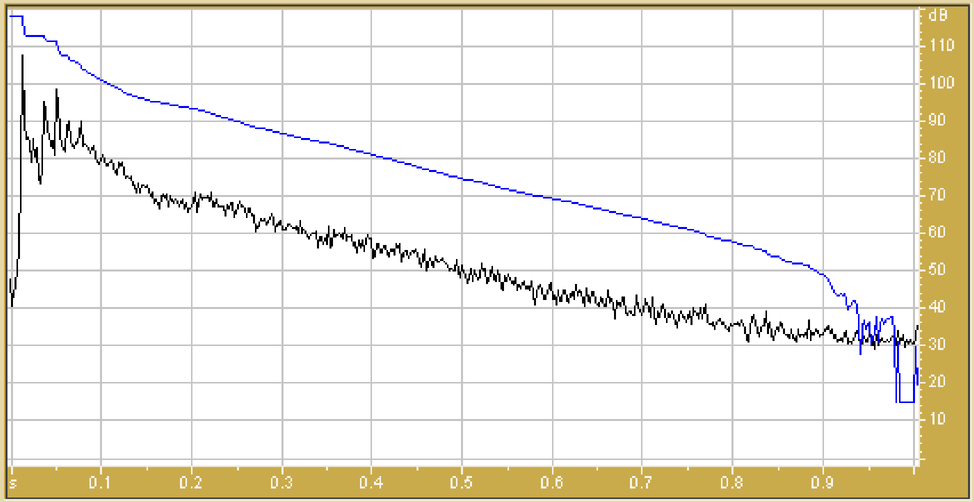
Left Channel

Freq. (Hz)	31.5	63	125	250	500	1k	2k	4k	8k	16k	Lin	A
Signal (dB)	-16.75	45.48	52.60	57.54	60.13	65.56	68.96	69.72	75.93	77.78	79.21	78.76
Noise (dB)	52.00	45.11	23.74	25.60	28.59	29.97	30.95	25.68	21.36	24.04	50.94	36.13
strenGth(dB)	-85.75	-23.52	-16.40	-11.46	-8.87	-3.44	-0.04	0.72	6.93	8.78	0.21	1.76
C50 (dB)	-14.13	-1.#J	3.27	9.91	12.74	13.03	13.08	11.61	14.91	17.70	14.26	13.93
C80 (dB)	-1.#J	-1.#J	9.08	12.72	15.70	15.84	16.01	14.94	18.59	22.95	17.80	17.33
D50 (%)	3.72	111.27	67.97	90.73	94.95	95.26	95.31	93.54	96.87	98.33	96.38	96.11
Ts (ms)	949.51	-73.36	45.37	18.75	12.36	8.27	7.47	9.18	5.07	2.50	5.25	5.71
EDT (s)	--	0.18	0.66	--	--	--	--	--	--	--	--	--
T20 (s)	--	0.05	0.70	0.56	0.65	0.65	0.70	0.68	0.51	0.42	0.55	0.57
r T20	--	0.90	0.98	0.96	0.98	0.99	0.99	0.99	0.99	0.98	1.00	1.00
T30 (s)	--	0.05	1.01	0.74	0.88	0.93	0.94	0.86	0.62	0.37	0.67	0.77
r T30	--	0.89	0.96	0.97	0.97	0.97	0.98	0.98	0.98	0.99	0.99	0.98
Tuser (s)	--	--	0.73	0.86	0.44	0.64	0.74	0.64	0.47	--	0.56	0.57
r Tuser	--	--	0.93	0.95	0.98	0.95	0.96	0.98	0.95	--	0.94	0.94

T_{20} = 0.65 s

Roman Theater in Taormina

Acoustical Parameters according to ISO3382



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Tuser limits: (-5. dB, -15. dB)

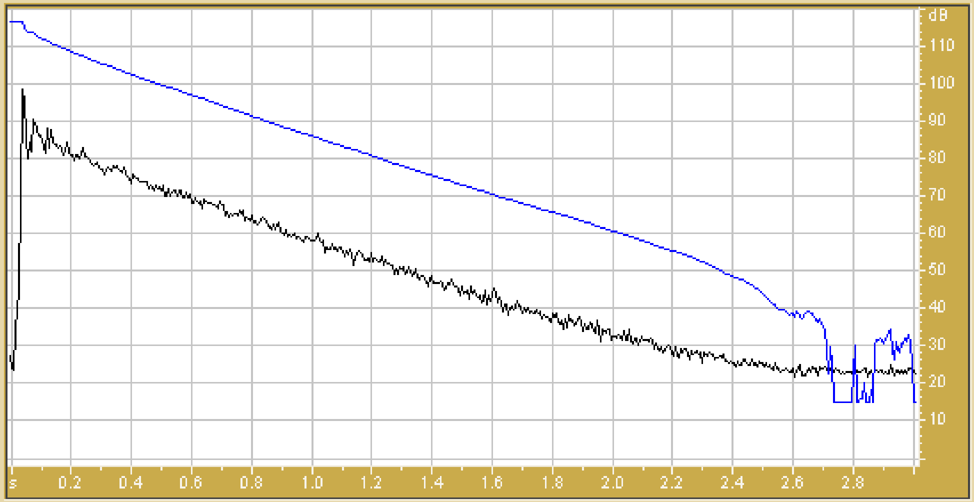
Left Channel

Freq. (Hz)	31.5	63	125	250	500	1k	2k	4k	8k	16k	Lin	A
Signal (dB)	34.89	52.35	60.71	64.11	64.73	68.79	73.13	75.78	78.99	74.23	82.86	82.05
Noise (dB)	37.40	24.47	23.02	24.00	26.52	25.38	22.14	21.45	25.15	29.60	37.59	31.62
strenGth(dB)	-34.11	-16.65	-8.29	-4.89	-4.27	-0.21	4.13	6.78	9.99	5.23	3.86	5.05
C50 (dB)	-1.85	0.80	-0.19	6.09	6.84	8.00	9.05	8.89	12.45	17.81	10.50	10.21
C80 (dB)	-2.18	5.56	13.17	12.41	11.20	13.09	14.79	14.59	18.58	27.80	16.38	15.94
D50 (%)	39.52	54.60	48.89	80.27	82.85	86.33	88.93	88.56	94.61	98.37	91.82	91.29
Ts (ms)	337.99	83.05	58.80	43.40	40.82	23.68	18.98	19.33	11.01	4.57	14.59	14.96
EDT (s)	--	0.74	0.63	--	0.39	0.49	--	0.45	--	--	--	--
T20 (s)	--	1.53	1.07	1.07	1.15	0.84	0.71	0.58	0.33	0.24	0.50	0.52
r T20	--	0.98	0.88	0.94	0.97	0.94	0.92	0.93	0.98	0.91	0.94	0.94
T30 (s)	--	1.23	1.11	1.11	1.22	1.08	0.89	0.76	0.46	0.22	0.75	0.74
r T30	--	0.97	0.97	0.98	0.99	0.97	0.96	0.96	0.95	0.98	0.94	0.94
Tuser (s)	--	--	0.18	0.44	0.59	0.43	0.32	0.32	0.36	--	0.34	0.35
r Tuser	--	--	0.88	0.93	0.96	0.97	0.97	0.98	0.86	--	0.94	0.95

$T_{20} = 1.15$ s

Parma Auditorium, Italy

Acoustical Parameters according to ISO3382



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Tuser limits: (-5. dB, -15. dB)

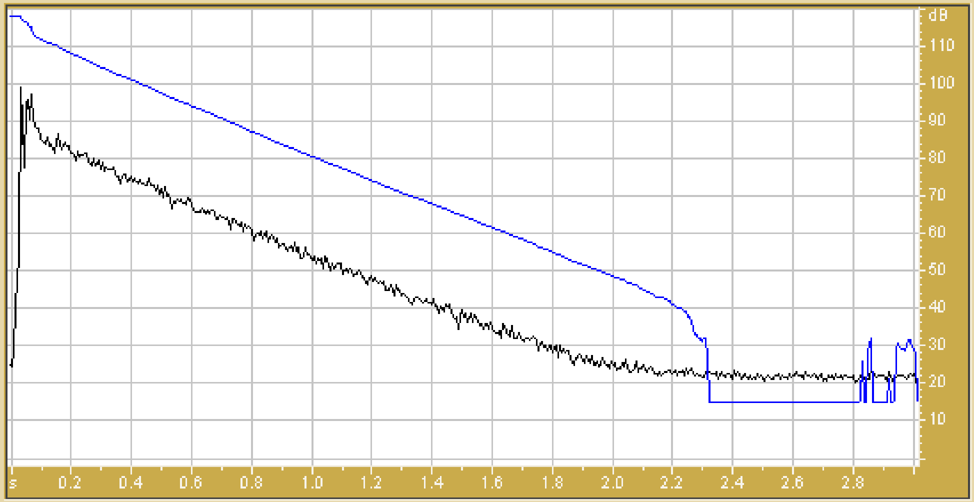
Left Channel

Freq. (Hz)	31.5	63	125	250	500	1k	2k	4k	8k	16k	Lin	A
Signal (dB)	40.84	57.24	68.80	66.26	67.20	70.03	73.41	74.09	77.50	75.02	82.52	81.08
Noise (dB)	20.40	26.31	23.57	24.89	22.64	20.25	19.91	17.27	23.54	20.46	33.16	28.11
strenGth(dB)	-28.16	-11.76	-0.20	-2.74	-1.80	1.03	4.41	5.09	8.50	6.02	3.52	4.08
C50 (dB)	2.38	-2.31	-5.27	-5.18	-1.30	1.21	1.29	0.09	4.29	8.19	2.33	2.04
C80 (dB)	4.35	-0.33	-0.29	-0.84	0.44	2.20	2.45	1.47	6.37	9.33	3.97	3.49
D50 (%)	63.36	37.01	22.92	23.29	42.57	56.89	57.36	50.51	72.87	86.82	63.12	61.53
Ts (ms)	145.30	159.46	155.87	138.71	122.80	98.06	94.93	100.07	44.10	15.99	69.01	75.79
EDT (s)	2.25	1.84	1.98	1.64	2.19	1.95	2.06	1.81	1.01	--	1.49	1.61
T20 (s)	3.12	2.76	2.75	2.48	2.08	2.37	2.35	1.98	1.20	0.56	2.05	2.08
r T20	0.99	0.99	0.97	0.99	1.00	1.00	1.00	1.00	1.00	0.96	1.00	1.00
T30 (s)	5.53	2.77	2.66	2.66	2.08	2.42	2.32	1.99	1.24	0.60	2.20	2.14
r T30	0.91	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	0.98	1.00	1.00
Tuser (s)	3.36	2.14	1.98	2.16	2.00	2.30	2.40	1.90	1.17	1.18	1.81	1.91
r Tuser	0.98	0.98	0.97	0.99	0.98	0.99	1.00	1.00	1.00	0.93	0.99	1.00

T_{20} = 2.08 s

Rome Auditorium, 700 seats

Acoustical Parameters according to ISO3382



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Tuser limits: (-5. dB, -15. dB)

