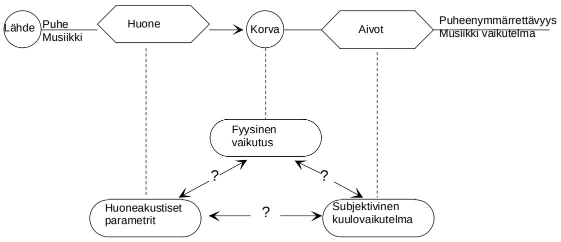
Geometric and statistical room acoustics

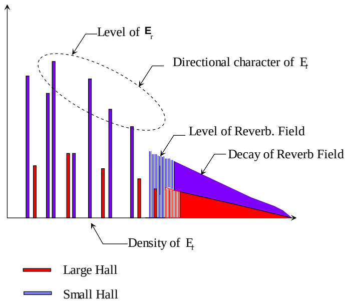
Psychology ?



Subjective descriptors of concert hall acoustics

- Spaciousness and envelopment
- Warmth
- Reverberation or Liveliness
- Intimacy
- Acoustic glare
- Balance and blend
- Ensemble and support
- Brilliance
- Loudness
- Clarity
- Background noise level

Small vs large hall ?



Rise and fall of a sound field

"The added effect. P_a, minus the effect absorped in the boundaries of the room, er equal to the change in the energy density"

$$P_a dt - \frac{1}{4WcA} = V \frac{dW}{dt} dt$$

Where:
- P_a is the added effect
- W is the energy density
- C is the speed of sound
- A is the overall absorption coefficeint of the boundaries of the room
- V is the volume of the room

Rise and fall of a sound field

When a sound source delivers a constant amount of energy into the room, a stationary energy density will be achieved (dW/dt => 0)

$$W_0 = 4\frac{P_a}{cA}$$

By solving the energy-balance equation, it can be shown that W as a function of time grows exponentially:

$$W = W_0(1 - e^{\left(\left(\frac{-cA}{4V}\right)t\right)}$$

Rise and fall of a sound field

Inversely, this means that when it the sound source is turned of when W is at its maximum, the decay will be exponential:

$$W = W_0(e^{\left(\left(\frac{-cA}{4V}\right)t\right)}$$

Expressing this as a logarithmic funktion:

$$\ln\left(W/W_0\right) = -\left(\frac{cA}{4V}\right)t$$

Rise and fall of a sound field

Reverberation time is defined as the time it takes for the energy density to drop to an in-audialbe level, defined as 10^{-6} or 60 dB:

$$\ln\left(W/W_0\right) = \ln\left(10^{-6}\right) = -\left(\frac{cA}{4V}\right)t => T = 55\frac{V}{cA}$$

Replacing c with the standard speed of sound, 340 m/s reveals the clasical Sabine equation.

Reverberation time: Sabines formular

$$R_{T60} = \frac{0{,}161V}{A + 4mV}$$

$$A = \sum \alpha * S$$

Reverberation time, m-factors

Temperature	**Humidity**	**2 000 Hz**	**4 000 Hz**	**8 000 Hz**
20ºC	30 %	0,012	0,038	0,136
20ºC	50 %	0,010	0,024	0,086

Average absorbtion

Statistic calclulation

$$\overline{\alpha} = \frac{\sum_i S_i \alpha_i}{\sum_i S_i}$$

From ray-traycing

$$\overline{\alpha}' = \frac{\sum_i H_i \alpha_i}{\sum_i H_i}$$

Mean Free path

$$l = \frac{4V}{S}$$

Reverberation-time: Eyring formular

$$RT_{60} = \frac{0{,}161V}{-S\ \ln(1-\bar{a})}$$

Reverberation-time: Fitzroi formular

$$RT_{60} = \frac{X}{S}\left(\frac{0{,}16V}{a_x S + 4mV}\right) + \frac{Y}{S}\left(\frac{0{,}16V}{\alpha_y S + 4mV}\right) + \frac{Z}{S}\left(\frac{0{,}16V}{\alpha_z S + 4mV}\right)$$

