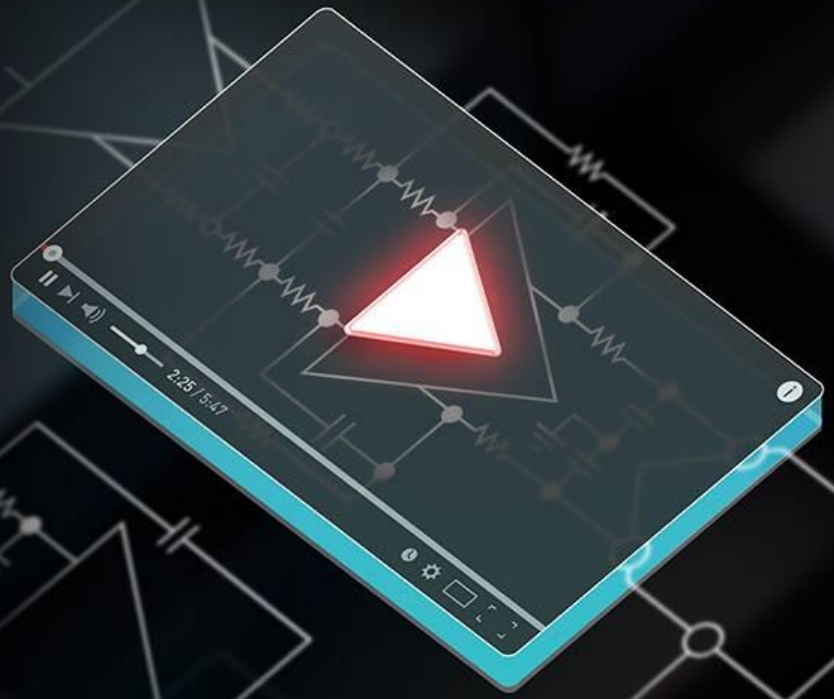
TI Precision Labs Seminar

Input voltage noise, input current noise and filtering techniques



Noise – 1 (calculation)

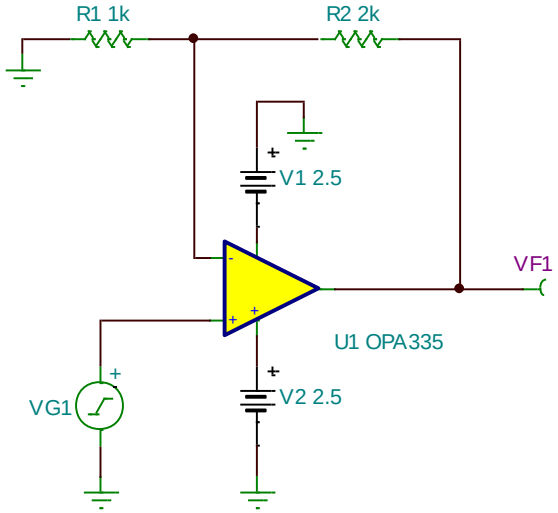
Intrinsic vs extrinsic noise

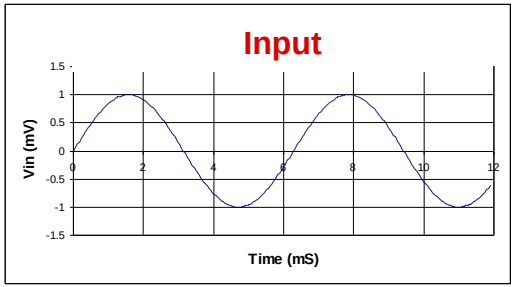
Intrinsic Noise

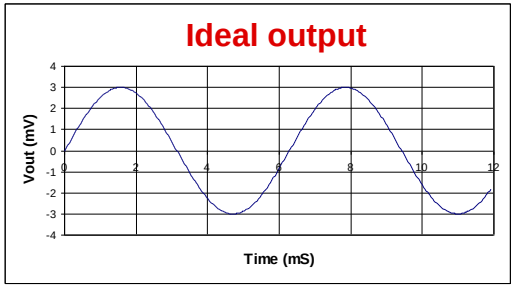
- From circuit components (e.g. resistors and amplifier)
- Specified in data sheet
- Can be predicted with calculations or simulations

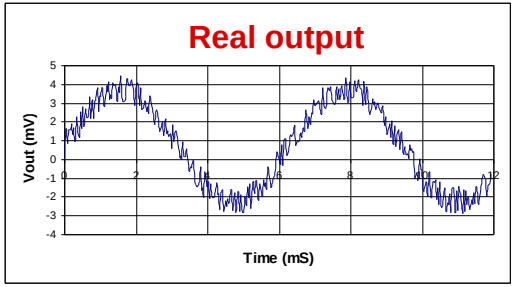
Extrinsic Noise

- From man-made sources (e.g. 60Hz, digital switching)
- Hard to predict
- Depends on interference source, and susceptibility of circuit

