2019.11.06

Acoustics VTAN01

1.Course info & Intro to Acoustics

NIKOLAS VARDAXIS

DIVISION OF ENGINEERING ACOUSTICS, LUND UNIVERSITY

Outline

Course Information

Introduction to Acoustics

Summary

Teachers

- **Lectures**
  - Delphine Bard, delphine.bard@construction.lth.se
  - Nikolas Vardaxis **nikolas.vardaxis@construction.lth.se** [contact person]
  - Mathias Barbagallo mathias.barbagallo@construction.lth.se

    → Division of Engineering Acoustics, V-building (5th floor).

- **Exercises, laboratories, project**
  - Nikolas & Mathias

- **Administration**
  - Cecilia Sandstedt, M-building (5th floor)

  cecilia.sandstedt@construction.lth.se

Course material

- Handed out material
  - Lecture notes
  - Exercise tasks (6 weeks)
  - Laboratory instructions (2)
  - Project task
  - Formulae

- Website (course material will be uploaded here):

  http://www.akustik.lth.se/utbildning/kurser/

Laboratories & Project task

Laboratories

- Two Lab sessions (in groups of 2-4 students)
  1. Recording, calibration and evaluation of sound
  2. Sound insulation measurement
- Approximately 2 hours on site
  - Preparation and post-processing time needed
- Results presented in form of a report
  - Either passed or returned for completion

Project task

- Performed in groups of 2-3 students
- Presented Wednesday, December 18th at 15:00-17:00

Examination

The final grade will be obtained as follows…

- Written exam (50%)
  - Tuesday 14th January at 08.00-13.00 in Sparta:A, Sparta:B.
  - Theoretical questions and exercises
  - Calculator and formulae sheet
  - Graded: *u, 3, 4, 5*
- Project task (50%)
  - Graded: *u, 3, 4, 5*
- Executed laboratories with passed reports

The course

- Time:
  - 4 h/week of lectures and 2 h/week exercises (Wednesdays / Fridays)
  - ~6 h laboratory exercises off-schedule
- Purpose

The purpose of the course in acoustics is to give knowledge of sound propagation in different media, namely in fluids such as air and in vibrating systems of solid structural elements, where different wave types (i.e. longitudinal waves, transversal waves and bending waves) together with their properties and phenomena involved (i.e. generation, transmission, radiation, reflection and absorption), are introduced.

Moreover, the topics of building acoustics and room acoustics will be extensively dealt with both from a practical as well as a theoretical point of view; introducing existing calculation models and measurement techniques to address the latter issues. A special focus is put into performing and evaluating sound measurements as well as into concepts of measurement accuracy. Psycho-acoustic notions are also given in the course.

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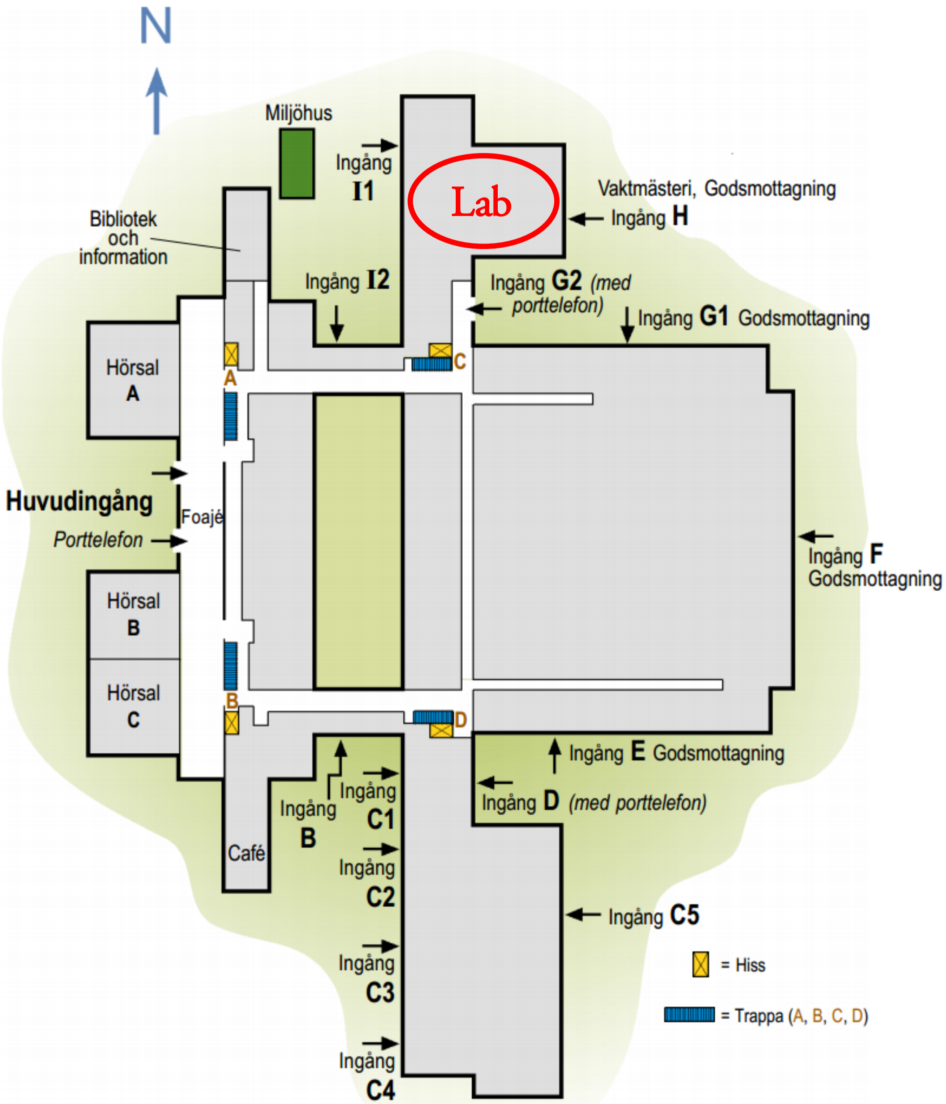
V-huset



N
Miljöhus
Ingång I1
Lab
Vaktmästeri, Godsmottagning
Ingång H
Bibliotek och information
Ingång I2
Ingång G2 (med porttelefon)
Ingång G1 Godsmottagning
Hörsal A
A
C
Huvudingång
Porttelefon
Foajé
Ingång F Godsmottagning
Hörsal B
Hörsal C
B
D
Ingång E Godsmottagning
Ingång D (med porttelefon)
Ingång B
Ingång C1
Café
Ingång C2
Ingång C5
Ingång C3
Ingång C4
= Hiss
= Trappa (A, B, C, D)

Outline

Course Information

Introduction to Acoustics

Summary

Learning outcomes

- Definition of sound
- Harmonic oscillations and complex notation
- Acoustic variables and levels
- Addition of correlated and uncorrelated sources
- Frequency domain representation

Why address sound issues?

- Noise affects people physiologically and psychologically

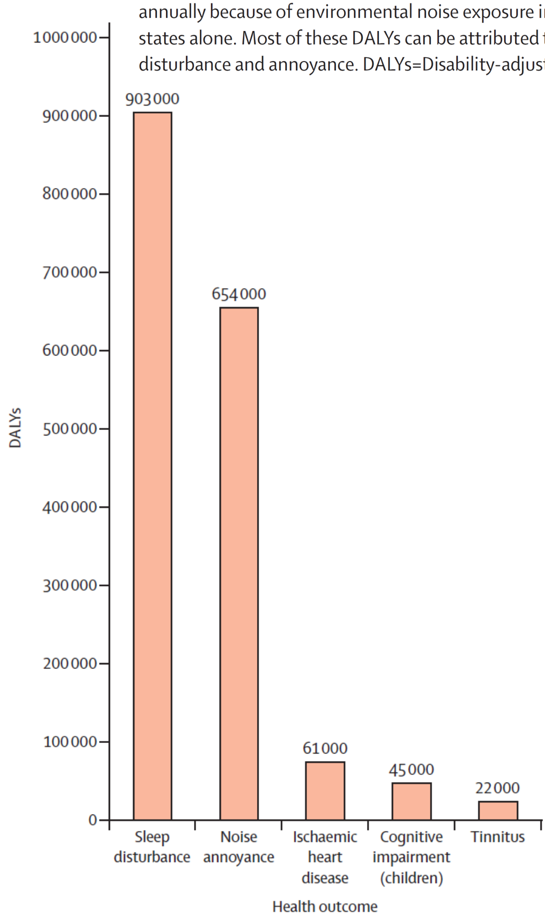
At least 25 % of EU citizens are exposed to noise in such extent that it affects health and quality of life.

Approximately 2 million people in Sweden are exposed to a noise level that exceeds the regulations set up by the Swedish parliament.

In Spain, 9-10 million people are subjected to noise levels that surpass those recommended by the WHO.

Disability-Adjusted Life Year (DALY)

DALYs attributed to environmental noise exposure in Europe.
According to WHO, more than 1 million healthy life years (DALYs) are lost annually because of environmental noise exposure in European A-member states alone. Most of these DALYs can be attributed to noise-induced sleep disturbance and annoyance. DALYs=Disability-adjusted life years.



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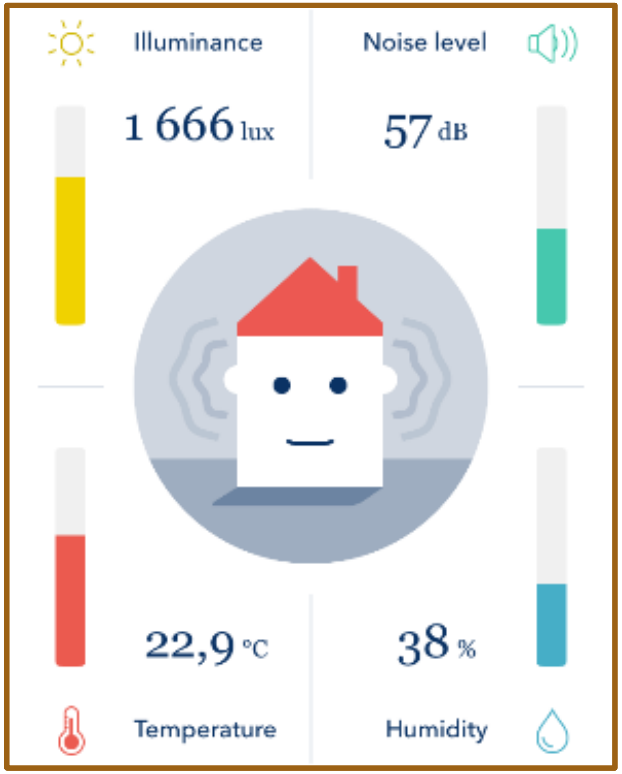
Indoor environmental quality



MC500 App

What is acoustics? (I)

- From the *Oxford Dictionary*:

a•cous•tic |əˈkoōstik|

adjective [attrib.]