Reverberation-time: Arau-Puchades formular

- Deducted from Fitzroi and Eyring
- Takes MFP into account

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Total absorption:

$$A = \sum_{i=1}^{n} \alpha_{s,i} S_i + \sum_{j=1}^{o} A_{obj,j} + \sum_{k=1}^{p} \alpha_{s,k} S_k + A_{air}$$

Where: n is the number of surfaces i;
o is the number of objects j;
p is the number of object arrays k.

Absorption of air in the room:

$$A_{air} = 4mV\left(1-\Psi\right)$$

Where: *m is the power attenuation coefficient in air, in Neper per metre;*
V is the volume of the empty enclosed space, in cubic metres;
Ψ is the object fraction.

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Object fraction

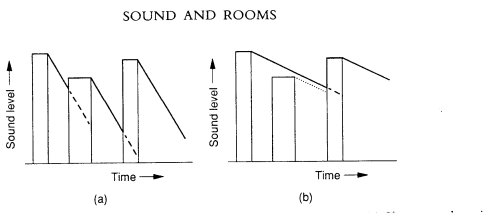
$$\Psi = \frac{\sum_{j=1}^{o} V_{obj,j} + \sum_{k=1}^{p} V_{obj,k}}{V}$$

Where: $V_{obj,j}$ is the volume of objects
$V_{obj,k}$ is the volume of arrays of objects

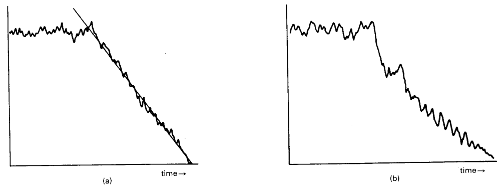
Reverberation time

$$T = \frac{55{,}3}{c_0} \frac{V\left(1-\Psi\right)}{A}$$

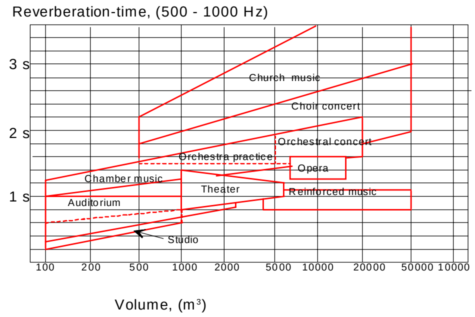
Reverberation time:



Reverberation time:



Reverberation time suggestions



Reverberation

- RT_{60}
- Early Decay Time, EDT
  - Decay from 0 dB to 10 dB times 6
- Bass Ratio, BR:

$$BR = \frac{RT_{125} + RT_{250}}{RT_{500} + RT_{1000}}$$

- Treble Ratio, TR: NOTE Möllers own, not proven

Reverberation: Frequency response

- Bass Ratio, BR:

$$BR = \frac{RT_{125} + RT_{250}}{RT_{500} + RT_{1000}}$$

- Treble Ratio, TR: NOTE Möllers own, not proven

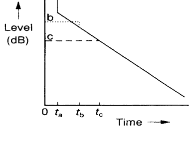
$$TR = \frac{EDT_{2000} + EDT_{4000}}{EDT_{500} + EDT_{1000}}$$