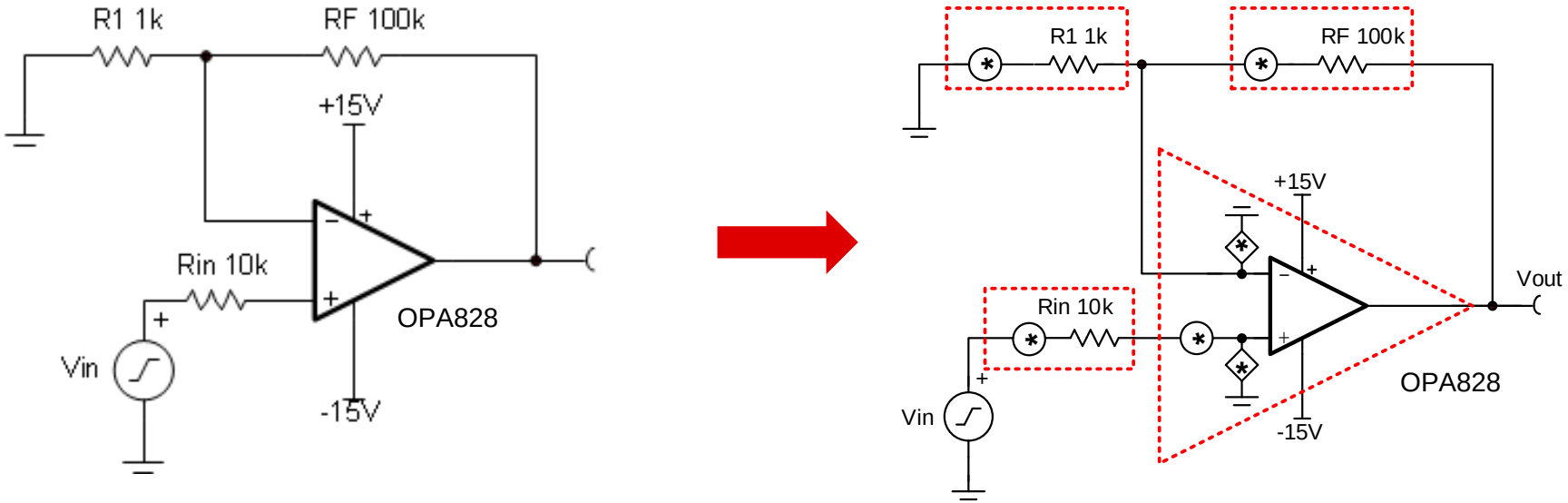




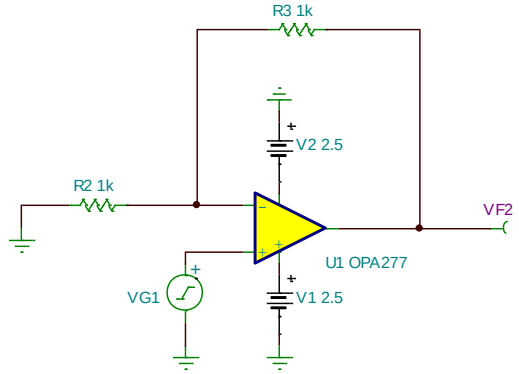


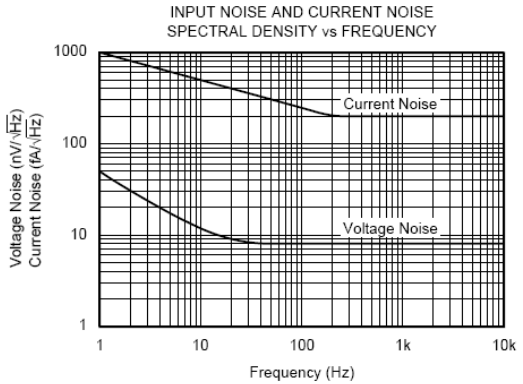


Noise: Model for amplifier and resistor



Noise analysis for simple op amp circuit





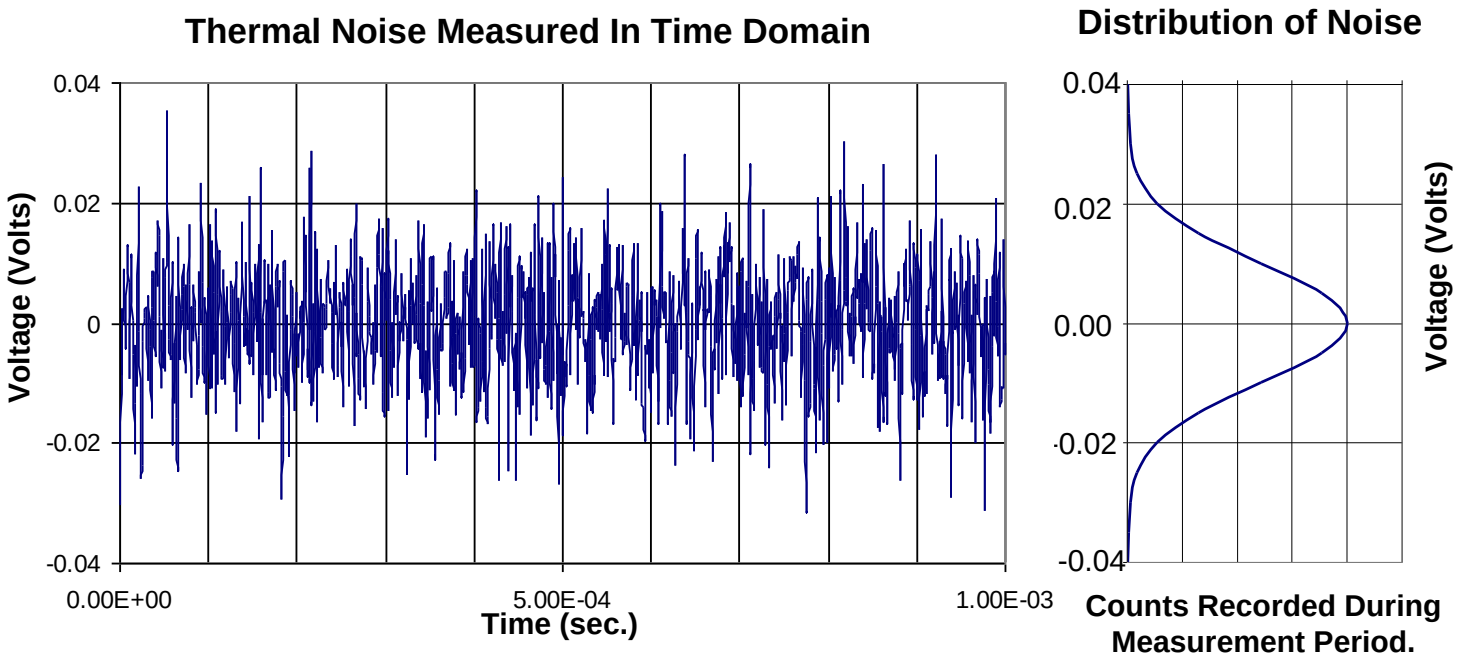
Noise sources

- Op amp voltage noise sources
- Op amp current noise sources
- Resistor noise

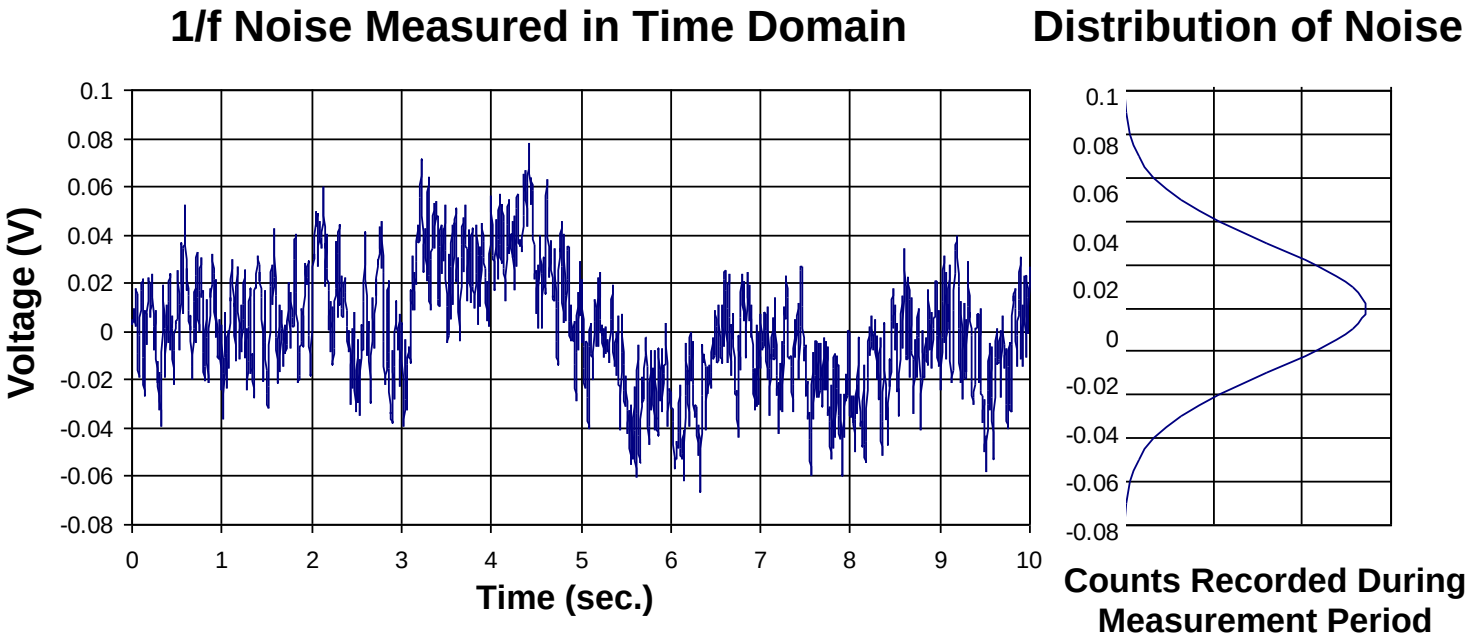
Calculation considerations

- Noise gain
- Noise bandwidth
- Convert spectral density to RMS
- Convert RMS

White noise (broadband noise)



1/f, flicker, or low frequency noise

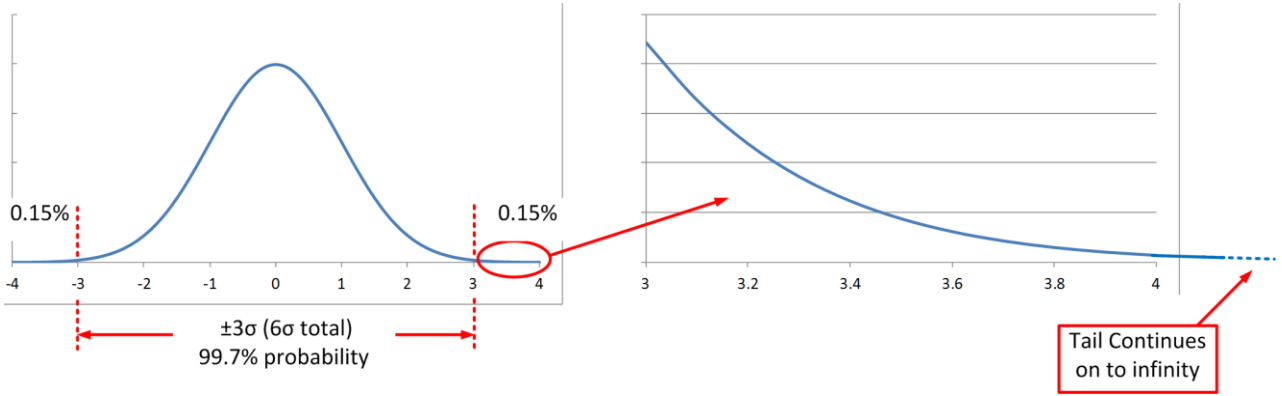


Commonly used terms

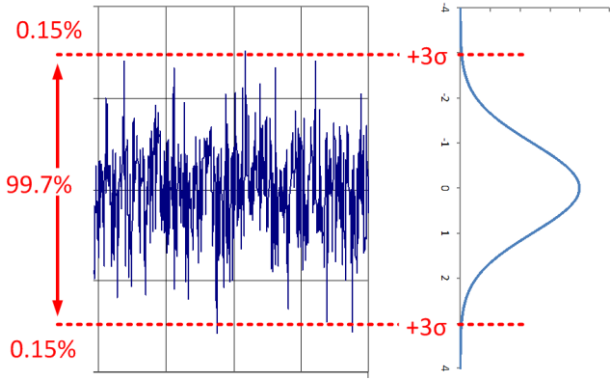
- **Broadband noise** – White noise, Johnson noise, Thermal noise, Resistor noise
- **1/f noise** – Pink noise, Flicker noise, Low frequency noise, Excess noise
- **Burst Noise** – Popcorn noise, Red noise random telegraph signals (RTS)

Strictly speaking, these terms are not 100% synonymous!

6σ estimate of peak-to-peak



6 x RMS ≈ peak-to-peak



Standard deviation relationship to peak-to-peak

Number of standard deviations	Percent chance of measuring voltage
2σ (same as ±1σ)	68.3%
3σ (same as ±1.5σ)	86.6%
4σ (same as ±2σ)	95.4%
5σ (same as ±2.5σ)	98.8%
6σ (same as ±3σ)	**99.7%**
6.6σ (same as ±3.3σ)	**99.9%**

Is standard deviation the same as RMS?

RMS vs. standard deviation (STDEV)

RMS = STDEV when the mean is zero (no DC component). Note that the two formulas are equal to each other if you set μ = 0 (zero average).

RMS

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2}$$

Where:

x_i – data samples

n – number of samples

Standard Deviation

$$\sigma = \sqrt{\sigma^2} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (x_i - \mu)^2}$$

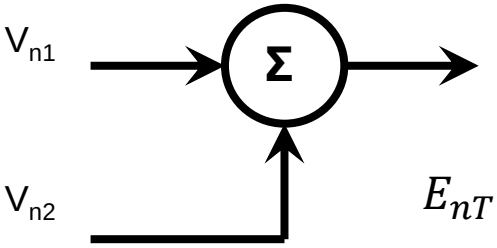
Where:

x_i – data samples

μ – average of all samples

n – number of samples

Vector addition of noise sources



$$E_{nT} = \sqrt{(E_{n1})^2 + (E_{n2})^2}$$

Uncorrelated noise

$$E_{nT} = \sqrt{(E_{n1})^2 + (E_{n2})^2 + 2CE_{n1}E_{n2}}$$

Noise with correlation factor

C = correlation factor from -1.0 to +1.0
Assume noise is uncorrelated unless otherwise known.

$$V_{n1} = 3mV_{RMS}$$

$$V_{n2} = 5mV_{RMS}$$

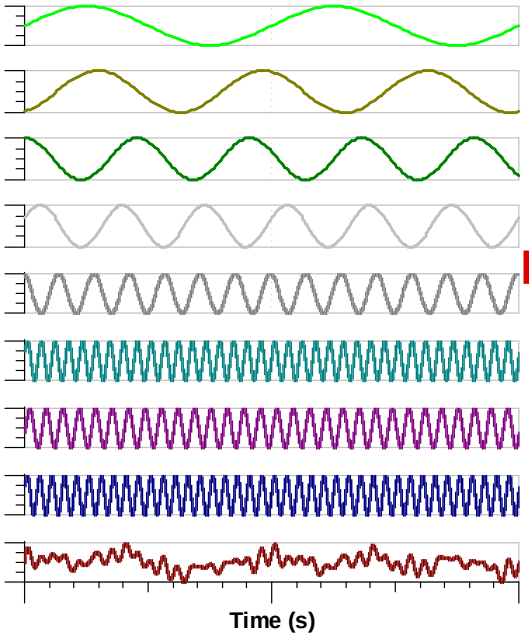
$$V_{nT} = \sqrt{V_{n1}^2 + V_{n2}^2} = \sqrt{3mV_{RMS}{}^2 + 5mV_{RMS}{}^2} = 5.83mV_{RMS}$$

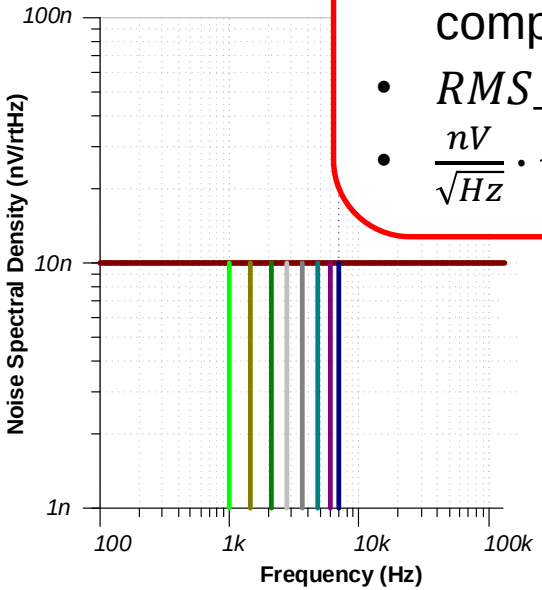
Rule of 3 for noise

When a noise source is 3 times greater than another source, the smaller source is negligible

$$\sqrt{3^2 + 1^2} = 3.162 \frac{nV}{\sqrt{Hz}}$$

What is spectral density?





- Noise density given in $nV/\sqrt{Hz}$, $fA/\sqrt{Hz}$, or $W/\sqrt{Hz}$
- Infinite number of sinusoidal components of equal amplitude
- $RMS\_Noise = NoiseDensity \cdot \sqrt{BW_n}$
- $\frac{nV}{\sqrt{Hz}} \cdot \sqrt{Hz} = nV$ ($\sqrt{Hz}$ cancels)

Resistor noise

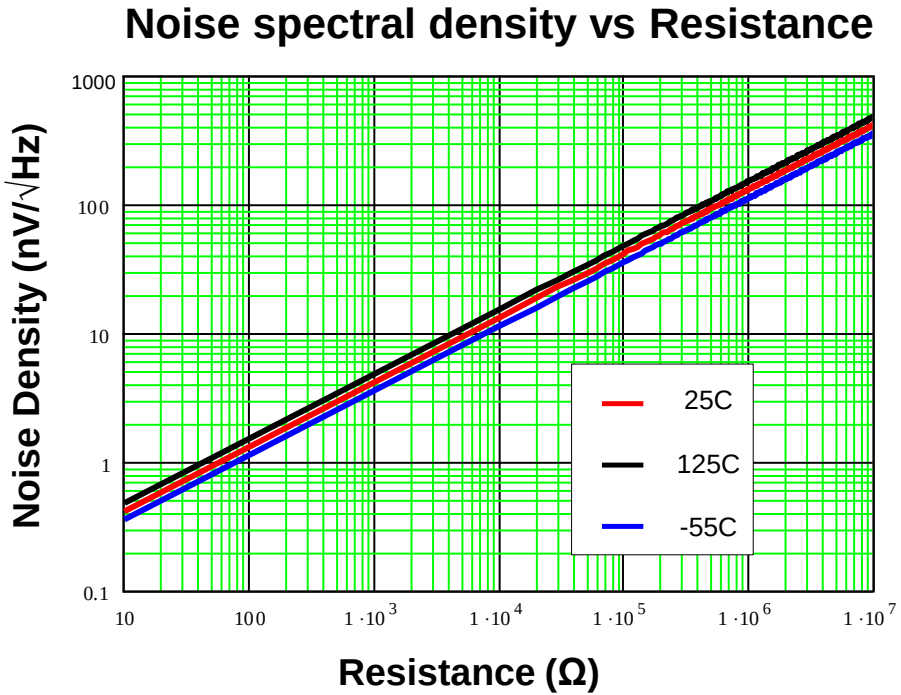
Voltage noise density:

$$e_{n_{density}} = \sqrt{4kT_K R}$$

Where:

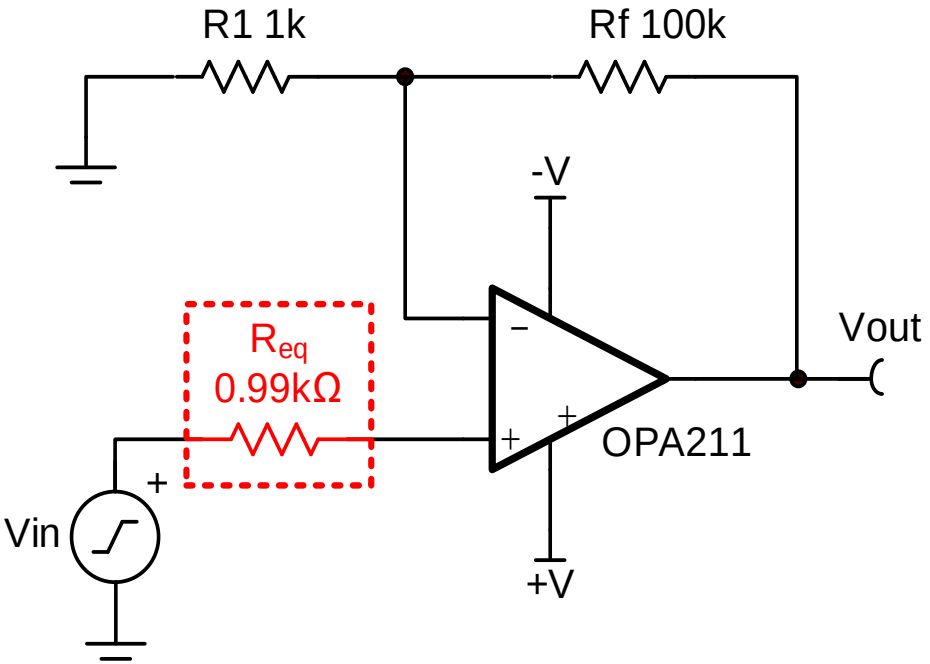
T_K	Temperature (K)
R	Resistance (Ω)
k	Boltzmann's constant (1.381E-23 joule/K)
$E_{density}$	Voltage noise spectral density ($V/\sqrt{Hz}$)

$$T_K = T_C + 273.15$$



Equivalent noise resistance

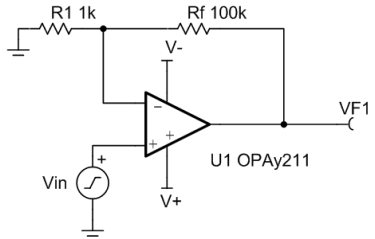
From a noise perspective (Rf||R1) act like a s resistor on non-inverting input.
This equivalent resistor is useful as amplifier noise defined at the non-inverting input



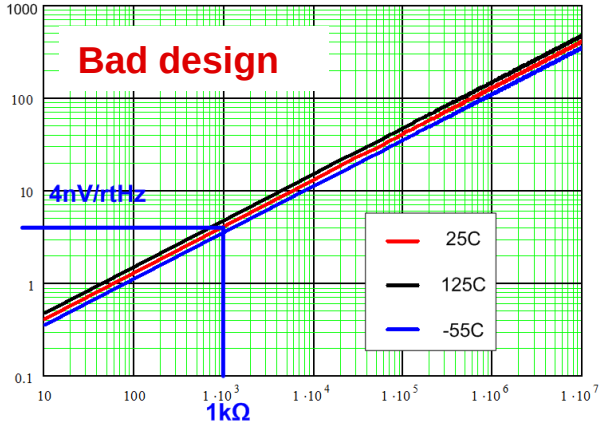
$R_{eq} = Rf \,||\, R1 = 0.99k\Omega \approx 1k\Omega$

Example: Resistor noise vs. op amp noise

Req = Rf || R1 = 0.99kΩ ≈ 1kΩ

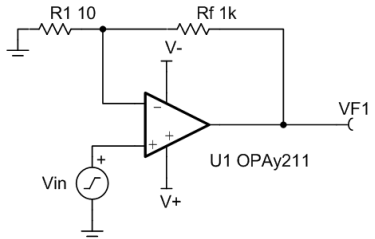


$e_{n\text{-}opa211}$ = 1.1nV/rtHz

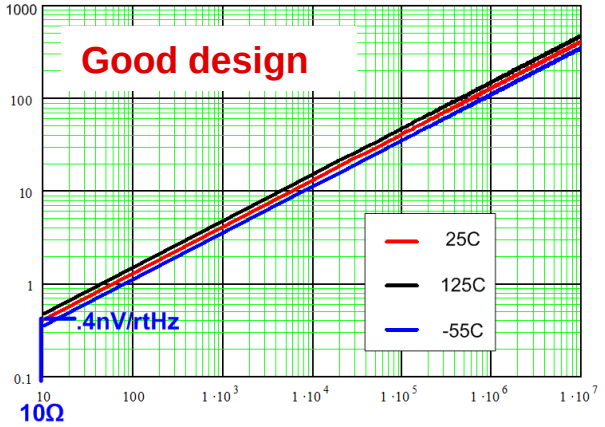


4nV/rtHz > 1.1nV/rtHz
so Resistor Noise dominates

Req = Rf || R1 = 9.9Ω ≈ 10Ω



$e_{n\text{-}opa211}$ = 1.1nV/rtHz

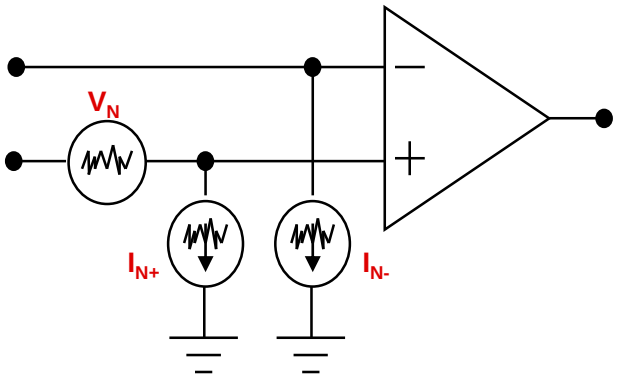


1.1nV/rtHz > 0.4nV/rtHz
so Op Amp Noise dominates

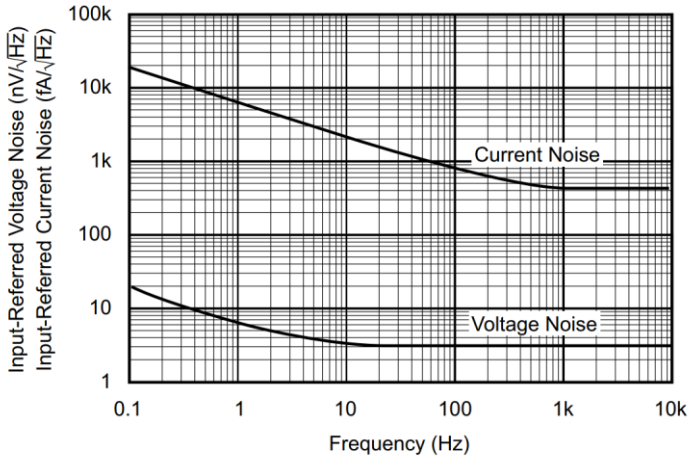
Op amp noise model

Noise model

(I_{N+} and I_{N-} are uncorrelated)



OPA227 data



Input Voltage and Current Noise Spectral Density vs Frequency

Noise gain for voltage noise source

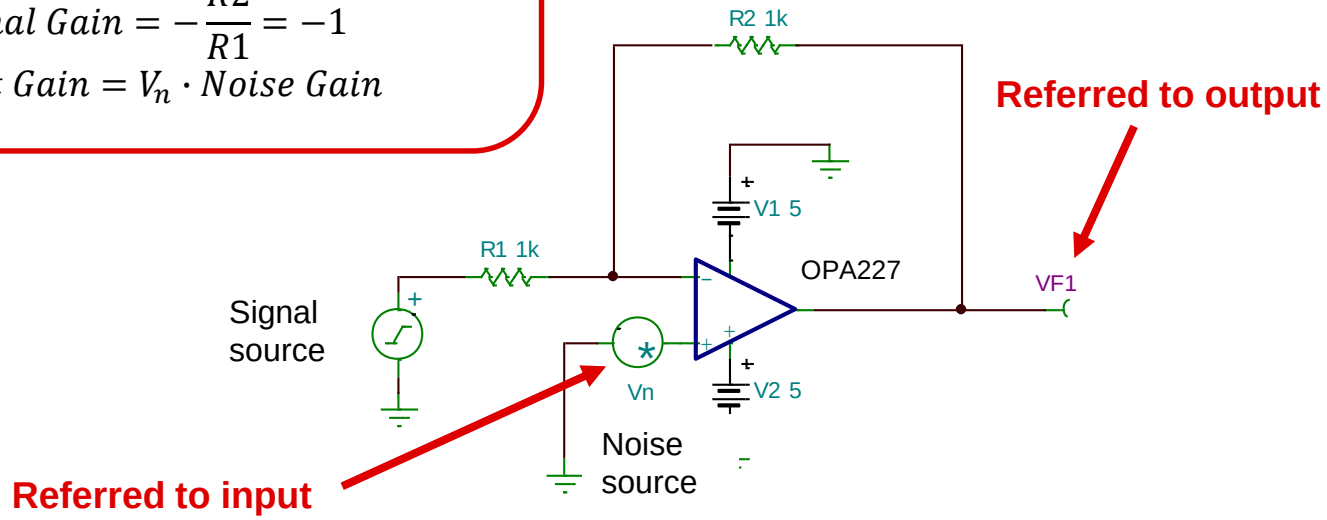
Noise gain – Gain seen by the noise source

Example:

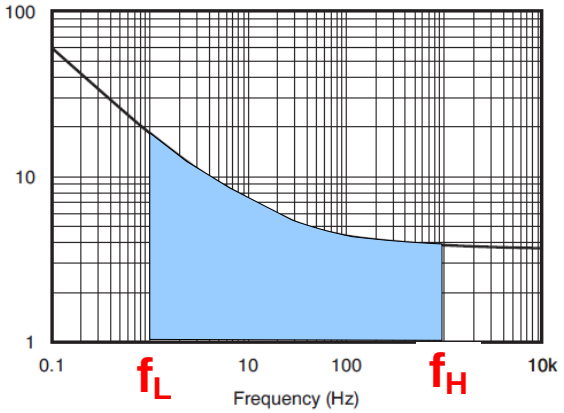
$$Noise\ Gain = \frac{R2}{R1} + 1 = 2$$

$$Signal\ Gain = -\frac{R2}{R1} = -1$$

$$Output\ Gain = V_n \cdot Noise\ Gain$$



Convert spectral density to peak-to-peak



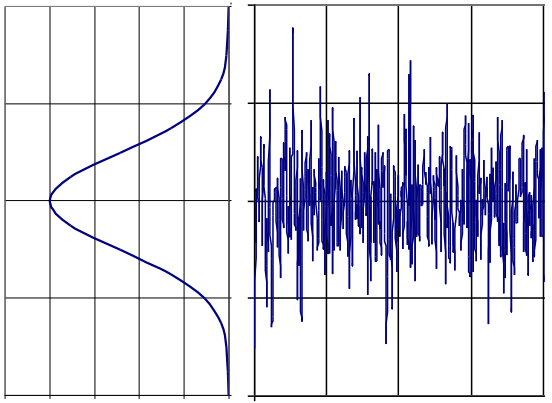
f_L f_H

Convert to RMS

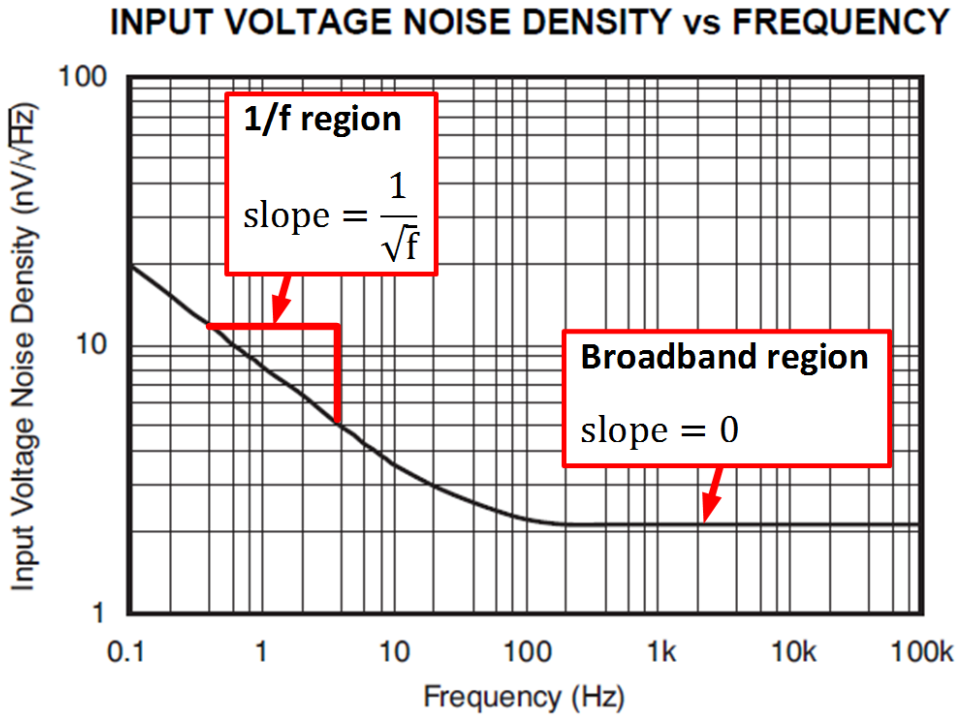
$$\sqrt{\int_{f_L}^{f_H} e_n^2 \, df} = E_{rms}$$

Convert to peak-to-peak

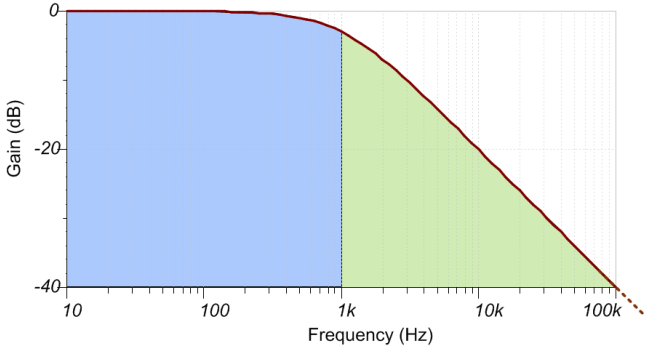
$$6 \cdot E_{rms} = E_{pp}$$



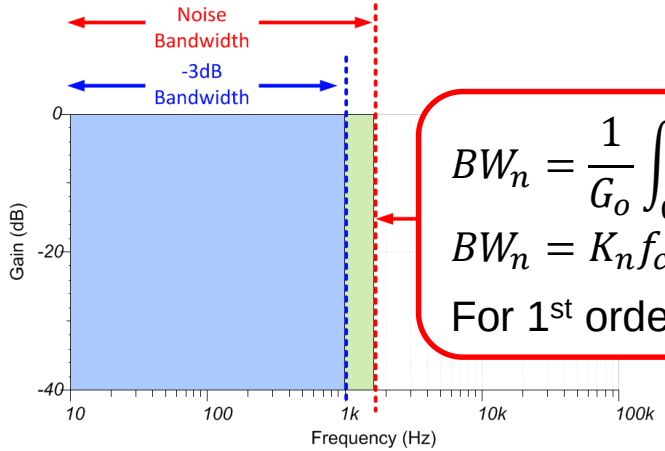
1/f and broadband region



Noise bandwidth: Brick wall filter



- Noise bandwidth accounts for all area under the gain curve.
- The equation below is used to develop a set of correction factors K_n for different filter orders (see next page).

