Noise Calculator, How Do You Use it in Design?

Jeff Coletti

One of Many Definitions

noise - electrical or acoustic activity that can disturb communication

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Another Definition

NOISE - the quality of lacking any predictable order or plan

Noise Categories

1. Extrinsic Noise—
   - 50 / 60 Hz Line Noise…RFI / EMI
   - Charge displacement (very hi-Z circuit)
   - Switching power supplies…Micro-phonic
   - Digital noise…Ground loops
   - Atmospheric…Cosmic
2. Intrinsic Noise—
   - Thermal Noise
   - Shot Noise
   - 1/f Noise
   - Popcorn (Burst) Noise

TEXAS INSTRUMENTS

Thermal Noise

$$e^2 = 4kTR\Delta f$$

Where:
- k = Temperature (ºK)
- R = Resistance (Ω)
- f = frequency (Hz)
- k = Boltzmann's constant (1.38E-23 joule/ºK)
- e = volts (V_{RMS})

TEXAS INSTRUMENTS

Also known as "Johnson Noise"– first observed by Schottky in 1918, first measured by Johnson in 1928 & soon after formalized by Nyquist.

Thermal noise is produced by random motion of charges.

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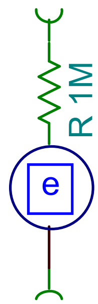
Thermal noise is produced by random motion of charges.

$e = \sqrt{4kTR\Delta f}$ (when Δf = 1Hz, "e" is the voltage noise spectral density)

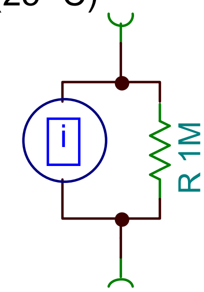
Resistor Thermal Noise

At: T = 298 ºK (25 ºC)

Thevenin Equivalent



Norton Equivalent



$e = \sqrt{4kTR\Delta f}$

e = 128 nV/sq rt Hz

Voltage noise spectral density

$i = \sqrt{4kT\Delta f/R}$

I = 128 fA/sq rt Hz

Current noise spectral density

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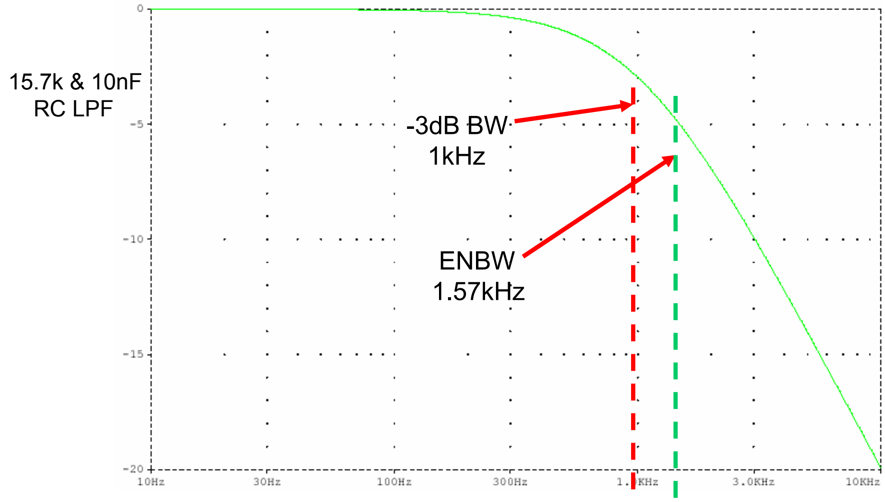
By simply using Ohm's Law we can obtain the mean- square short- circuit noise current from

$i2 = e2/R2 = 4kT\Delta f/R$

$i = \sqrt{4kT\Delta f/R}$ (when Δf = 1Hz, "i" is the current noise spectral density)

Low- Pass ENBW Example



Correction factor for 1- pole filter = 1.57,   1kHz (-3dB BW) * 1.57 = 1.57kHz ENBW