Sound levels, Classic

$$L = L_w + 10\log\left(\frac{Q}{4\pi r^2} + \frac{4}{A}\right)$$

$$L - L_0 = 10\log\left(100/r^2 + 31200 \cdot T/V\right)$$

Sound levels: Revised theory



$$d = \frac{100}{r^2}$$

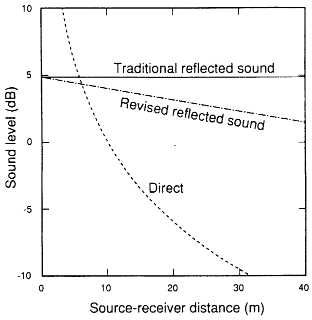
$$e_r = \left(31200 \cdot T/V\right) \cdot e^{-0,04 \cdot r/T} \cdot \left(1 - e^{-1,11/T}\right)$$

$$l = \left(31200 T/V\right) e^{-0,04 r/T} \cdot e^{-1,11/T}$$

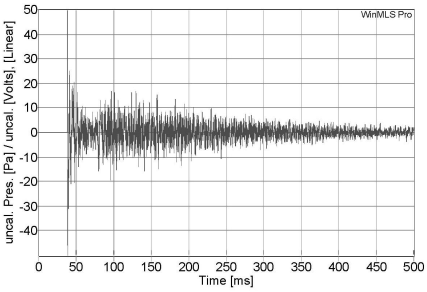
$$L - L_0 = 10 \cdot \log\left(d + e_r + l\right)$$

$$C_{80} = 10 \cdot \log\left[\left(d + e_r\right)/l\right]$$

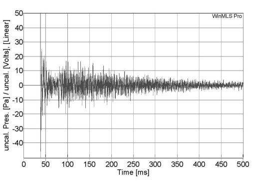
Sound levels: Revised theory



Examples of Impulse response



Omni and Fig8 Impulse responses



Omni microphone

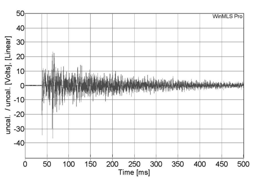


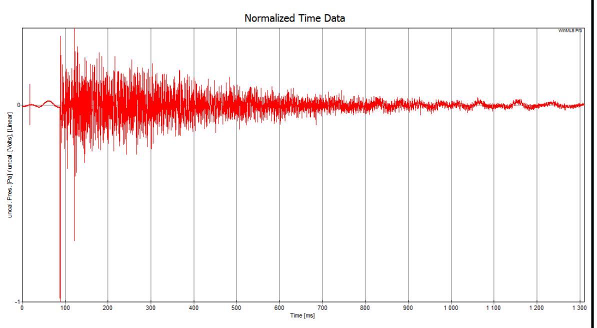
Figure of 8 microphone

Schroeder Integration

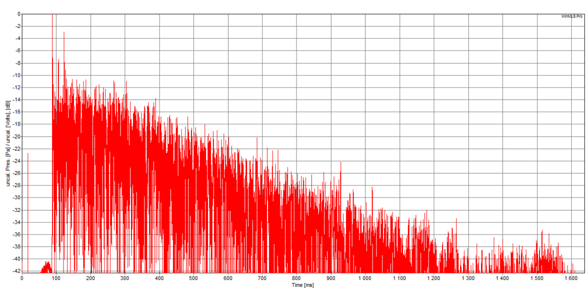
- Essentially reverse integration of the impulse response

$$R_{schr}(t_0) = 10 \log \frac{\int_{t=t_0}^{\infty} h^2(t)dt}{\int_{t=0}^{\infty} h^2(t)dt}$$

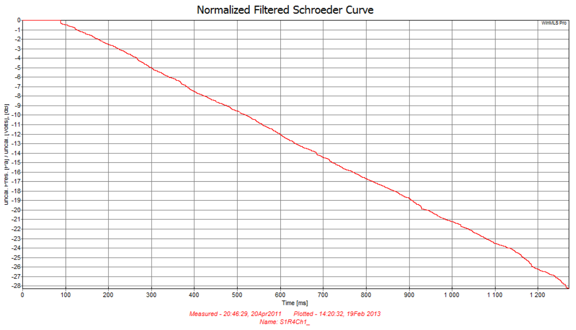
Impulse response



Energy-Time Curve



Schroeder curve



Descriptors of the impulse response

- Critical distance:

$$d_c = r_{reverb} = \sqrt{\frac{V}{100\pi RT_{60}}} = \sqrt{\frac{A}{16\pi}} \approx 0{,}057\sqrt{\frac{V}{RT_{60}}} \approx \sqrt{\frac{A}{50}}$$

