Audio Measurements Workshop

Fons Adriaensen
Casa della Musica, Parma

- Techniques and tools to measure

  * Soundcards

  * Analog hardware

  * DSP software

- Theory

  * Levels, decibels, noise, calibration,...

- Tools

  * jaaa, jnoisemeter, jsignal,...

- Practice

- Why measure things ?

    * Verify your design and programming.

    * Have you been ripped off ?

    * To know limits and create a level of confidence.

    * Curiosity.

- Always expect the unexpected. It happens. If your measurements are exactly as you imagined they would be, then

    * Congratulations !

    * It's time to verify things and ask some questions.

- Audio measurements often involve a mix of electrical and acoustic units as well as purely numerical values, and conversions between them. This can be very confusing unless you have a solid grip on the basics.

- Signals

    * Levels, power, impedance, balancing, . . .

    * Measurement methods.

- Decibels.

    * Reference levels, . . .

- Acoustic units and levels.

- Noise.

    * Distribution, spectrum, density.

    * Measurement methods and standards.

    * Thermal noise.

    * Equivalent input noise.

- Understanding audio specs.

    * Microphones.

- Calibration.

- Measured in Volts (V).

  * Rough levels: mics: 1 mV, consumer: 100 mV, pro: 1 V.
  * Current: $i = u/Z$ (A).
  * Power: $P = i * u = u^2/Z = i^2 * Z$ (W).

- Analog audio connections are almost always voltage driven.

  * Input impedance is much higher than output impedance.
  * Allows splitting the signal without level changes.
  * Exception: long analog lines (rarely used today).

- For numerical signals (no physical units), 'power' means the square of amplitude.

- The 'gain' of AD and DA converters requires some care to define without ambiguity as one side uses physical units and the other not.

- Balanced connections:

  * Inputs take difference of two signals, cancels interference.

  * Different kinds of outputs and inputs are not always compatible.

- Outputs

  * Impedance balanced – very common.

  * Antiphase outputs – different variations.

  * Differential – rare.

  * Floating – requires transformer.

- Inputs:

  * Differential with unbalanced impedance – very common.

  * Differential with balanced impedance.

  * Floating — requires transformer.

  * Common mode rejection of input defines performance.