1 relating to sound or the sense of hearing : *dogs have a much greater acoustic range than humans.*

• (of building materials) used for soundproofing or modifying sound : *acoustic tiles.*

• (of an explosive mine or other weapon) able to be set off by sound waves.

2 (of music or musical instruments) not having electrical amplification : *acoustic guitar.*

• (of a person or group) playing such instruments.

noun

1 (usu. **acoustics**) the properties or qualities of a room or building that determine how sound is transmitted in it : *Symphony Hall has perfect acoustics.*

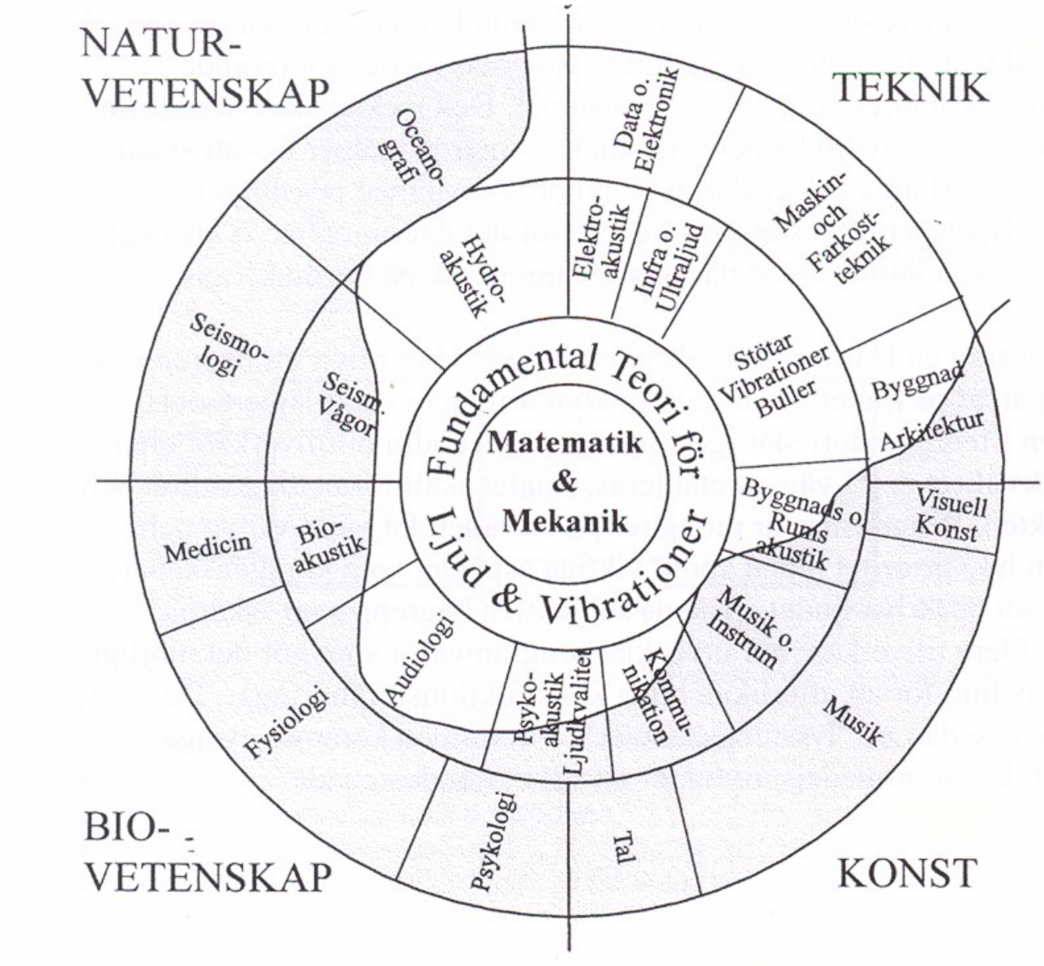
• (**acoustic**) the acoustic properties or ambience of a sound recording or of a recording studio.

2 (**acoustics**) [treated as sing.] the branch of physics concerned with the properties of sound.

3 a musical instrument without electrical amplification, typically a guitar.

- **Acoustics**: part of physics studying generation, transmission, reception, absorption, reproduction and control of sound
  - Environmental ac., building ac., room ac., psychoac., musical ac., underwater ac…

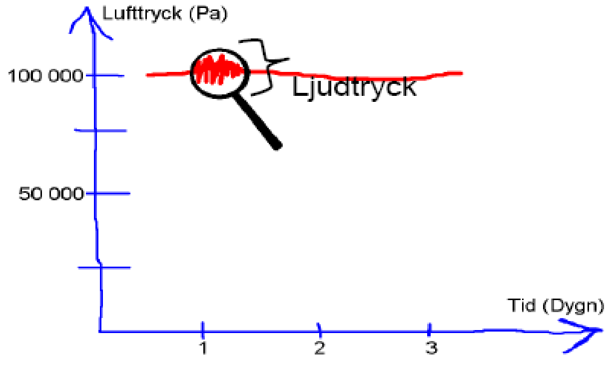
What is acoustics? (II)



Sound & Noise

- **Sound**: oscillations produced in an elastic medium by a vibratory source producing variations in the atmospheric pressure
  - Characteristics:
    - Pitch
    - Quality
    - Loudness

$$p_{tot}(t) = p_{atm} \pm p(t)$$



- **Noise:** random (unwanted) sound

Time & frequency domains (I)

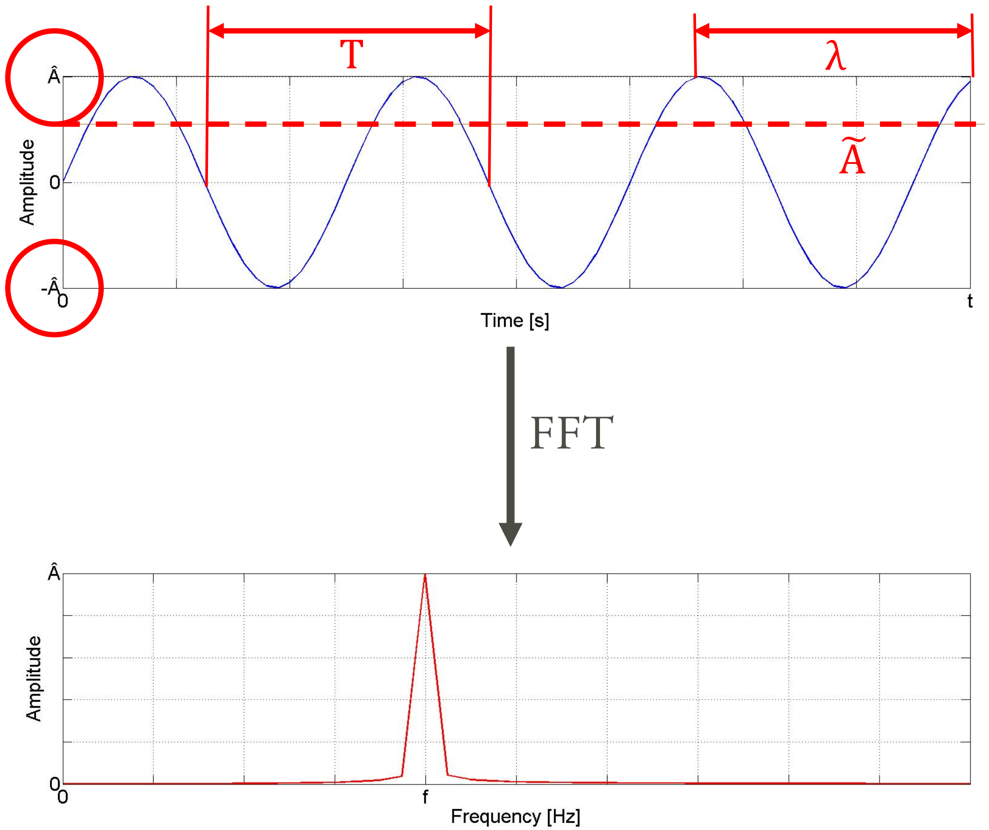
Harmonic signal: $y(t) = \hat{A}\sin(\omega t) = \hat{A}\cos(\omega t + \varphi) = \hat{A}\sin(2\pi f \cdot t)$

- Amplitude: $\hat{A}$
- Period [s]: $T = {}^{1}/_{f}$
- Frequency [Hz]: $f = {}^{1}/_{T}$
- Wavelength [m]: $\lambda = cT = {}^{c}/_{f}$
- Propagation Speed [m/s]: $c = f\lambda$

  NOTE: $c \neq v$

- Effective value (RMS):

$$A_{RMS} = \tilde{A} = \sqrt{\frac{1}{\Delta t}\int_{t_0}^{t_0+\Delta t} y^2(t)\,dt}\,, \quad \tilde{A}_{\substack{\text{harmonic}\\ \text{signal}}} = {}^{\hat{A}}/_{\sqrt{2}}$$



- Frequency domain

Complex notation

- Equivalent description: $p(t) = \hat{A}\cos(\omega t + \varphi)$

$$p(t) = \mathrm{Re}\left[Ae^{-i(\omega t+\varphi)}\right] = \mathrm{Re}\left[\underline{A}e^{-i\omega t}\right]$$

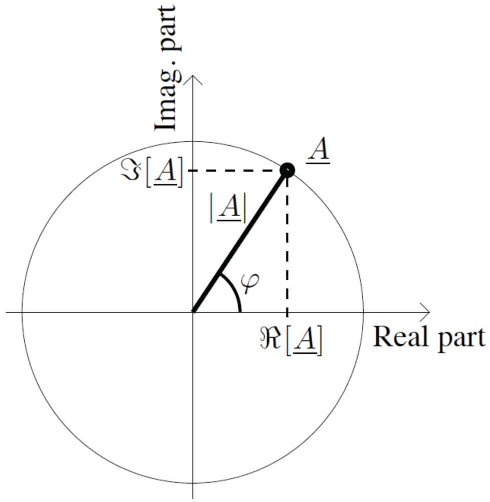
where the complex amplitude is defined as: $\underline{A} = Ae^{i\varphi}$

and $e^{i\varphi} = \cos(\varphi) + i\sin(\varphi)$

- The peak value and initial phase are

$$A = |\underline{A}|$$

$$\tan(\varphi) = \frac{\mathrm{Im}[\underline{A}]}{\mathrm{Re}[\underline{A}]}$$