- Number of reflections per t

$$D_e(t_0) = 4\pi c^3 \frac{t_0^2}{V}$$

- Mixing Time:

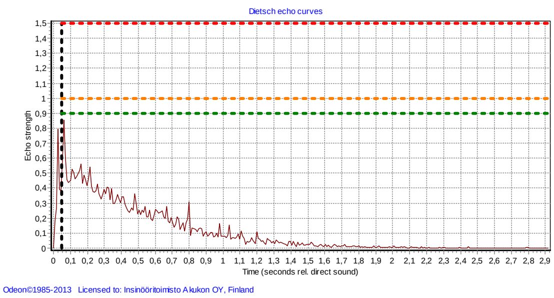
$$t_{stat} = \sqrt{\frac{V}{4\pi c^3}\frac{\Delta N}{\Delta t}} \qquad \frac{\Delta N}{\Delta t} \approx 2000$$

Dietsch/Kraak echo curve

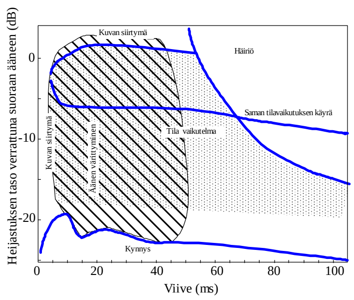
- *Defining a kind of gravity curve as in eq. 10, the Dietsch/Kraak echo curve can be* found by differentiation. Dietsch and Kraak suggest n to be 1 for music and 2/3 for pure speech signals, and correspondingly τ=14 ms and 9 ms. The critical values for echo detection will then be 1.8 and 1.0. It is recommendable to use n=0.8 and τ =12 ms for a variety of signals.

$$t_g(\tau) = \frac{\int_{t=0}^{\tau} |h(t)|^n t \cdot dt}{\int_{t=o}^{\tau} |h(t)|^n dt} \qquad EC(\tau) = \frac{\Delta t_g(\tau)}{\Delta \tau}$$

Dietsch Echocurve



Effect of reflections, 45º from the side



Measurement standards

- ISO 3382
- ”Gade”
  - Setup used in a series of measurements done by A C Gade in 1990:ies
  - Less points than ISO but same geometry in all spaces
- ISO 18233:2006 ”Acoustics — Application of new measurement methods in building and room acoustics”
  - Describes MLS and swept-sine measurements
  - Measurement theory

ISO 3382

- ISO 3382-1: Measurement of room acoustic parameters - Part 1 Performance spaces
- ISO 3382-2: Measurement of room acoustic parameters - Part 2 Reverberation time in ordinary rooms
  - **Measurement setup, number of points etc**
  - **Methods of uncertainty calculations**

ISO 3382-1 Performance spaces

Table A.1 — Acoustic quantities grouped according to listener aspects

Subjective listener aspect	Acoustic quantity	Single number frequency averaging [a] Hz	Just noticeable difference (JND)	Typical range [b]
Subjective level of sound	Sound strength, G, in decibels	500 to 1 000	1 dB	−2 dB; +10 dB
Perceived reverberance	Early decay time (EDT) in seconds	500 to 1 000	Rel. 5 %	1,0 s; 3,0 s
Perceived clarity of sound	Clarity, C_{80}, in decibels	500 to 1 000	1 dB	−5 dB; +5 dB
	Definition, D_{50}	500 to 1 000	0,05	0,3; 0,7
	Centre time, T_S, in milliseconds	500 to 1 000	10 ms	60 ms; 260 ms
Apparent source width (ASW)	Early lateral energy fraction, J_{LF} or J_{LFC}	125 to 1 000	0,05	0,05; 0,35
Listener envelopment (LEV)	Late lateral sound level, L_J, in decibels	125 to 1 000	Not known	−14 dB; +1 dB

[a] The single number frequency averaging denotes the arithmetical average for the octave bands, except for L_J which shall be energy averaged [see (A.17)].