ζ

impedance balanced

antiphase outputs

antiphase outputs

+G

-G

-1

differential

+ x

+ x

transformer balanced

+ x

+ x
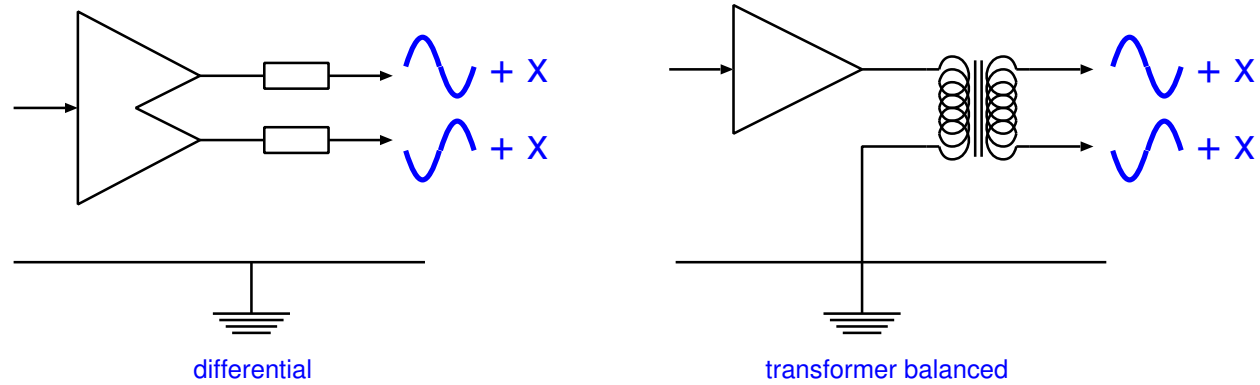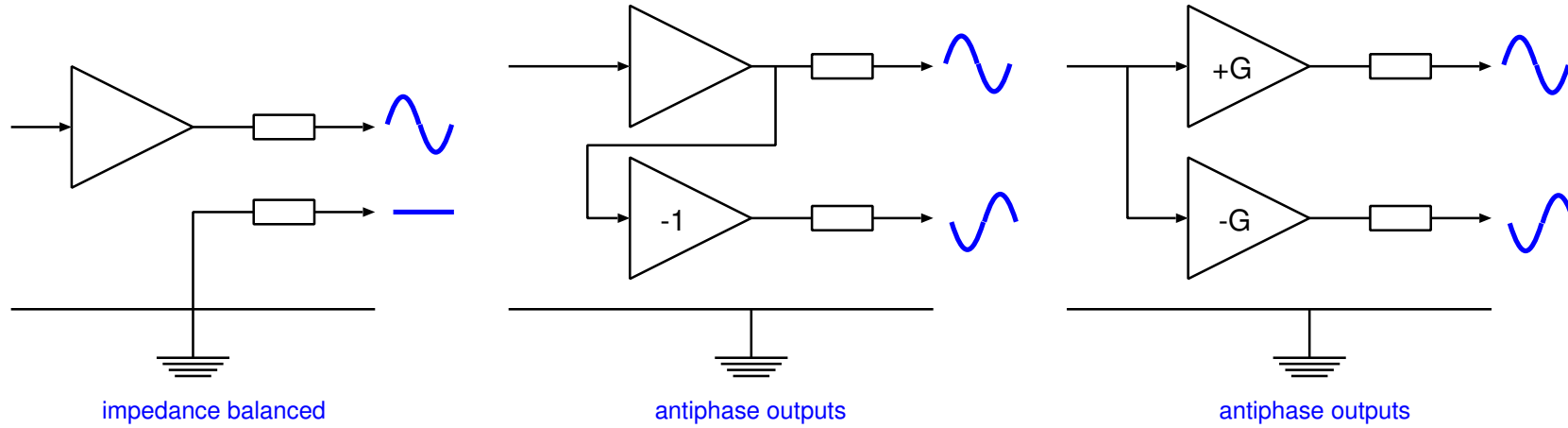
- A 'perfect' differential input ignores the common signal.

- Real-life balanced inputs are not perfect.

- The Common Mode Rejection Ratio indicates
  by how much the common signal is attenuated.

- CMRR is usually a function of frequency.

- Typical figures:

  * Cheap: 20...25 dB

  * Reasonable: 40 dB

  * Transformer balanced: 80...90 dB

- Common mode signals can be the source of large errors.

- Common mode input or output impedances are usually
  not the same as the differential impedance.
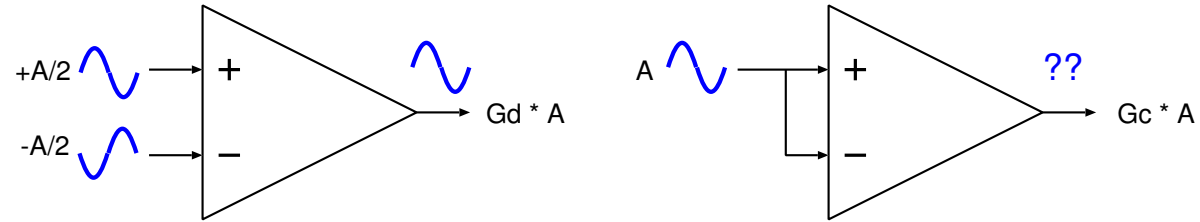
CMRR = Common Mode Rejection Ratio = Gd / abs (Gc)
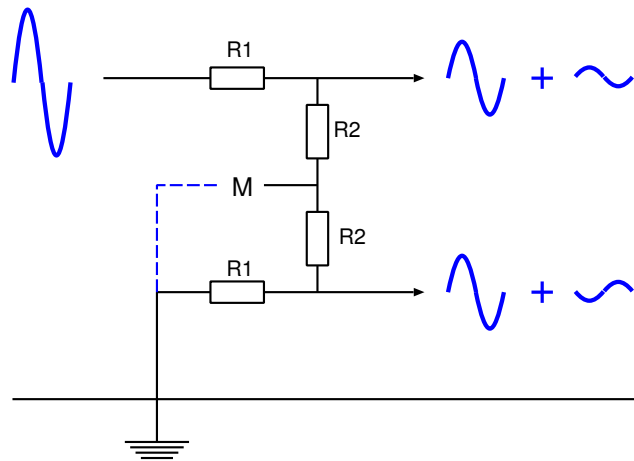
Unbalanced signal with balanced attenuator.
If M is not connected to ground the common mode signal is not attenuated.