16.2.5 Equivalent Noise Bandwidth

Equivalent noise bandwidth is the ratio of the input noise power to the noise power in the output of an FFT filter times the input data sampling rate. Every signal contains some noise. That noise is generally spread over the frequency spectrum of interest, and each narrowband filter passes a certain amount of that noise through its main lobe and sidelobes. White noise is used as the input signal and the noise power out of each filter is compared to the noise power into the filter to determine the equivalent noise bandwidth of each passband filter. In other words, equivalent noise bandwidth represents how much noise would come through the filter if it had an absolutely flat passband gain and no sidelobes. It should be noted that leakage to the side lobes not only decreases the magnitude of the main lobe but also increases the frequency resolution (spreading) of the main lobe. The width of the spread is compared to the rectangular window, which has a main lobe width of 1. Table 16.1 shows the equivalent bandwidth spread to be greater than 1 for all window functions.

http://books.google.com/books?id=QxJivJTjLy8C&pg=PA183&lpg=PA183&dq=Filter+Equivalent+Noise&source=web&ots=B6C0imt-iE&sig=UKhOqs3jhnDlNpLKfKzKAk0eDGs&hl=en&sa=X&oi=book_result&resnum=6&ct=result#PPA183,M1

Filter Equivalent Noise BW

Butterworth (fco = 3 dB)

Order	EqNBW
1	1.5708
2	1.1107
3	1.0472
4	1.0262
5	1.0166
6	1.0115
7	1.0084
8	1.0065
9	1.0051
10	1.0041

Chebyshev (fco = ripple)

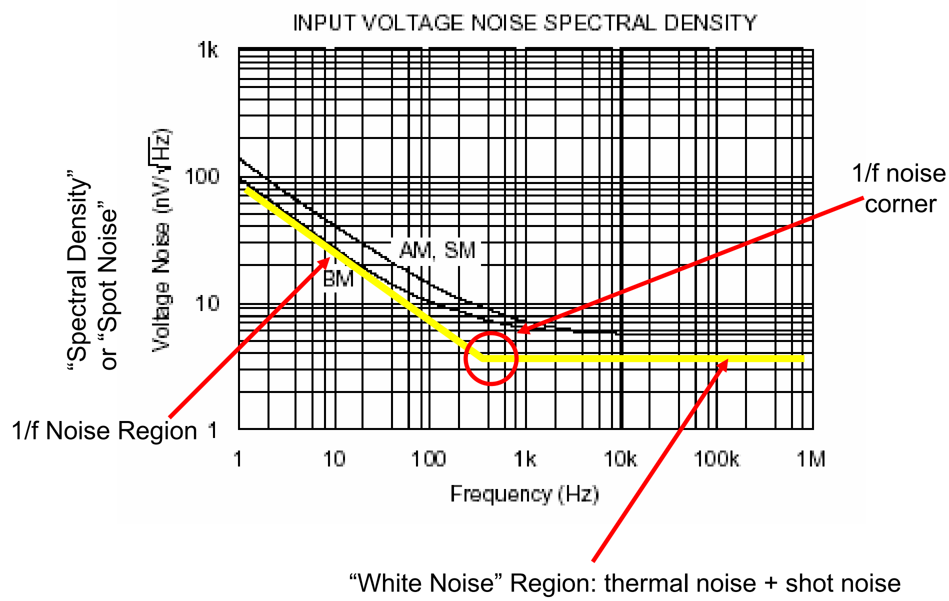
Ripple / Order	0.01 dB	0.1 dB	0.25 dB	0.5 dB	1.0 dB
2	3.6672	2.1444	1.7449	1.4889	1.2532
3	1.9642	1.4418	1.2825	1.1666	1.0411
4	1.5039	1.2326	1.1405	1.0656	0.9735
5	1.3114	1.1417	1.0780	1.0208	0.9433
6	1.2120	1.0937	1.0448	0.9970	0.9272
7	1.1537	1.0653	1.0251	0.9828	0.9175
8	1.1166	1.0471	1.0125	0.9736	0.91133
9	1.0914	1.0347	1.0038	0.9674	0.9071
10	1.0736	1.0258	0.9977	0.9629	0.9041

Bessel (fco = 3 dB)