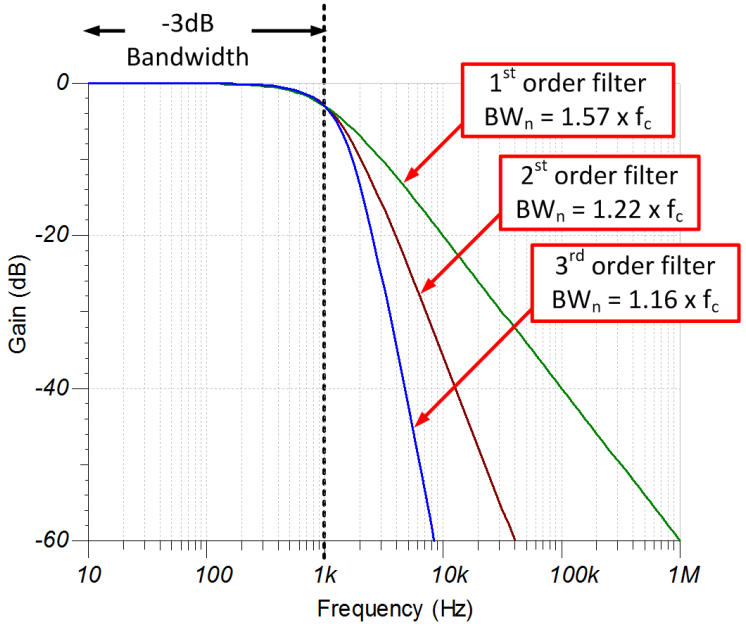


$$BW_n = \frac{1}{G_o}\int_0^\infty G(f)df$$

$$BW_n = K_n f_c$$

For 1st order $K_n = 1.57$

Noise bandwidth: Brick wall factor



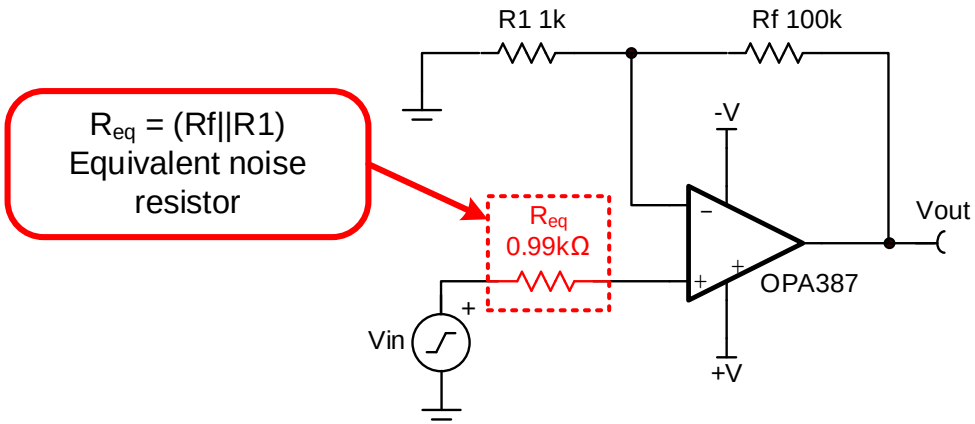
Noise bandwidth:

$BW_n = f_H * K_n$

Number of poles	K_n Brick wall correction factor
1	1.57
2	1.22
3	1.16
4	1.13
5	1.12

Noise bandwidth example

PARAMETER		TEST CONDITIONS	MIN	TYP	MAX	UNIT
OPA387 | OFFSET VOLTAGE						
GBW	Gain-bandwidth product			5.7		MHz



$$f_c = \frac{GBW}{Gain} = \frac{5.7MHz}{101} = 56.4kHz$$

$$BW_n = K_n \cdot f_c = (1.57) \cdot (56.4kHz)$$

$$BW_n = 88.6kHz$$

Broadband noise equations

$$BW_n = K_n * f_H$$

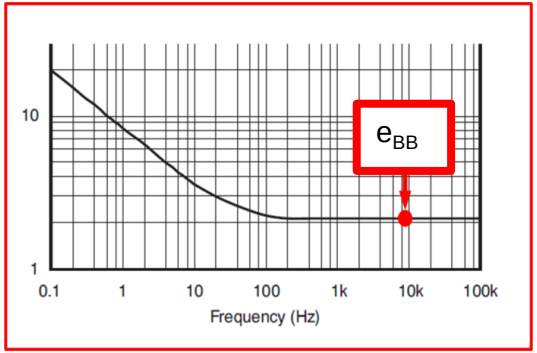
Where:

BW_n	Noise bandwidth (bandwidth of brick wall filter)
K_n	Brick wall correction factor, includes the “skirt” of the low pass filter
f_H	-3dB upper cutoff frequency

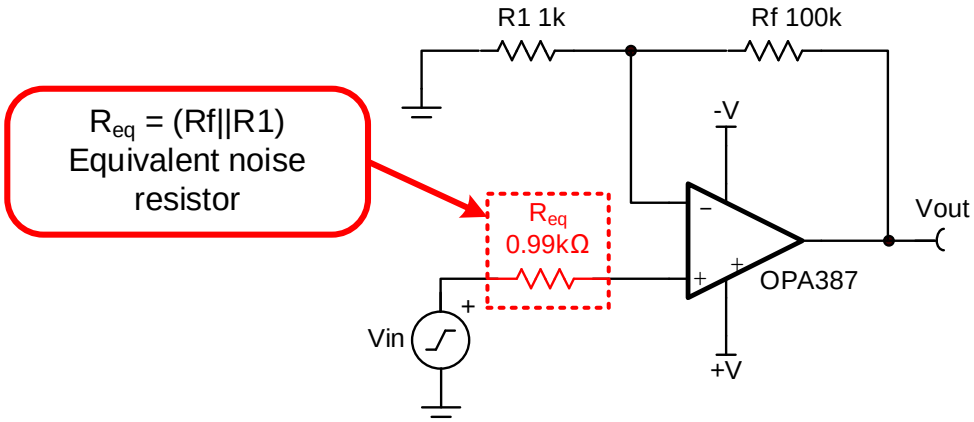
$$E_{n_{BB}} = e_{BB}\sqrt{BW_n}$$

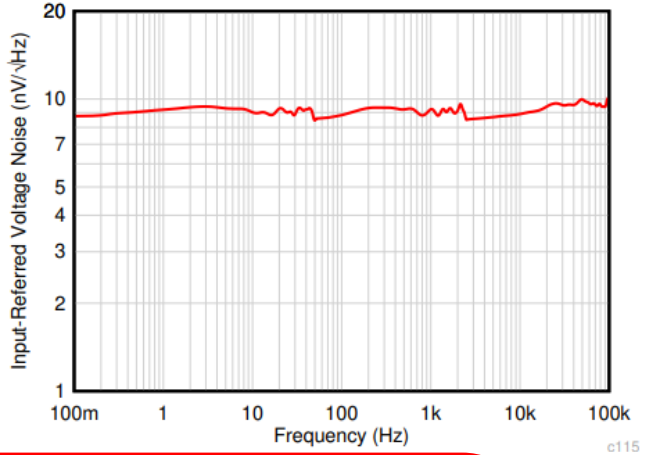
Where:

$E_{n_{BB}}$	Total RMS broadband noise
e_{BB}	Broadband voltage noise spectral density
BW_n	Noise bandwidth



Example: Calculating RMS broadband noise





$BW_n = 88.6kHz$ (from previous example)

$$e_n = \sqrt{(e_{nOPA})^2 + (e_{nReq})^2} = \sqrt{(9\,nV/\sqrt{Hz})^2 + (4\,nV/\sqrt{Hz})^2} = 9.8\,nV/\sqrt{Hz}$$

$$E_{nRTI} = e_n\sqrt{BW_n} = (9.8\,nV/\sqrt{Hz})\sqrt{88.6kHz} = 2.92\mu V\ RMS$$

$$E_{nRTO} = E_{nRTI}G_n = (2.92\mu V)(101) = 295\mu V\ RMS$$

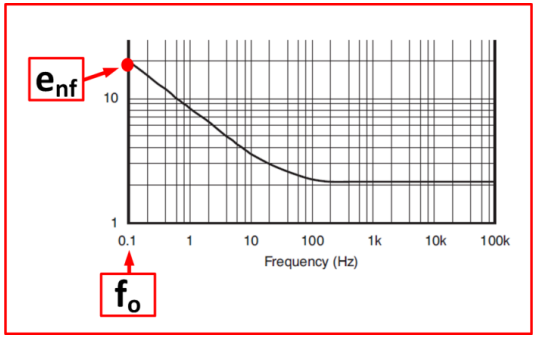
$$E_{nRTO(PP)} = 6E_{nRTO} = 1.77\text{mVpp}$$

1/f noise equations

$$e_{n_{normal}} = e_{nf}\sqrt{f_o}$$

Where:

$e_{n_{normal}}$	1/f voltage noise spectral density normalized to 1Hz
e_{nf}	Noise at lowest given frequency on the 1/f curve
f_o	Lowest given frequency on the 1/f curve



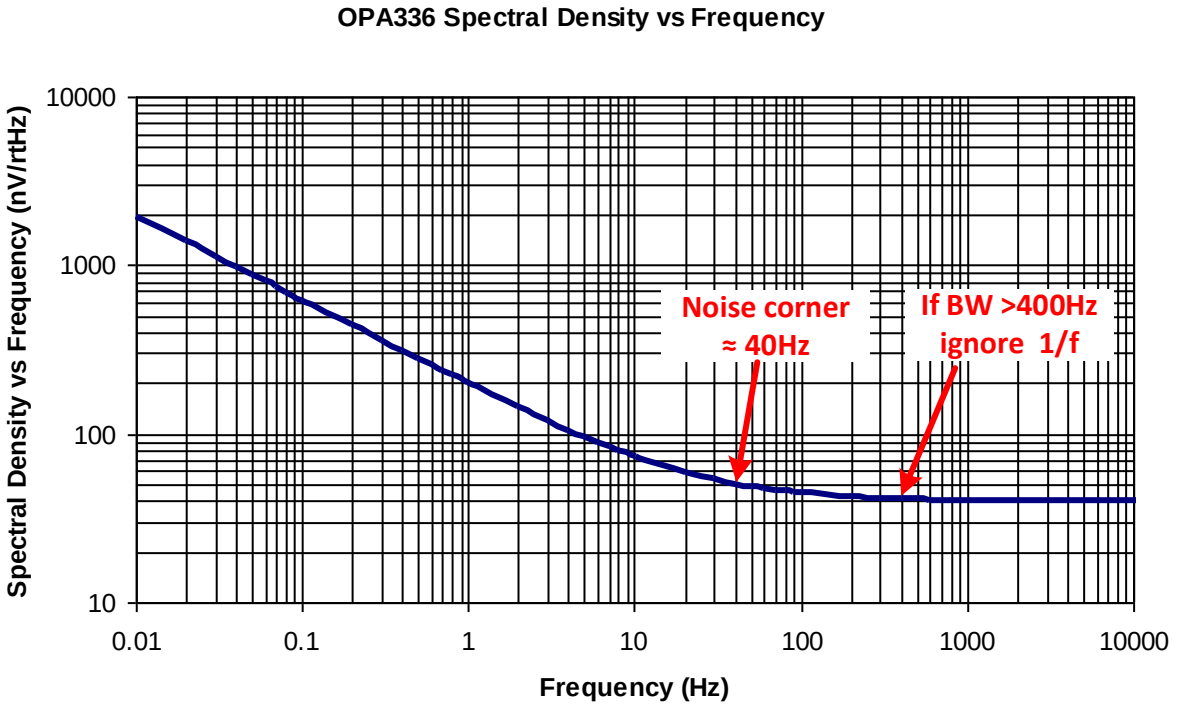
$$E_{n_{flicker}} = e_{n_{normal}}\sqrt{\ln\left(\frac{f_H}{f_L}\right)}$$

Where:

$E_{n_{flicker}}$	Total RMS 1/f noise
$e_{n_{normal}}$	1/f voltage noise spectral density normalized to 1Hz
f_H	Upper cutoff frequency
f_L	Lower cutoff frequency (typically set to 0.1Hz)

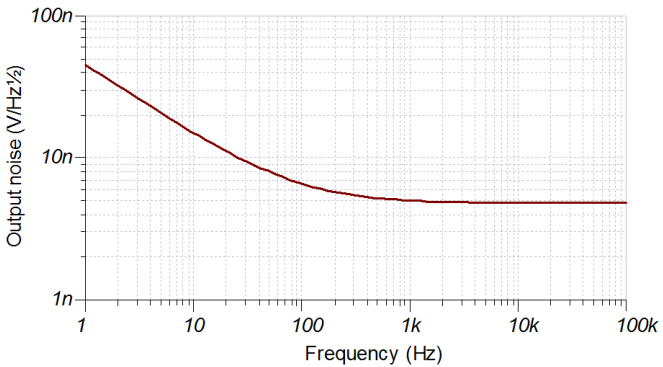
When does the flat 1/f noise matter

If the closed loop bandwidth is one decade beyond the noise corner, 1/f noise can be ignored and broadband will dominate.