- Defined by filter, detector, ballistics.

- Filter: flat, lowpass, A, C, ITU 468,...

- Detector: what is measured.

  * Peak or pseudo peak value.
  * Average of absolute value.
  * RMS.

- Ballistics: response to level variations.

  * Rise and fallback times.
  * Burst response, can be different from rise time.

- RMS = Root Mean Square =

    * The square root of the average value of the square of the signal.

    * The average power expressed as an amplitude.

- The RMS value is independent of the relative phases of the different frequencies in a signal.

- 'Mean' or 'average' means some form of lowpass filter:

    * Rectangular window.

    * First or second order IIR, which is an exponential window.

- AC voltages are always shown as an RMS value, even if the meter is not an RMS one. In that case the measured value is correct only when the signal is a sine wave (e.g. almost all multimeters, VU, . . .)

- Logarithmic unit used to indicate ratios.

- 1 dB = 0.1 Bell. One Bell is a ratio of 10 to 1.

- Always a ratio of powers or something proportional to power.

    10 * log10 (ratio of powers)
    20 * log10 (ratio of amplitudes)

- Absolute measurements require a reference value.

- Memo trick: the 1/3 octave band frequencies: 1, 1.25, 1.6, 2, 2.5, 3.16, 4, 5, 6.3, 8, 10. Each step is 1 dB for powers or 2 dB for amplitudes.

- 0 dBm = a power of 1 mW. A standard impedance is assumed.

  * Audio: usually 600 ohm
  * RF: 50 or 75 ohm.

- 0 dBu = 0.7746 Volt, the voltage corresponding to 1 mW in 600 ohm. Quite often 'dBm' is used when 'dBu' is meant.

- 0 dBV = 1 Volt. Simple and easy. 0 dBV = +2.22 dBu.

- 0 dB FS = the amplitude of a maximum level sine wave in a digital system.

  If this is RMS, and the range is ± 1, then the actual RMS amplitude of a sine wave at 0 dB FS is not 1 but sqrt (0.5) = 0.7071.

- Sound Pressure Level (SPL) is measured in Pascal (Pa).

- 0 dB SPL = an RMS sound pressure of 2 * 10^{-5} Pascal.

  * This is the threshold of human hearing at 1 kHz.
  * A sound pressure of 1 Pa is +94 dB SPL.

- For electrical signals we have $i = u/R$ and $P = u * i = u^2/R$.

- For acoustic signals we have $v = p/Z$ and $I = p * v = p^2/Z$.

  * p = sound pressure (Pa)
  * v = particle velocity (m / s)
  * Z = acoustic impedance (N s / m^3)
  * I = acoustic intensity (W / m^2)

- The acoustic impedance of air at 20 degrees Celsius is 413.3 N s / m^3.

- Note: electrical current and power are scalars, but particale velocity and intensity are vectors – they have a direction.

We have a sound source with an acoustic power of 1 Watt.
What is the SPL at a distance of 3 meters ?

- The power is spread over the surface of a sphere with radius 3 m.

- This surface is $4 * \pi * R^2$ or 113.1 m^2.

- So the intensity I is 1 W / 113.1 m^2, or 8.842e-3 W / m^2.

- Now $I = p^2/Z$, or $p = \sqrt{I * Z}$.

- Hence the pressure is sqrt $(8.842e\text{-}3 * 413.3) = 1.91$ Pa.

- 1.91 Pa $= 20 * \log10 (1.91) + 94 = 99.6$ dB SPL.