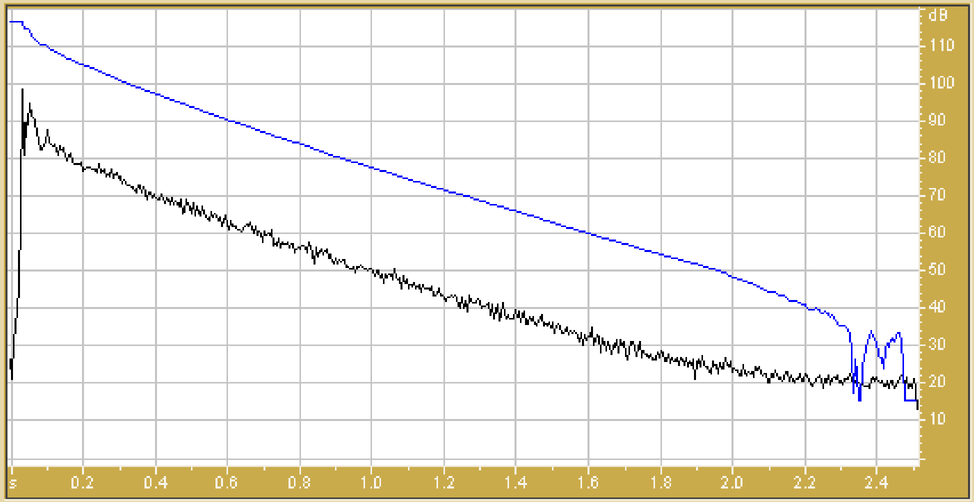
Left Channel

Freq. (Hz)	31.5	63	125	250	500	1k	2k	4k	8k	16k	Lin	A
Signal (dB)	37.50	58.10	69.58	67.65	69.29	70.45	74.74	78.03	76.63	74.34	83.48	82.62
Noise (dB)	17.10	19.19	23.26	19.21	18.71	16.64	18.07	20.72	21.58	19.77	30.42	26.83
strenGth(dB)	-31.50	-10.90	0.58	-1.35	0.29	1.45	5.74	9.03	7.63	5.34	4.48	5.62
C50 (dB)	-0.90	3.27	0.60	2.07	0.19	0.67	2.73	5.41	5.29	12.80	4.45	4.32
C80 (dB)	0.61	3.81	2.54	3.12	2.19	2.20	3.94	6.93	7.59	17.00	6.04	5.85
D50 (%)	44.81	67.98	53.45	61.70	51.11	53.86	65.24	77.67	77.16	95.02	73.58	72.99
Ts (ms)	181.27	107.51	111.52	100.03	108.51	104.34	81.09	48.46	39.77	15.22	57.02	58.14
EDT (s)	2.63	2.43	1.62	1.74	1.96	1.95	1.51	0.98	0.74	0.35	1.11	1.14
T20 (s)	3.16	2.36	1.75	2.00	2.04	1.90	1.85	1.49	0.93	0.44	1.72	1.68
r T20	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	0.96	1.00	1.00
T30 (s)	3.18	2.44	1.74	1.99	2.06	1.91	1.82	1.52	0.94	0.47	1.75	1.72
r T30	0.98	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	0.99	1.00	1.00
Tuser (s)	2.91	2.77	2.00	2.14	2.05	2.15	1.82	1.49	0.93	0.23	1.64	1.60
r Tuser	0.96	0.99	0.97	0.99	0.99	1.00	1.00	1.00	1.00	0.97	1.00	1.00

$T_{20} = 2.04$ s

Rome Auditorium, 1200 seats

Acoustical Parameters according to ISO3382



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Store Reference Signal

Switch to Right Channel

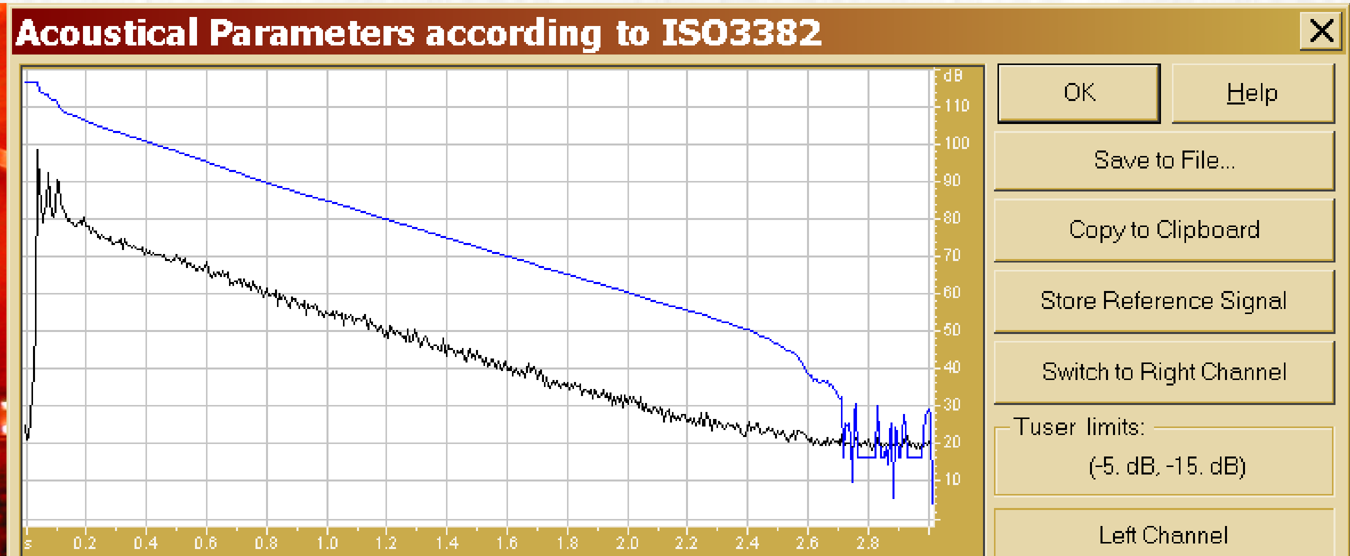
Tuser limits:
(-5. dB, -15. dB)

Left Channel

Freq. (Hz)	31.5	63	125	250	500	1k	2k	4k	8k	16k	Lin	A
Signal (dB)	41.68	55.83	63.54	63.62	66.86	69.45	72.19	74.06	75.73	75.25	81.57	80.17
Noise (dB)	14.69	19.18	20.03	19.76	21.60	18.02	15.16	15.39	14.61	18.90	28.70	24.38
strenGth(dB)	-27.32	-13.17	-5.46	-5.38	-2.14	0.45	3.19	5.06	6.73	6.25	2.57	3.17
C50 (dB)	-0.12	0.32	1.54	-0.71	1.21	2.84	3.33	3.65	6.56	14.58	5.52	4.51
C80 (dB)	3.97	2.65	2.57	3.19	4.53	5.05	4.58	5.72	9.42	19.34	7.60	6.51
D50 (%)	49.33	51.82	58.78	45.91	56.94	65.81	68.28	69.83	81.90	96.63	78.10	73.87
Ts (ms)	118.18	106.65	112.36	109.72	77.08	71.11	66.21	53.80	30.77	9.37	41.90	49.13
EDT (s)	0.88	1.59	1.91	1.85	1.40	1.40	1.46	0.90	0.54	--	0.81	0.91
T20 (s)	2.60	1.96	1.75	1.84	2.10	1.89	1.77	1.29	0.81	0.33	1.55	1.54
r T20	0.93	0.95	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.98	0.99	1.00
T30 (s)	3.43	2.13	1.79	1.96	2.17	1.95	1.79	1.38	0.83	0.39	1.68	1.67
r T30	0.96	0.98	0.99	0.99	1.00	1.00	1.00	1.00	1.00	0.99	1.00	1.00
Tuser (s)	--	1.19	1.67	1.94	1.99	1.94	1.65	1.23	0.73	0.26	1.34	1.38
r Tuser	--	0.92	0.99	0.98	0.99	0.99	1.00	0.99	1.00	0.95	0.99	0.99

T_{20} = 2.10 s

Rome Auditorium, 2700 seats



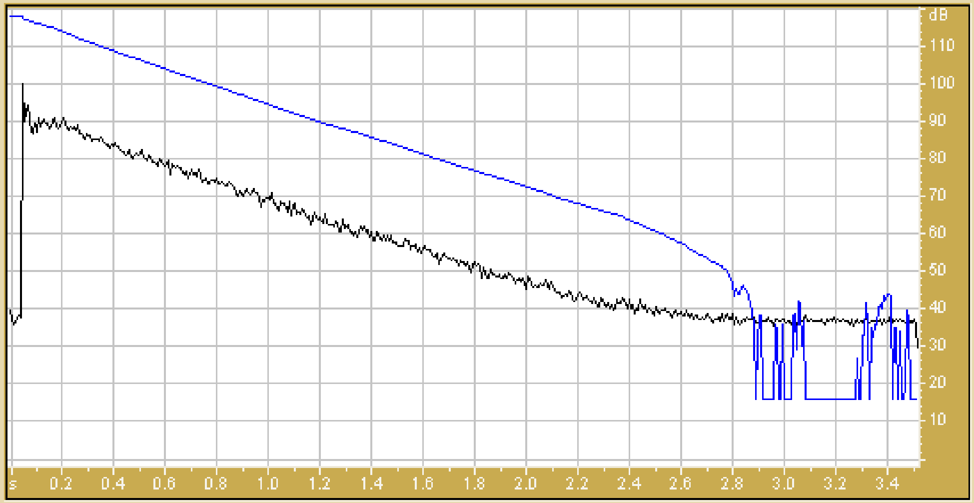
Freq. (Hz)	31.5	63	125	250	500	1k	2k	4k	8k	16k	Lin	A
Signal (dB)	40.58	59.81	66.22	64.73	66.68	68.14	72.38	73.32	74.61	73.03	80.75	79.52
Noise (dB)	19.20	19.22	22.29	20.72	18.69	15.32	14.60	19.69	17.64	21.56	29.76	25.03
strenGth(dB)	-28.42	-9.19	-2.78	-4.27	-2.32	-0.86	3.38	4.32	5.61	4.03	1.75	2.52
C50 (dB)	0.53	-2.67	-9.51	-4.67	1.95	-0.17	2.55	2.21	6.04	14.50	3.35	3.16
C80 (dB)	1.11	4.58	-1.16	1.18	4.65	4.47	5.96	6.04	10.09	20.48	6.98	6.87
D50 (%)	53.05	35.08	10.07	25.45	61.03	49.02	64.25	62.45	80.07	96.57	68.39	67.44
Ts (ms)	175.38	108.12	169.98	127.01	84.20	94.07	66.34	61.19	27.13	5.14	52.67	54.43
EDT (s)	2.65	0.83	2.13	1.81	1.58	1.76	1.44	1.04	0.74	--	1.11	1.07
T20 (s)	2.94	2.69	2.23	2.27	2.56	2.52	2.37	1.88	0.98	0.40	2.13	2.15
r T20	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00	0.98	0.98	0.99	1.00
T30 (s)	--	2.61	2.13	2.29	2.63	2.59	2.37	1.86	1.05	0.45	2.24	2.23
r T30	--	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99	1.00	1.00
Tuser (s)	3.09	2.56	2.48	2.34	2.31	2.59	2.44	1.76	0.78	0.47	1.84	1.91
r Tuser	0.96	0.92	0.98	0.99	0.99	1.00	0.99	0.99	0.96	0.93	0.97	0.98

$T_{20} = 2.56$ s

Bergamo’s Cathedral, Italy

T_{20} = 2.95 s

Acoustical Parameters according to ISO3382



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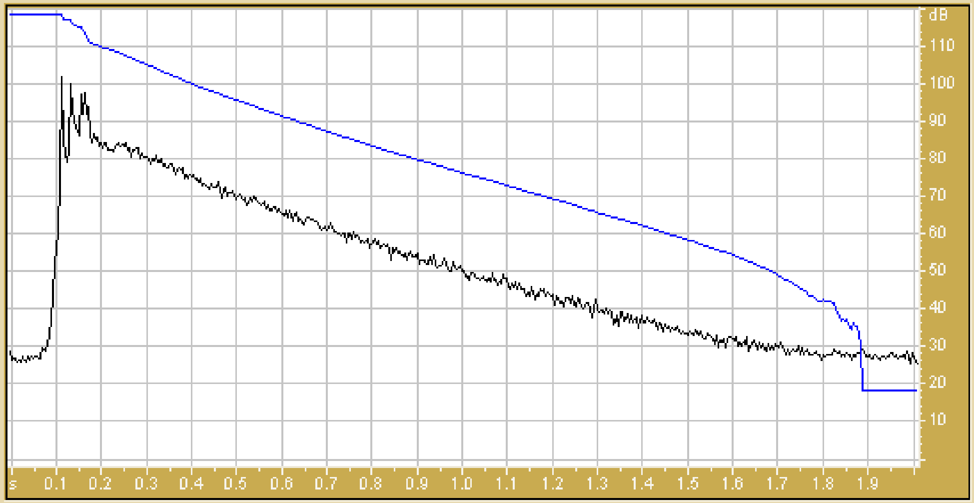
Tuser limits: (-5. dB, -15. dB)

