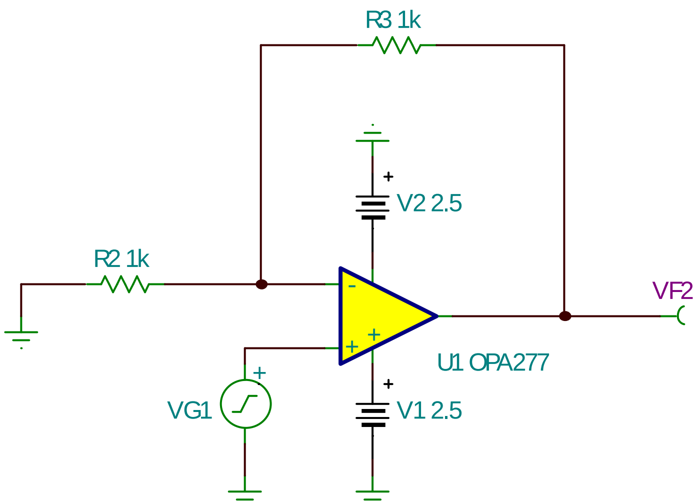
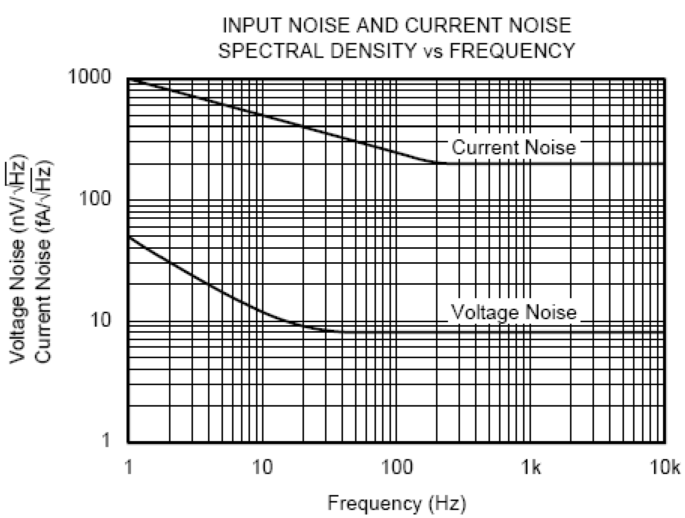
Hand Calculation Technique

Noise Analysis for Simple Op-Amp Circuit





Noise Sources

Op-Amp Voltage Noise Source

Op-Amp Current Noise Sources

Resistor Noise Sources

Calculation Considerations

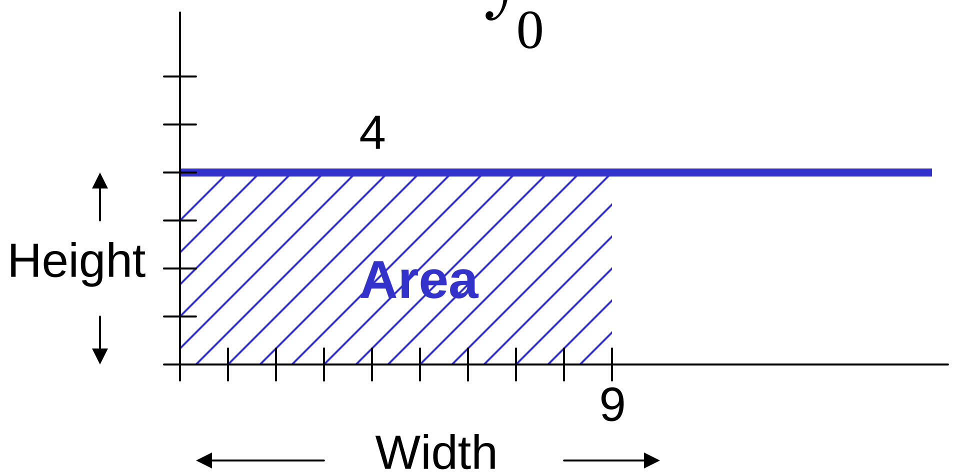
Convert Noise Spectrum to Noise Voltage
- External Filter Bandwidth Limit
- Op-Amp Closed Loop Bandwidth