[b] Frequency-averaged values in single positions in non-occupied concert and multi-purpose halls up to 25 000 m^3.

Objective parameter: Strength

$$G = \frac{\int_0^\infty p^2(t)dt}{\int_0^\infty p_{10m}^2(t)dt} \Rightarrow \frac{E(0,\infty)}{E_{1m}(0)} + 20 \Rightarrow L_{pl} - L_{pl:1m} + 20$$

Objective descriptor: Early/late ratios

Clarity:

$$C_{80} = 10Log\left(\frac{\int_{0ms}^{80ms} p^2 dt}{\int_{80ms}^{\infty} p^2 dt}\right) dB \quad C_{80} = 10LOG\left(\frac{E(0,80ms)}{E(80,\infty ms)}\right) dB$$

Deutlichkeit or Destinctness, D_{50}:

$$D_{50} = \left(\frac{E(0,50ms)}{E(0,\infty ms)}\right)$$

Objective descriptors: Spacial impression

$$L_{fc} = \frac{\int_{0ms}^{80ms} h^2(t)\cos(\theta)dt}{\int_{0ms}^{80ms} h^2(t)dt}$$

$$L_f = \frac{E_{fig8}(5,80ms)}{E_{omni}(0,80ms)}$$

Objective descriptors: Late Strength

$$\mathrm{G}_{1,\mathrm{late}} = 10\log\left(\frac{\int_{0,08}^{\infty} P_F^2(t)dt}{\int_{0}^{\infty} P_A^2(t)dt}\right), dB$$

Objective descriptors: Stage

Support factor or Early Support, ST1 or ST_{early}

$$ST_{early} = 10Log\left(\frac{E(20,100ms)}{E(0,10ms)}\right)dB$$

Total Support , ST_{total}

$$ST_{total} = 10Log\left(\frac{E(20,1000ms)}{E(0,10ms)}\right)dB$$

Clarity on Stage, CS

Early Decay Time on Podium, EDTP

Other descriptors 1

- Bass Ratio:
  - Ratio between reverberation time at 125 and 250 Hz octave to the reverberation time in 500 and 1000 Hz octaves
- Treble Ratio: (H.Möller NOT PROVEN!!)
  - Ratio of the EDT at 2000 and 4000 Hz octaves to EDT in 500 and 1000 Hz octaves
- Early Strength and Late Strength
  - As strength but calculated for first 80 ms or after 80 ms.

Other descriptors 2

- Inter Aural Cross correlation Function (IACF)

$$\Phi_{l,r}(\tau) = \frac{\int_{t_1}^{t_2} p_1(t) p_r r(t+\tau) dt}{\sqrt{\int_{t_1}^{t_2} p_l^2 dt \int_{t_1}^{t_2} p_r^2 dt}}$$

- Inter Aural Cross-correlation Coefficient (IACC)

$$IACC = \max(|\Phi_{l,r}(\tau)|) \quad , -1\ \text{ms} < \tau < 1\ \text{ms}$$

$IACC_A$ or $IACC_{Total}$	t_1 = 0 ms	t_2 = 1000 ms
$IACC_{Early}$	t_1 = 0 ms	t_2 = 80 ms
$IACC_{Late}$	t_1 = 80 ms	t_2 = 1000 ms

$$BQI = [1 - IACC_{E3}]$$

Other descriptors 3

- ESI = LF + G(early)/60
  - Where: ESI is Effective Spatial Impression
    LF is the measured Lateral Fraction
    G(early) is the early Strength (0 – 80 ms)

Vocabulary

Criteria	Descriptor	
Clarity	Muddy	Clear
Reverberance	Dead	Live
Envelopment	Expansive	Constricted
Intimacy	Remote	Intimate
Loudness	Loud	Quiet
Balance: treble re mid frequencies	Weak	Loud.
Balance: bas re mid frequencies	Weak	Loud.
Balance: Singers/soloists re orchestra	Weak	Loud.