Left Channel

Freq. (Hz)	31.5	63	125	250	500	1k	2k	4k	8k	16k	Lin	A
Signal (dB)	65.57	69.05	74.03	74.18	73.97	75.53	79.15	77.20	79.13	77.28	85.83	85.19
Noise (dB)	38.61	33.66	38.17	30.88	34.26	38.45	29.24	30.55	34.73	39.42	45.69	42.37
strenGth(dB)	-3.43	0.05	5.03	5.18	4.97	6.53	10.15	8.20	10.13	8.28	6.83	8.19
C50 (dB)	-9.09	1.85	-0.54	-4.63	-3.77	-3.62	-4.66	-1.99	-0.24	5.38	-2.15	-2.48
C80 (dB)	-7.19	2.24	0.42	-3.92	-2.73	-2.35	-3.08	-0.68	1.24	7.09	-0.96	-1.16
D50 (%)	10.97	60.49	46.88	25.62	29.54	30.28	25.50	38.74	48.59	77.56	37.85	36.08
Ts (ms)	519.50	170.85	200.45	258.34	223.19	188.11	188.95	137.04	87.99	31.25	161.16	151.22
EDT (s)	6.22	3.81	3.78	3.51	3.36	2.79	2.66	2.20	1.47	1.20	2.62	2.38
T20 (s)	4.70	4.58	4.05	3.34	2.95	2.80	2.52	2.13	1.44	0.83	3.04	2.51
r T20	0.99	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	0.99	1.00	1.00
T30 (s)	4.53	4.65	3.91	3.38	3.05	2.80	2.54	2.11	1.46	0.86	3.31	2.58
r T30	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Tuser (s)	5.73	4.01	3.65	3.49	3.22	2.94	2.48	2.18	1.38	0.98	2.89	2.47
r Tuser	0.97	0.98	0.99	0.99	0.99	1.00	1.00	1.00	1.00	0.98	1.00	1.00

Teatro Valli, Reggio Emilia, Italy

Acoustical Parameters according to ISO3382



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Switch to Right Channel

Tuser limits: (-5. dB, -15. dB)

Left Channel

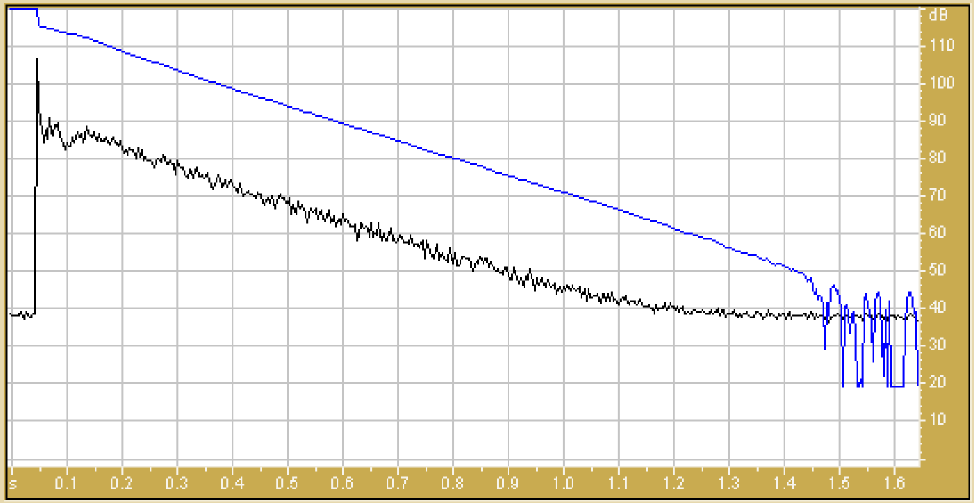
Freq. (Hz)	31.5	63	125	250	500	1k	2k	4k	8k	16k	Lin	A
Signal (dB)	33.24	50.79	63.47	66.10	68.38	67.96	73.18	76.32	79.64	82.10	83.65	83.26
Noise (dB)	13.25	32.82	24.81	23.47	23.70	21.12	21.84	21.52	23.02	29.94	35.88	30.56
strenGth(dB)	-35.76	-18.21	-5.53	-2.90	-0.62	-1.04	4.18	7.32	10.64	13.10	4.65	6.26
C50 (dB)	1.55	1.19	-5.72	-1.74	0.52	2.71	5.06	1.40	1.62	10.18	2.94	2.63
C80 (dB)	3.61	1.97	5.83	7.28	7.97	5.57	7.58	6.06	8.20	17.01	8.46	7.78
D50 (%)	58.81	56.81	21.12	40.11	53.00	65.09	76.24	57.99	59.23	91.24	66.31	64.72
Ts (ms)	147.19	136.86	101.13	73.80	56.28	56.96	44.84	62.36	49.52	17.35	45.61	49.03
EDT (s)	--	2.08	1.01	0.72	0.71	1.37	0.94	0.92	0.57	--	0.60	0.71
T20 (s)	2.70	2.42	1.96	1.91	1.55	1.54	1.47	1.30	0.98	0.50	1.25	1.24
r T20	0.95	0.94	0.98	0.99	1.00	1.00	1.00	1.00	1.00	0.93	1.00	1.00
T30 (s)	--	1.94	2.16	1.92	1.68	1.58	1.55	1.37	1.03	0.57	1.38	1.34
r T30	--	0.95	0.99	1.00	1.00	1.00	1.00	1.00	1.00	0.97	1.00	1.00
Tuser (s)	4.12	3.41	1.81	1.64	1.46	1.47	1.35	1.30	1.07	--	1.22	1.23
r Tuser	0.89	0.98	0.95	0.99	0.98	1.00	1.00	0.99	0.98	--	0.98	0.99

T_{20} = 1.55 s

Sydney Opera House

Sydney Opera House – opera theatre

Acoustical Parameters according to ISO3382



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Store Reference Signal

Switch to Right Channel

Tuser limits:
(-5. dB, -15. dB)

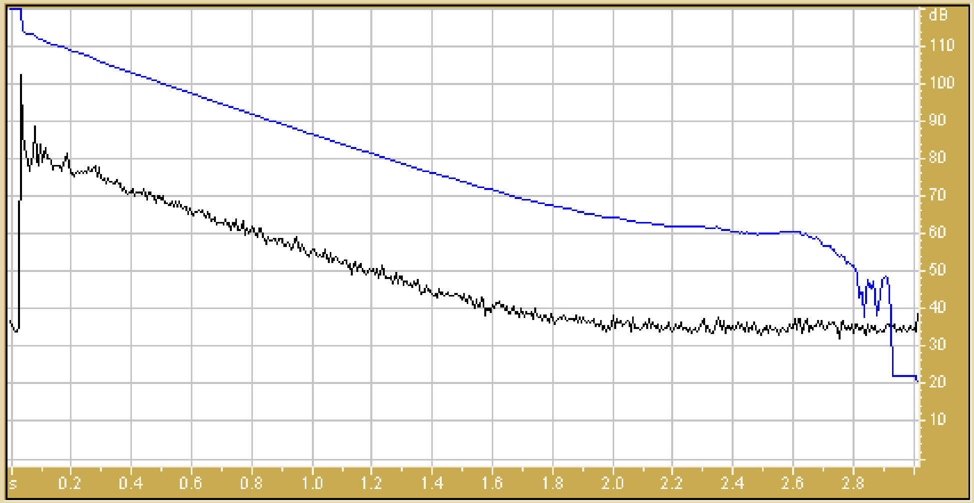
Left Channel

Freq. (Hz)	31.5	63	125	250	500	1k	2k	4k	8k	16k	Lin	A
Signal (dB)	49.24	54.40	58.63	66.96	69.31	72.03	75.13	76.58	79.23	78.34	83.52	83.43
Noise (dB)	25.42	22.49	28.87	27.96	26.81	27.35	28.96	30.15	35.24	42.75	42.27	40.17
strenGth(dB)	-19.76	-14.60	-10.37	-2.04	0.31	3.03	6.13	7.58	10.23	9.34	4.52	6.43
C50 (dB)	-3.90	5.88	4.07	3.65	5.22	2.78	1.23	6.20	8.49	13.08	5.86	5.38
C80 (dB)	-0.95	6.44	4.67	4.30	6.01	3.89	2.47	7.35	10.22	16.21	7.06	6.58
D50 (%)	28.92	79.46	71.83	69.83	76.88	65.49	57.04	80.67	87.59	95.31	79.41	77.52
Ts (ms)	173.44	73.67	65.81	51.86	41.45	60.87	69.27	31.33	17.73	6.53	32.46	35.49
EDT (s)	1.61	--	1.38	--	1.56	1.39	1.44	1.48	1.19	--	1.45	1.45
T20 (s)	1.83	1.49	1.11	1.03	1.16	1.22	1.29	1.24	0.95	0.58	1.19	1.21
r T20	0.99	0.97	0.98	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00
T30 (s)	2.35	1.76	1.22	1.10	1.13	1.26	1.32	1.24	0.96	0.58	1.22	1.24
r T30	0.97	0.97	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Tuser (s)	1.79	2.03	1.42	1.10	1.19	1.25	1.17	1.30	1.04	0.65	1.22	1.23
r Tuser	0.96	0.96	0.99	0.95	0.96	0.99	1.00	0.99	0.99	0.98	0.99	0.99

T_{20} = 1.16 s

Sydney Opera House – concert hall

Acoustical Parameters according to ISO3382



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Store Reference Signal

Switch to Right Channel

Tuser limits:
(-5. dB, -15. dB)

Left Channel

Freq. (Hz)	31.5	63	125	250	500	1k	2k	4k	8k	16k	Lin	A
Signal (dB)	47.96	54.02	60.13	64.65	66.68	67.98	71.92	74.09	77.29	75.28	81.04	80.90
Noise (dB)	26.93	24.28	28.63	26.57	29.40	31.53	29.73	29.51	29.51	34.79	39.49	37.93
strenGth(dB)	-21.04	-14.98	-8.87	-4.35	-2.32	-1.02	2.92	5.09	8.29	6.28	2.04	3.90
C50 (dB)	1.64	6.28	-2.48	4.81	5.38	1.91	2.48	7.66	11.70	17.81	7.46	7.17
C80 (dB)	2.35	10.09	-1.49	5.85	6.15	2.50	3.40	8.73	13.71	21.43	8.48	8.16
D50 (%)	59.36	80.93	36.12	75.16	77.53	60.84	63.91	85.38	93.66	98.37	84.77	83.91
Ts (ms)	175.15	59.66	143.27	59.08	51.70	97.17	85.17	30.95	11.33	4.33	33.05	35.31
EDT (s)	2.65	0.46	1.81	1.71	2.00	2.57	2.57	1.47	--	--	1.64	1.78
T20 (s)	4.66	1.87	1.78	2.11	2.04	2.29	2.30	1.92	1.19	0.47	2.06	2.10
r T20	0.89	0.97	0.98	0.99	1.00	1.00	1.00	1.00	0.99	0.93	1.00	1.00
T30 (s)	--	4.13	1.73	1.95	2.07	2.26	2.32	1.97	1.26	0.63	2.13	2.17
r T30	--	0.86	0.99	0.99	1.00	1.00	1.00	1.00	1.00	0.95	1.00	1.00
Tuser (s)	2.25	1.44	2.27	2.06	2.09	2.27	2.25	1.92	0.84	1.02	1.98	2.04
r Tuser	0.97	0.92	0.97	0.98	1.00	1.00	1.00	0.99	0.96	0.92	0.99	0.99

