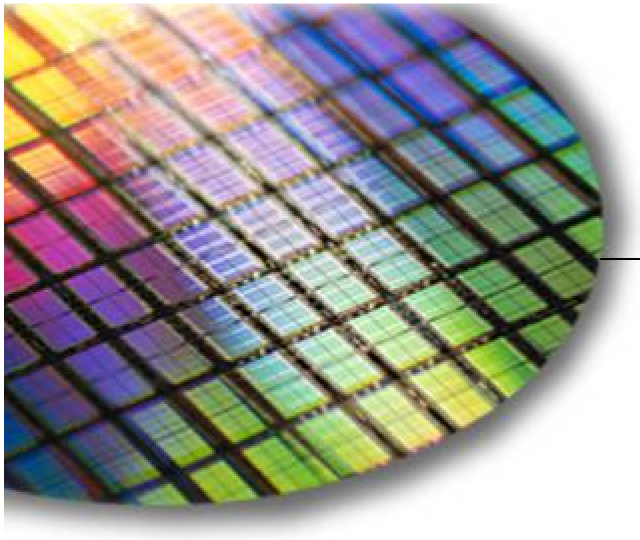


The World Leader in High Performance Signal Processing Solutions

Amplifier Noise Principles for the Practical Engineer

Matt Duff
Applications Engineer – Instrumentation Amplifiers
Analog Devices, Inc.

ANALOG DEVICES

Outline

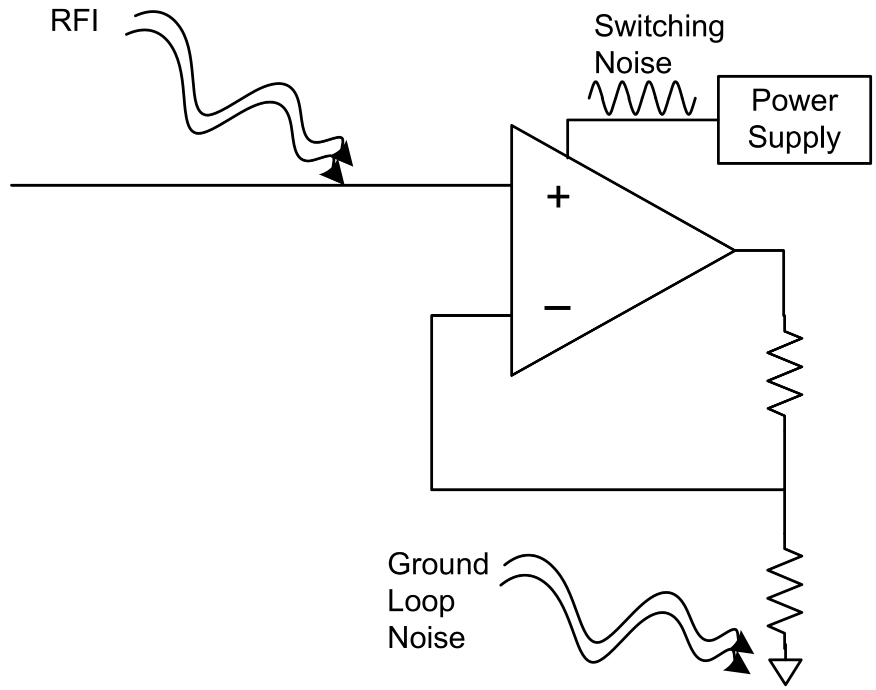
- Noise
  - Extrinsic
  - Intrinsic
- Three main sources of intrinsic noise
  - Resistance
  - Amplifier
    - Voltage Noise
    - Current Noise
  - ADC
- Why so many units?
  - nV/rt(Hz), µVrms, µVp-p
  - Unit conversion
- Noise Math & Shortcuts
- Tips
  - Applying gain
  - Source resistance
  - Feedback resistance

Where does noise come from?