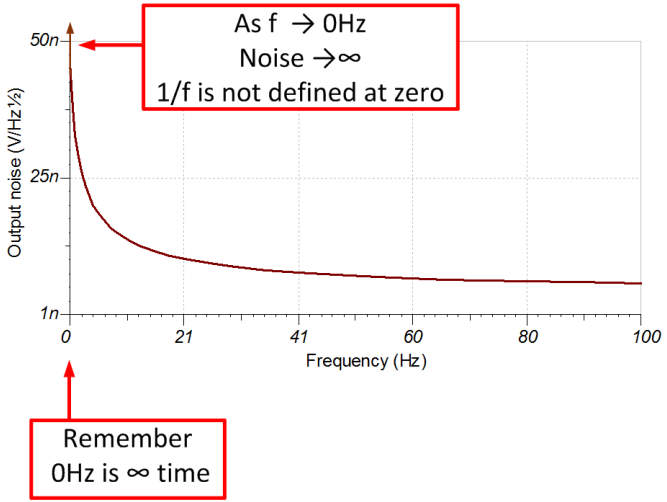


1/f noise on a linear axis

Logarithmic x-axis



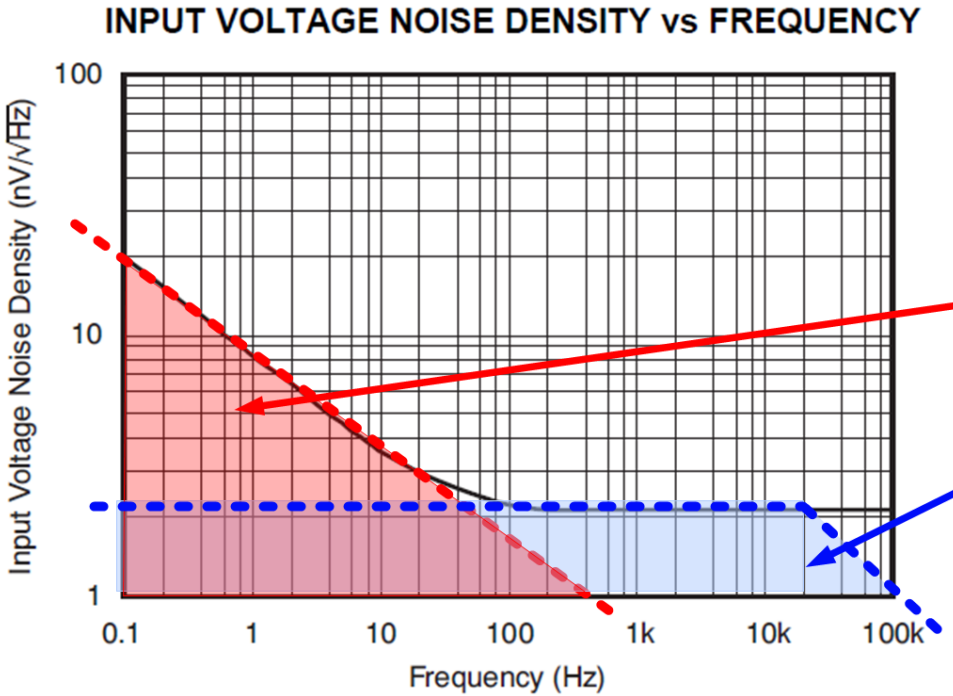
Linear x-axis



1/f Voltage Noise Component:

$$E_{n_{flicker}} = e_{n_{normal}} \sqrt{\ln\left(\frac{f_H}{f_L}\right)}$$

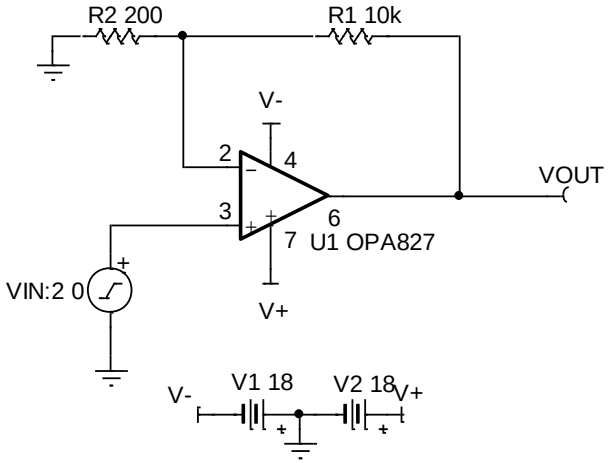
Combining 1/f and broadband



$$E_{nTotal} = \sqrt{E_{nFlicker}^2 + E_{nBB}^2}$$

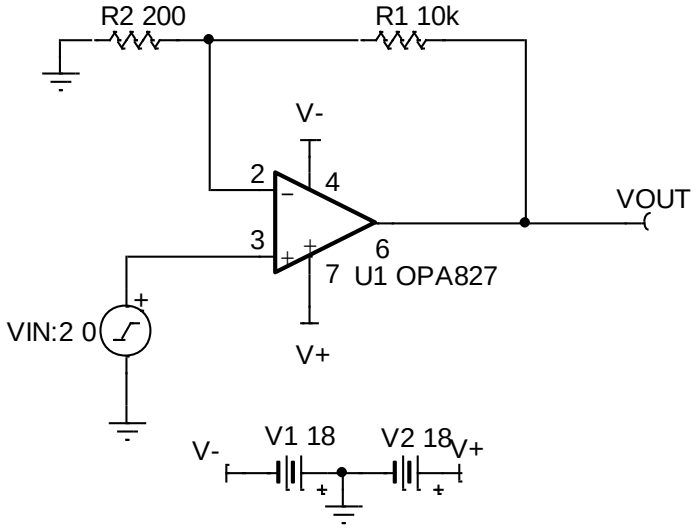
Calculation exercise

1. Find the total noise due to:
   a. Resistance
   b. Op amp broadband voltage noise
   c. Op amp 1/f voltage noise
   d. Op amp current noise
   e. Compute the total combined noise



Solutions

a. Resistance



$$k_n = 1.38 \cdot 10^{-23}$$

$$T_n = 273.15 + 25 = 298.15$$

$$R_n = \frac{R_f \cdot R_1}{R_f + R_1} = \frac{10k\Omega \cdot 200\Omega}{10k\Omega + 200\Omega} = 196\Omega$$

$$G_n = \frac{R_f}{R_1} + 1 = \frac{10k\Omega}{200\Omega} + 1 = 51$$

$$F_c = \frac{GBW}{G_n} = \frac{22MHz}{51} = 431kHz$$

$$BW_n = K_n \cdot f_c = (1.57) \cdot 431kHz = 677kHz$$

$$E_{nr} = \sqrt{4 \cdot K_n T_n R_n BW_n} = \sqrt{4 \cdot (1.38 \cdot 10^{-23}) \cdot (298.15) \cdot (196) \cdot (677 \cdot 10^3)} = 1.48\mu V$$

Solutions

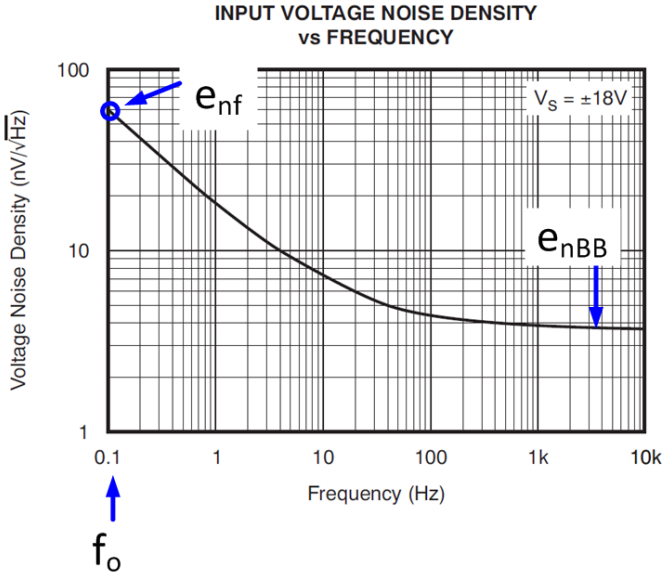
b. Op amp broadband voltage noise

$$E_{nBB} = (e_{nBB})\sqrt{BW_n} = (3.8\,nV/\sqrt{Hz})\sqrt{(677kHz)} = 3.13\mu V\ rms$$

c. Op amp 1/f voltage noise

$$e_{n_{normal}} = e_{nf}\sqrt{f_o} = (60\,nV/\sqrt{Hz})\sqrt{0.1Hz} = 19nV$$

$$E_{n_{flicker}} = e_{n_{normal}}\sqrt{\ln\left(\frac{f_H}{f_L}\right)} = (19nV)\sqrt{\ln\left(\frac{677kHz}{0.1Hz}\right)} = 75.4nV\ rms$$



Solutions

OPA827	Test condition	Typical
Input current noise density	F= 1 kHz, Vs = ±18V, Vcm = 0V	$2.2\ \mathrm{fA}\sqrt{Hz}$

d. Op amp current noise

$$e_{ni} = R_{eq} \cdot i_n = (196\Omega)\left(2.2\ \mathrm{fA}/\sqrt{\mathrm{Hz}}\right) = 0.00043\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$$
$$E_{ni} = e_{ni}\sqrt{BW_n} = \left(0.00043\ \mathrm{nV}/\sqrt{\mathrm{Hz}}\right)\sqrt{677\mathrm{kHz}} = 0.353\mathrm{nV\ rms}$$

e. Total combined noise

$$E_{n\_total} = \sqrt{E_{nr}{}^2 + E_{nBB}{}^2 + E_{nflicker}{}^2 + E_{ni}{}^2}$$
$$E_{n\_total\_in} = \sqrt{(1.48\mu V)^2 + (3.13\mu V)^2 + (75.4nV)^2 + (0.353nV)^2} = 3.48\mu V\ \mathrm{rms}$$
$$E_{n\_total\_out} = G_n E_{n\_total\_in} = (51)(3.48\mu V) = 177\mu V\ \mathrm{rms}$$
$$E_{n\_total\_out\_pp} = 6E_{n\_total\_out} = 6(177\mu V) = 1.07\mathrm{mVpp}$$

Noise – 2 (simulations/filtering)

Pros and cons of noise simulation

Simulation

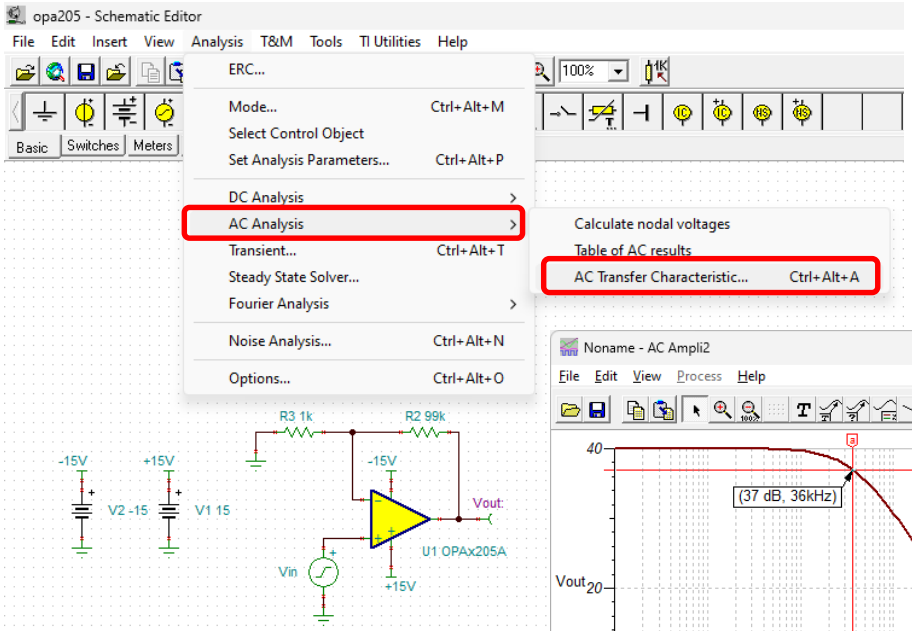
- Simple – seconds to complete
- Requires an accurate simulation model
- Simple wiring errors can produce incorrect results, but the simulator may not provide any errors or warnings
- Lacks intuition as regarding dominant source of error