T_{20} = 2.04 s

Sydney Opera House – the studio

Acoustical Parameters according to ISO3382

OK | Help | Save to File... | Copy to Clipboard | Store Reference Signal | Switch to Right Channel

Tuser limits: (-5. dB, -15. dB)

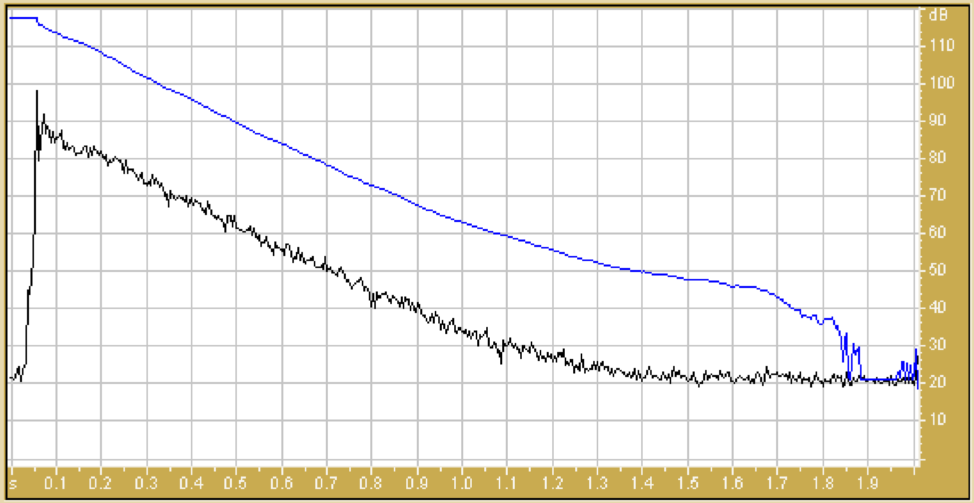
Left Channel

Freq. (Hz)	31.5	63	125	250	500	1k	2k	4k	8k	16k	Lin	A
Signal (dB)	49.27	55.55	57.72	62.65	66.97	70.52	73.05	74.05	77.54	77.81	81.67	81.49
Noise (dB)	25.54	23.70	29.30	23.56	20.31	18.40	17.20	18.27	19.95	25.05	34.59	27.23
strenGth(dB)	-19.73	-13.45	-11.28	-6.35	-2.03	1.52	4.05	5.05	8.54	8.81	2.67	4.49
C50 (dB)	2.78	3.19	1.46	6.44	9.24	10.57	10.69	12.35	14.83	18.40	12.47	12.56
C80 (dB)	6.17	8.05	5.39	9.23	11.09	13.39	13.12	15.23	18.30	23.10	15.32	15.36
D50 (%)	65.46	67.58	58.30	81.51	89.35	91.93	92.15	94.50	96.82	98.57	94.65	94.75
Ts (ms)	104.32	63.34	72.58	37.49	19.27	14.84	14.86	8.42	5.46	2.91	8.70	8.66
EDT (s)	0.88	0.62	1.16	0.55	--	--	--	--	--	--	--	--
T20 (s)	1.67	0.96	1.47	0.83	0.76	0.68	0.68	0.61	0.50	0.37	0.63	0.61
r T20	0.90	0.96	0.96	0.98	0.99	0.99	0.99	1.00	0.98	0.99	1.00	1.00
T30 (s)	1.83	1.29	1.44	0.83	0.74	0.70	0.68	0.63	0.49	0.36	0.68	0.64
r T30	0.93	0.96	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Tuser (s)	0.97	0.54	1.20	0.78	0.74	0.57	0.60	0.57	0.41	--	0.54	0.53
r Tuser	0.97	0.99	0.99	0.98	0.98	0.99	0.98	0.98	0.89	--	0.99	0.99

$T_{20} = 0.76$ s

Teatro Regio in Parma (Italy)

Acoustical Parameters according to ISO3382



OK | Help | Save to File... | Copy to Clipboard | Store Reference Signal | Switch to Right Channel

Tuser limits: (-5. dB, -15. dB)

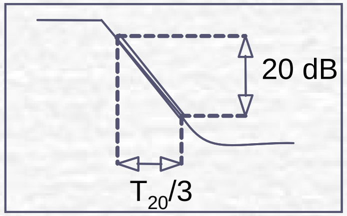
Left Channel

Freq. (Hz)	31.5	63	125	250	500	1k	2k	4k	8k	16k	Lin	A
Signal (dB)	48.60	53.48	57.25	60.89	66.81	69.76	72.43	71.61	71.65	69.16	78.55	78.63
Noise (dB)	25.21	18.88	13.32	19.41	19.37	16.96	14.38	13.67	15.59	21.50	28.76	24.01
strenGth(dB)	-20.40	-15.52	-11.75	-8.11	-2.19	0.76	3.43	2.61	2.65	0.16	-0.45	1.63
C50 (dB)	-5.46	1.37	0.23	0.25	0.77	0.46	1.29	2.25	6.99	11.14	2.57	2.41
C80 (dB)	-3.70	2.80	3.48	1.82	4.26	2.61	3.24	4.88	10.51	15.60	4.93	4.69
D50 (%)	22.15	57.81	51.30	51.45	54.44	52.67	57.36	62.67	83.33	92.86	64.40	63.55
Ts (ms)	202.12	123.81	102.50	86.64	67.18	76.24	67.54	52.41	20.87	10.71	53.18	54.42
EDT (s)	2.26	1.79	1.64	1.18	1.09	1.20	1.16	1.16	0.69	0.38	1.12	1.13
T20 (s)	2.94	2.51	1.56	1.21	1.11	1.07	0.98	0.87	0.68	0.47	1.01	0.97
r T20	0.93	0.99	0.98	0.99	1.00	1.00	1.00	1.00	0.99	0.99	1.00	1.00
T30 (s)	2.88	2.17	1.65	1.39	1.18	1.05	1.00	0.87	0.65	0.42	1.07	0.99
r T30	0.96	0.98	0.99	0.99	1.00	1.00	1.00	1.00	0.99	0.99	1.00	1.00
Tuser (s)	1.95	2.45	1.36	0.97	1.17	1.05	0.94	0.95	0.85	0.40	1.02	0.99
r Tuser	0.96	0.96	0.89	0.99	1.00	1.00	0.99	0.98	0.98	0.98	0.99	0.99

$T_{20} = 1.11$ s

Acoustical Parameters (ISO 3382)

- Reverberation Time T_{20}:



- Clarity C_{80}:

$$C_{80} = 10 \cdot \lg\left[\frac{\int_0^{80ms} p^2(\tau)\cdot d\tau}{\int_{80ms}^{\infty} p^2(\tau)\cdot d\tau}\right]$$

- Definition D:

$$D = \frac{\int_0^{50ms} p^2(\tau)\cdot d\tau}{\int_0^{\infty} p^2(\tau)\cdot d\tau}\cdot 100$$

- Center Time T_S:

$$T_S = \frac{\int_0^{\infty} \tau \cdot p^2(\tau)\cdot d\tau}{\int_0^{\infty} p^2(\tau)\cdot d\tau}$$

Acoustical Parameters (ISO 3382)

- Strength: $$G = SPL - L_W + 31 \qquad dB$$
- IACC: $$\rho(\tau) = \frac{\int_{-\infty}^{\infty} h_d(\tau) \cdot h_s(\tau + t) \cdot d\tau}{\sqrt{\int_{-\infty}^{\infty} h_d^2(\tau) \cdot d\tau \cdot \int_{-\infty}^{\infty} h_s^2(\tau + t) \cdot d\tau}}$$
- LF: $$LF = \frac{\int_{5ms}^{80ms} h_Y^{\,2}(\tau) \cdot d\tau}{\int_{0ms}^{80ms} h_W^{\,2}(\tau) \cdot d\tau}$$
- LFC: $$LFC = \frac{\int_{5ms}^{80ms} h_Y(\tau) \cdot h_W(\tau) \cdot d\tau}{\int_{0ms}^{80ms} h_W^{\,2}(\tau) \cdot d\tau}$$

Analysis of spatial attributes

Acoustical Parameters according to ISO3382

OK
Help
Save to File...
Copy to Clipboard
Store Reference Signal
Switch to Right Channel
Tuser limits:
(-5. dB, -15. dB)
Left Channel

Freq. (Hz)	31.5	63	125	250	500	1k	2k	4k	8k	16k	Lin	A
Signal (dB)	35.30	53.48	58.95	61.75	67.78	69.42	72.84	71.00	69.81	64.01	78.36	78.03
Noise (dB)	5.47	15.64	15.97	19.10	16.34	11.56	14.42	11.43	12.25	15.69	25.44	21.01
strenGth(dB)	-33.70	-15.52	-10.05	-7.25	-1.22	0.42	3.84	2.00	0.81	-4.99	-0.64	1.03
C50 (dB)	2.00	-0.40	-5.43	-2.89	-2.28	-3.03	-1.34	-0.08	2.45	3.82	-0.82	-0.85
C80 (dB)	4.20	1.39	1.41	-0.85	1.15	0.16	0.58	1.74	5.37	9.25	1.58	1.35
D50 (%)	61.34	47.71	22.27	33.96	37.16	33.25	42.35	49.54	63.73	70.65	45.30	45.13
Ts (ms)	152.56	145.12	150.74	160.39	125.06	125.79	123.81	93.17	46.44	28.61	103.75	105.73
EDT (s)	2.14	2.47	2.05	2.67	1.99	1.99	2.12	1.70	1.08	0.81	1.85	1.87
T20 (s)	3.24	2.64	2.66	2.29	2.09	2.23	2.17	1.85	1.09	0.56	2.11	2.10
r T20	1.00	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.99	1.00	1.00
T30 (s)	4.26	3.04	2.81	2.30	2.11	2.26	2.17	1.91	1.14	0.57	2.15	2.13
r T30	0.96	0.98	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Tuser (s)	3.51	2.37	2.77	2.46	2.13	2.19	2.13	1.74	1.03	0.42	2.02	2.00
r Tuser	0.98	0.95	0.99	0.99	0.99	1.00	1.00	1.00	1.00	0.99	1.00	1.00