© P. Andersson

NOTE 1: The complex number "i" is sometimes also expressed as "j"

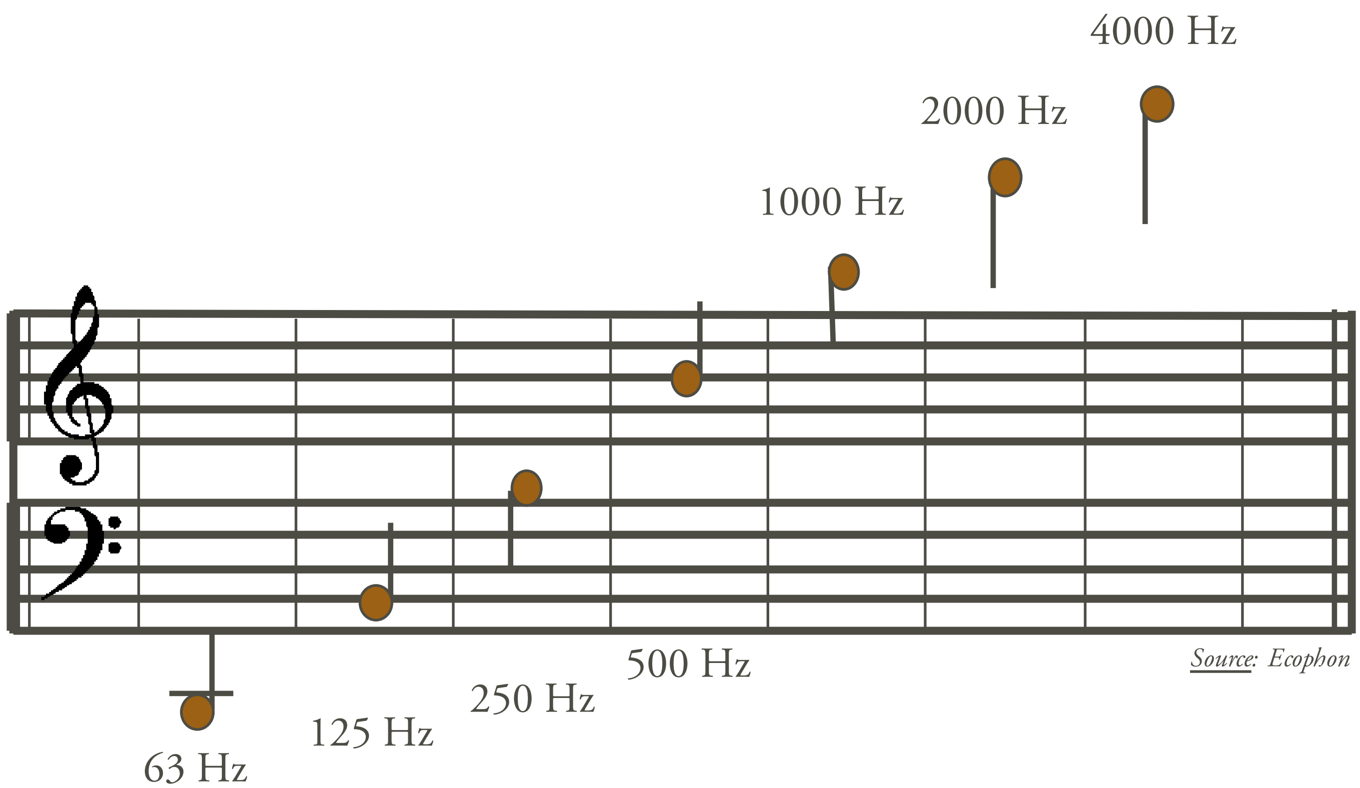
NOTE 2: $\varphi_{\cos} = \varphi_{\sin} - \frac{\pi}{2}$

Equivalences

Source: Sven Spanne: *Komplex Analys*

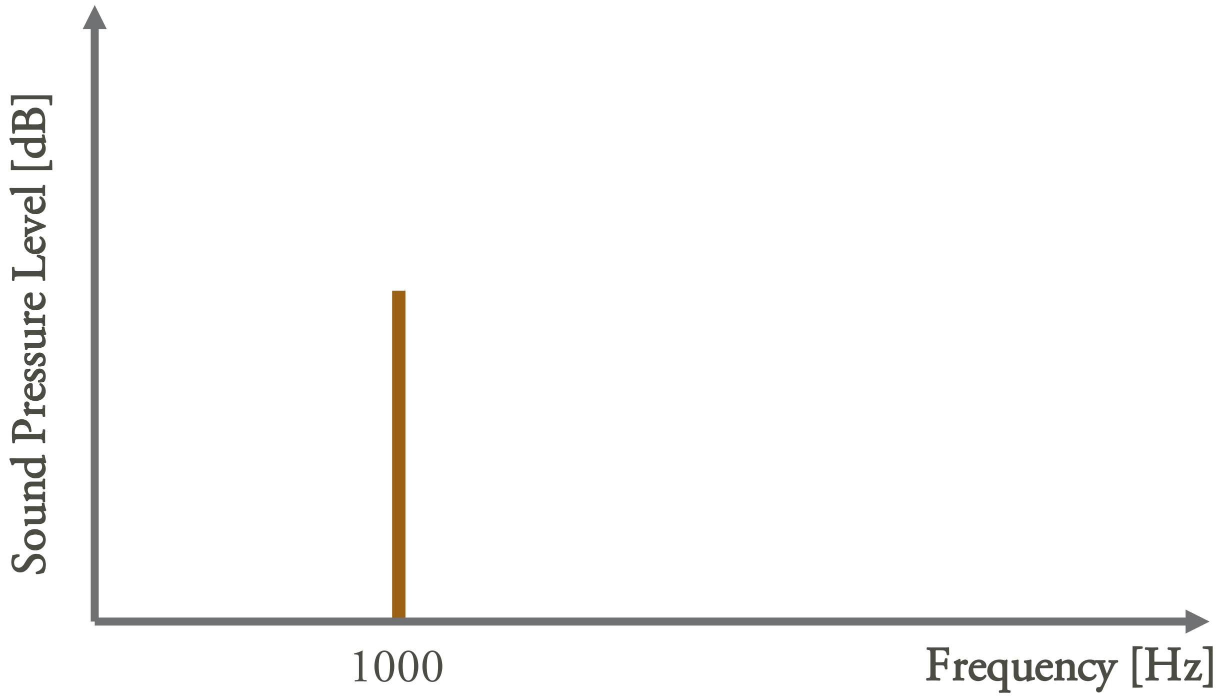
$$
\begin{tikzcd}[column sep=large, row sep=huge]
 & \boxed{\mathrm{Re}(\mathcal{A}e^{i\omega t})} \arrow[dl, leftrightarrow, "{\mathcal{A} = a - ib}"', "{\begin{array}{l} a = \mathrm{Re}\,\mathcal{A} \\ b = -\,\mathrm{Im}\,\mathcal{A} \end{array}}"] \arrow[dr, leftrightarrow, "{\begin{array}{l} A = |\mathcal{A}| \\ \delta = \arg \mathcal{A} \end{array}}", "{\mathcal{A} = Ae^{i\delta}}"'] & \\
\boxed{a\cos\omega t + b\sin\omega t} \arrow[rr, leftrightarrow, "{\begin{array}{l} a = A\cos\delta \\ b = -A\sin\delta \end{array}}"'] & & \boxed{A\cos(\omega t + \delta)}
\end{tikzcd}
$$