We have an SPL of 1 Pa (+94 dB) and a microphone with a membrane of 5 cm^2 (1 inch diameter). How much acoustic power does the mic receive ?

- $I = p^2/Z = 1 / 413.3$ W / m^2.

- $P = I * S$ ($S =$ surface area) so

- Power $=$ 5e-4 / 413.3 $=$ 1.21e-6 Watt

- This should be compared to thermal noise power (later).

- A random or pseudo random signal.

- Probabilty distribution

  - Rectangular, Gaussian,...
  - We normally don't hear differences in distribution.
  - A sum of many independent random values will have a Gaussian distribution.
  - Filtered noise tends to have a Gaussian distribution.

- Density spectrum

  - Noise density $N_0 =$ power per Hz.
  - At any particular frequency there is zero power.
  - White noise: constant density. $P = B * N_0$
  - Pink noise: density proportional to $1/F$.
  - White and pink noise must be limited in bandwidth, or they would have either infinite power or zero density.

ζ

- Requires either a true RMS meter, or one that is very tightly specified.

- Meter ballistics must be slow to have a stable value.

- Usually weighted using a standard frequency response.

- If no other filter is used the bandwidth must be defined.

- A number without specified measurement method is meaningless.

- Standard methods

  * 20 kHz equivalent bandwidth + RMS   dB(20kHz)
  * IEC-A filter + RMS   dB(A)
  * IEC-C filter + RMS   dB(C).
  * ITU468 filter and pseudo-peak meter   dB(ITU468)

- dB(A) is typically 1.9 dB lower than 20 kHz equivalent BW.
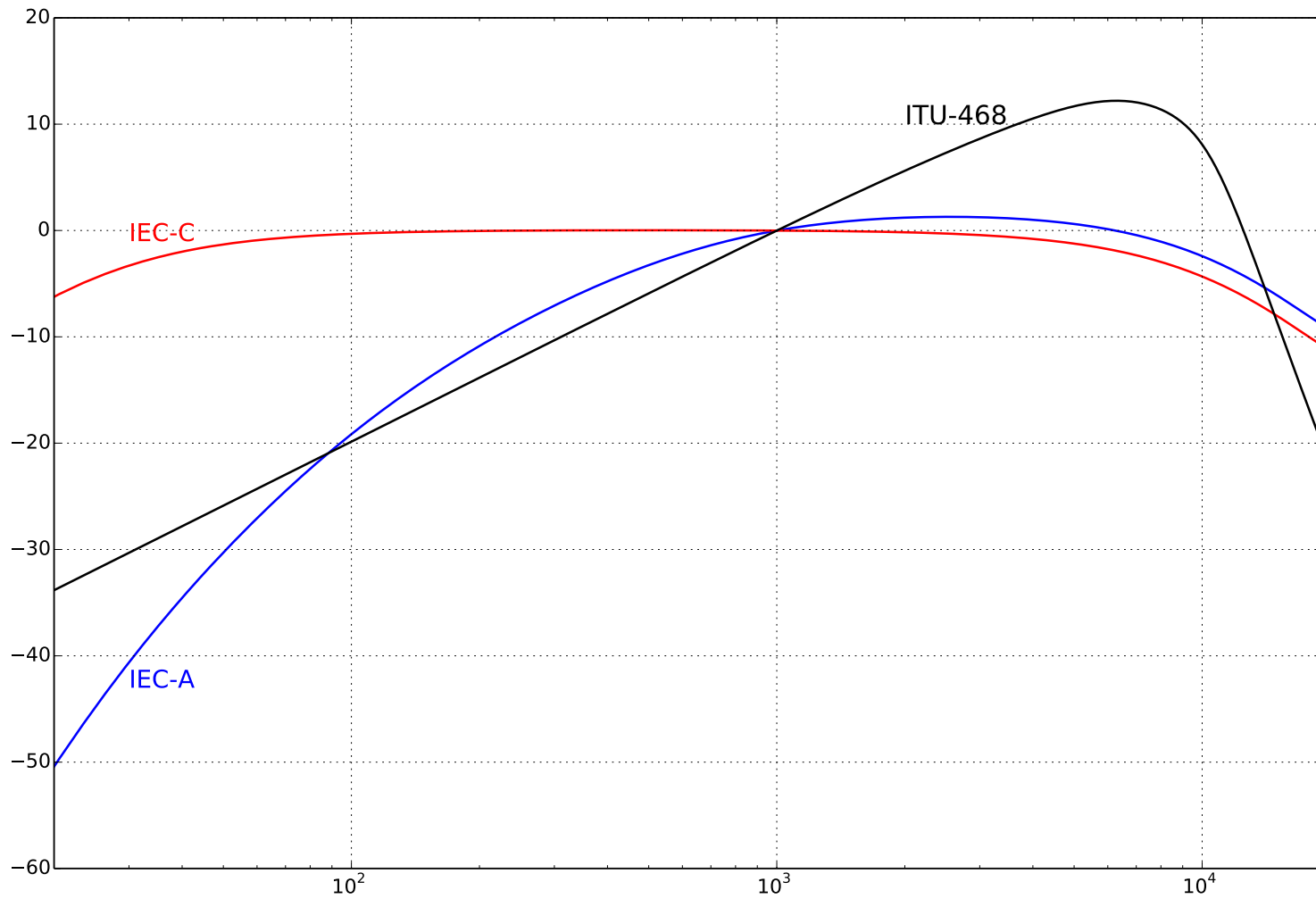
- The 'best' method for measuring mics and mic preamps.