Order	EqNBW
1	1.57
2	1.56
3	1.08
4	1.04
5	1.04
6	1.04

Reference: http://www.rfcafe.com/references/electrical/filter_eqnbw.htm

Amplifier Noise Spectrum

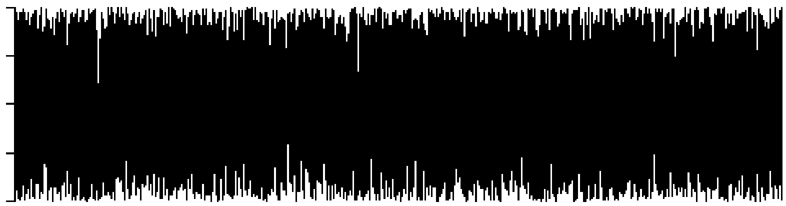


TEXAS INSTRUMENTS

Noise Temporal Behavior

$$P(f) = 1 / f^{beta}$$

Po : 0



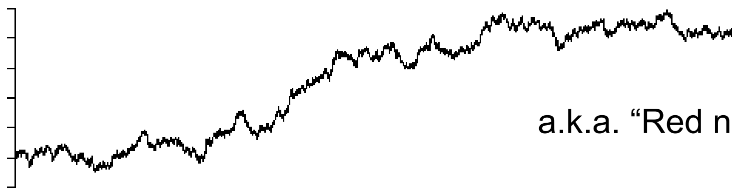
1/f noise spectrum when **beta = 1**, equal power per octave

http://astronomy.swin.edu.au/~pbourke/fractals/noise/

TEXAS INSTRUMENTS

Noise Temporal Behavior

2-pole LPF (integrate) white noise and
you get Brownian noise, **beta = 2**



a.k.a. “Red noise”

http://astronomy.swin.edu.au/~pbourke/fractals/noise

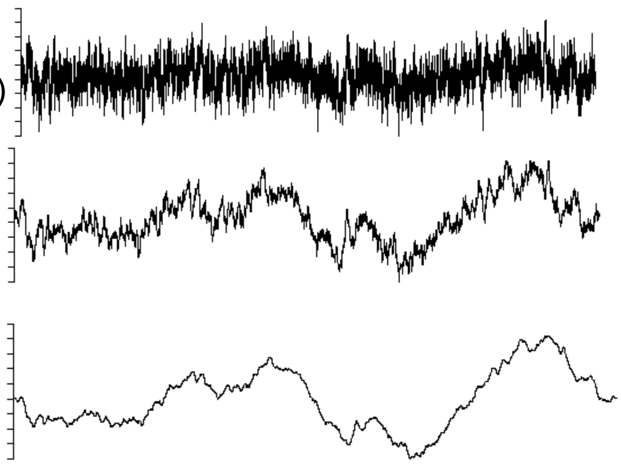
TEXAS INSTRUMENTS

Noise Temporal Behavior

beta = 1
1/f noise
(“flicker noise”)

beta = 2
Brownian noise
(“random walk”)