Different frequencies

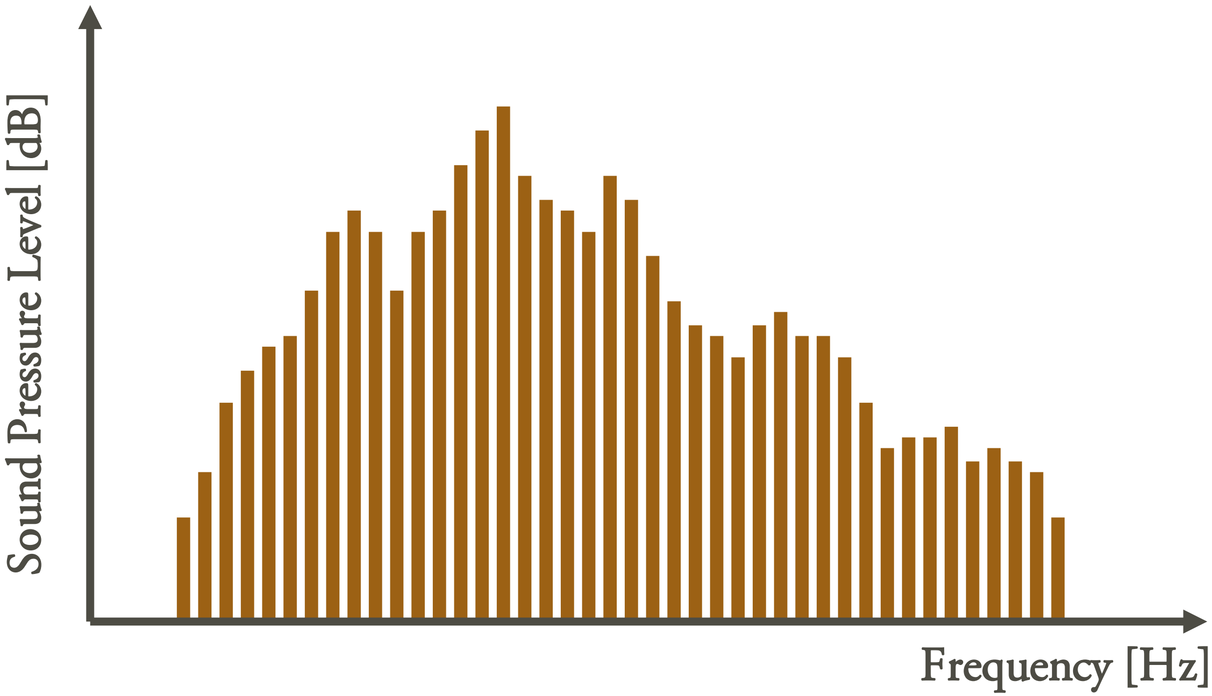


Source: *Ecophon*

Spectrum of a tone

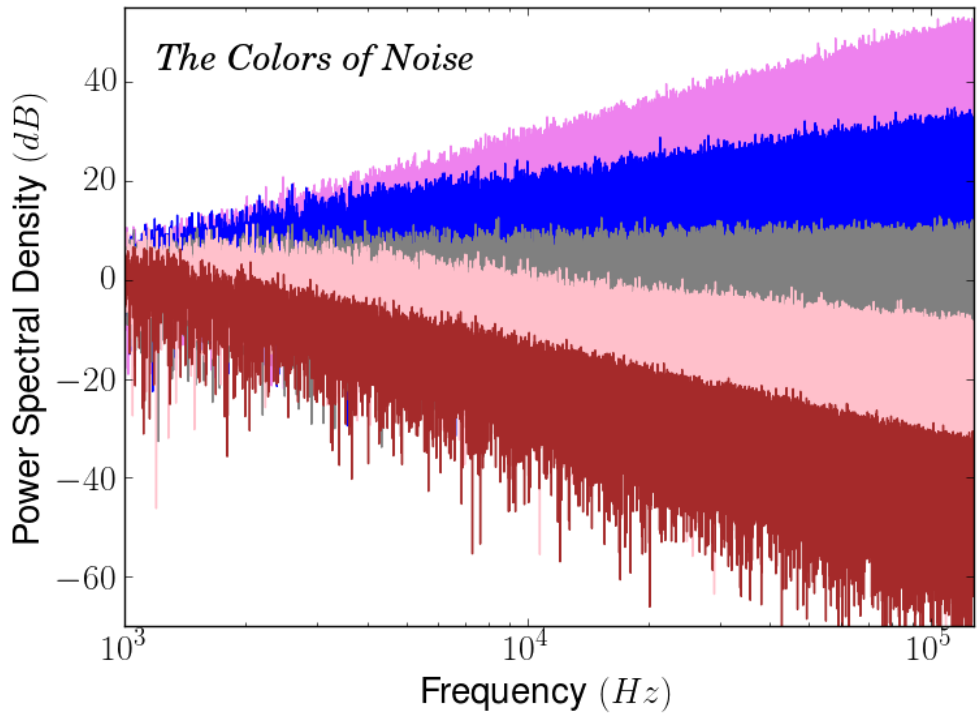


Spectrum of noise



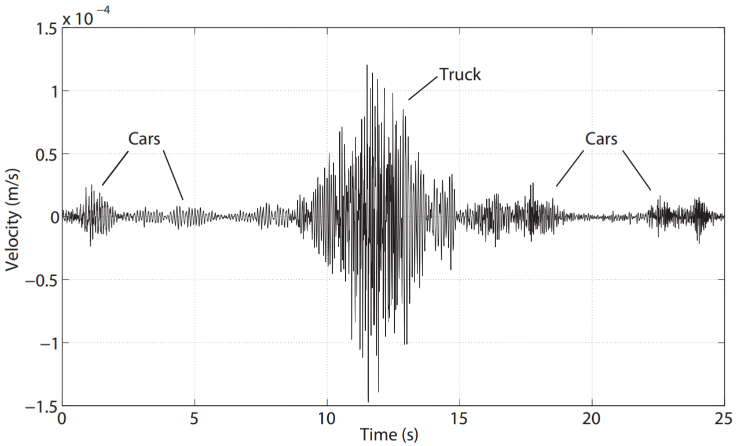
Frequency domain – Noise

- **Noise:** Classified by ”colours”
  - Violet noise: +6 dB/octave
  - Blue noise: +3 dB/octave
  - White noise: flat spectrum
  - Pink noise: -3 dB/octave
  - Brown noise: -6 dB/octave

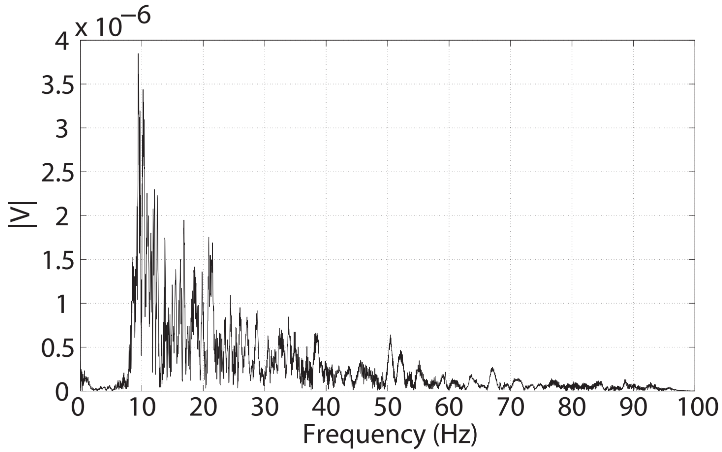


Time & frequency domains (II)

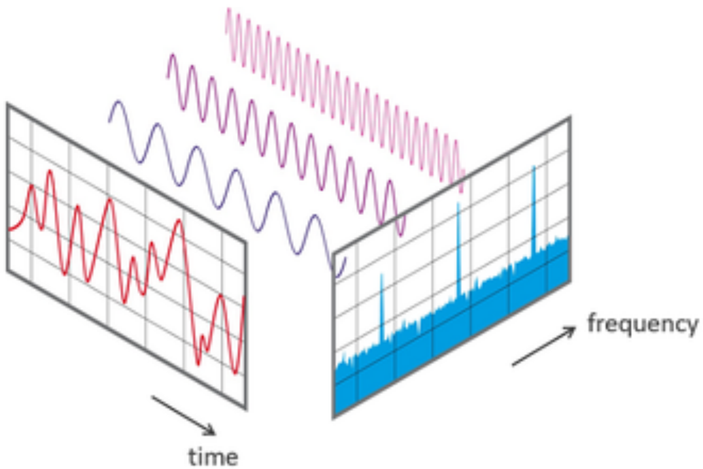
- A more complex time signal (traffic load)



FFT

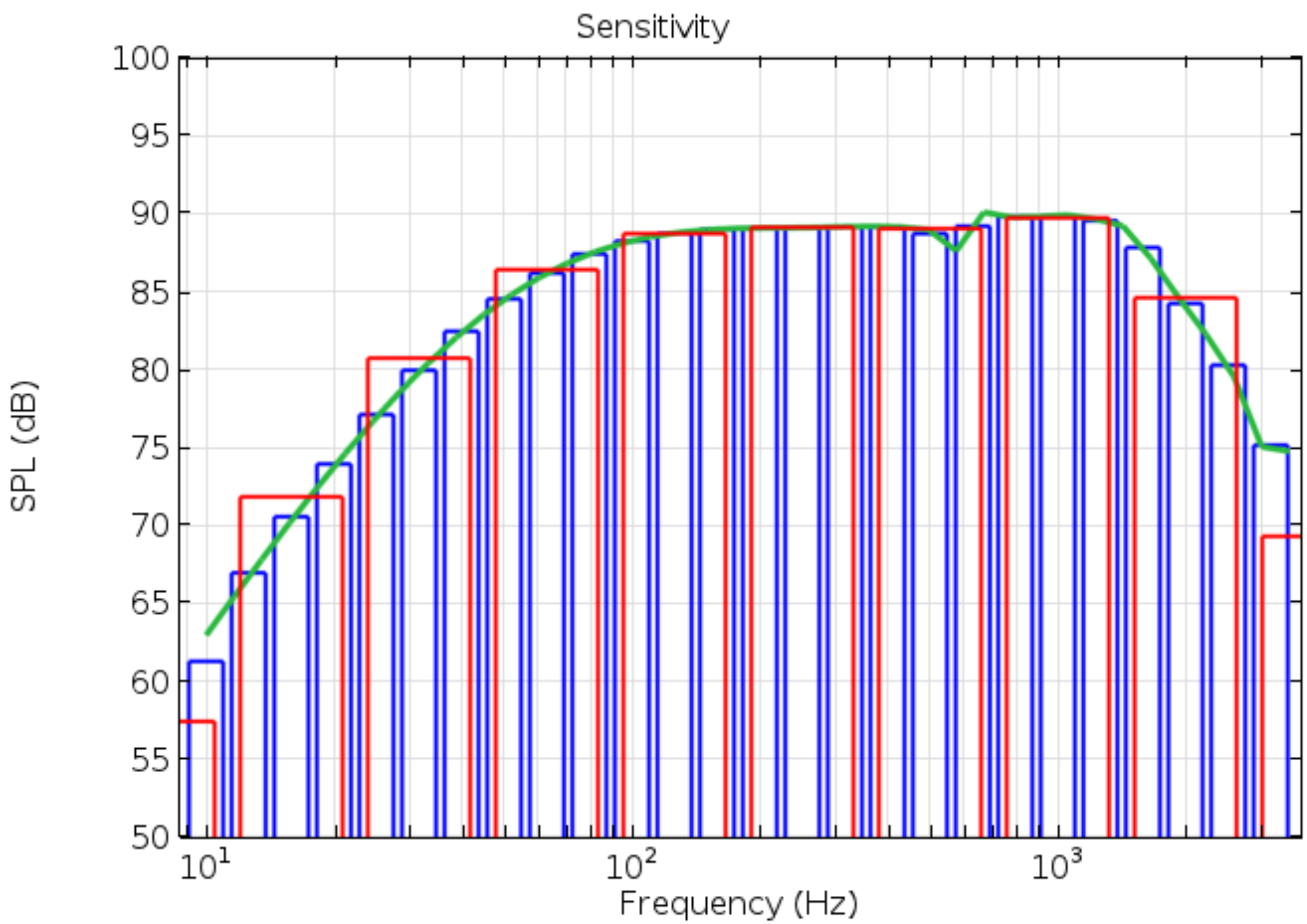


- Narrow band analyses
  - Impractical, time-consuming
  - Octave & 1/3 octave bands



NOTE: Spectrum (any magnitude plotted against frequency)

Time & frequency domains (II)



Frequency responses:

Narrow band

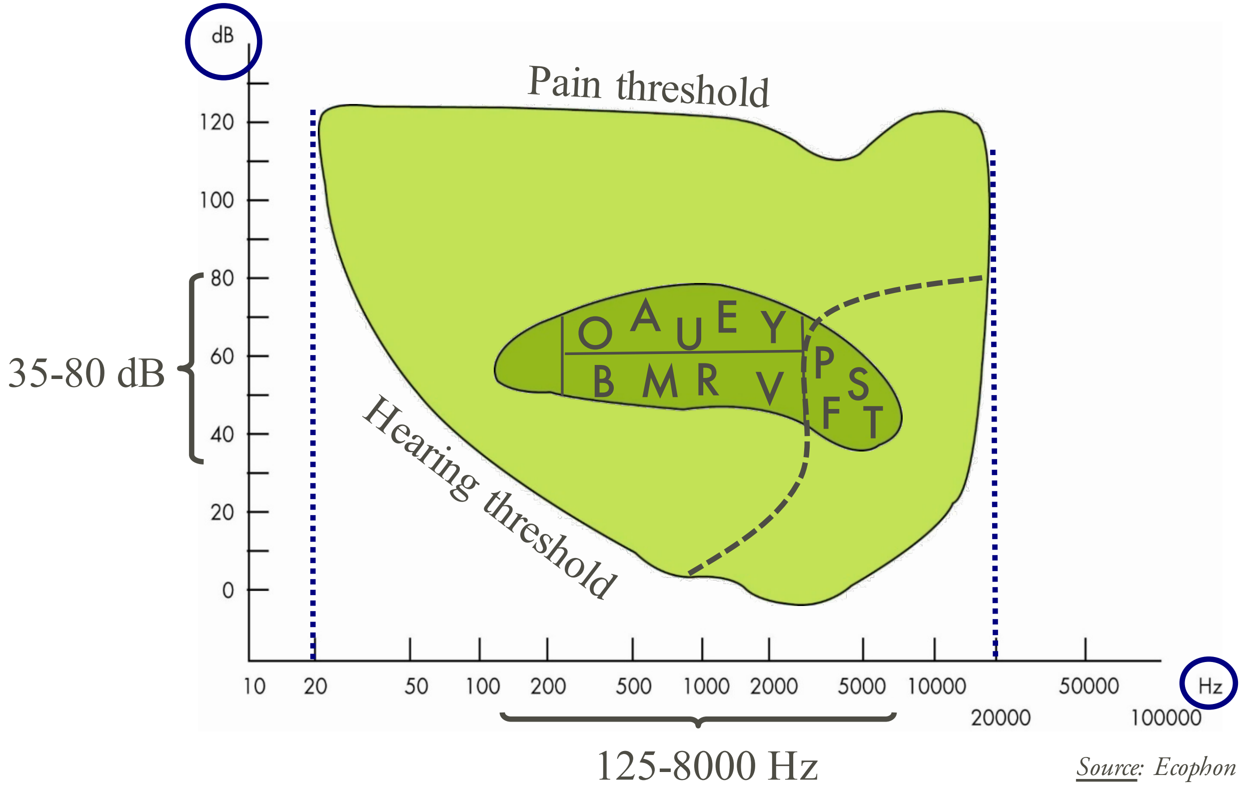
Octave bands

1/3 octave bands

[www.comsol.com/blogs/new-octave-band-plot-for-acoustics-simulations-in-version-5-2/]

Audible range

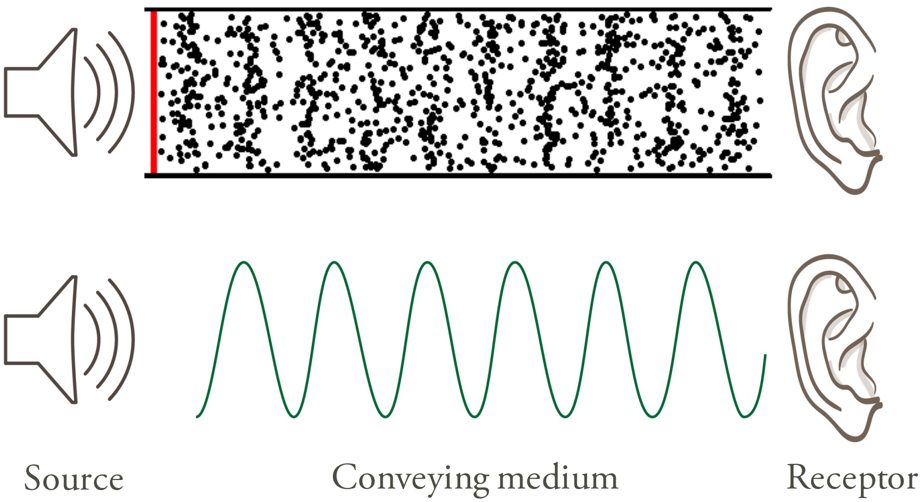
- Normal vs. Impaired



Source: Ecophon

Hearing process

- Pressure waves
- For a sound to be perceived
  - Frequency: 20 Hz – 20 kHz
  - Sound pressure level (SPL): frequency dependent
- Inner ear detects: $\Delta p \in [20\ \mu Pa, 200\ Pa]$ → wide range
  - Use of logarithmic scale (in decibels)



The decibel (dB) & SPL

- Logarithmic way of describing a ratio
  - Ratio: velocity, voltage, acceleration…
  - Need of a reference
- Sound pressure level (SPL / L_p)

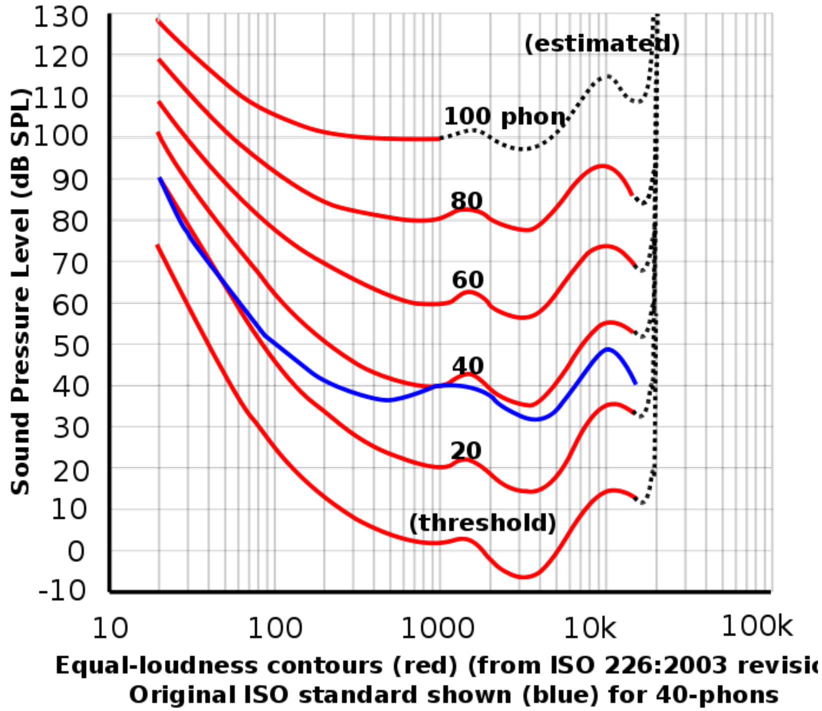
$$L_p = 10\log\left(\frac{\tilde{p}^2}{p_{ref}^2}\right) = 20\log\left(\frac{\tilde{p}}{p_{ref}}\right)$$

$$\tilde{p} = \tilde{p}(f) \equiv \text{RMS pressure}$$
$$p_{ref} = 2\cdot 10^{-5}\ \text{Pa} = 20\ \mu\text{Pa}$$
$$p_{atm} = 101\ 300\ \text{Pa}$$
$$p_{tot}(t) = p_{atm} \pm p(t)$$

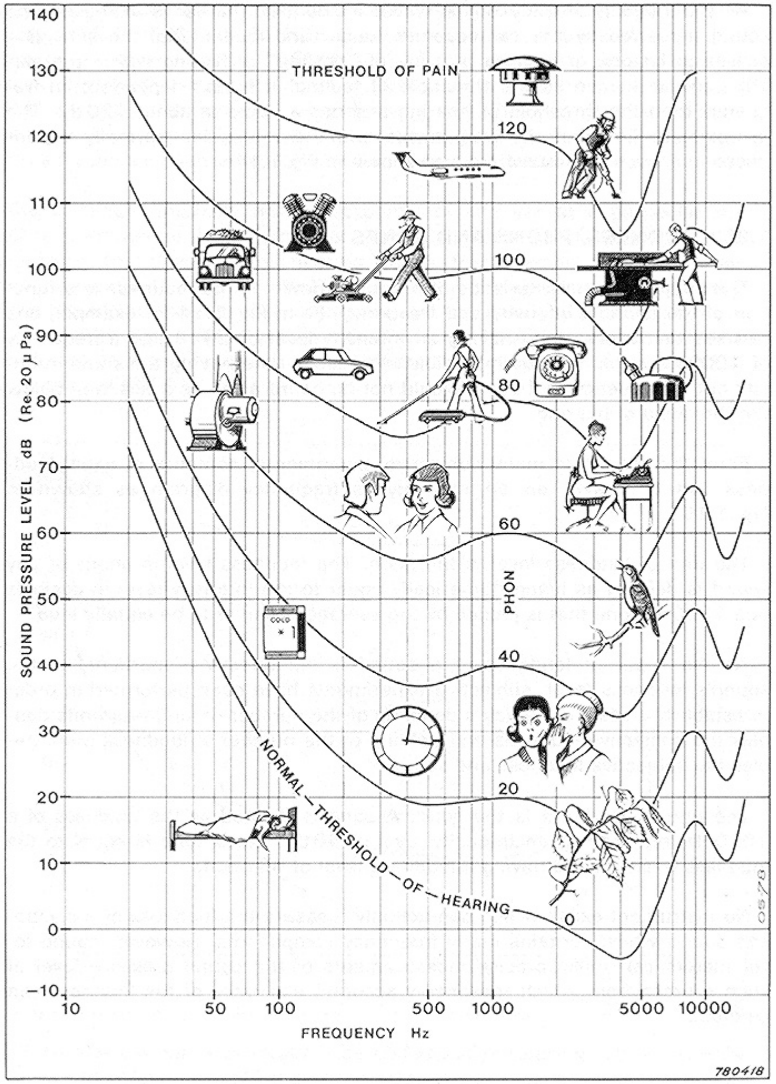
  - $\tilde{p}$ measured with microphones
  - Frequency response of human hearing changes with amplitude

Frequency weightings

- Frequency response of human hearing changes with amplitude
- How to relate the objective measure to the subjective experience of sound?