Noise Gain

Calculus Reminder

$$\int_0^9 4\,dx = 4 \cdot 9 = 36$$

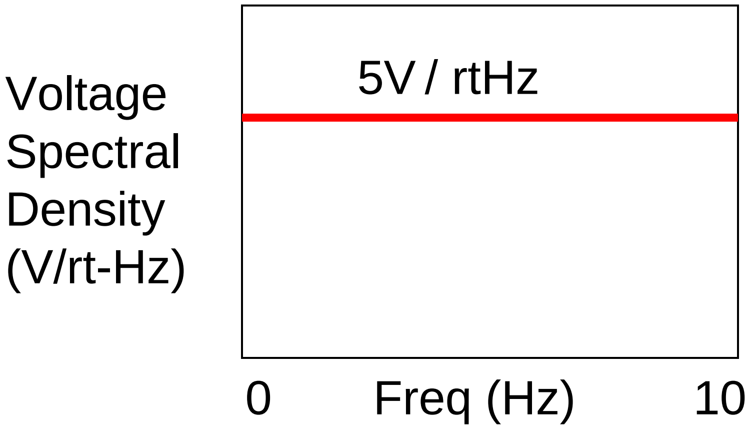
Height x Width



Integral = Area under the curve

Convert Noise Spectrum to Noise Voltage

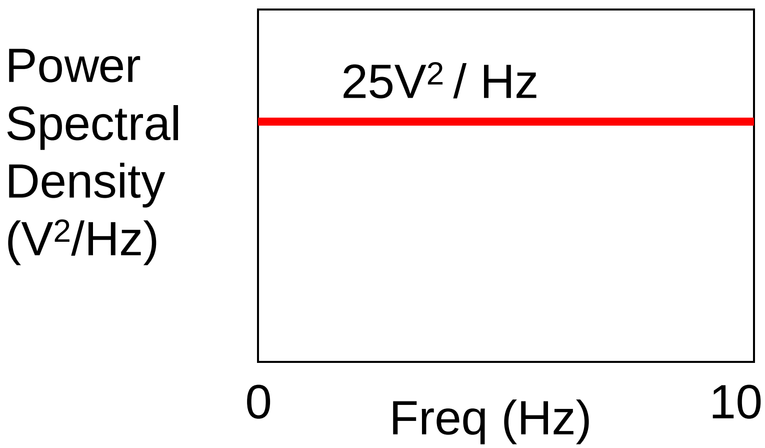
(Broadband Only – Simple Case)



You can't integrate the **Voltage** spectral density curve to get noise

$$\int_{0}^{10} V\_spec\_dens \; df = 5 \cdot \frac{V}{\sqrt{Hz}} \cdot 10 \cdot Hz = 50 \cdot \frac{V \cdot Hz}{\sqrt{Hz}}$$

Wrong



You integrate the **Power** spectral density curve to get noise

$$NoisePower = \int_{0}^{10} (V\_spec\_dens)^2 \, df = 25 \cdot \frac{V^2}{Hz} \cdot 10 \cdot Hz = 250 \cdot V^2$$

$$NoiseVoltage = \sqrt{NoisePower} = \sqrt{250 \cdot V^2} = 15.811V$$ RMS

Correct

Convert Noise Spectrum to Noise Voltage (Broadband Only – Simple Case)

You integrate the **Power** spectral density curve to get noise

$$\text{NoisePower} = \int_0^{10} (\text{V\_spec\_dens})^2 \, df = 25 \cdot \frac{V^2}{Hz} \cdot 10 \cdot Hz = 250 \cdot V^2$$

$$\text{NoiseVoltage} = \sqrt{\text{NoisePower}} = \sqrt{250 \cdot V^2} = 15.811V \quad \text{RMS}$$

Correct

$$\text{Noise Power} = \frac{V^2}{Hz} * \text{BW (Hz)}$$

$$\text{Noise Voltage} = \frac{V}{\sqrt{Hz}} * \sqrt{\text{BW (Hz)}}$$

Noise Gain for Voltage Noise Source

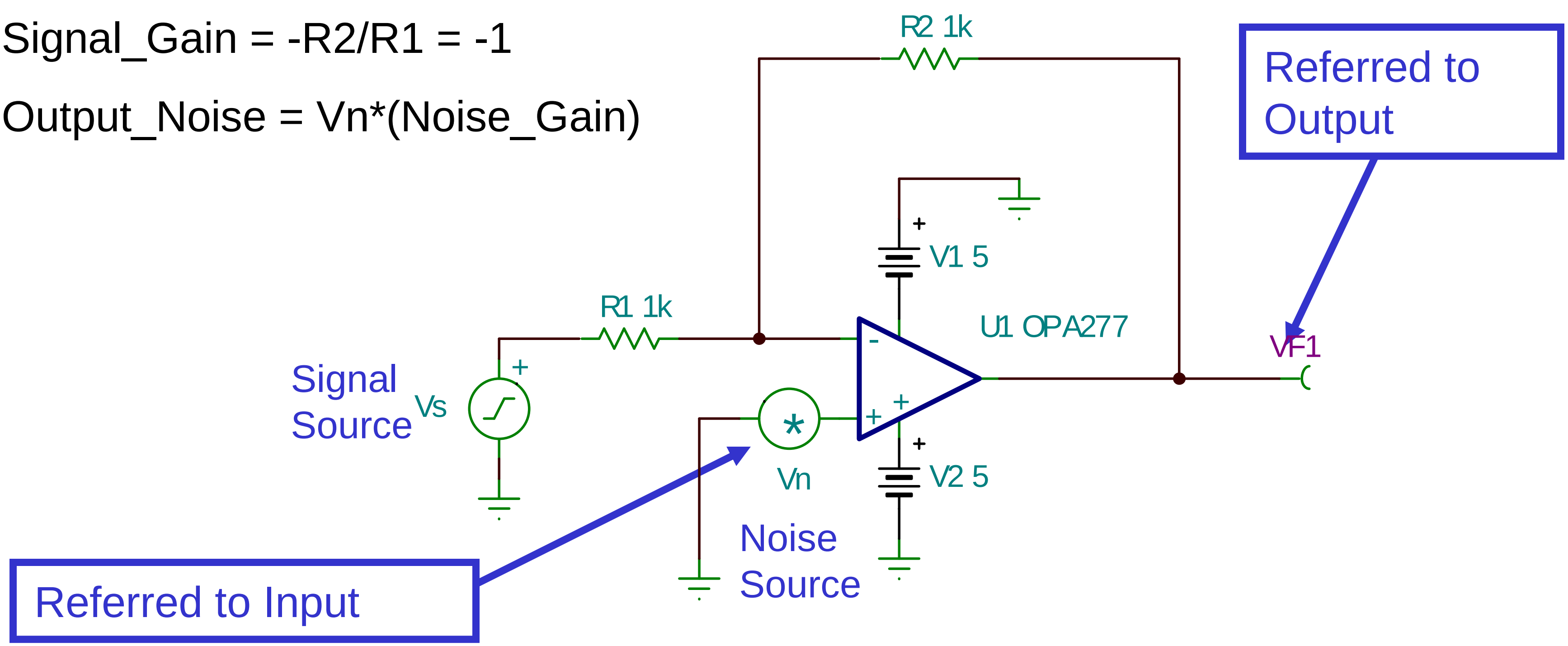
Noise Gain – Gain seen by the noise source.