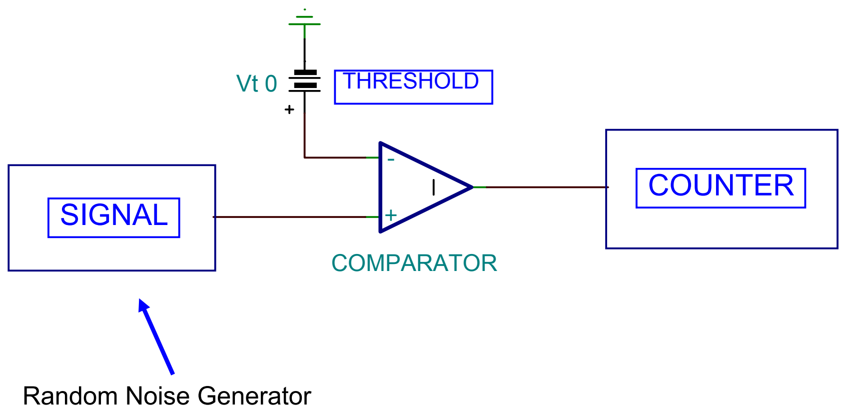
beta = 3



http://astronomy.swin.edu.au/~pbourke/fractals/noise/

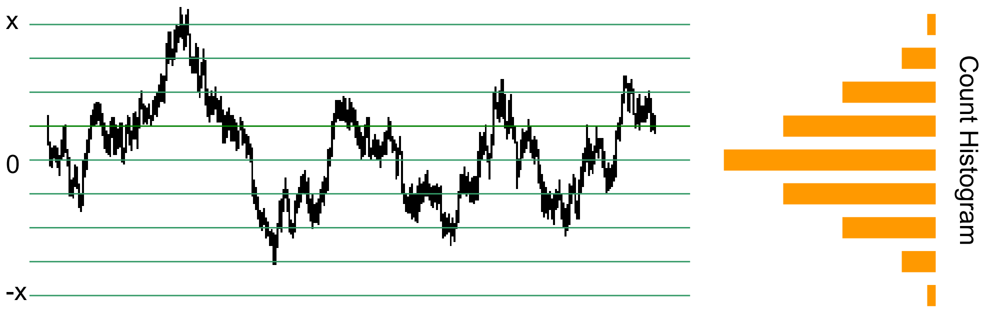
A Noise Experiment

Vary Vt from x to –x & record counter reading



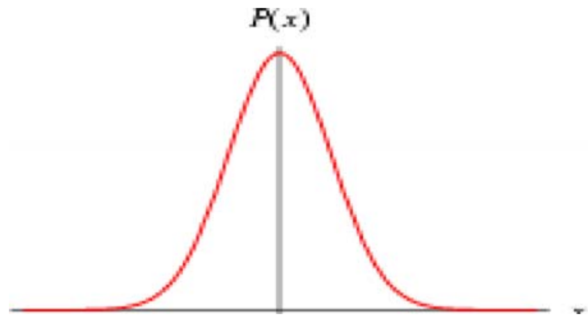
Finding the Amplitude Distribution

A counter records the input signal amplitude as a function of "x"– the comparator threshold.



Take a large number of samples "N"

Distribution Curve Terms

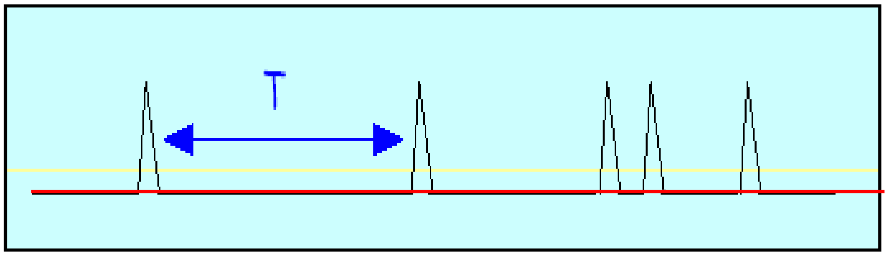


Math majors: "Normal Distribution"

Physics majors: "Gaussian Distribution"

Sociology Majors: "Bell Curve"

Shot Noise



Shot noise is a series of quantized charge packets (pulses of fixed amplitude) with a completely random time (T) of arrival. This figure represents an extremely low current where individual electrons can be seen. Although not common, this type of noise is encountered in photon- counting detectors using a cooled photomultiplier tube (PMT).

Note that the quantized nature of shot noise has completely different probability statistics than Gaussian noise. Shot noise obeys Poisson statistics, although at higher current it approaches Gaussian.

The mean (red) power of shot noise depends on its amplitude (nq/T)

Shot Noise

$$i^2 = 2qI\Delta f$$

Where: I is the current in amps (A)
q is the electronic charge, 1.6E-19 c

The current noise spectral density of shot noise is: $i = \sqrt{2qI}$

shot noise is not Gaussian.

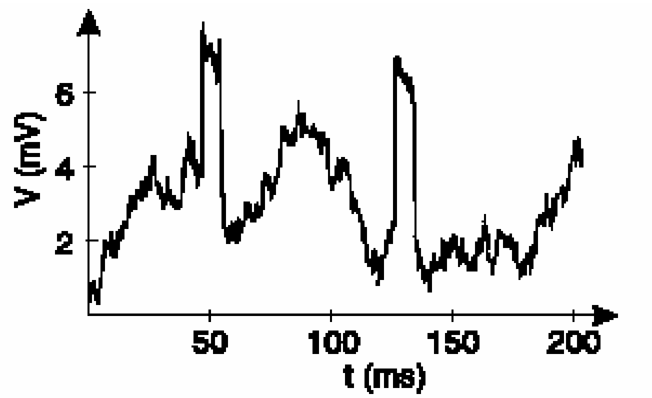
Reference: http://homepages.cae.wisc.edu/~gubner/fpphist.shtml

Shot noise is generated by the random emission of electrons (such as from a cathode or photocathode) or by the random passage of charge carriers (electrons and holes) across a potential barrier. It was first reported by Campbell in 1909.