Vocabulary

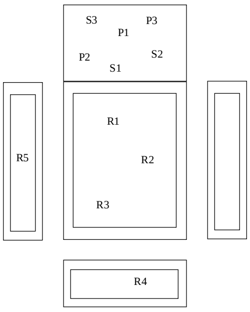
Reverberance	Early Decay Time
Liveness	Early Decay Time, Reverberation Time
Fullness of tone	Reverberation time
Spaciousness,	Early Lateral Energy Fractions, InterAural-Cross-Correlation (early)
Apparent source width	Early Lateral Energy Fractions, InterAural-Cross-Correlation (early)
Envelopment	Late Lateral Energy Fractions, InterAural-Cross-Correlation (late)
Intimacy	Early Lateral Energy Fractions, InterAural-Cross-Correlation (late)
Clarity	Clarity C_{80}
Blend	Details of the initial part of the impulse response
Warmth	Strength at bass frequencies, Bass Ratio
Brilliance	Strength at high frequencies, Treble Ratio
Timbre	Frequency dependency of parameters
Stage Support	Support ST_1
Hall response	Late Support ST_{late}
Ensemble	Clarity and Early Decay Time on stage

Gade setup

Source Positions
- **S1**: typical soloist position, typically 1 – 1,5 m from the middle.
- **S2**: middle of the right side of strings, in general about 1/3 back from the front and about ¼ in from the side
- **S3**: far left in the second row of the winds, in general 2/3 back from the front and ¼-2/5 in from the side.

Receiver positions on stage
- **P1**: solo oboist, in general about 3/5 from front dead center
- **P2**: middle of left side strings, between first and second violins, in general mirror of S2
- **P3:** far right in second row of the winds, in general a mirror of S3.
- **1 m**:1 m from S positions towards middle of stage

Receiver positions in the audience area
- **R1**: ¼ of the length of the stalls from the front, 2/5 of the width of the stalls from audience left
- **R2**: ½ the length of the stalls from the front, ¼ of the width from audience right
- **R3**: 1/5 of the length of the stalls from the back, 1/3 of the width of the stalls from audience left
- **R4**: on first back balcony, halfway back, 2/5 of the width from audience right
- **R5**: on left side balcony, halfway back and halfway in.



Denotations

f		125	250	500	1000	2000	4000
S1R1		1,1	2,5	20,9	20,9	11,8	4,4
S1R2		22,6	23,8	21,2	22,7	27,5	44,6
S1R3		15,8	8,8	17,6	20	29,2	44,1
S1R4		14,9	19,2	22,5	30,8	40	28,6
S2R1		33,5	28,5	23	35,8	34	34,6
S2R2		11,7	25,3	19	27,1	32,3	33,6
S2R3		9,2	7,4	23,9	21,1	29,4	27,3
S2R4		9,3	16	32,1	31	34,2	28,9
S3R1		10,3	39,4	20,6	21,9	30,6	20,7
S3R2		13	4,7	15,2	27,5	27,2	34,8
S3R3		8,5	21,5	20,3	22,2	26,1	34
S3R4		17,3	18,1	16,7	21	26,7	35
Average		13,93	17,93	21,08	25,17	29,08	30,88
StDev		8,15	10,82	4,33	5,16	6,75	10,67
Min		1,10	2,50	15,20	20,00	11,80	4,40
Max		33,50	39,40	32,10	35,80	40,00	44,60
Var		32,40	36,90	16,90	15,80	28,20	40,20
LF(mid)	23,13	%					
LF_4	19,53	%					