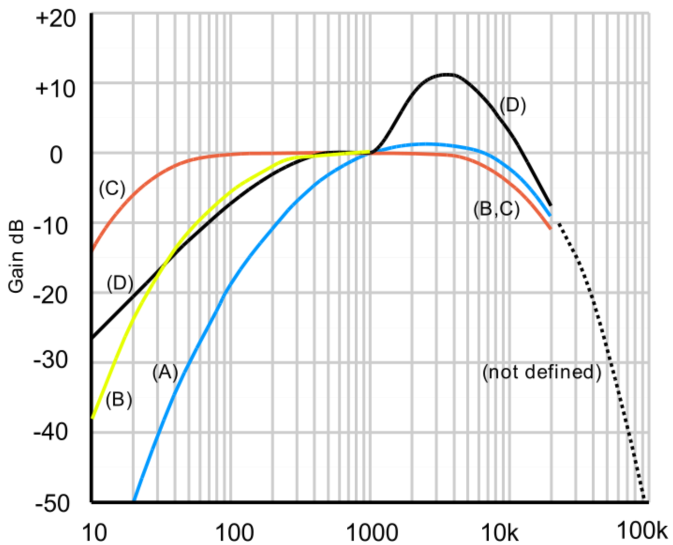


Frequency weightings – Examples of SPL



Frequency weightings

- Filters and calculation



A-weighting (blue), B (yellow), C (red), and D-weighting (blk)

$$L_{weighted} = 10\log\left(\sum 10^{\frac{(L_n + weighting)}{10}}\right)$$

Frekvens [Hz]	A-filter [dB]	B-filter [dB]	C-filter [dB]
10	-70.4	-38.2	-14.3
12.5	-63.4	-33.2	-11.2
16	-56.7	-28.5	-8.5
20	-50.5	-24.2	-6.2
25	-44.7	-20.4	-4.4
31.5	-39.4	-17.1	-3.0
40	-34.6	-14.2	-2.0
50	-30.2	-11.6	-1.3
63	-26.2	-9.3	-0.8
80	-22.5	-7.4	-0.5
100	-19.1	-5.6	-0.3
125	-16.1	-4.2	-0.2
160	-13.4	-3.0	-0.1
200	-10.9	-2.0	0
250	-8.6	-1.3	0
315	-6.6	-0.8	0
400	-4.8	-0.5	0
500	-3.2	-0.3	0
630	-1.9	-0.1	0
800	-0.8	0	0
1000	0	0	0
1250	0.6	0	0
1600	1.0	0	-0.1
2000	1.2	-0.1	-0.2
2500	1.3	-0.2	-0.3
3150	1.2	-0.4	-0.5
4000	1.0	-0.7	-0.8
5000	0.5	-1.2	-1.3
6300	-0.1	-1.9	-2.0
8000	-1.1	-2.9	-3.0
10000	-2.5	-4.3	-4.4
12500	-4.3	-6.1	-6.2
16000	-6.6	-8.4	-8.5
20000	-9.3	-11.1	-11.2

Frequency weightings (I)

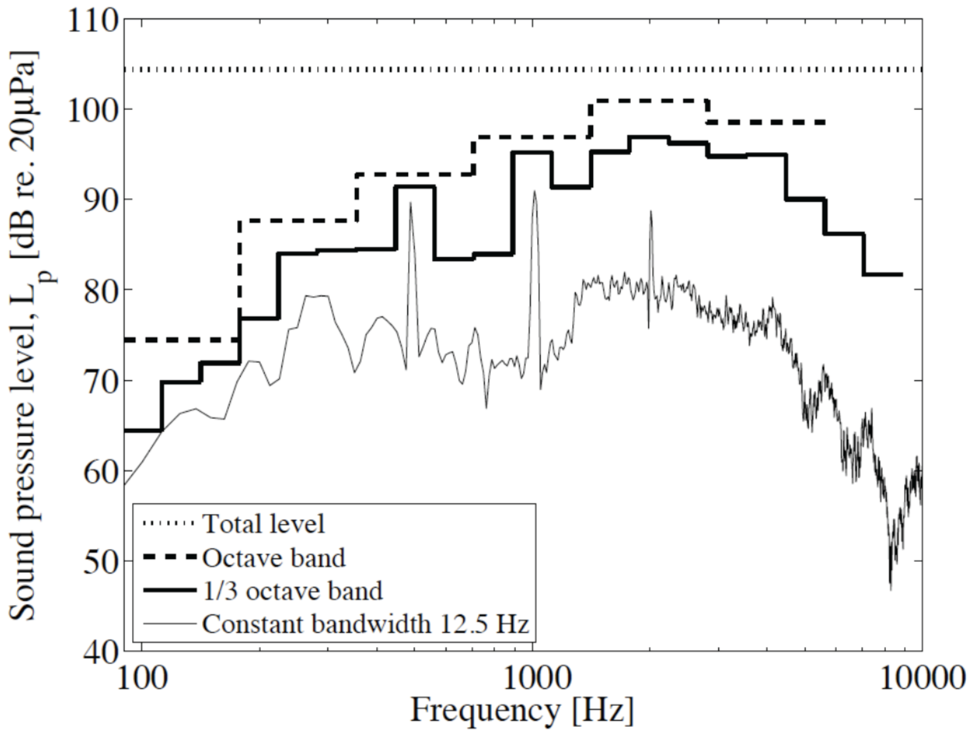
- Correlate objective sound measurements with subjective human response
  - A-weighting [dB(A)/dBA]: designed to reflect the response of how the human ear perceives noise, i.e. 20 Hz-20 kHz
    - » Only really accurate for relatively quiet sounds and pure tones?
    - » Low frequency noise is suppressed (wind turbine noise?)
  - C-weighting [dB(C)/dBC]: developed for high level aircraft noise
  - Z-weighting: zero frequency weighting (un-weighted values)
  - B-weighting: covers the mid-range between the A- and C-weighting
  - D-weighting: designed for use when measuring high level aircraft noise

Fallen into disuse

*Filters are defined in the standard IEC 61672

Frequency bands

- A sound in the frequency domain may be looked at in several ways.
    - Narrow bands;
    - Third-octave bands;
    - Octave bands;
    - Total value.



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Octave and 1/3-octave bands

If f_n is the cut-off lower frequency and f_{n+1} the upper one, the ratio of the band limits is given by:

$$\frac{f_{n+1}}{f_n} = 2^k$$

where k=1 for full octave and k=1/3 for one-third octave band

ISO 266 Standard Frequencies for Acoustic Measurements		
ISO Band numbers	**Octave band center frequency**	**One-third octave band center frequencies**
1	1.25 Hz	
2, 3, 4	2 Hz	1.6 Hz, **2 Hz**, 2.5 Hz
5, 6, 7	4 Hz	3.15 Hz, **4 Hz**, 5 Hz
8, 9, 10	8 Hz	6.3 Hz, **8 Hz**, 10 Hz
11, 12, 13	16 Hz	12.5 Hz, **16 Hz**, 20 Hz
14, 15, 16	31.5 Hz	25 Hz, **31.5 Hz**, 40 Hz
17, 18, 19	63 Hz	50 Hz, **63 Hz**, 80 Hz
20, 21, 22	125 Hz	100 Hz, **125 Hz**, 160 Hz
23, 24, 25	250 Hz	200 Hz, **250 Hz**, 315 Hz
26, 27, 28	500 Hz	400 Hz, **500 Hz**, 630 Hz
29, 30, 31	1000 Hz	800 Hz, **1000 Hz**, 1250 Hz
32, 33, 34	2000 Hz	1600 Hz, **2000 Hz**, 2500 Hz
35, 36, 37	4000 Hz	3150 Hz, **4000 Hz**, 5000 Hz
38, 39, 40	8000 Hz	6300 Hz, **8000 Hz**, 10000 Hz
41, 42, 43	16000 Hz	12500 Hz, **16000 Hz**, 20000 Hz

NOTE 1: Convert octave band to 1/3-octave band level reduction of -4.771dB for each 1/3 octave band:

$$L_p = 10\log\left(\frac{1}{3}\right)$$

NOTE 2: Octave band level of three 1/3-octave band levels:

$$L_{oct} = 10\log\left(\sum_{i=1}^{3} 10^{\frac{L_{p,i}}{10}}\right)$$

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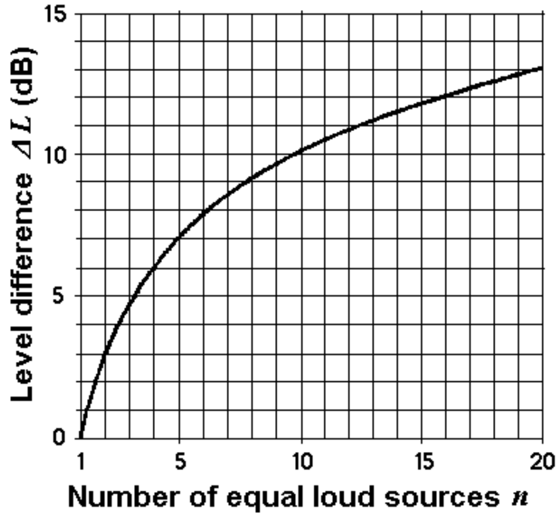
Summation of noise

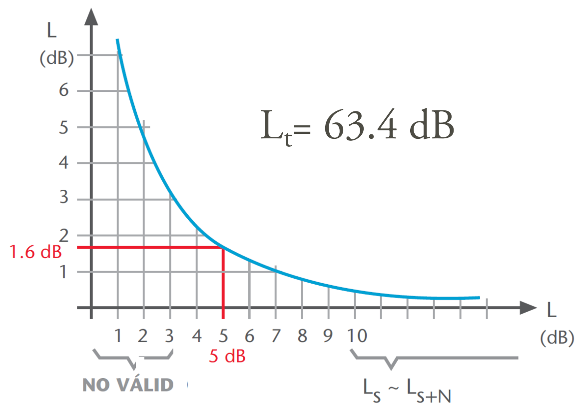
- Graphical methods
  - Adding equally loud incoherent sources
  - Adding two different sources
    - » e.g. L_1=61 dB / L_2=55 dB

L_t= 62 dB

$$L_{p,tot} = 10\log\left(\sum_{n=1}^{N} 10^{\frac{L_{p,n}}{10}}\right)$$



  - Substracting two different sources
    - » e.g. L_{S+N}=65 dB / L_N=60 dB



L_t= 63.4 dB

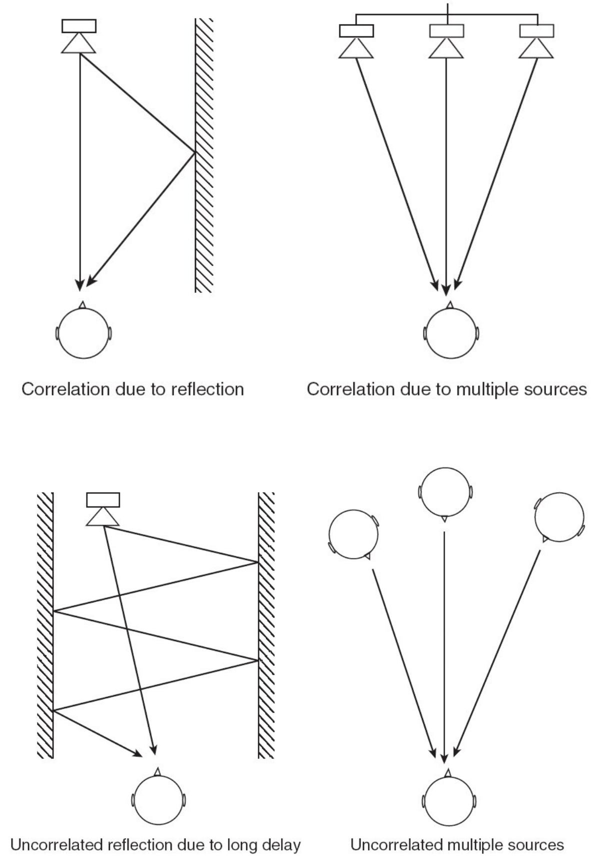
Summation of noise (I)