Ando's Parameters

Iacc
IACC: 0.34427
Tau IACC: 0.0 [ms]
W IACC: 0.010417 [ms]

dt1
18.219 [ms] Left
25.448 [ms] Right

T sub
1.4649 [s] Left
1.4459 [s] Right

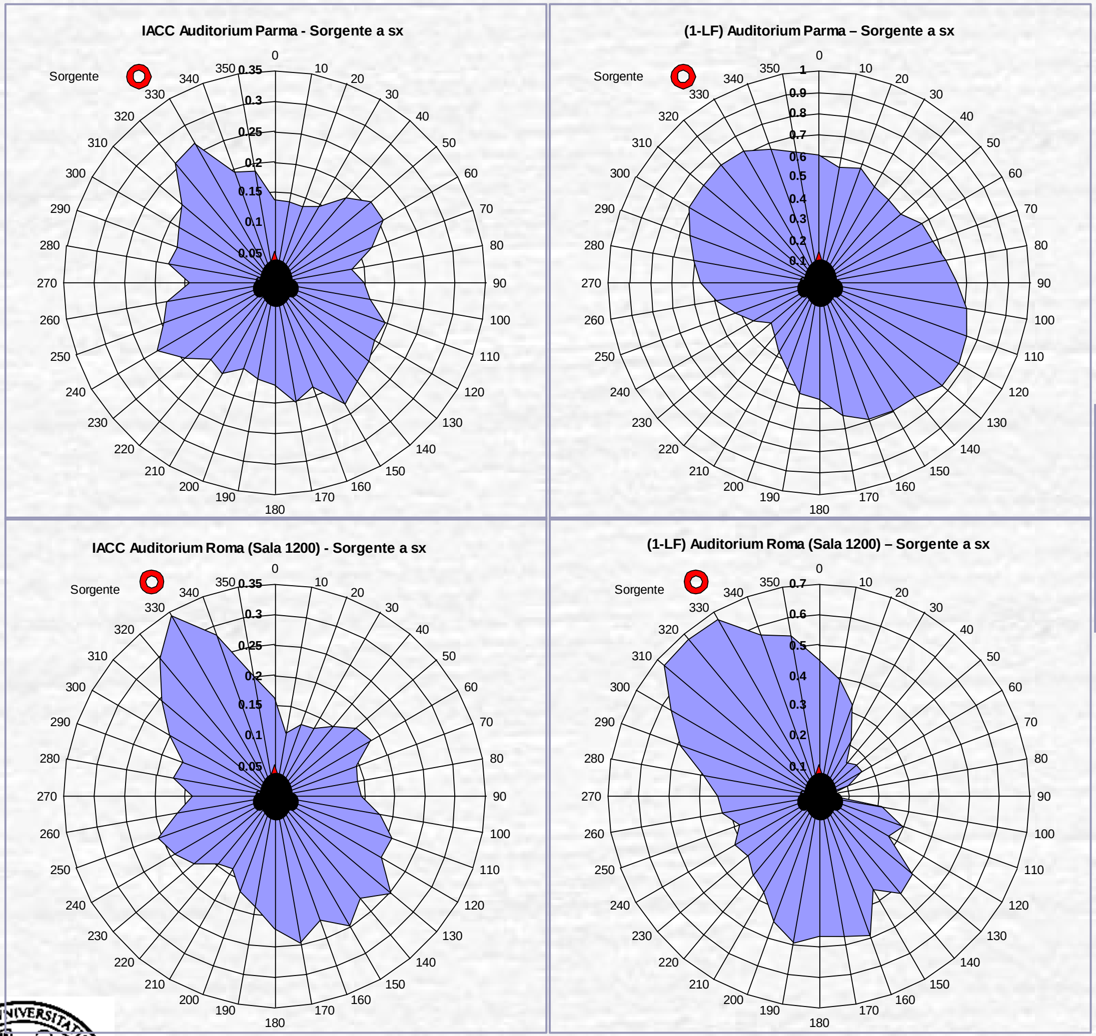
OK
Clipboard

Lateral Fraction

OK
Clipboard

LF: 0.13895
LE: 0.12264
LFC: 0.093835

Polar diagrams of IACC and (1-LF)



Auditorium	1-LF	IACC
Parma	0.725	0.266
Roma	0.676	0.344

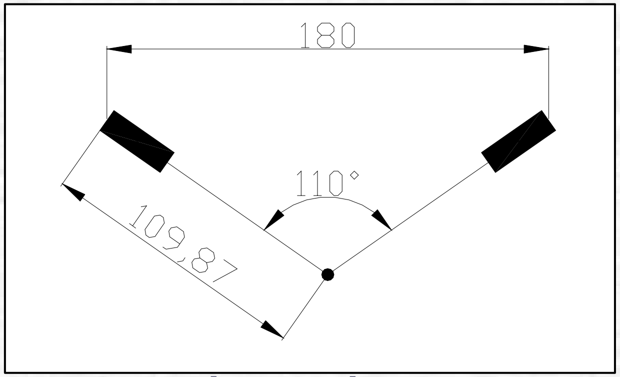
Auralization by convolution

- The basic method consists in convolution of a dry signal with a set of impulse responses corresponding to the required output format for surround (2 to 24 channels).
- The convolution operation can nowadays be implemented very efficiently on a modern PC through an ancient algorithm (equally-partitioned FFT processing, Stockam 1966).

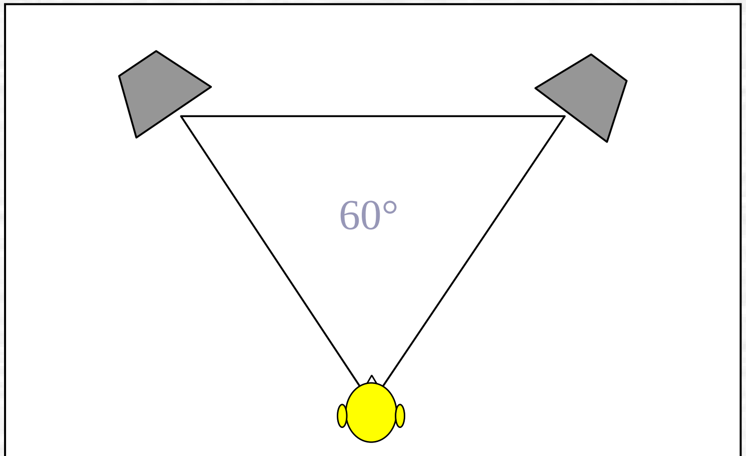
Auralization types

- Stereo (ORTF on 2 standard loudspeakers at +/- 30°)
- Rotation-tracking reproduction on headphones (Binaural Room Scanning)
- Full 3D Ambisonics 1st order (decoding the B-format signal)
- ITU 5.1 (from different 5-mikes layouts)
- 2D Ambisonics 3rd order (from Mark Poletti's circular array microphone)
- Wave Field Synthesis (from the circular array of Soundfield microphones)
- Hybrid methods (Ambiophonics)

ORTF Stereo



2 Microphones

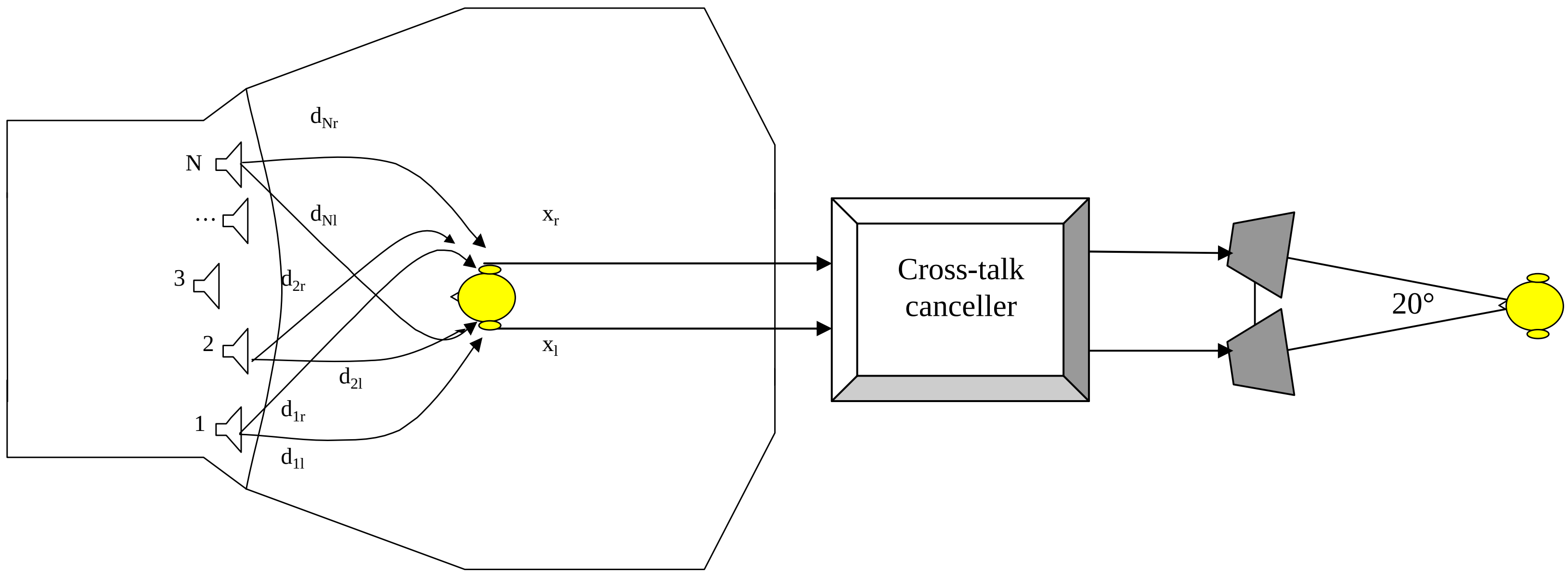


2 Loudspeakers

Playback occurs over a pair of loudspeakers, in the standard configuration at angles of +/- 30°, each being fed by the signal of the corresponding microphone

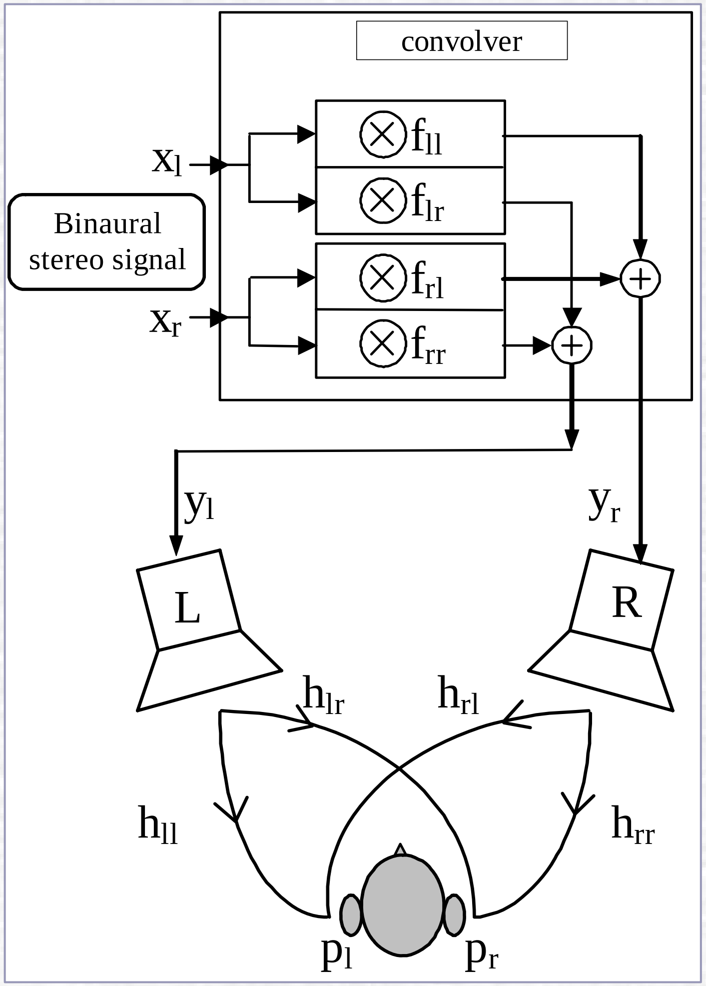
Binaural (Stereo Dipole)

Original 2-channels recording of the signals coming from N sources



Reproduction occurs over 2 loudspeakers angled at +/- 10°, being fed through a “cross-talk cancellation” digital filtering system

Binaural (Stereo Dipole#2)