Example:

Noise_Gain = (R2/R1) + 1 = 2

Signal_Gain = -R2/R1 = -1

Output_Noise = Vn*(Noise_Gain)



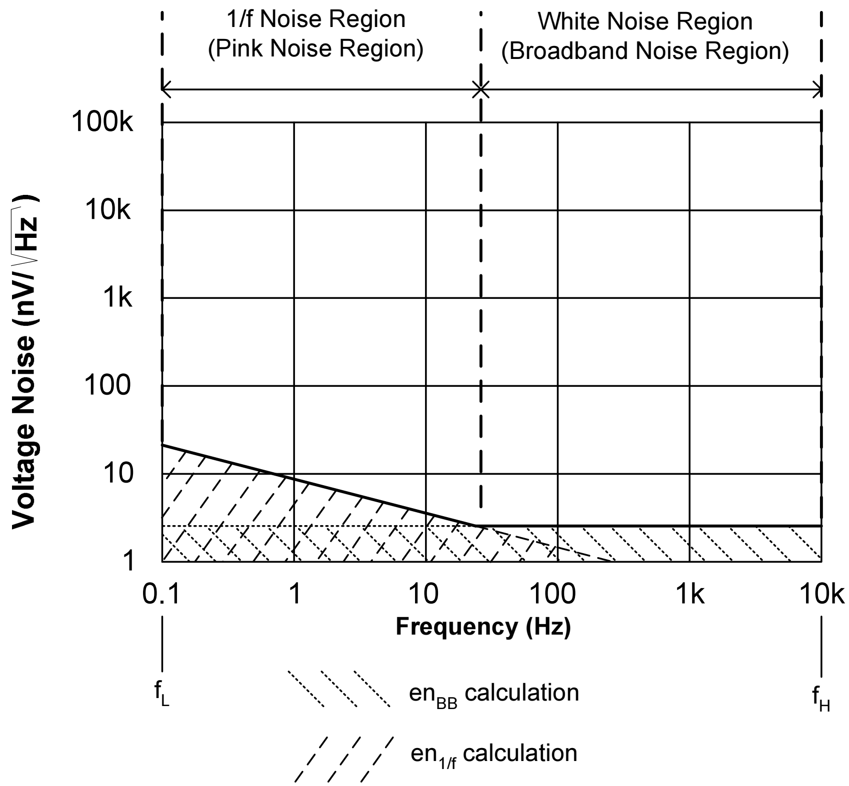
Texas Instruments

Understanding The Spectrum:
Total Noise Equation (Current or Voltage)

$$e_{nT} = \sqrt{[(e_{n1/f})^2 + (e_{nBB})^2]}$$

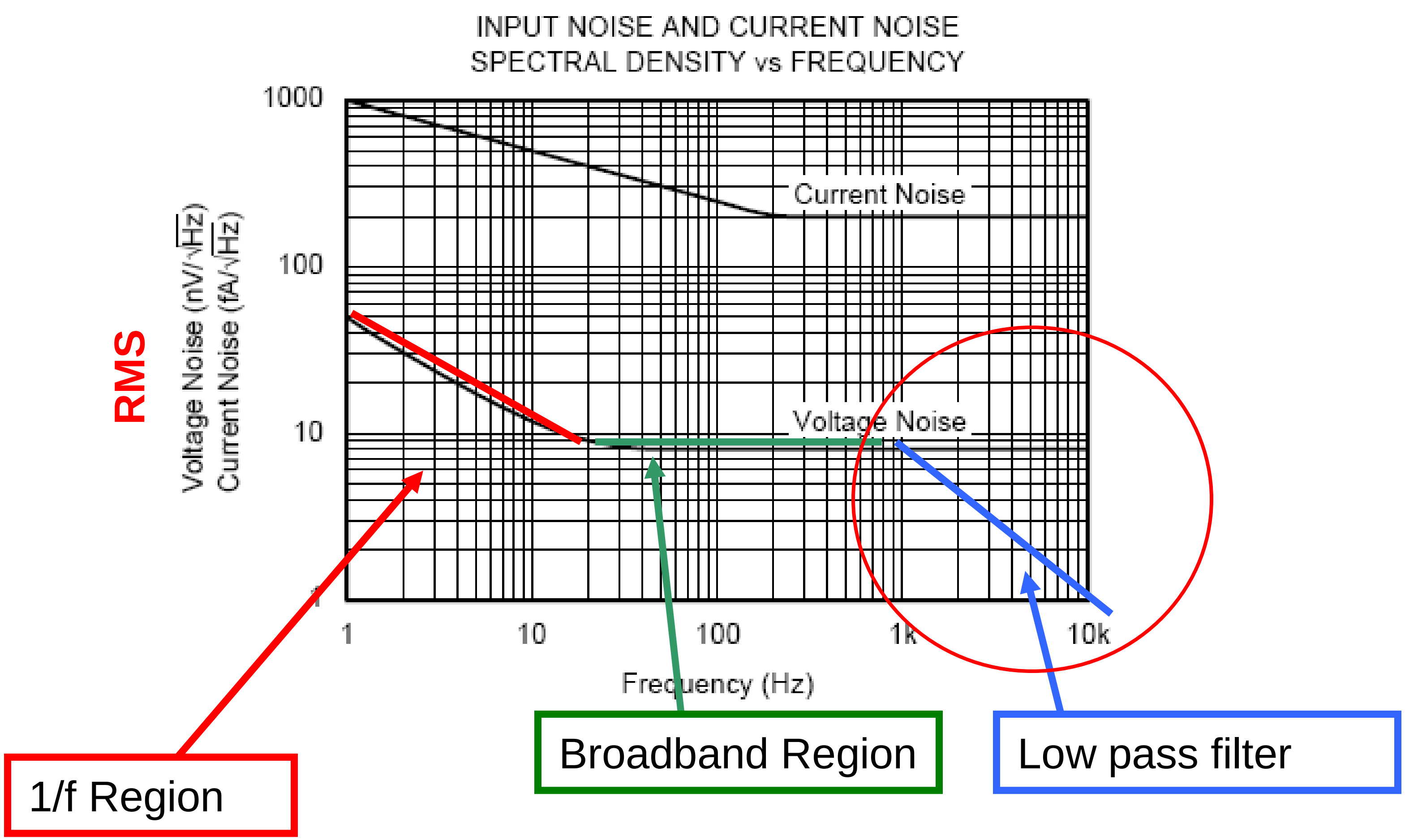
where:

e_{nT} = Total rms Voltage Noise in volts rms
$e_{n1/f}$ = 1/f voltage noise in volts rms
e_{nBB} = Broadband voltage noise in volts rms



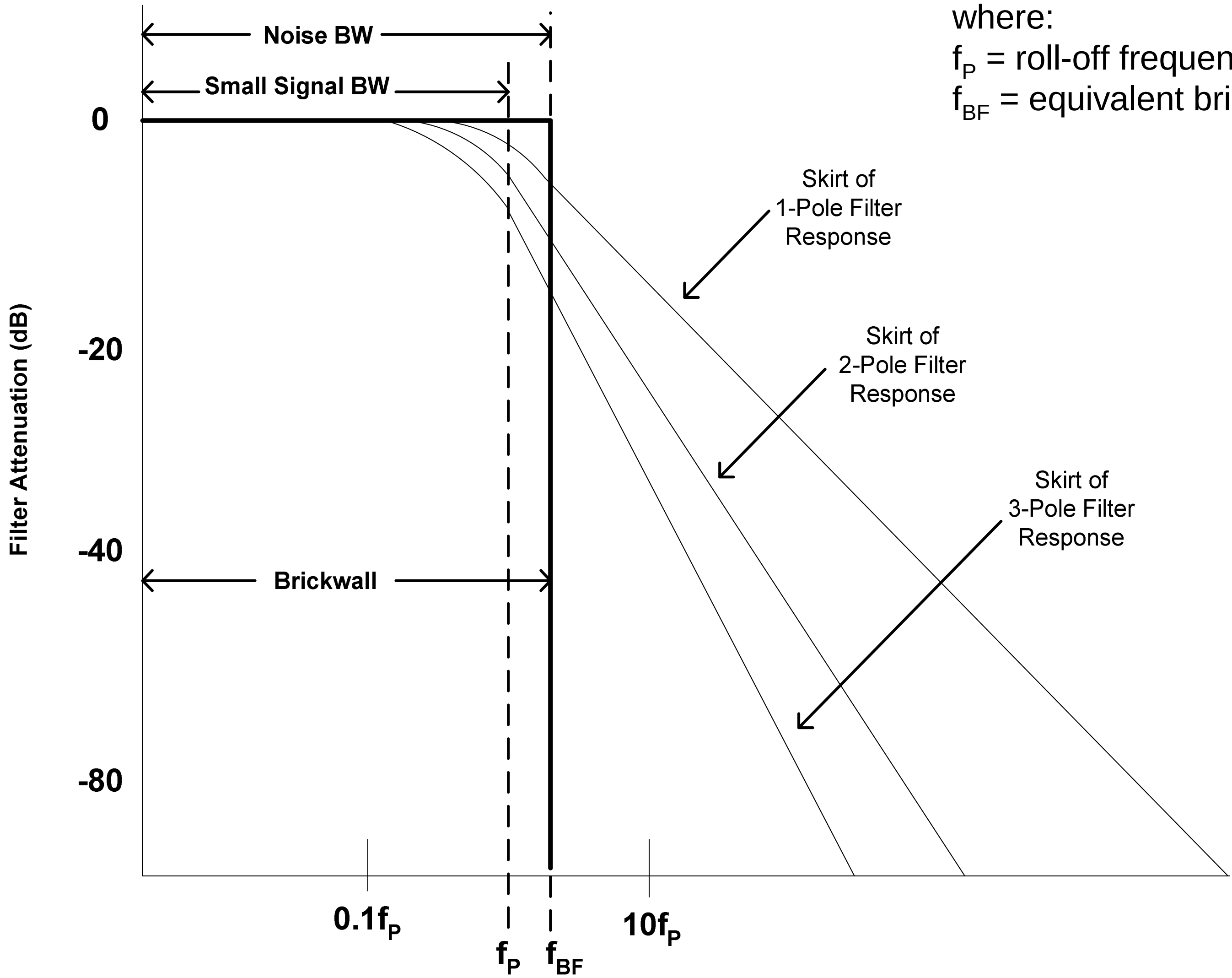
Low Pass Filter Shapes the Spectrum

How do we convert this plot to noise?