- Types of sources
  - Correlated (or coherent)
    - » Constant phase difference, same frequency
    - » Interferences (constructive/destructive)

$$L_{p,tot} = 20\log\left(\sum_{n=1}^{N} 10^{\frac{L_{p,n}}{20}}\right)$$

  - Uncorrelated (or incoherent)

$$L_{p,tot} = 10\log\left(\sum_{n=1}^{N} 10^{\frac{L_{p,n}}{10}}\right)$$



The total RMS pressure: $$\tilde{p}_{tot}^2 = \tilde{p}_1^2 + \tilde{p}_2^2 + \frac{2}{\Delta t}\int_{t_0}^{t_0+\Delta t} p_1(t)p_2(t)\,dt$$

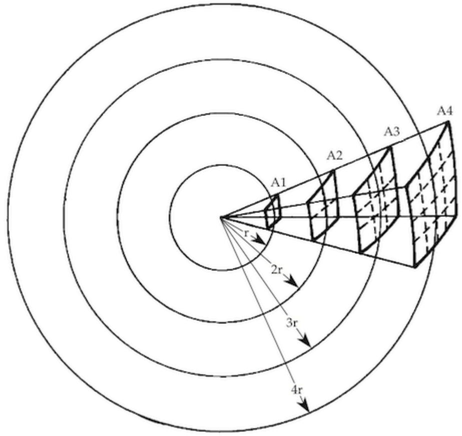
For uncorrelated sources, the 3rd term vanishes

Sound (acoustic) intensity

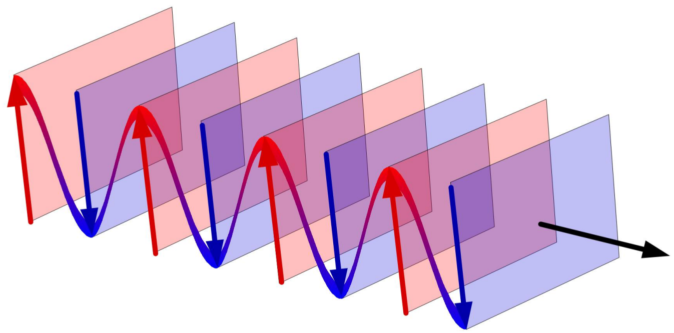
- Sound power per unit area [W/m²]
  - Vector quantity: energy flow and direction

$$I = \langle pv \rangle = \frac{1}{\Delta t}\int_0^T p(t)v(t)dt$$

  - In a free field: $I = \frac{\widetilde{p^2}}{\rho c}$; $I \propto p^2$



- Types of propagation
  - Plane: $I \equiv \text{constant}$;
  - Cylindrical: $I(r) \propto \frac{1}{r}$
  - Spherical: $I(r) \propto \frac{1}{r^2}$; $I(r) = \frac{\Pi}{4\pi r^2}$

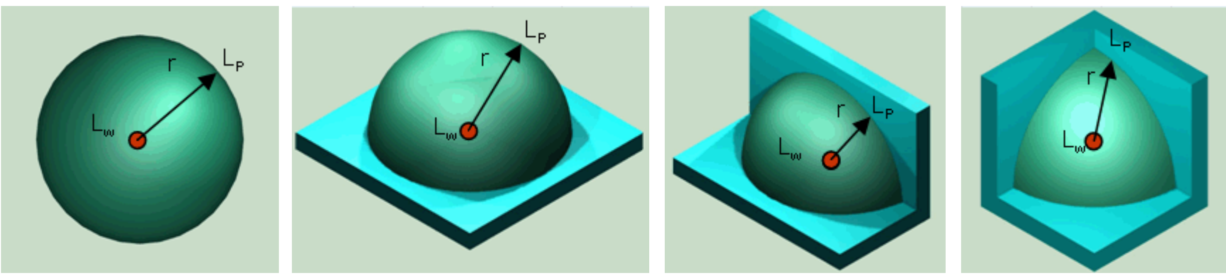


- In decibels… $L_I = 10\log\left(\frac{I}{I_0}\right)$; $I_0 = 10^{-12}\,{}^{W}/_{m^2}$

Notes / Definitions (I)

- Sound emission
  - Sound power continuously emitted from a sound source

- Sound power level (SWL / L_W / L_Π) or acoustic power
  - Total sound energy emitted by a source per unit time
    - » Constant regardless of the room
    - » Independent of the distance from the sound source
    - » Theoretical value
  - Units: Watts [W] or decibels [dB] (re: 10^{-12} W)



Source: www.sengpielaudio.com

$$L_W = L_p + \left|10 \log\left(\frac{Q}{4\pi r^2}\right)\right|$$

- Q=1: Full sphere
- Q=2: Half sphere
- Q=3: Quarter sphere
- Q=4: Eighth sphere

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Notes / Definitions (II)

- Sound pressure level (SPL / L_P)
  - Sound field quantity
  - Relation between sound pressure and distance from source: $p \propto \frac{1}{r}$
  - Decreases by (–)6 dB for doubling of the distance from the source to 1/2 (50%) of the sound pressure initial value (spherical propagation)

$$L_{p,2} = L_{p,1} + \left| 20 \log\left(\frac{r_1}{r_2}\right) \right|$$

NOTE: A sound source produces sound power and this generates a sound pressure fluctuation in the air. Sound power is the distance independent cause of this, whereas sound pressure is the distance-dependent effect.

- Sound intensity level (SIL / L_I)
  - Sound energy quantity
  - Relation between sound intensity and sound pressure: $I \propto p^2$
  - Decreases by (–)6 dB for doubling of the distance from the source to 1/4 (25%) of the sound intensity initial value (spherical propagation)

$$L_{I,2} = L_{I,1} + \left| 10 \log\left(\frac{r_1^2}{r_2^2}\right) \right|$$

Sound (acoustic) intensity – Example

- **Ex:** In a rock concert, measurements are performed next to you yielding a value of 90 dB. Which level will a person who is 5 times further away from the speakers perceive, assuming…
  - … plave wave propagation?
  - … cylindrical wave propagation?
  - … spherical wave propagation?

Theoretical question…

- What is the relationship between the intensity level L_I and the sound pressure level L_p? Are they both the same? Justify your answer.

Do not mix up concepts (I)…

- Sound Pressure (SPL), Sound Power (SWL), and Sound Intensity (SIL) acoustic quantities that can be expressed in dB. They describe different aspects of sound, and the decibels for each represent different measurement quantities.

  - SPL:
    - Amplitude level of sound at a specific location in space (scalar quantity)
    - Dependent on the location and distance to the source
    - Measured in Pascals [Pa]
  - SWL:
    - Rate at which sound is emitted from an object
    - Independent of location or distance
    - Measured in Watts [W]
  - SIL:
    - Sound power flow per unit of area
    - Sound intensity is measured in [W/m^2]

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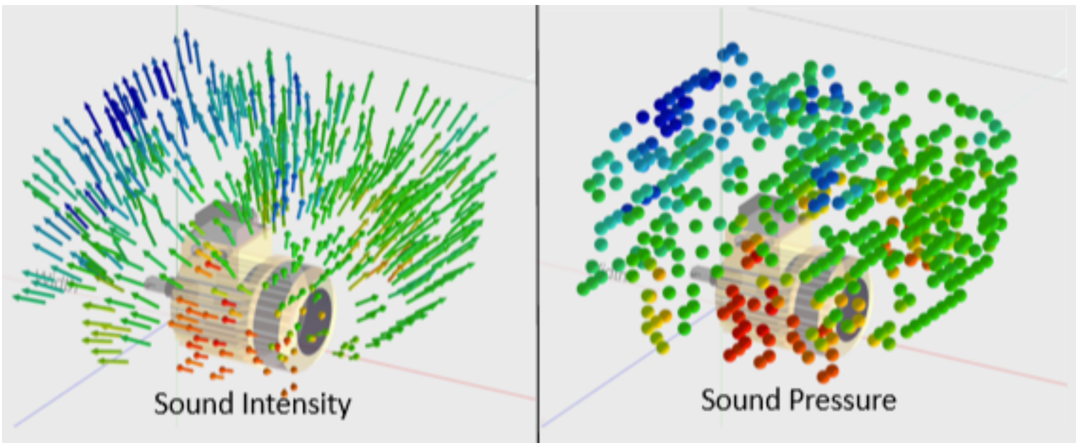
Do not mix up concepts (II)…

- Zero levels…
  - SPL:
    - Threshold of hearing: p_0=20 µPa → L_p(f = 1 kHz)=0 dB
  - SIL:
    - Threshold of hearing: $I_0=1\cdot10^{-12}$ W/m^2 → L_I(f = 1 kHz)=0 dB



Amplitudes are the same / Directions are the difference (easier to troubleshot with SI)

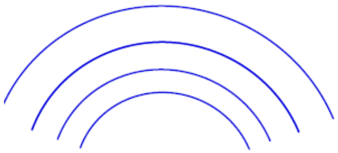
Do not mix up concepts (III)…

Receiver ⟷ Sound Pressure Level

$$L_p = 10 \log_{10} \frac{p^2}{p_o^2}$$

$$p_o = 2 \times 10^{-5} N/m^2$$

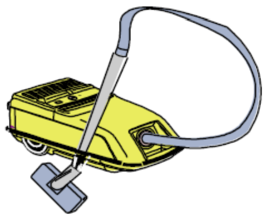
$$= 20 \mu Pa$$



Path ⟷ Sound Intensity Level

$$L_i = 10 \log_{10} \frac{I}{I_0}$$

$$I_o = 1 pW/m^2$$



Source ⟷ Sound Power Level

$$L_w = 10 \log_{10} \frac{W}{W_o}$$

$$W_o = 1 pW$$

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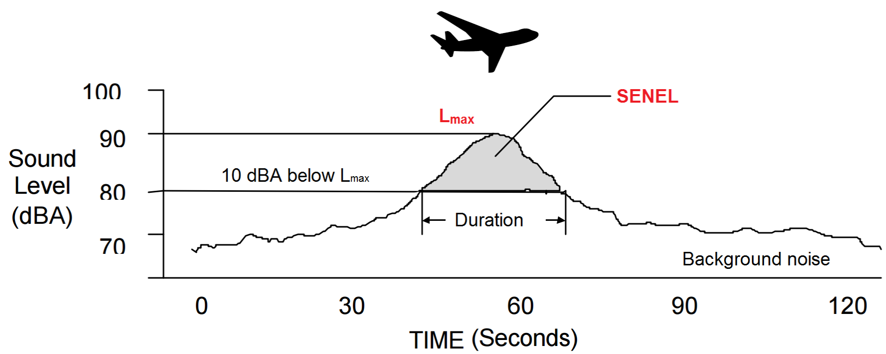
BEYOND MEASURE