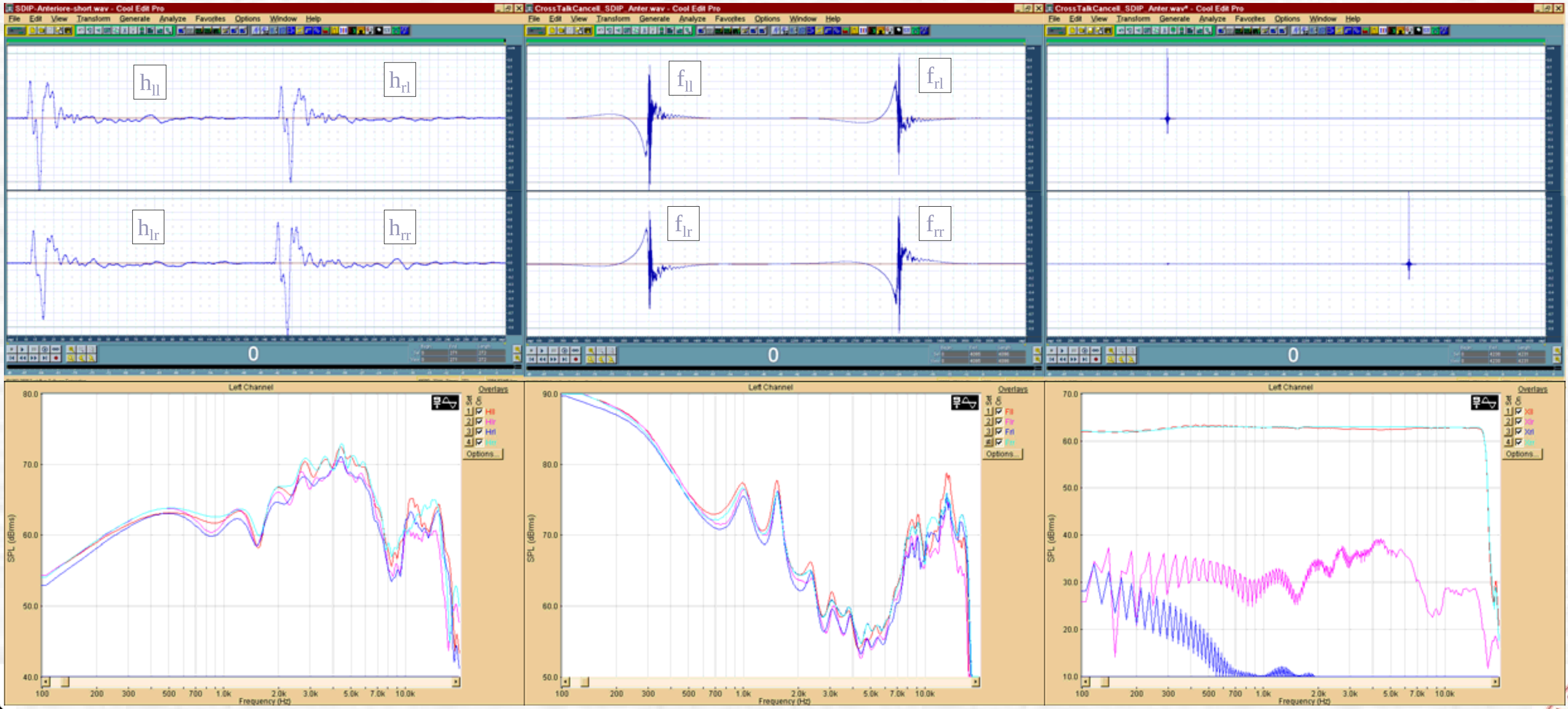


Binaural (Stereo Dipole#3)

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

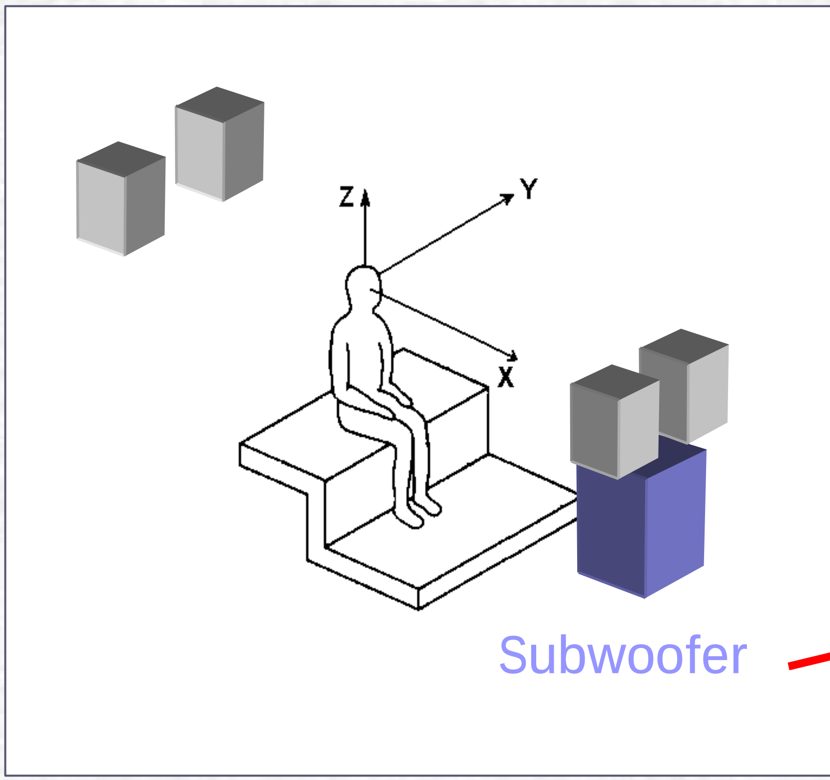
$$C(\omega) = FFT(h_{ll}) \cdot FFT(h_{rr}) - FFT(h_{lr}) \cdot FFT(h_{rl})$$

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



Binaural (Dual Stereo Dipole)

Scheme



advantages:

- 3D sound reproduction
- Rotating of the head
- The cross-talk filters could equalise also the loudspeakers

disadvantages:

- ~~Low frequencies~~
- Coloration outside the “sweet spot”

Binaural (Dual Stereo Dipole#2)

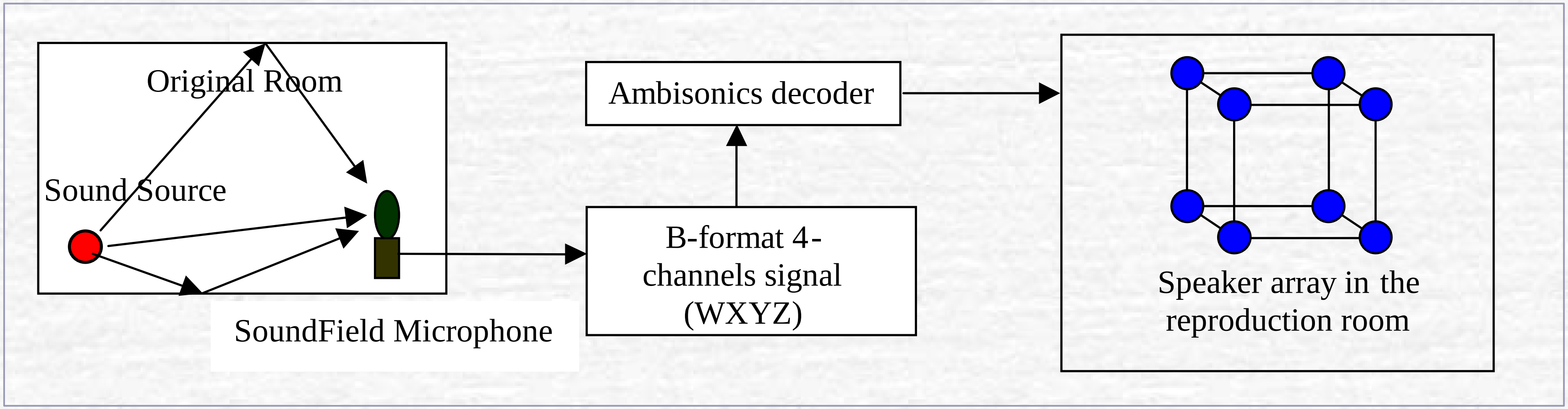
Frontal

Rear

Quested 2108 monitors

Quested F11P monitors

Ambisonics 3D 1st order



Reproduction occurs over an array of 8-24 loudspeakers, through an Ambisonics decoder

Rooms for Ambisonics 3D 1st order

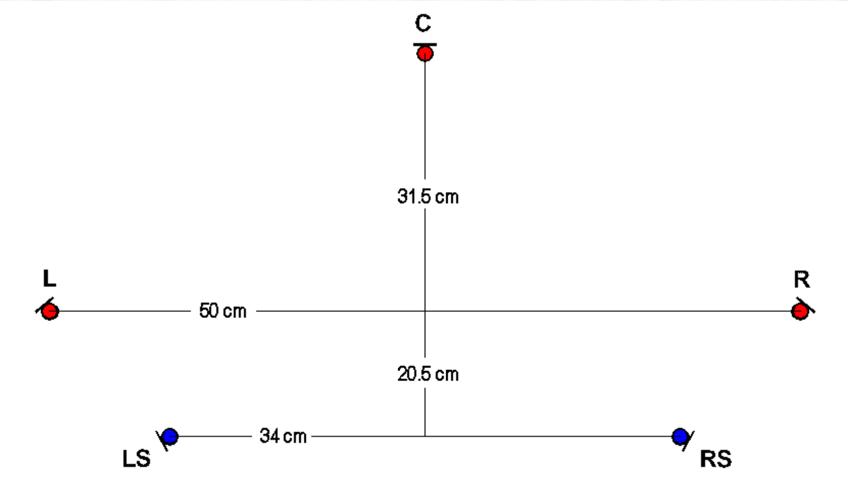
University of Parma

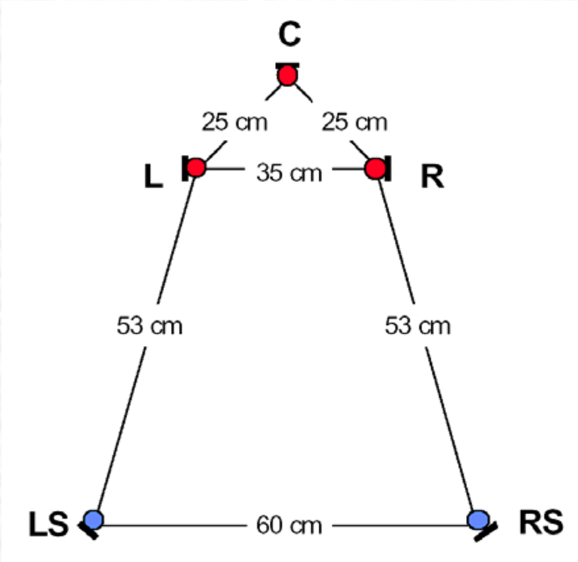
University of Bologna

ITU 5.1 surround

- Williams MMA

Schematic of the setup
C : Cardioid, 0°
L, R : Cardioid, ± 40°
LS, RS : Cardioid, ± 120°





- INA-5

Schematic of the setup
C : Cardioid, 0°
L, R : Cardioid, ± 90°
LS, RS : Cardioid, ± 150°