Real Filter Correction vs Brickwall Filter

where:
f_P = roll-off frequency of pole or poles
f_{BF} = equivalent brickwall filter frequency



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Frequency (f)

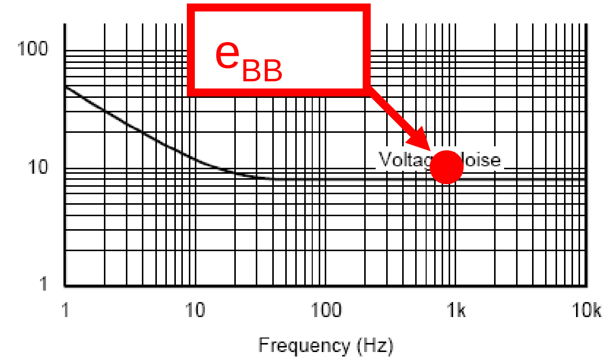
AC Noise Bandwidth Ratios for n^{th} Order Low-Pass Filters

$BW_n = (f_H)(K_n)$ Effective Noise Bandwidth

Real Filter Correction vs Brickwall Filter

Number of Poles in Filter	Kn AC Noise Bandwidth Ratio
1	1.57
2	1.22
3	1.16
4	1.13
5	1.12

Broadband Noise Equation



$BW_n = (f_H)(K_n)$

where:
BW_n = noise bandwidth for a given system
f_H = upper frequency of frequency range of operation
K_n = "Brickwall" filter multiplier to include the "skirt" effects of a low pass filter

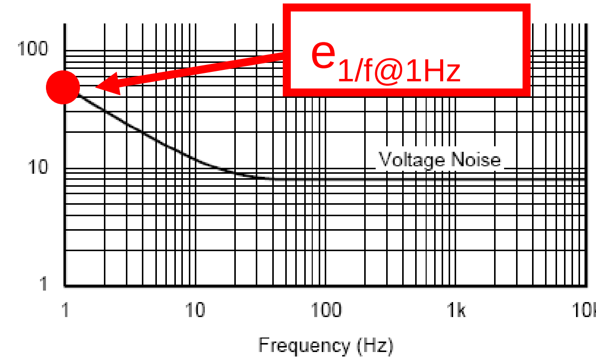
$en_{BB} = (e_{BB})(\sqrt{[BW_n]})$

where:
en_{BB} = Broadband voltage noise in volts rms
e_{BB} = Broadband voltage noise density ; usually in nV/ √ Hz
BW_n = Noise bandwidth for a given system

TEXAS INSTRUMENTS

1/f Noise Equation

(see appendix for derivation)



$$e_{1/f@1Hz} = (e_{1/f@f})(\sqrt{[f]})$$

where:

$e_{1/f@1Hz}$ = normalized noise at 1Hz (usually in nV)

$e_{1/f@f}$ = voltage noise density at f ; (usually in nV/ √ Hz)

f = a frequency in the 1/f region where noise voltage density is known

$$en_{1/f} = (e_{1/f@1Hz})(\sqrt{[\ln(f_H/f_L)]})$$

where:

$en_{1/f}$ = 1/f voltage noise in volts rms over frequency range of operation

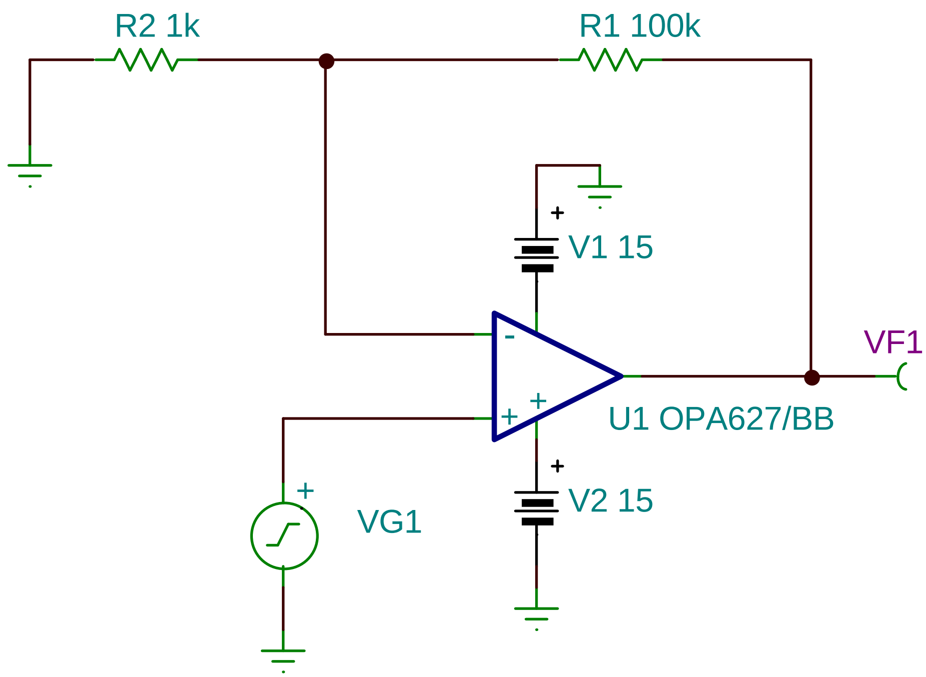
$e_{1/f@1Hz}$ = voltage noise density at 1Hz; (usually in nV)

f_H = upper frequency of frequency range of operation

(Use BW_n as an approximation for f_H)