- Originally developed to measure noise on long analog audio lines.

- Filter emphasizes the most critical frequency region.

- Pseudo-peak meter having

  * a very slow response, as required for noise,

  * but very sensitive to short bursts and impulsive noise
    e.g. from a switching power supply or digital electronics.

- Typical measured values are around 9 dB higher than A-weighted.

- Used mostly in Europe, Americans use dB(A) because it looks better.

- The 'Dolby variant' uses lower gain and an average meter, but it is not and official standard.
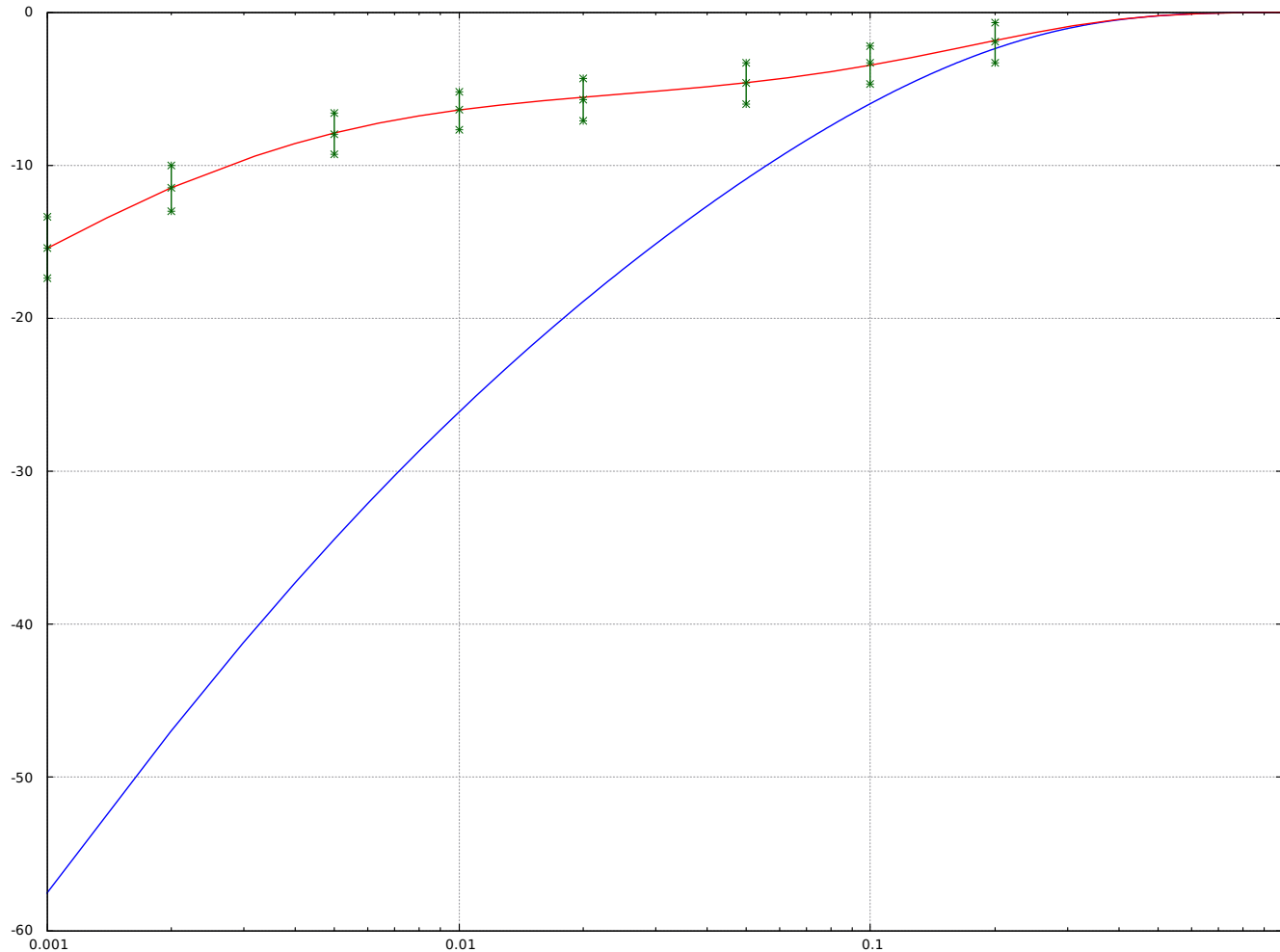
Step response and ■ burst response of the ITU468 meter.
■ Burst response specification.