ITU 5.1 surround

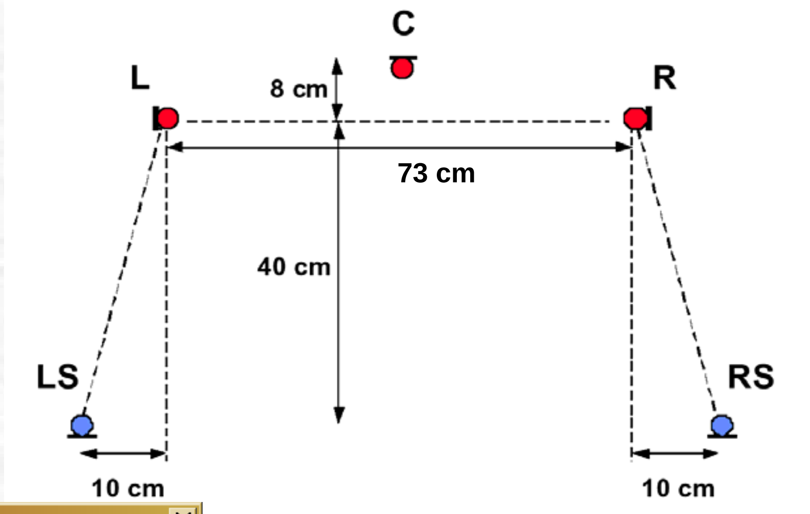
OCT

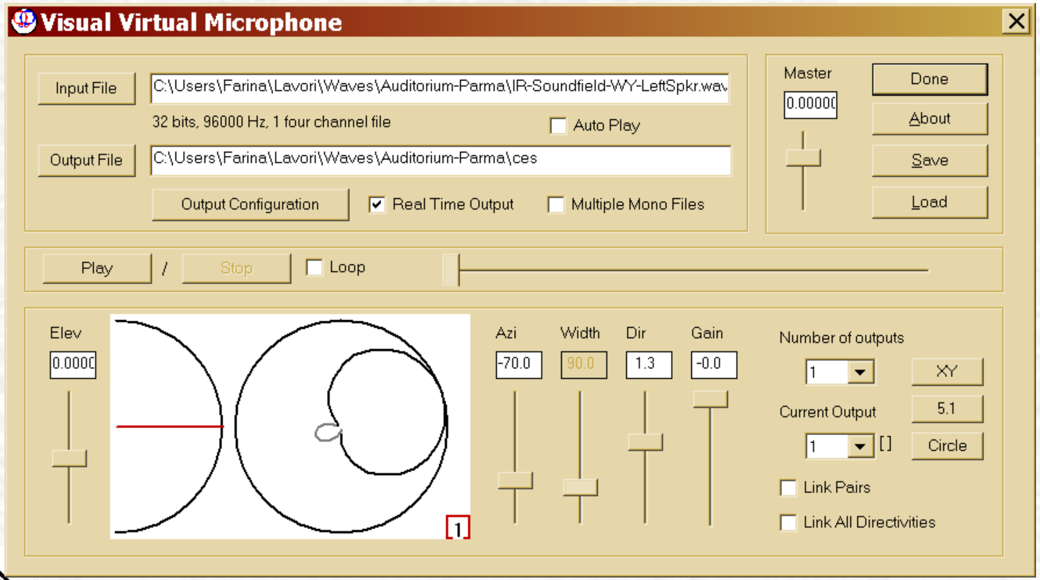
Schematic of the setup

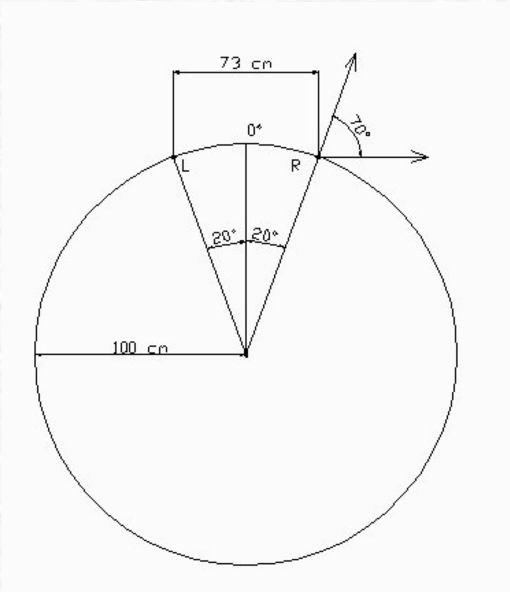
C : Cardioid, 0°

L, R : Super Cardioid, ± 90°

LS, RS : Cardioid, ± 180°

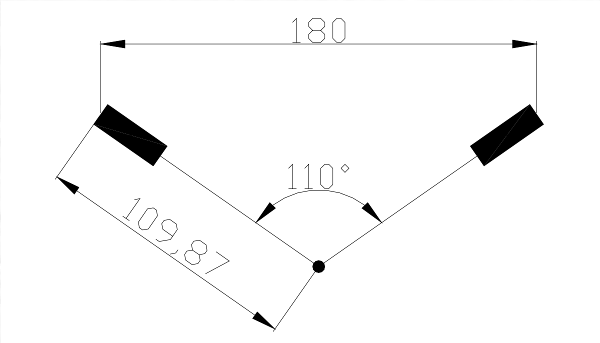




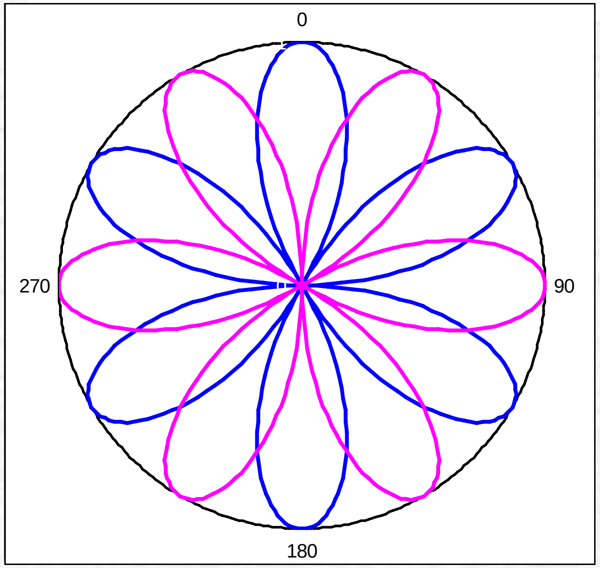


Virtual high-order microphones (M. Poletti)

One of the two ORTF cardioid is employed, which samples 36 positions along a 110 mm-radius circumference

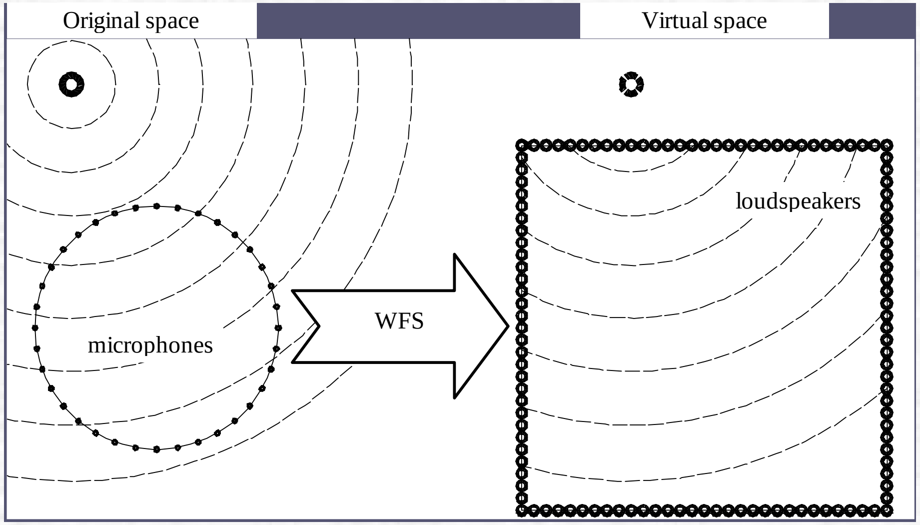


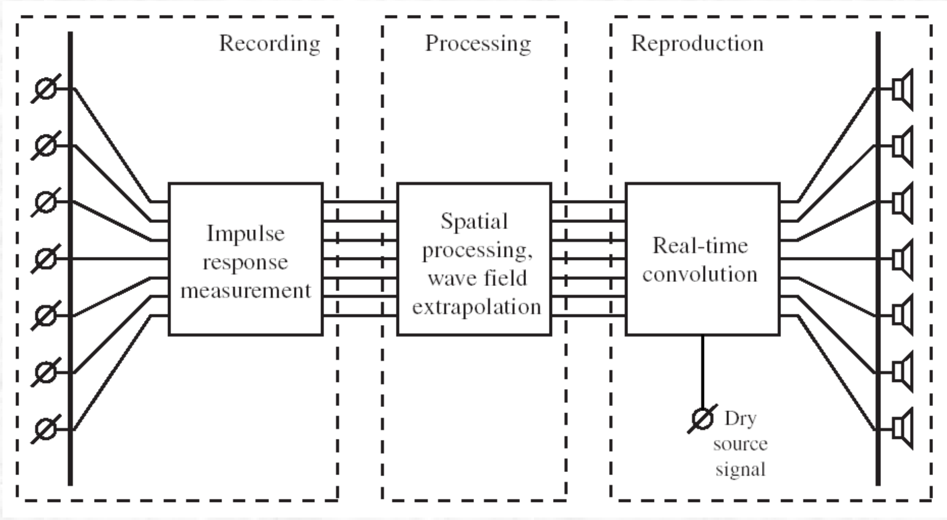
From these 36 impulse responses it is possible to derive the response of cylindrical harmonics microphones (2D Ambisonics) up to 5th order.



Wave Field Synthesis (WFS)