f_L = lower frequency of frequency range of operation

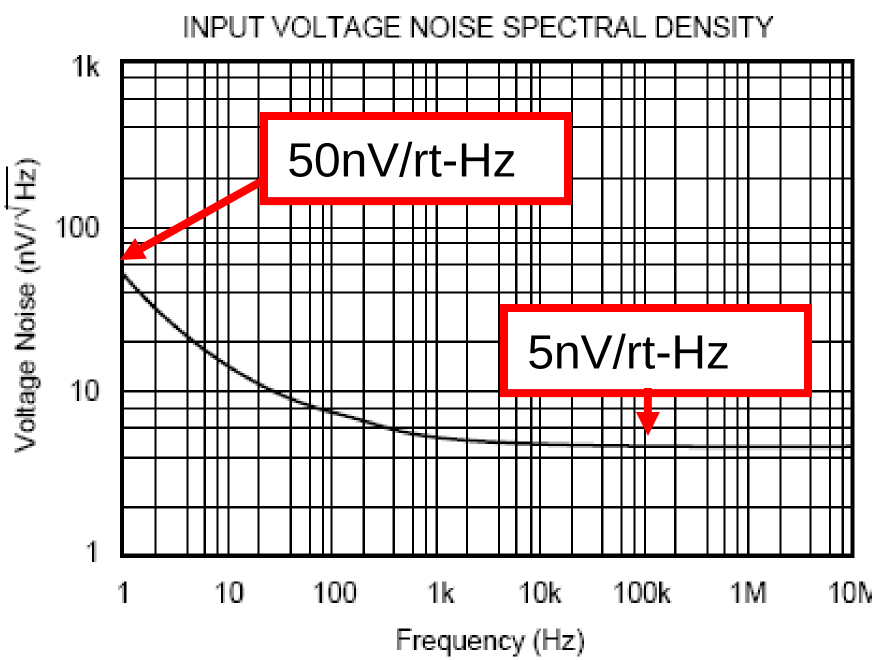
Example Noise Calculation

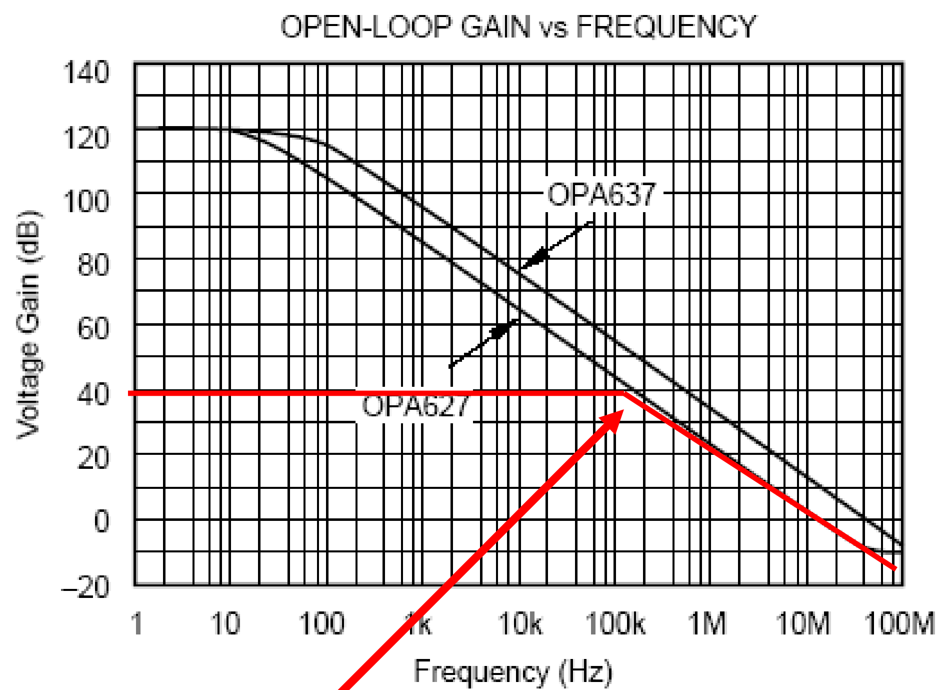


Given:
OPA627
Noise Gain of 101

Find (RTI, RTO):
Voltage Noise
Current Noise
Resistor Noise

Voltage Noise Spectrum and Noise Bandwidth





Unity Gain Bandwidth = 16MHz

Closed Loop Bandwidth = 16MHz / 101 = 158kHz

Example Voltage Noise Calculation

Voltage Noise Calculation:

Broadband Voltage Noise Component:

$BW_n \approx (f_H)(K_n)$ (note Kn = 1.57 for single pole)

$BW_n \approx (158kHz)(1.57) = 248kHz$

$en_{BB} = (e_{BB})(\sqrt{BW_n})$

$en_{BB} = (5nV/\sqrt{Hz})(\sqrt{248kHz}) = 2490nV\ rms$

1/f Voltage Noise Component:

$e_{1/f@1Hz} = (e_{1/f@f})(\sqrt{f})$

$e_{1/f@1Hz} = (50nV/\sqrt{Hz})(\sqrt{1Hz}) = 50nV$

$en_{1/f} = (e_{1/f@1Hz})(\sqrt{[\ln(f_H/f_L)]})$ **Use $f_H = BW_n$**

$en_{1/f} = (50nV)(\sqrt{[\ln(248kHz/1Hz)]}) = 176nV\ rms$

Total Voltage Noise (referred to the input of the amplifier):