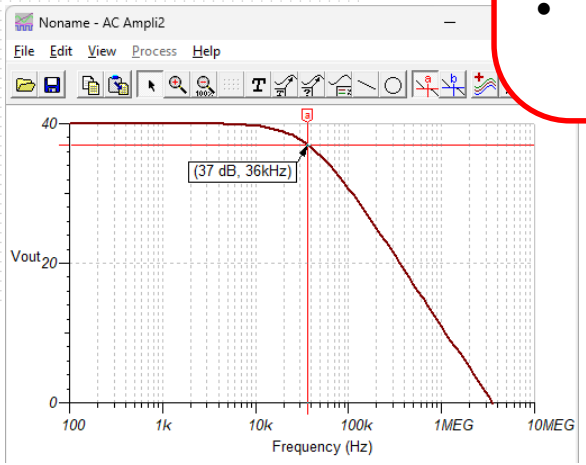
Hand-calculation

- Can be complex with many individual steps
- Provides intuition as to the dominate error source: resistor noise, amp current noise, amp voltage noise, 1/f noise

Best solution: do both and make sure results compare well

Verify the circuit before noise simulation





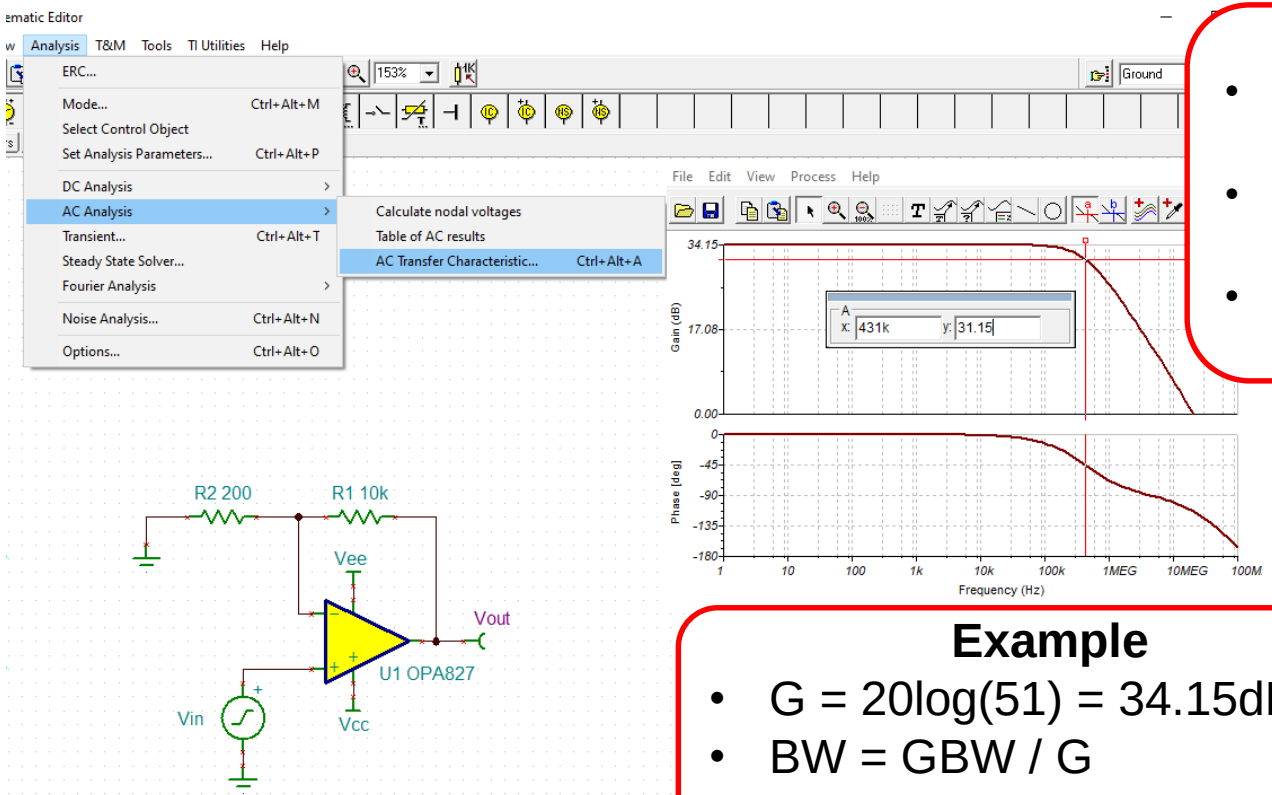
Verify circuit

- Run a simulation other than noise
- AC gain and bandwidth are a good verification
- Check DC gain and -3dB bandwidth vs hand-calculation

Example

- G = 20log(100) = 40dB
- BW = GBW / G
  3.6MHz/100 = 36kHz

Verify the circuit before noise simulation



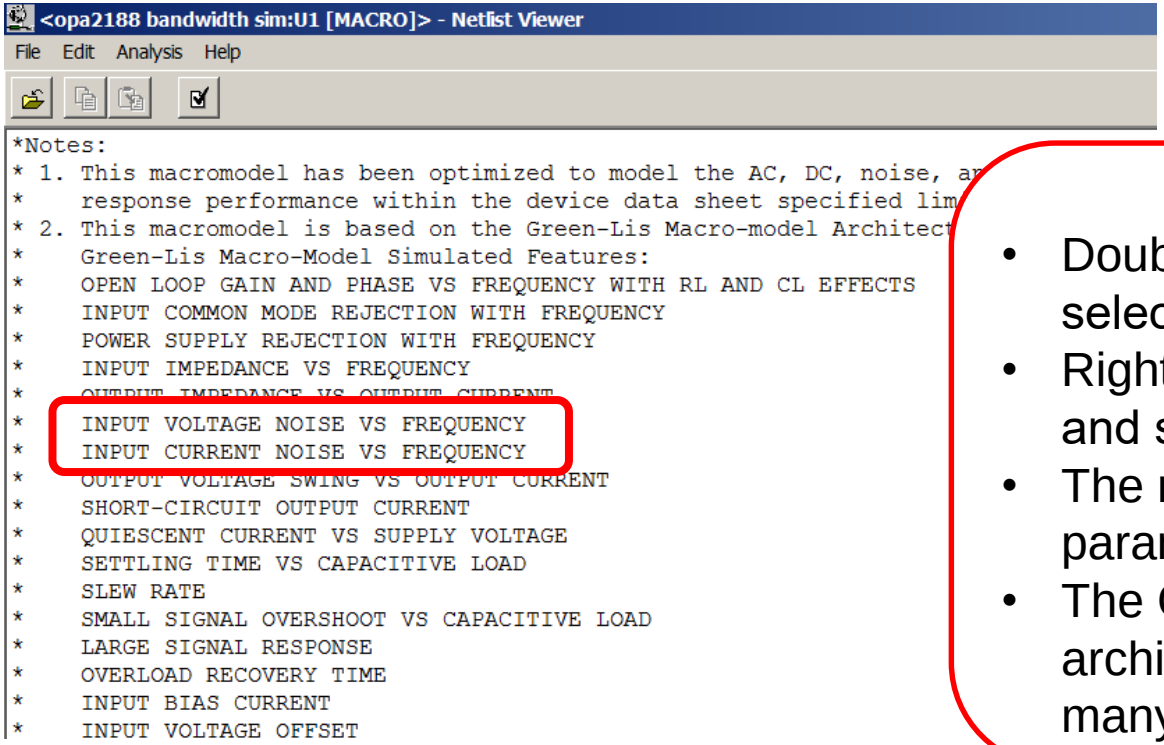
Verify circuit

- Run a simulation other than noise
- AC gain and bandwidth are a good verification
- Check DC gain and -3dB bandwidth vs hand-calculation

Example

- G = 20log(51) = 34.15dB
- BW = GBW / G
  22MHz/51 = 431kHz

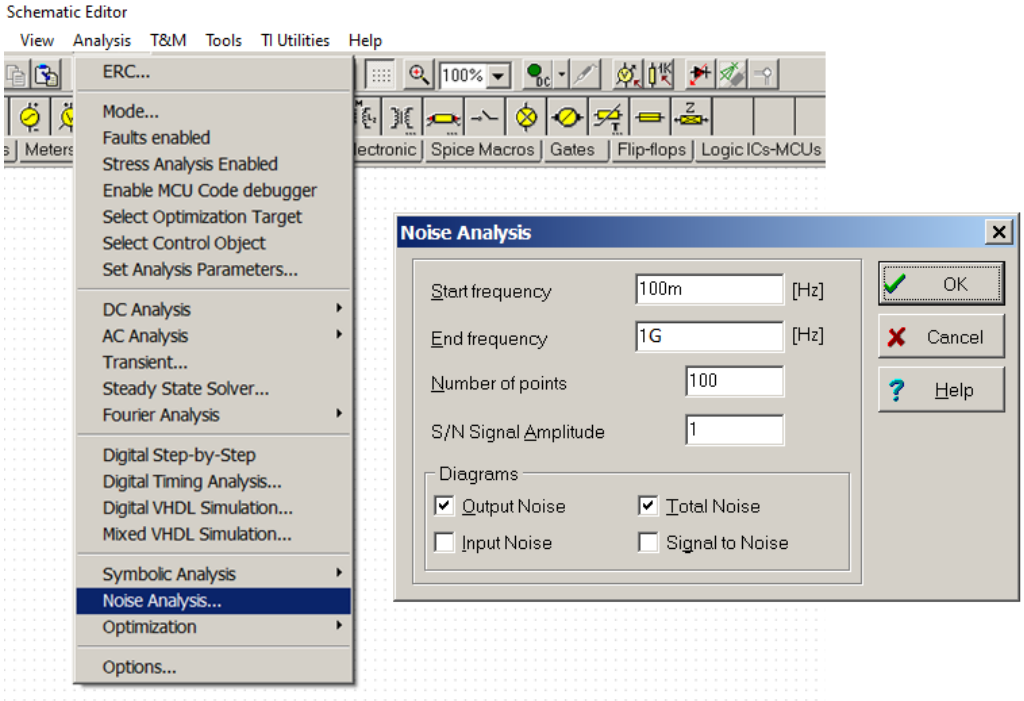
Is noise included in the SPICE model?