The mean-square shot noise current in the frequency band Δf is given by an equation developed by Schottky between 1918 to 1928:

Although shot noise is a type of white noise, it does not have the same statistical distribution as thermal noise–

Burst Noise Characteristics



Burst noise is primarily a current noise.

Reference: http://www.wat.edu.pl/review/optor/11(1)45.pdf

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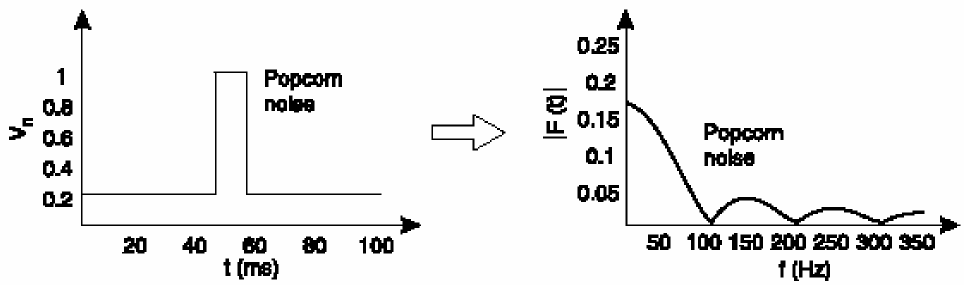
Burst noise (also known as “Popcorn Noise”) is thought to be caused by lattice defects but it is not completely understood.
Microscale beta shifts are also suspected. This type of noise is usually associated with bipolar transistors but it is also seen in pyroelectric detectors.

Burst Noise Characteristics



Time Domain

Frequency Domain

Reference: http://www.wat.edu.pl/review/optor/11(1)45.pdf

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A representation of a typical noise burst is shown on the left as it would appear on an oscilloscope. Performing an FFT on this waveform yields the spectrum shown on the right. Note that the majority of the pulse energy is concentrated at low frequencies but a portion of it is spread over much higher frequencies.

From the Data Sheet

PARAMETER	CONDITION	OPA277P, U OPA2277P, U MIN	TYP(1)	MAX	UNITS
NOISE					
Input Voltage Noise, f = 0.1 to 10Hz			0.22		μVp-p
			0.035		μVrms
Input Voltage Noise Density, f = 10Hz e_n			12		nV/√Hz
f = 100Hz			8		nV/√Hz
f = 1kHz			8		nV/√Hz
f = 10kHz			8		nV/√Hz
Current Noise Density, f = 1kHz i_n			0.2		pA/√Hz

PARAMETER	CONDITION	OPA132P, U OPA2132P, U MIN	TYP	MAX	UNITS
NOISE					
Input Voltage Noise					
Noise Density, f = 10Hz			23		nV/√Hz
f = 100Hz			10		nV/√Hz
f = 1kHz			8		nV/√Hz
f = 10kHz			8		nV/√Hz
Current Noise Density, f = 1kHz			3		fA/√Hz

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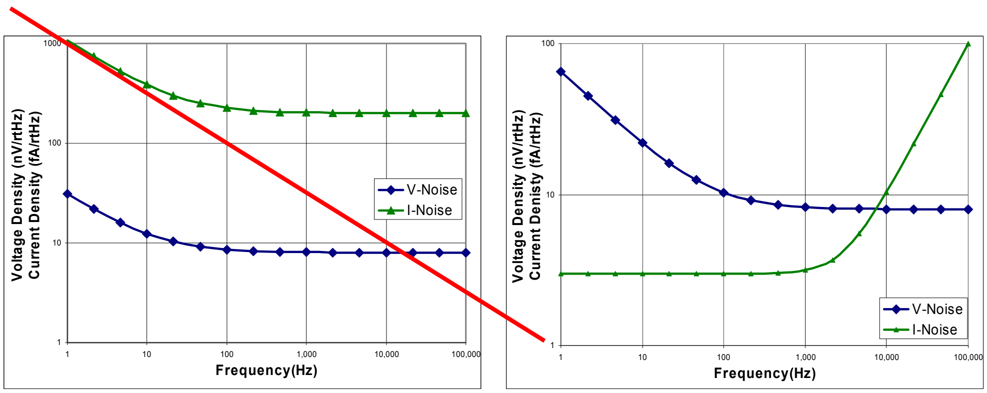
Typical Curves