ζ

- Aka Johnson or Nyquist noise. Generated by thermal motion of electric charge carriers in all conductors.

- Essentially white (up to very high frequencies).

- Power density is proportional to absolute temperature.

- Power $P = 4kBT$

  - $k =$ Boltzmann's constant, 1.381 * 10^{-23} Joule / Kelvin
  - $B =$ Bandwidth in Hz
  - $T =$ Temperature in Kelvin.

- At room temperature and a BW of 20 kHz this means
  * Power $P = 3.24 * 10^{-16}$ Watt
  * RMS voltage $v_n = 18$ nV * $\sqrt{R}$
  * For R = 150 ohm v_n is 220 nV = -133.1 dBV = -130.9 dBu

- Other noise sources are present in real-life electronics, but mostly at low frequencies (below 100 Hz).

- All components of an electronic circuit generate thermal noise.

- It is always possible to model an amplifier or an AD converter as a 'perfect' noiseless one with a single noise source at the input.

- EIN = noise measured at the output / gain.

- The noise generated near the input will contribute most, as it is amplified.

- For a well-designed amplifier, EIN will be independent of gain as long as the gain is high.

- Other low level signals may be present (e.g. 50 or 60 Hz and harmonics).

ζ

- The EIN of mic preamps is usually measured with at maximum gain with a source impedance of 150 ohm.

- Some preamps can be a dB or so less noisy when measured with a lower impedance source or short-circuit.

- The EIN can be compared to the self-noise of the mic to find out which generates most noise.

- Some example values:
  note: 150 ohm generates -135 dBV(A)

Preamp	EIN dBV(A)
RME Micstasy	-131.2
Aphex 1788A	-129.0
Sony SPR-V110	-133.5
Behringer PRO8	-132.9
Edirol UA5	-122.2