Open the net list

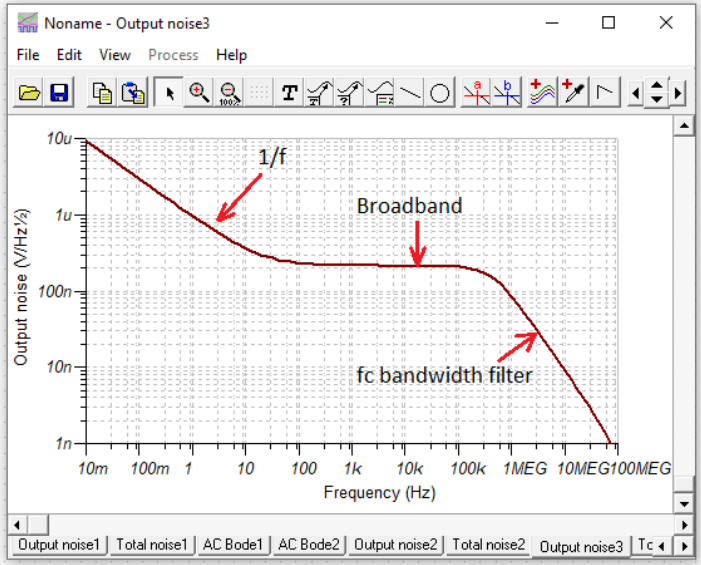
- Double click on TINA symbol and select “enter macro”.
- Right click on PSPICE symbol and select “View Pspice Model”
- The model header lists parameters covered by the model
- The Green-Williams-Lis architecture covers noise and many other parameters

Running a noise analysis simulation

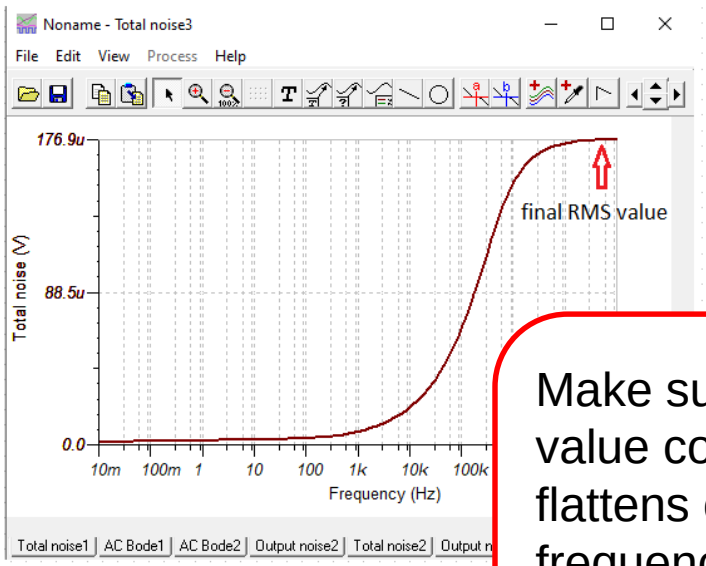


- Select Analysis > Noise Analysis
- Enter frequency range, number of points per decade, and diagrams
- **Output Noise** = Noise spectral density
- **Total Noise** = RMS integrated noise

Simulation results



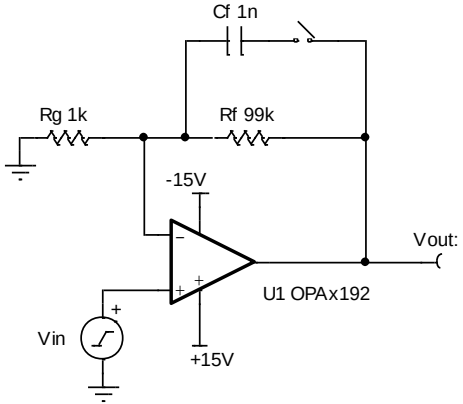
Spectral density

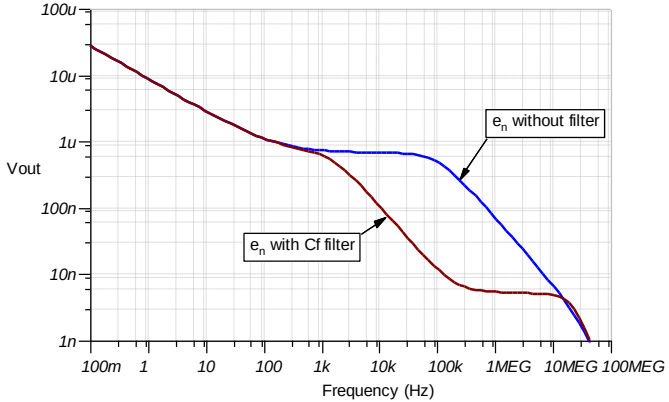


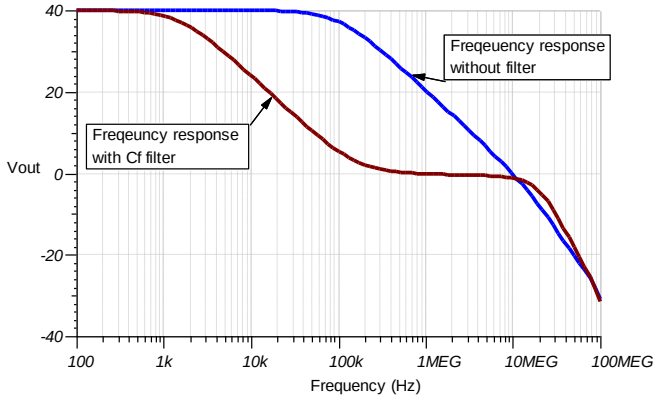
Integrated RMS noise

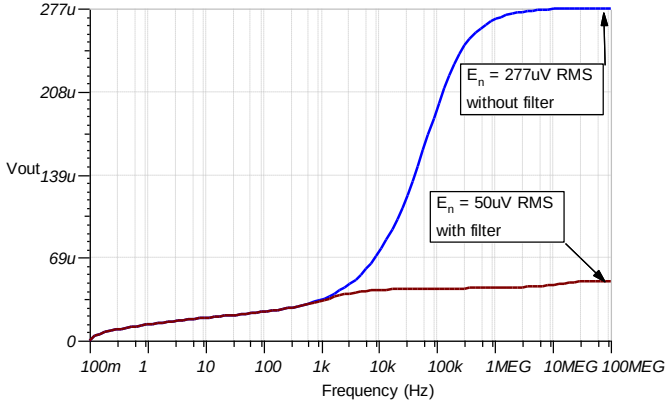
Make sure final RMS value converges or flattens out at high frequency.
If not, increase frequency range and re-simulate