1/f

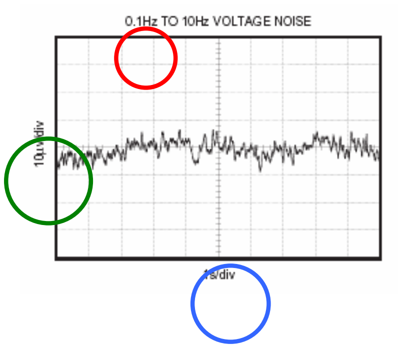


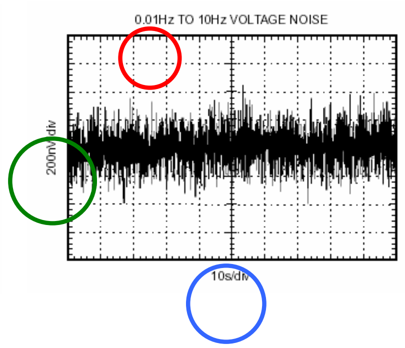
OPA277 -Bipolar **OPA132 -FET**

Data Sheet Noise Info

Op amp and amplifier data sheets may specify Voltage noise two ways—

1. Input voltage noise density @ a spec'd frequency in nV/√Hz.
2. Voltage noise within a frequency band of 0.1Hz to 10Hz in $\mu V_{P\text{-}P}$
3. Graphical low- frequency noise plots such as these:





Choose one…

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Source Resistance Noise

Noise from source resistance:

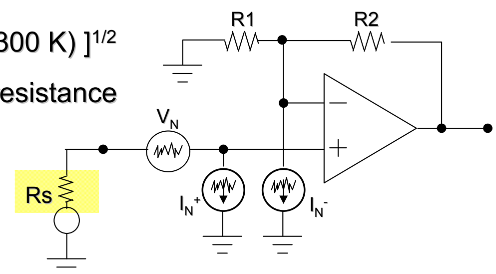
$Vn = (4\ R\ k\ T\ B)^{1/2}$ (total noise Bandwidth)

$Vn = (4\ R\ k\ T)^{1/2}$ (noise density)

e.g. for 10kΩ source:

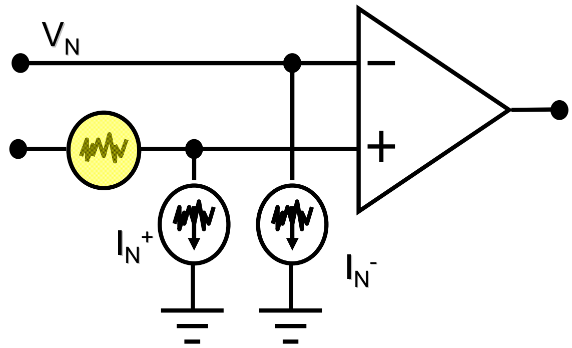
$Vn = [\ 4\ (10{,}000\Omega)\ (1.38 \times 10^{-23})\ (300\ K)\ ]^{1/2}$

$= 12.\underline{8}\ nV/\sqrt{Hz}$ from source resistance



Voltage Noise

A time-varying component of offset voltage.



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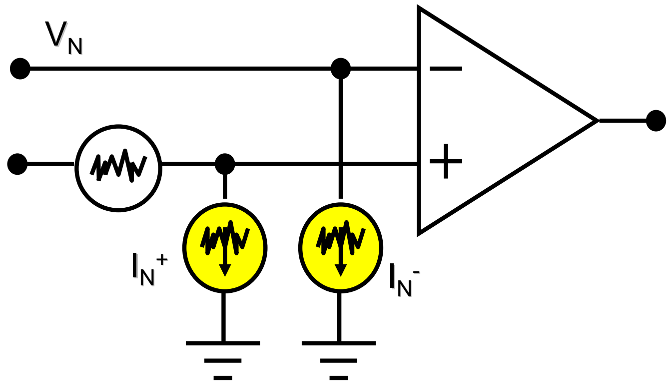
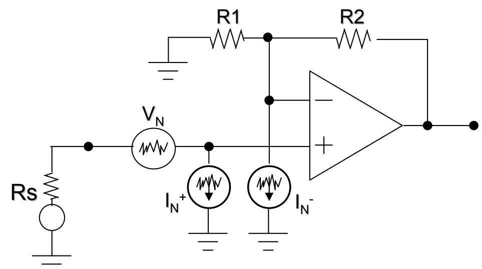
Current Noise

A time-varying component of
input bias current.