A   Gain = 1 + R1 / R2   B
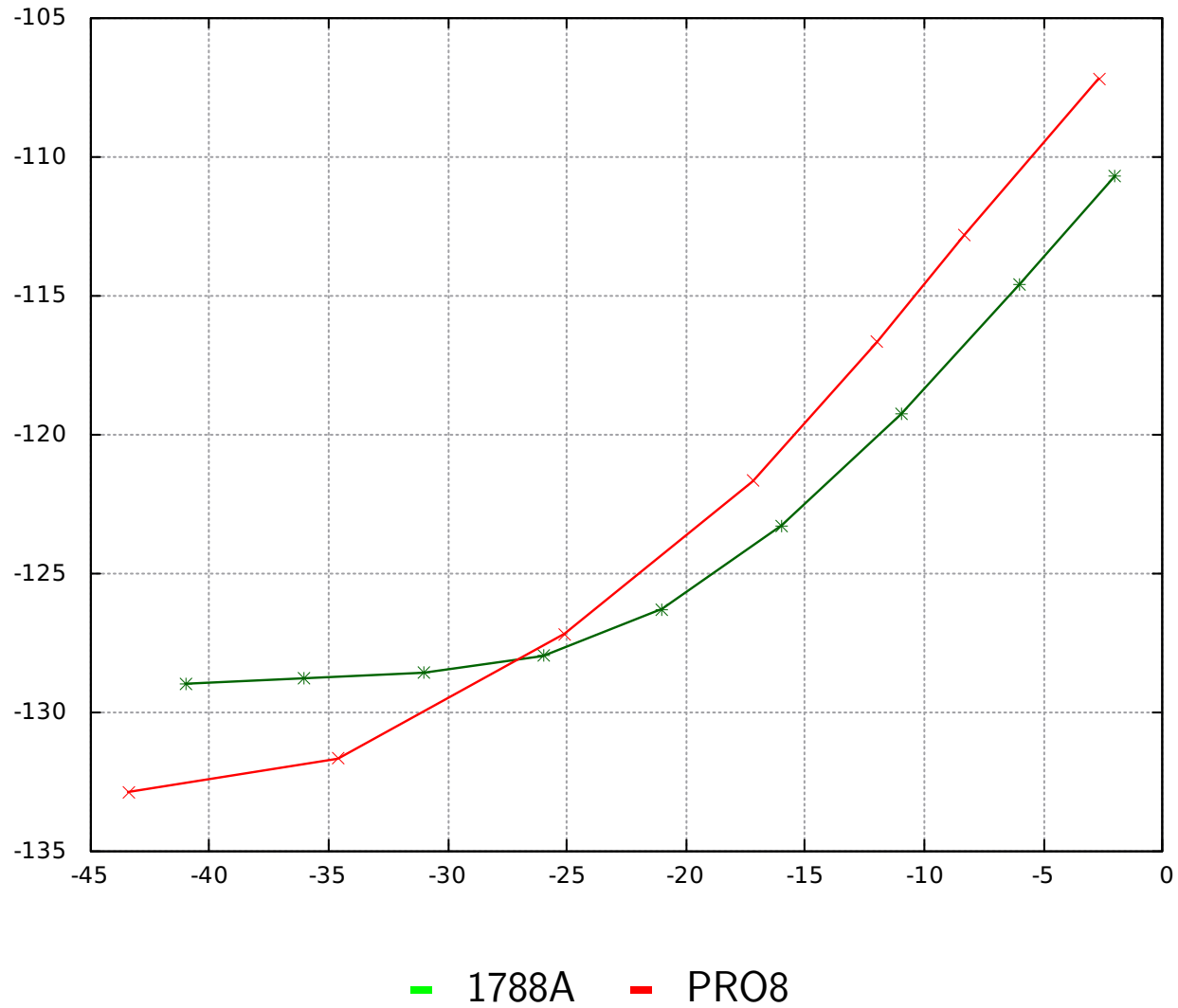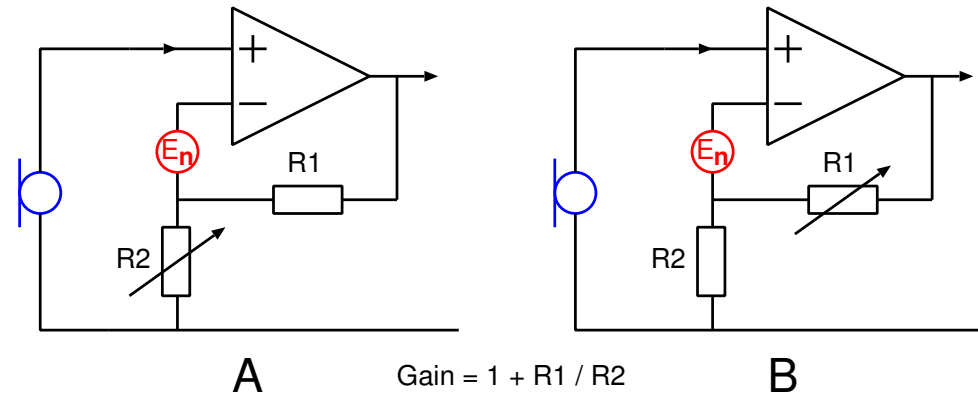
$$
\begin{aligned}
E_n \;=\; & \text{thermal noise due to R1 } \| \text{ R2} \\
+\; & \text{amplifier input noise voltage} \\
+\; & \text{amplifier input noise current } \times \text{R1 } \| \text{ R2}
\end{aligned}
$$