Noise metrics (I)

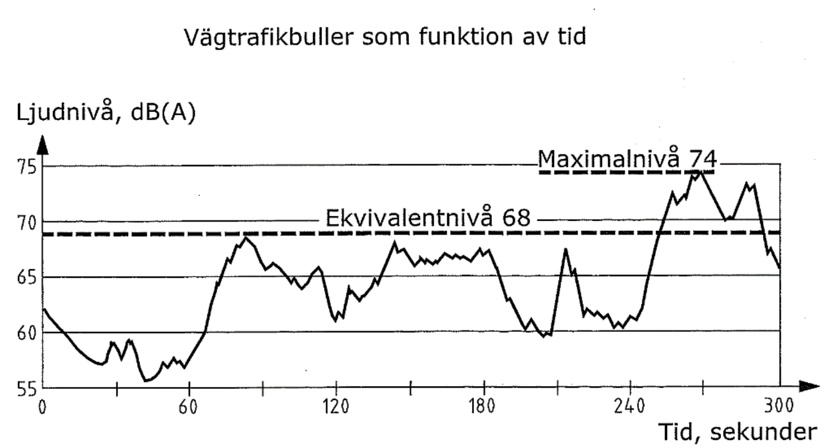
- Single event noise metrics:
  - Maximum sound level (L_{max}):
    - Accounts only for sound amplitude [dB/dBA…]
  - Sound exposure level (SEL) & Single event noise exposure level (SENEL)
    - Total “noisiness” of an event. It takes duration into account
    - SENEL=SEL if measured for the period when the level is within 10 dB of L_{max}
  - Day and night average sound level (DNL or L_{den})
  - Community noise equivalent level (CNEL)
  - Effective perceived noise level (EPNL)
  - Time above threshold
  - …



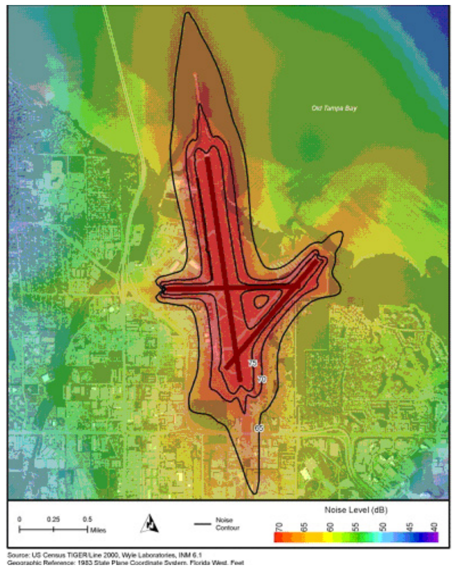
Noise metrics (II)

- Cumulative exposure metrics
  - Equivalent SPL during the measurement time T (units: dB, dBA…)

$$L_{eq,T} = 10\log\left(\frac{1}{T}\int_0^T \frac{p^2(t)}{p_{ref}^2}dt\right) = 10\log\left(\frac{1}{T}\int_0^T 10^{\left(\frac{L_p(t)}{10}\right)}dt\right)$$



Figur 4:9. Ljudnivåns variation under 5 minuter på en livligt trafikerad innerstadsgata. Ekvivalentnivå 68 dB(A), maximalnivå 74 dB(A).



Ex: Calculate the $L_{eq,8h}$ that corresponds to 105 dBA for 15 min.

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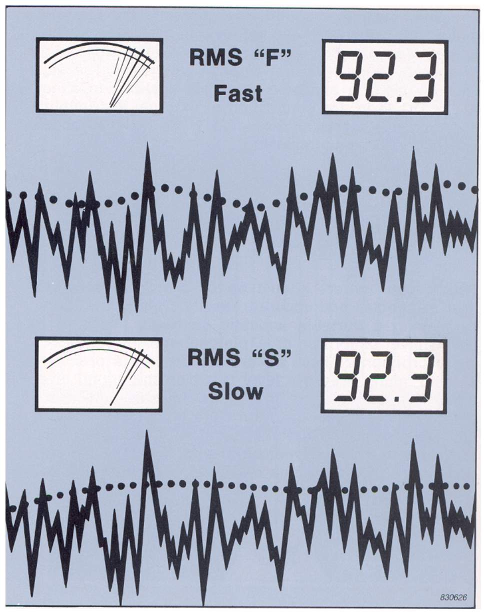
Measurement of SPL

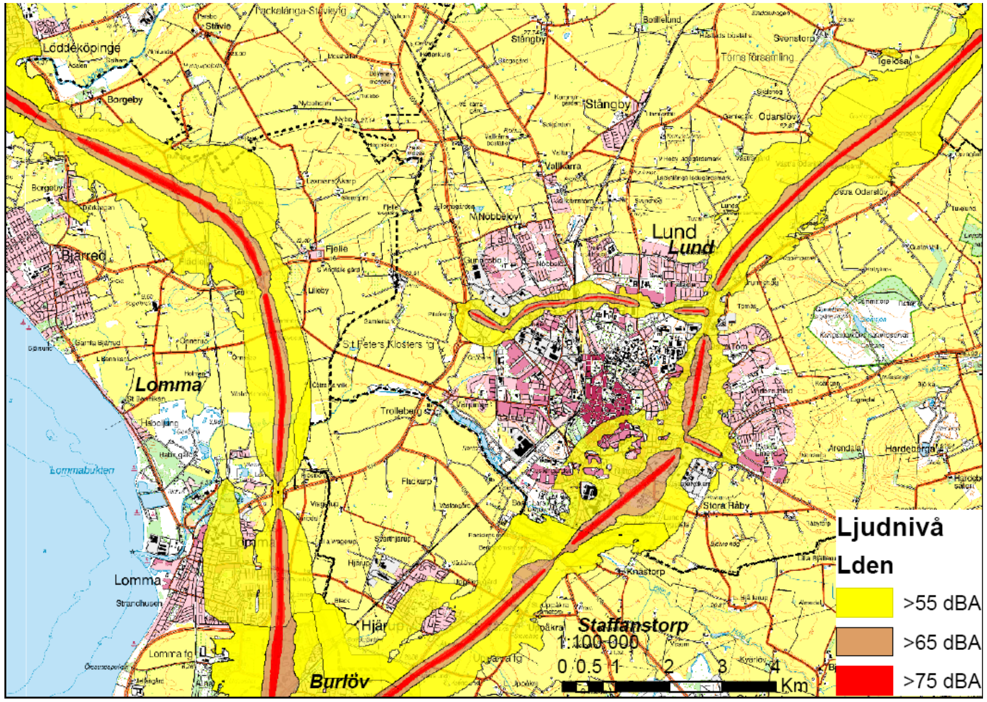
- Sound level meter
  - Microphone measures acoustic levels omni-directionally
  - Sampling: *Fast* (0.125 s), *Slow* (1 s), *Peak* (impulse value 35 ms)
  - Weighting filters (A, C…) built-in
  - Calculation of $L_{eq,T}$, building acoustic indicators, traffic noise…
  - Calibrated
  - *… more about this during labs and the "Measurement Techniques" lecture*



Regulations – Environmental noise

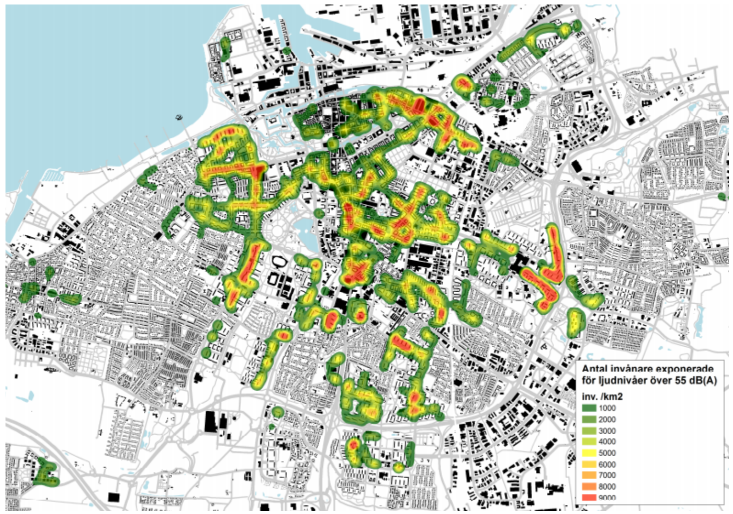
- Infrastrikturprop. 1996/97:53
- Noise-maps

Location	Measure	Road	Track	Flight
Indoors	$L_{Aeq,24h}$	30	30	30
Indoors	L_{AFmax}	45	45	45
Outside (façade)	$L_{Aeq,24h}$	55	60	55
Outside	L_{AFmax}	70	70	70



Malmö – actions for noise exposure 2014

- Citizens exposed to: >30 dBA indoors: 48 000
  >55 dBA outdoors: 126 000
- Estimated cost (incl. health care and loss of work): 1100 MSEK
- Proposed long term measures (250 MSEK):
  - Source: Lower speed limit, silent asphalt, driving style and silent car/tires
  - Sound reduction: Noise barriers, allowance for improvement of reduction at dwellings
  - Focus on sensitive places, e.g. schools, pre-schools and parks



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Outline

Course Information

Introduction to Acoustics

Summary

Summary

- Definition of sound
- Harmonic oscillations and complex notation
- Acoustic variables and levels
- Frequency domain representation
- Addition of correlated and uncorrelated sources

- Study from the literature
  - [1] A.D.Pierce, Acoustics: An Introduction to Its Physical Principles and Applications - Ch. 1, 2.
  - [2] T.E.Vigran, Building Acoustics - Ch. 3

← Our main reference and a bible for acoustics engineering in the Nordic countries.

Thank you for your attention!

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