The Noise Model

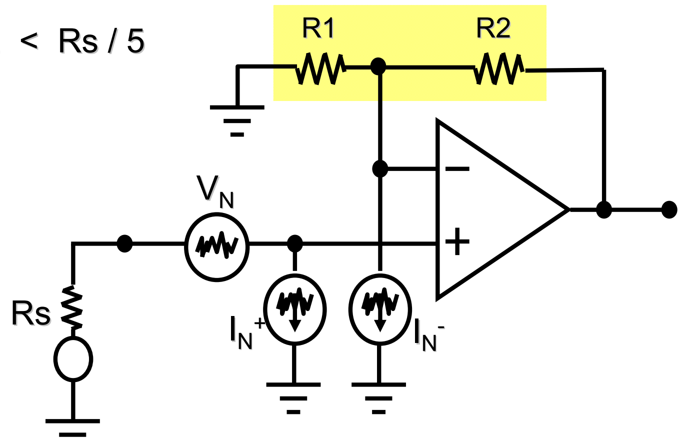


- Rs : Thermal noise => to RTI noise
- V_N : Op amp V_N => RTI noise
- I_N^+ : (I_N^+) (Rs) => RTI noise
- I_N^- : (I_N^-) (R1 // R2) => RTI noise
- R1 : (Thermal noise) (G-1)/G => RTI noise
- R2 : (Thermal noise)/G => RTI noise

Feedback Resistors

- Add thermal noise
- React with op amp's current noise

Make: R1 // R2 < Rs / 5



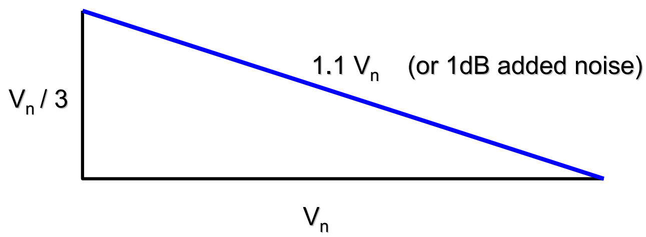
Noise “adds” as right-angle vectors

Or

Root Sum Square (RSS)

NOT …….RMS

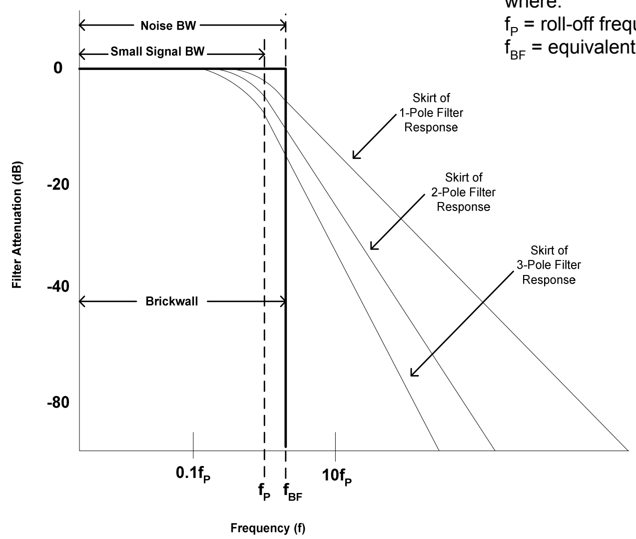
$$\mathbf{V_{nt}} = \sqrt{\mathbf{V_{n1}^2} + \mathbf{V_{n2}^2}} = \sqrt{\mathbf{V_{n1}^2} + \left(\frac{\mathbf{V_{n1}}}{\mathbf{3}}\right)^2}$$



When a noise source is one-third or less than the dominate source, it is virtually insignificant.

Real Filter Correction vs Brickwall Filter

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



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 Noise Bandwidth Ratio
1	1.57
2	1.22
3	1.16
4	1.13
5	1.12

STDEV Relationship to Peak-to-Peak

Number of Standard Deviations	Percent chance of measuring voltage
2σ (same as ±σ)	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%

Is standard deviation the same as RMS?