- Except at low gains, R2 $\ll$ R1 and R1$\|$R2 $\simeq$ R2.

- A: For lower gain R2 increases and E_n increases.

- B: R2 is fixed and E_n is almost constant.

- Very few manufacturers of 'prosumer' HW provide specs that have any real meaning, or that can be compared to others. This is of course entirely intentional.

- Example: M-Audio 'octane technology' mic inputs. All you are supposed to know about those is: signal/noise ratio = 97 dB.

- Specs that don't define measurement conditions are completely useless.

- Even levels are ambiguous. In pro audio +4 dBu is the 'work level', peak level is at least 15 dB higher. Yet cards that can be switched between a peak output of -10 dBu and +4 dBu are presented as supporting pro signal levels.

- Most equipment reviews that can be found on the web don't verify or even mention any technical specs. They are at best useless, if not completely bogus (the author got a free sample).

- If specs are not completely unambiguous, the only sane reaction is to mistrust them, and spend your money on something else.

- When recording low-level signal (acoustic instruments, voice, natural sounds, . . .) the combination of microphone and preamp will determine performance.

- The important values are sensitivity and self-noise.

- Sensitivity is usually specified as the output for 1 Pa (+94 dB) SPL.

- Self noise is the acoustic level corresponding to the noise generated by the microphone, usually dB(A) or dB(ITU468).

- Comparing specs for dynamic and condensor mics may require some calculations.

- Sensitivity and impedance are specified. Self noise is thermal noise corresponding to impedance. Given sensitiviy, this can be converted to SPL.

- Example: Beyer M160: 1.0 mV/Pa, 200 ohm.

    1.0 mV = -60 dBV.

    Thermal noise is 18 nV * $\sqrt{200}$ = 254 nV = -131.9 dBV.

    Self noise is -131.9 + 94 + 60 dB = 22.1 dB = 20.2 dB(A).

- Example: Shure SM58: 1.85 mV/Pa, 300 ohm.

    1.85 mV = -54.7 dBV

    Thermal noise is 18 nV * $\sqrt{300}$ = 312 nV = -130.1 dBV.

    Self noise is -130.1 + 94 + 54.7 dB = 18.6 dB = 16.7 dB(A).

- To use the full dynamic range a preamp with an EIN better than -130 dBV is required.

- Sensitivity and self noise and/or S/N ratio are specified. S/N ratio is relative to 1 Pa, so self noise + S/N ratio = +94 dB. Given sensitivity, either can be converted to noise voltage.

- Example: Neumann KM184: 15 mV/Pa, self noise 13 dB(A).

  15 mV = -36.5 dBV.

  Noise voltage = 13 - 36.5 - 94 dBV(A) = -117.5 dBV(A).

- Example: Neumann TLM103: 23 mV/Pa, self noise 7 dB(A).

  23 mV = -32.8 dBV.

  Noise voltage = 7 - 32.8 - 94 dBV(A) = -119.8 dBV(A).

- A preamp with an EIN of around -122 dBV(A) or better will allow the full dynamic range of these mics to be used.

Questions and answers, hands-on practice.