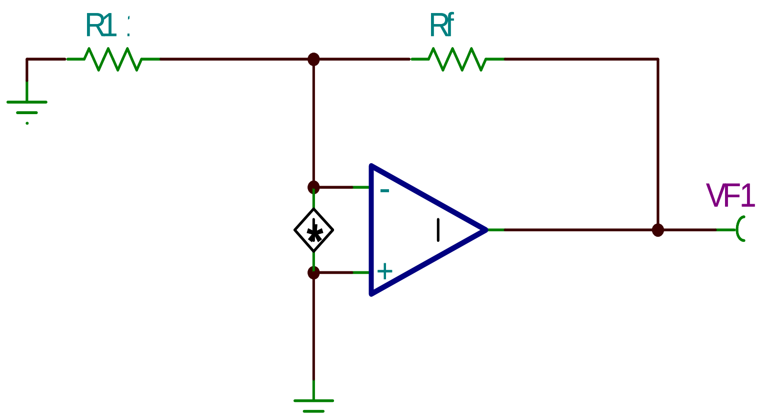
$en_T = \sqrt{[(en_{1/f})^2 + (en_{BB})^2]}$

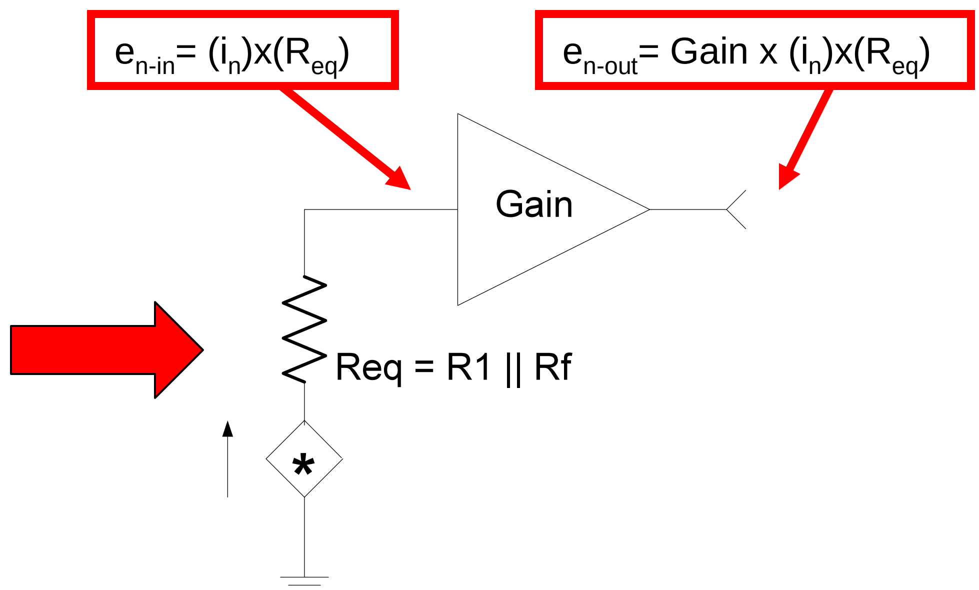
$en_T = \sqrt{[(176nV\ rms)^2 + (2490nV\ rms)^2]} = 2496nV\ rms$

Example Current Noise Calculation

PARAMETER	OPA627BM, BP, SM OPA637BM, BP, SM MIN	TYP	MAX	UNITS
NOISE				
Input Voltage Noise				
Noise Density: f = 10Hz		15	40	nV/√Hz
f = 100Hz		8	20	nV/√Hz
f = 1kHz		5.2	8	nV/√Hz
f = 10kHz		4.5	6	nV/√Hz
Voltage Noise, BW = 0.1Hz to 10Hz		0.6	1.6	µVp-p
Input Bias Current Noise				
Noise Density, f = 100Hz		1.6	2.5	fA/√Hz
Current Noise, BW = 0.1Hz to 10Hz		30	60	fAp-p

Note: This example amp doesn't have 1/f component for current noise.





Example Current Noise Calculation

Broadband Current Noise Component:
$BWn \approx (f_H)(K_n)$
$BWn \approx (158kHz)(1.57) = 248kHz$

$i_{nBB} = (i_{BB})(\sqrt{BW_n})$
$i_{nBB} = (2.5fA/\sqrt{Hz})(\sqrt{248kHz}) = 1.244pA$ rms

$R_{eq} = R_f \,||\, R_1 = 100k \,||\, 1k = 0.99k$

$e_{ni} = (I_n)(R_{eq}) = (1.244pA)(0.99k) = 1.23nV$ rms   neglect

Since the Total Voltage noise is $e_{nvt} = 2496nV$ rms
the current noise can be neglected.

PARAMETER	OPA627BM, BP, SM OPA637BM, BP, SM MIN	TYP	MAX	UNITS
NOISE				
Input Voltage Noise				
Noise Density: f = 10Hz		15	40	nV/√Hz
f = 100Hz		8	20	nV/√Hz
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Voltage Noise, BW = 0.1Hz to 10Hz		0.6	1.6	µVp-p
Input Bias Current Noise				
Noise Density, f = 100Hz		1.6	2.5	fA/√Hz
Current Noise, BW = 0.1Hz to 10Hz		30	60	fAp-p