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Calculating Noise Vpp from Noise Vrms

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

Peak-to-Peak Amplitude	Crest Factor (CF)	Probability of Having a Larger Amplitude
2 X rms	1	32%
3 X rms	1.5	13%
4 X rms	2	4.6%
5 X rms	2.5	1.2%
6 X rms *	3	0.3%
7 X rms	3.5	0.05%

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

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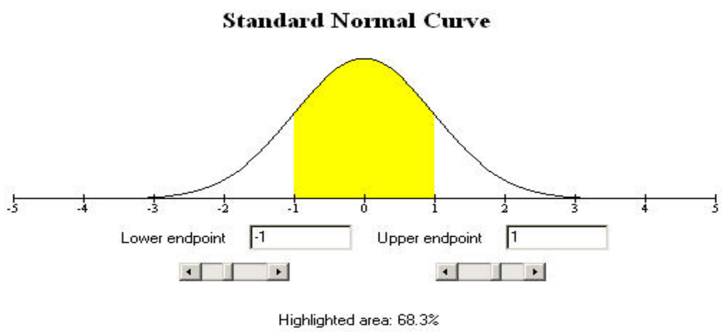
Standard Deviation σ



Probability that instantaneous value is less than RMS value

1σ = 68.3%
2σ = 95.5%
3σ = 99.73%
4σ = 99.9937%

Probability that instantaneous value is greater than RMS value

1σ = 31.7%
2σ = 4.5%
3σ = 0.27%
4σ = 0.0063%

Reference: http://stat-www.berkeley.edu/~stark/Java/NormHiLite.htm

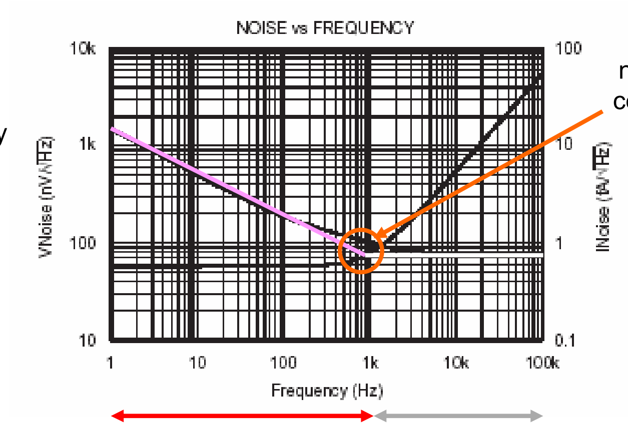
TEXAS INSTRUMENTS

The Limit to LP Filtering

CMOS INA321 voltage noise spectral density

White: white noise region

Pink: 1/f (pink) noise region



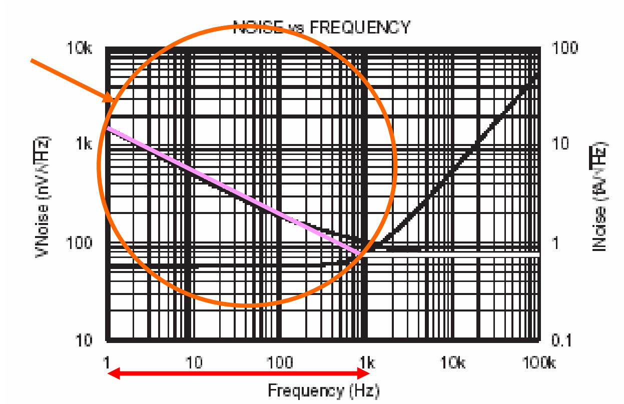
1/f noise corner

LP filtering in this region produces no improve-ment in noise. Why?

LP filtering in this region reduces noise by the square- root of BW.

The Dreaded 1/f Region

LP filtering in this region produces no improvement in noise. Why?



Because in the 1/f noise region the noise density increases at the same rate that you reduce the bandwidth! In the INA321 example above look at what reducing the BW by a factor of 100 (from 1kHz to 10Hz) does. White noise would be reduced by a factor of √ 100 or 10 but in the 1/f region the noise increased by a factor of 10 as the √ BW was reduced by 10– no improvement!