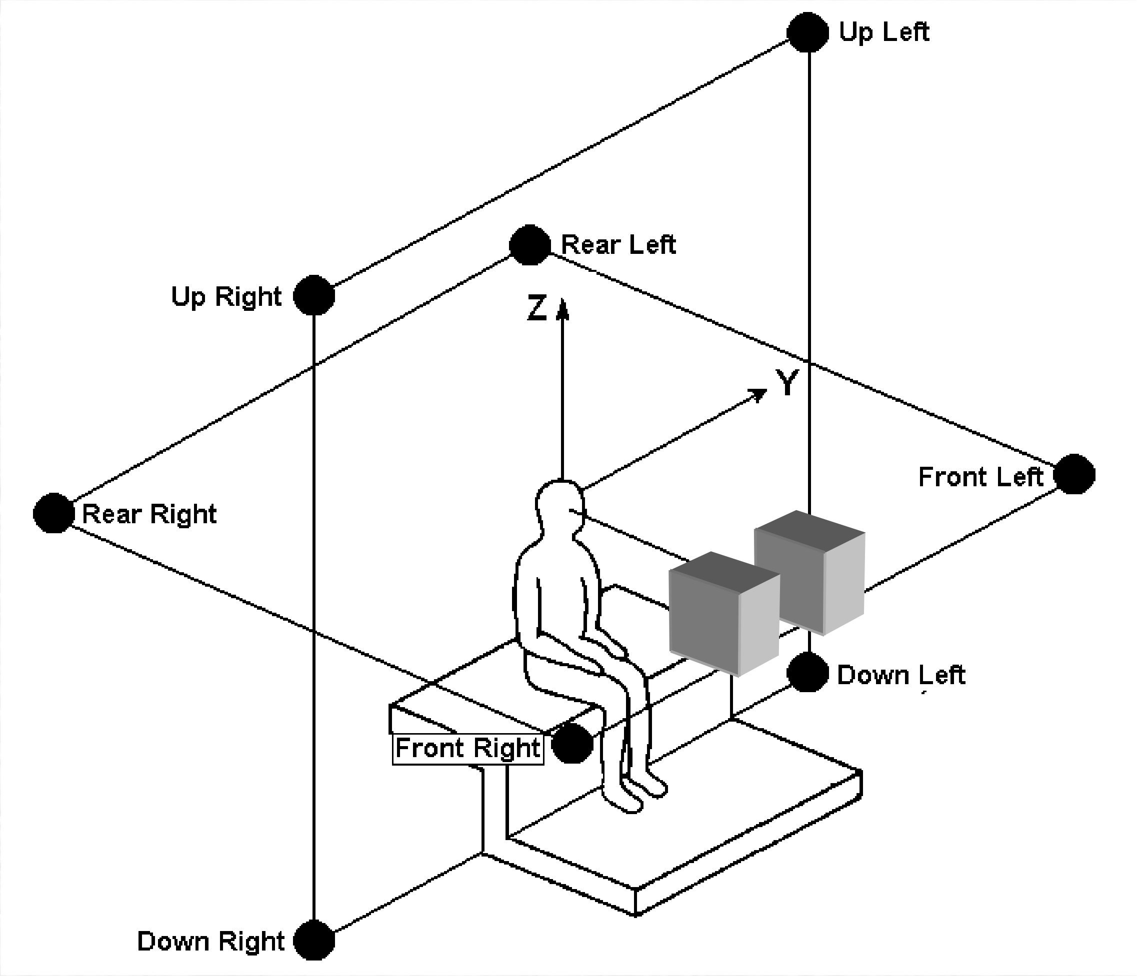
Flow diagram of the process



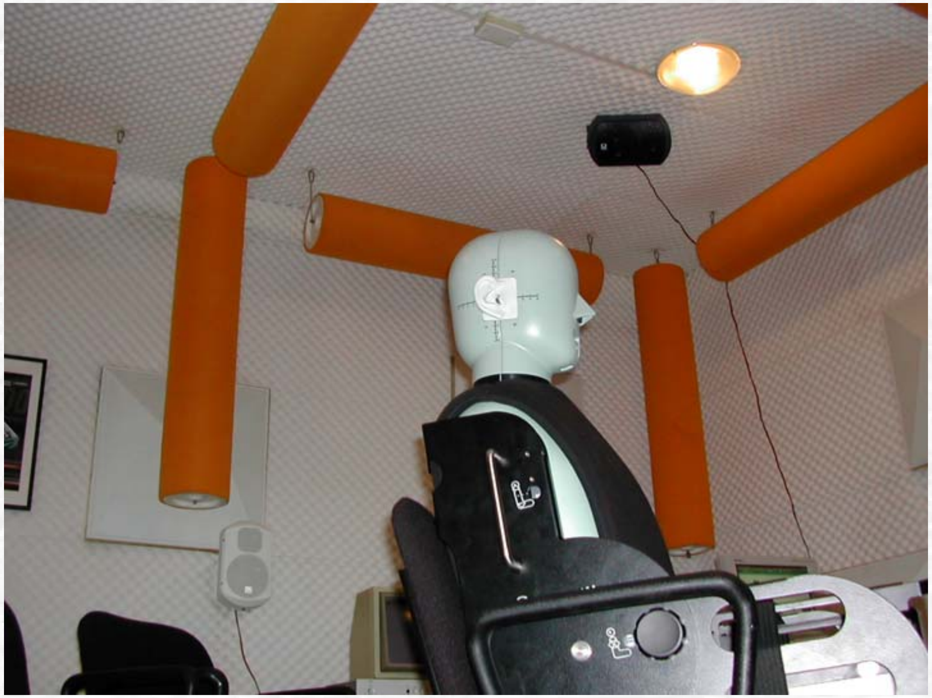


Hybrid methods (Ambiophonics)

Ambiophonics 3D (10 loudspeakers):



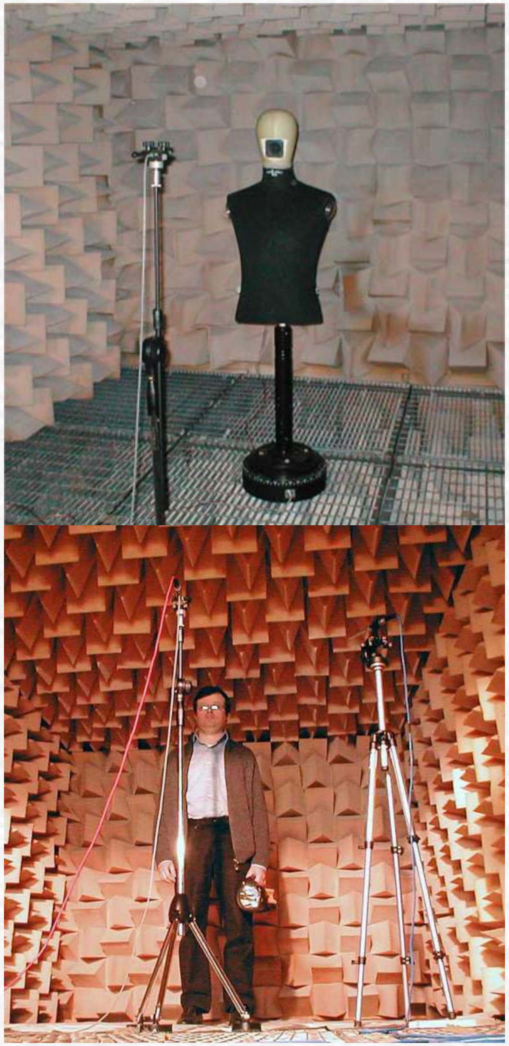
Hybrid methods (Ambiophonics#2)



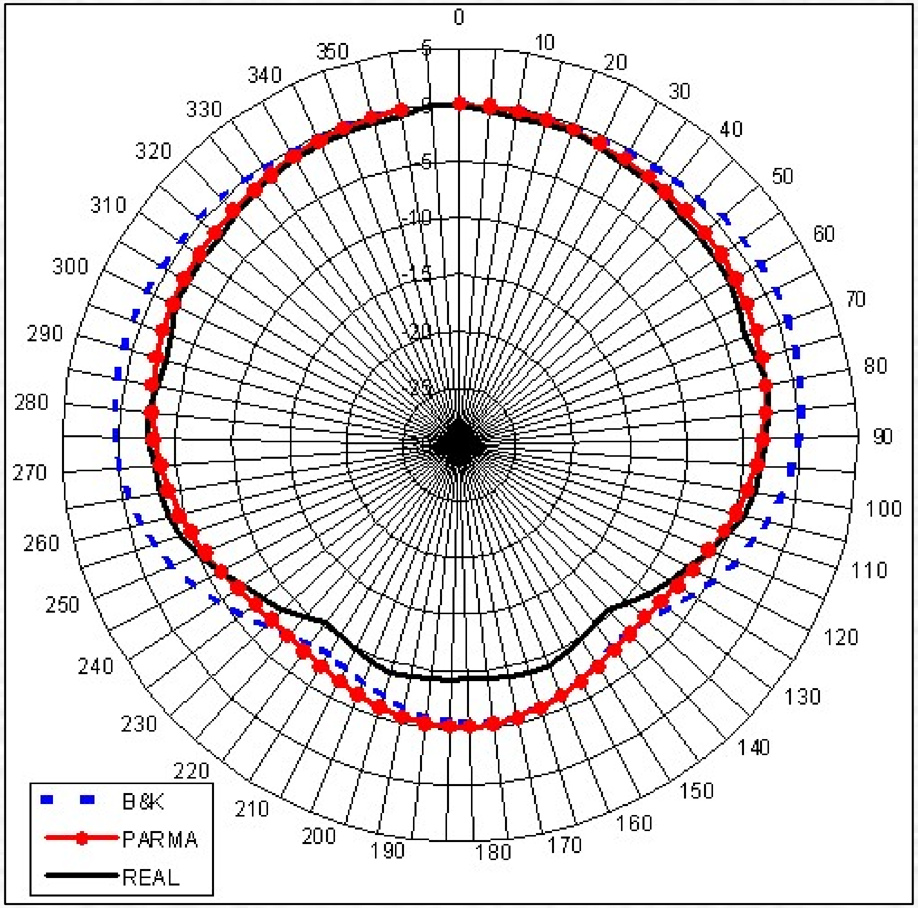
Conclusions

- The spatial informations have to be accurately sampled, making it possible to store, analyze and preserve these “3D acoustical photographies” of existing musical spaces for the posterity
- Many different kinds of impulse-response measurements are required for different 3D auralization methods: a proper set-up should include all different approaches
- Once the impulse responses are stored in suitable multichannel formats, they become available for surround productions with today technologies (ITU 5.1, 1st order Ambisonics) and future, more advanced methods (high order Ambisonics, WFS, Ambiophonics)
- The only point which requires substantial enhancements: sound sources used for IR measurements

Future enhancements

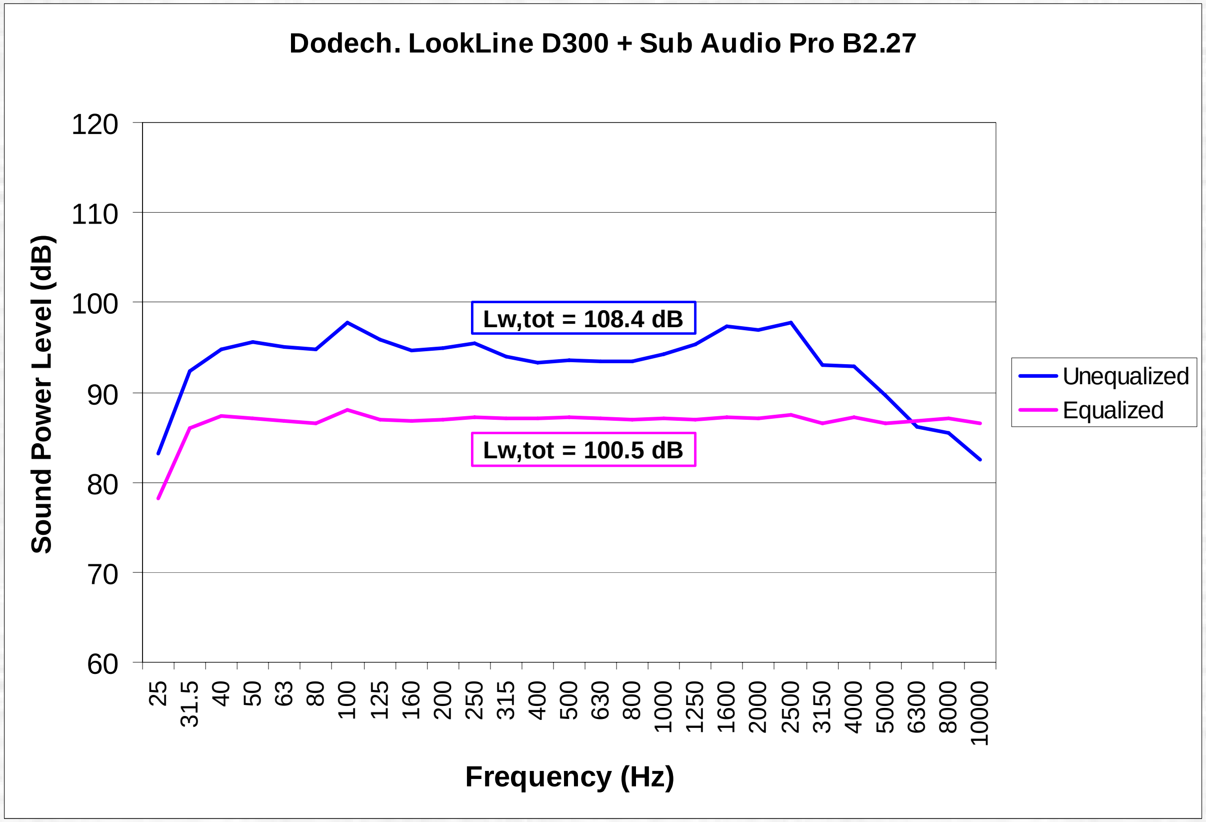


- Sound source for realistic emulation of an human singer



Future enhancements

- Omnidirectional sound source with enhanced power frequency response



Acknowledgements

- This research was started thanks to the support of Waves, Tel Aviv, Israel (www.waves.com)
- For years 2004 and 2005 the research is also supported by the Italian Ministry for the University and Research (MIUR)

- During 2004 a new web site will be started:

  www.acoustics.net

  This will provide free access to the whole data-base, and it will be possible to add contributions.