Example Resistor Noise Calculation

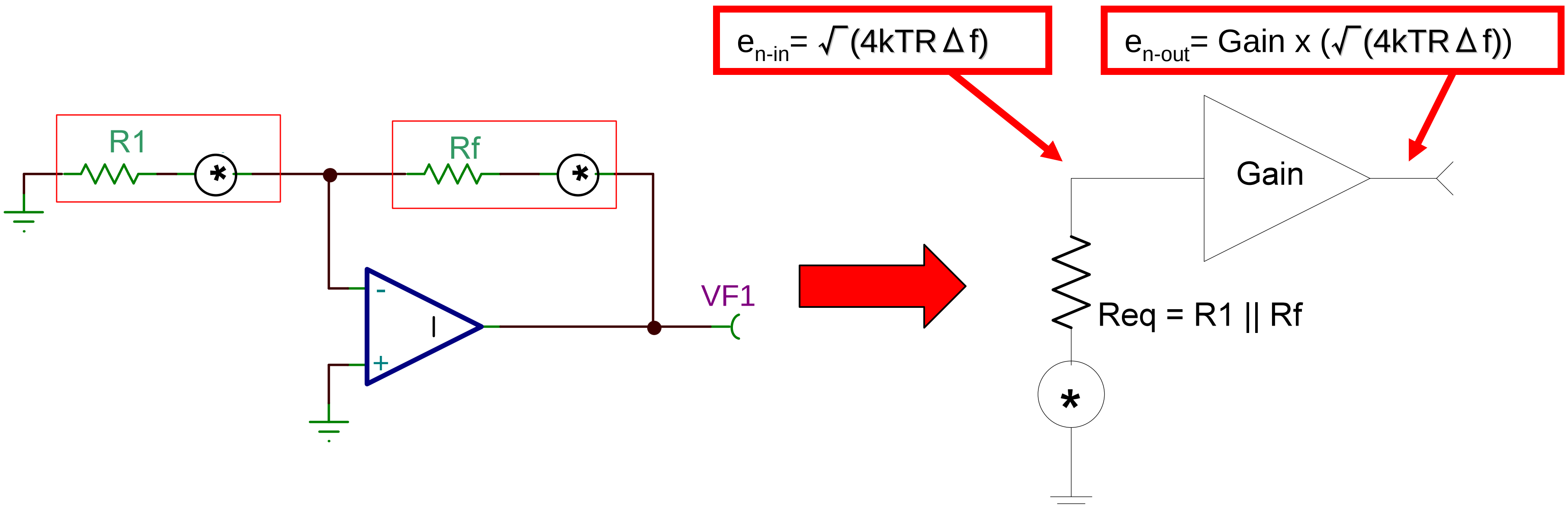
$e_{nr} = \sqrt{(4kT_K R \Delta f)}$

where:

$R = Req = R1||Rf$

$\Delta f = BW_n$

$e_{nr} = \sqrt{(4\,(1.38E\text{-}23)\,(273 + 25)\,(0.99k)(248kHz))} = 2010nV\ rms$



Total Noise Calculation

Voltage Noise From Op-Amp RTI:
e_{nv} = 2510nV rms

Current Noise From Op-Amp RTI (as a voltage):
e_{ni} = 1.24nV rms

Resistor Noise RTI:
e_{nr} = 2020nV rms

Total Noise RTI:
$e_{n\ in} = \sqrt{}((2510nV)^2 + ((1.2nV)^2 + ((2010nV)^2) = 3216nV\ rms$

Total Noise RTO:
$e_{n\ out} = e_{n\ in} \times gain = (3216nV)(101) = 325uV\ rms$

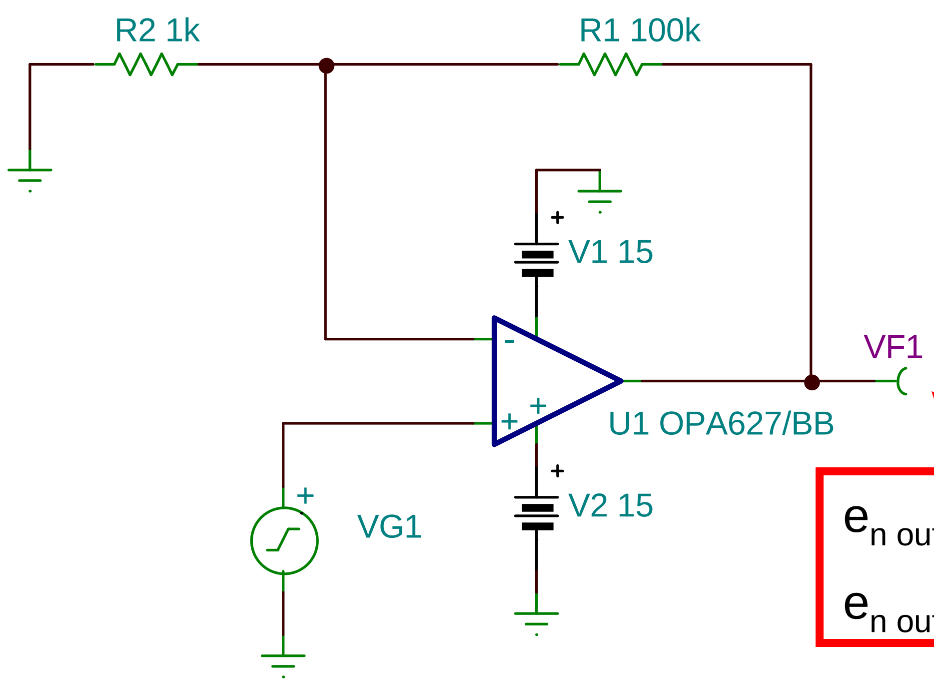
Calculating Noise Vpp from Noise Vrms

Relation of Peak-to-Peak Value of AC Noise Voltage to rms Value

Peak-to-Peak Amplitude	Probability of Having a Larger Amplitude
2 X rms	32%
3 X rms	13%
4 X rms	4.6%
5 X rms	1.2%
6 X rms *	0.3%
6.6 X rms	0.1%

***Common Practice is to use:**
Peak-to-Peak Amplitude = 6 X rms

Peak to Peak Output For our Example



$e_{n\ out}$ = 325uV rms

$e_{n\ out\ p\text{-}p}$ = (325uV rms)x6 = 1.95mVp-p