Another simulation example: Filtering

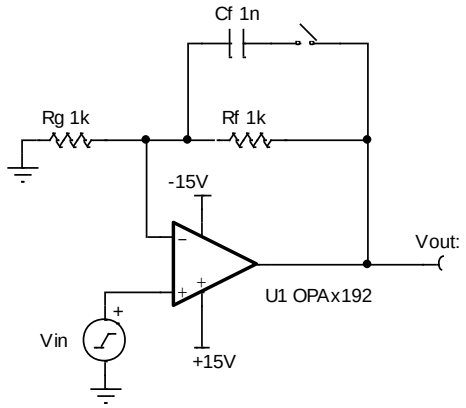


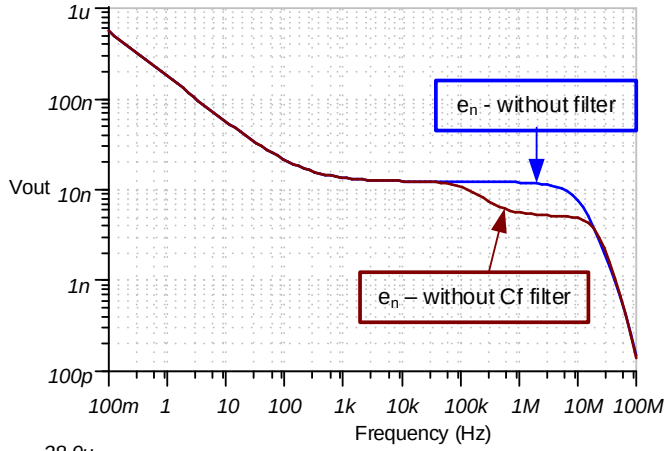


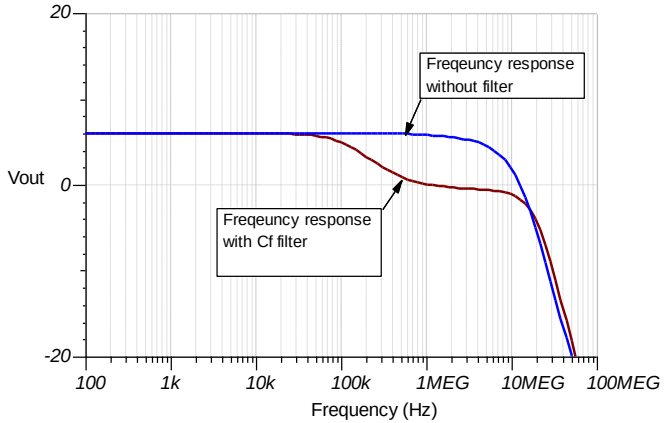


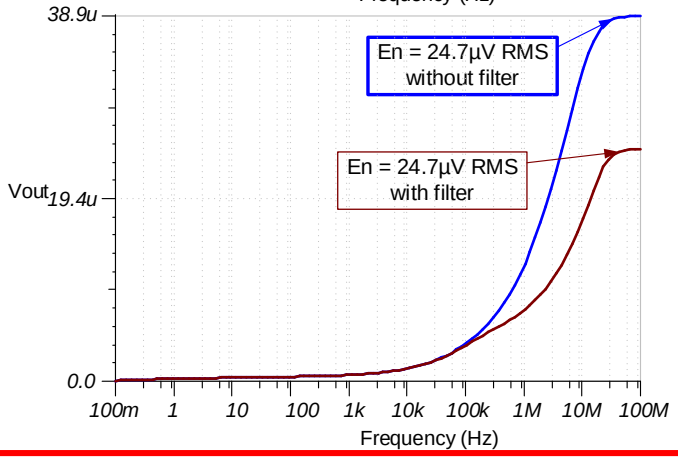


C_F is less effective in low gain

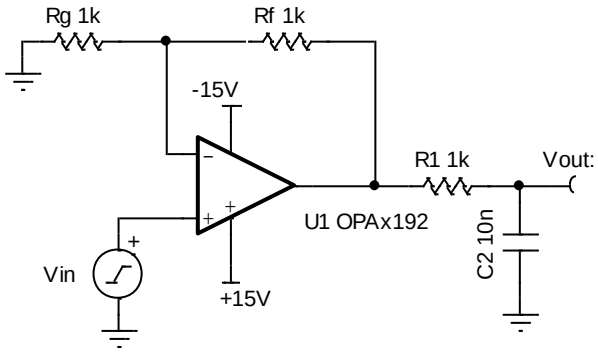


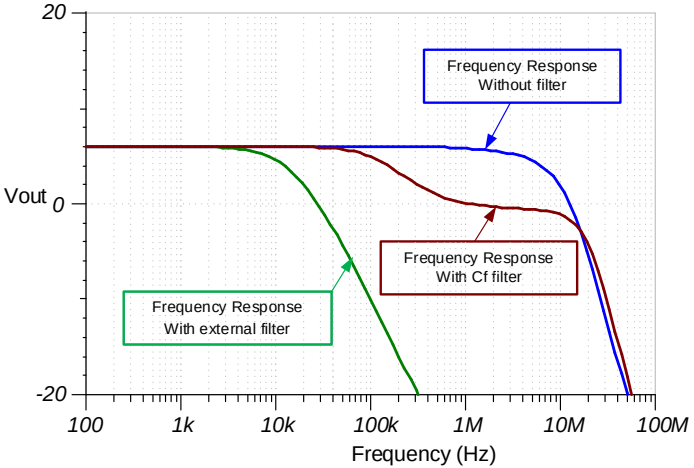


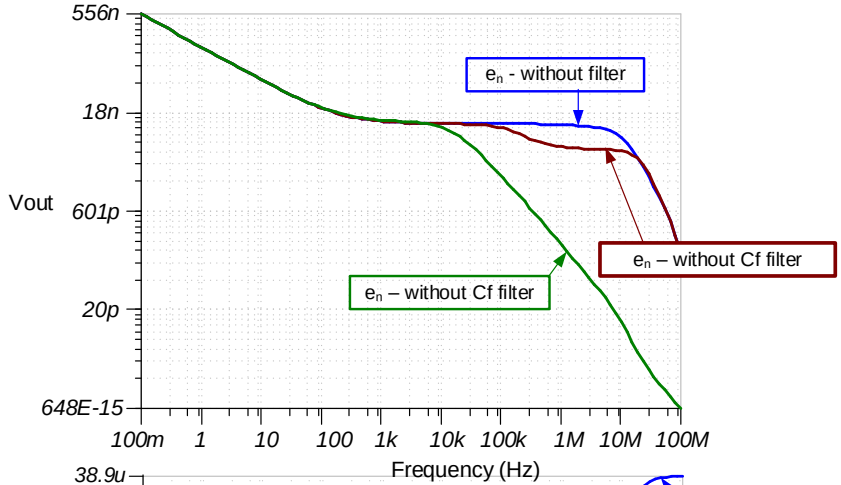


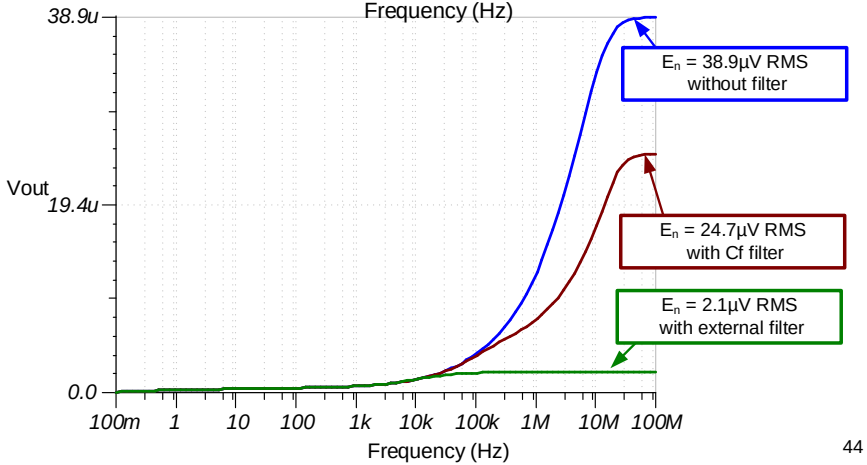


C_F vs. external filter









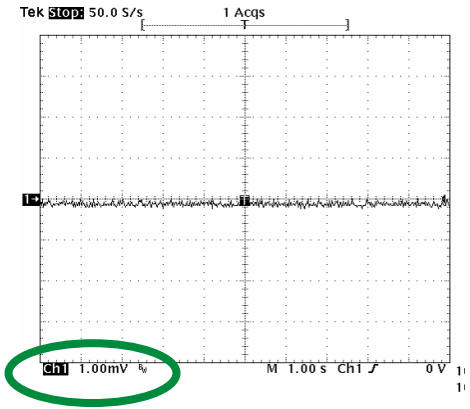
Oscilloscope noise floor

BEST

Noise floor = $0.2mV_{PP}$

BW limit = 20MHz

BNC connection

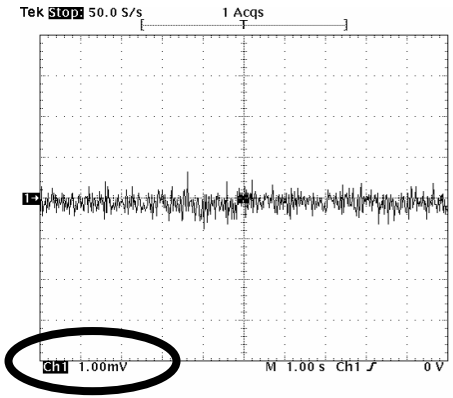


OK

Noise floor = $0.8mV_{PP}$

BW = 400MHz

BNC connection

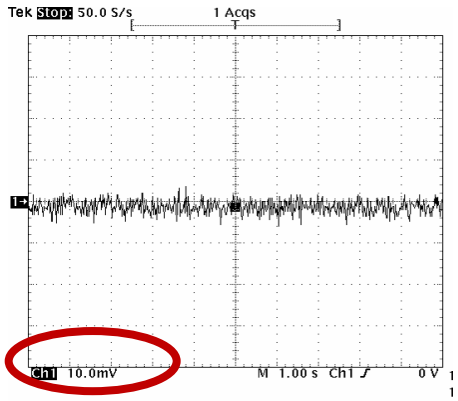


WORST

Noise floor = $8mV_{PP}$

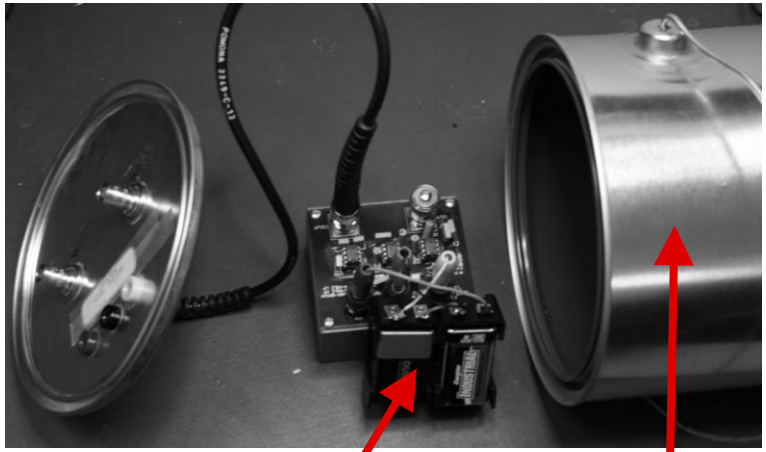
BW = 400MHz

10x scope probe



Best practices for measuring intrinsic noise

- Check your test equipment noise floor
  - BNC shorting cap for scope
- Configure equipment for lowest bandwidth possible
  - Where Equipment(BW) ≥ System(BW)
  - Use bandwidth limit feature on scope
- Eliminate extrinsic noise sources
  - Use battery or liner supply
  - Use shielded enclosure
  - Use shielded cables
  - This may be a temporary change for troubleshooting



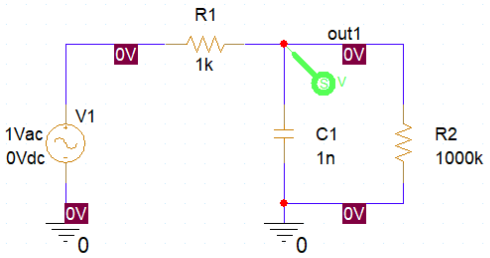
Battery power for low noise supply

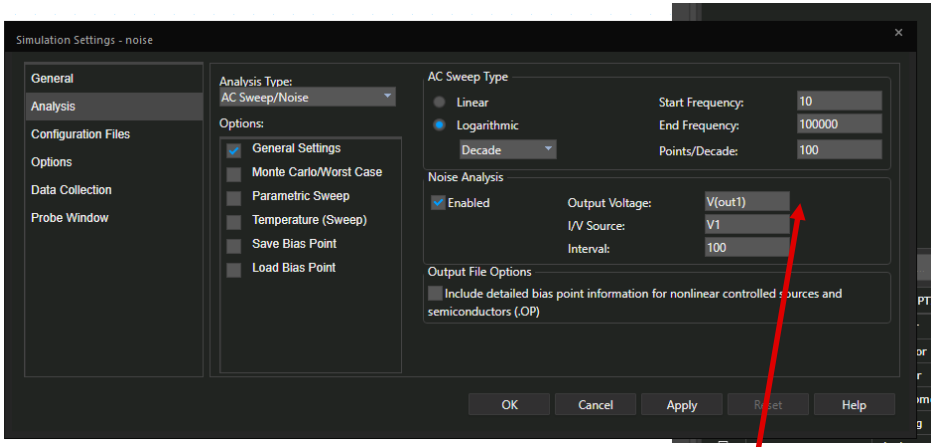
Steel paint can as RFI / EMI shield. This also minimizes thermal drift.

Thank you

Extra Slides cover PSPICE for TI noise analysis

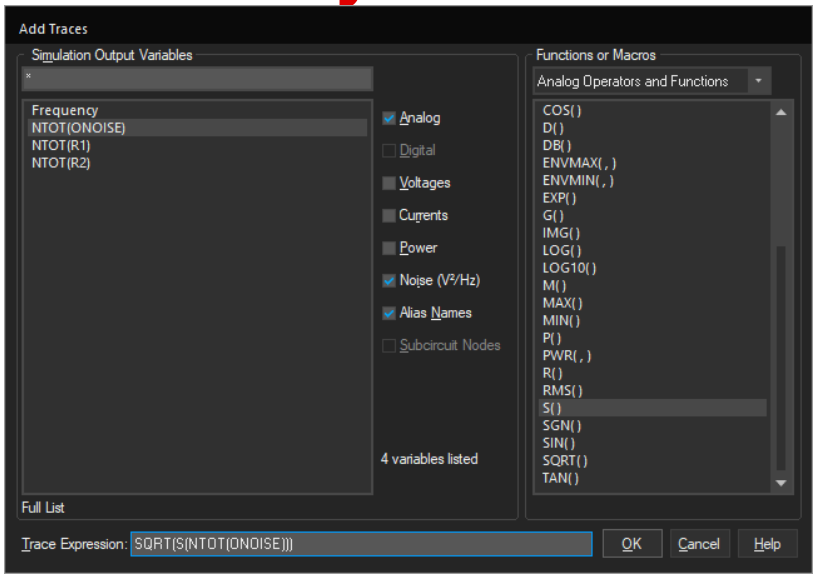
PSPICE: AC sweep and noise analysis

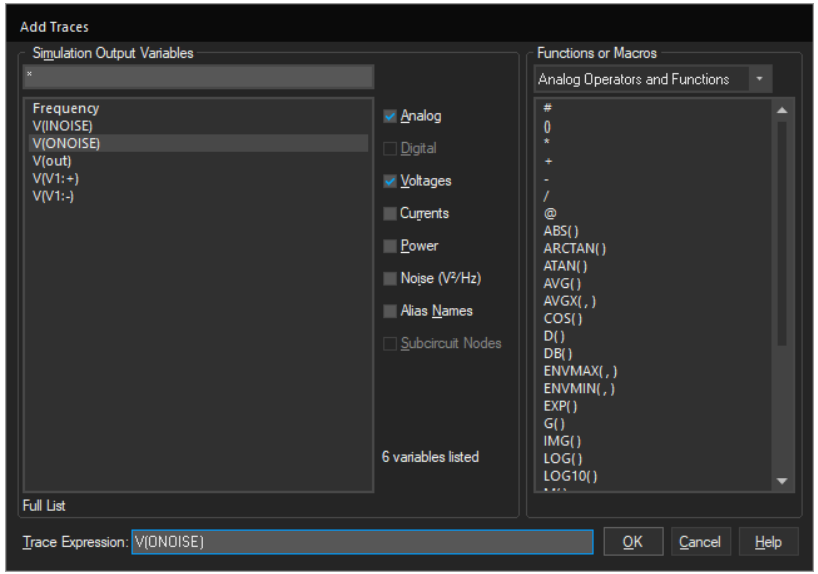




Where ***output voltage: V(net_name)*** is used to plot voltage noise for ***net_name.*** In this case the net name is ***out1***
V/I Source: source_name – In this example the source name is ***V1***

Noise analysis





Integrated Total RMS noise

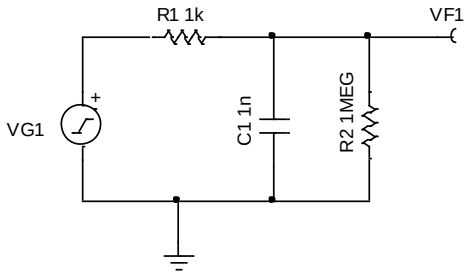
- "S" is the integral function
- SQRT is the square root function
- NTOT(ONOISE) = Noise power in V^2/Hz

$$E_n = \sqrt{\int P_n}$$

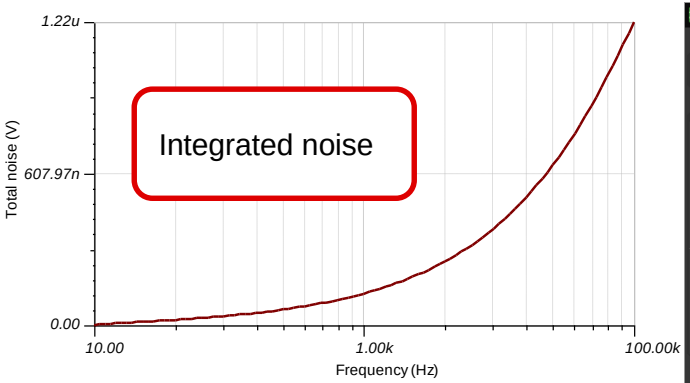
Voltage Noise Spectral Density

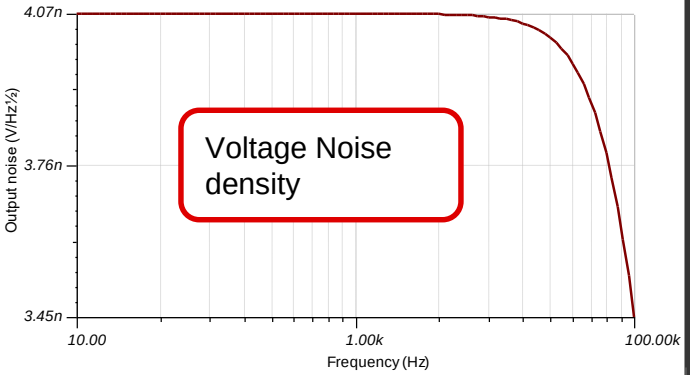
- V(ONOISE) is the noise density in V/rtHz at the output
- V(INOISE) is the input noise density
- Note: the "Noise" check box will give noise power in V^2/Hz

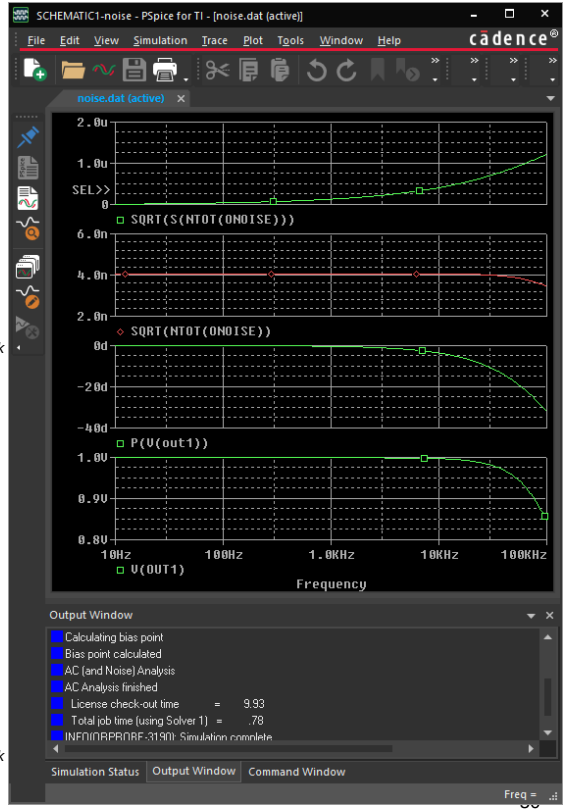
Noise analysis



This slide shows the two traces for noise density and integrated noise match TINA. By default PSPICE plots noise power which isn't very useful







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