- Extrinsic
- Intrinsic

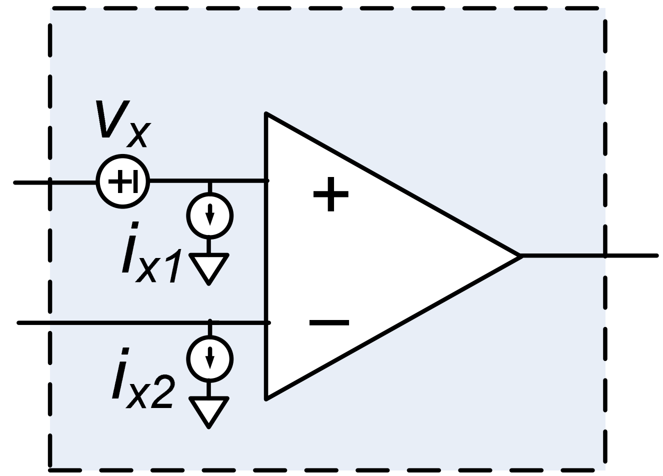
Extrinsic Noise

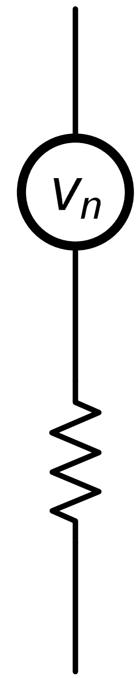
- **Noise coupling in from external sources**
- **Examples**
  - **RFI Coupling**
  - **Power Supply Noise**
  - **Ground loops**
    - Digital circuitry
    - 50/60 Hz
- **Not focus of this talk**



Intrinsic Noise

- **Intrinsic**
  - **Internal noise from components in signal chain**
    - Sensor
    - Resistors
    - Amplifier
    - A/D
  - **Specified on the datasheet**
  - **Focus of this talk**

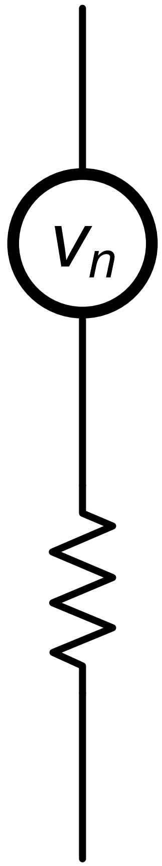




Main Sources of Intrinsic Noise

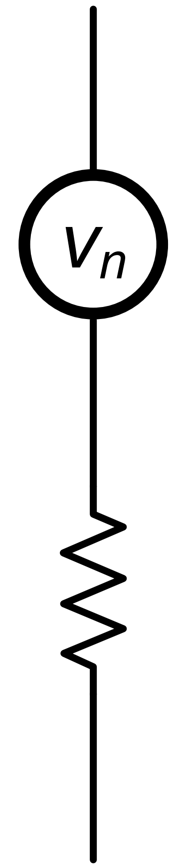
- Resistor
- Amplifier
- A/D

Resistor noise



Types of Resistor noise

- **Excess Noise**
  - **Depends on type:**
    - Carbon composition = bad performance
    - Thick film = OK performance
    - Thin film, wirewound = good performance
  - **Increases with applied voltage**
  - **1/f characteristic**
  - **Can ignore if using good resistors**
- **Intrinsic thermal noise**
  - **Independent of type**
  - **Independent of voltage applied**
  - **White noise characteristic**
  - **Need to calculate in design**



Thermal noise of an ideal resistor

$$v_n = \sqrt{4k\ T\ R\ \Delta f}$$

bandwidth

rms noise

constant

Temperature (in Kelvin)

resistance

Too Complicated!

Resistor noise shortcut

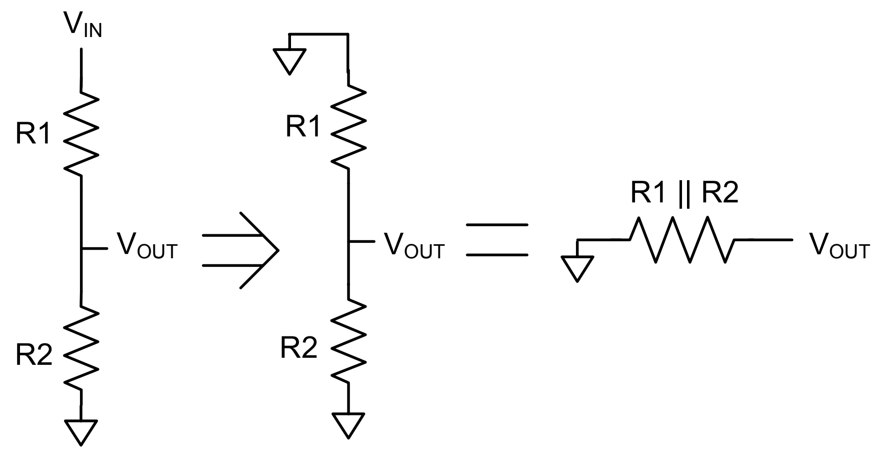
1 kΩ→ 4 nV/√(Hz)

Noise scales as square root of resistance

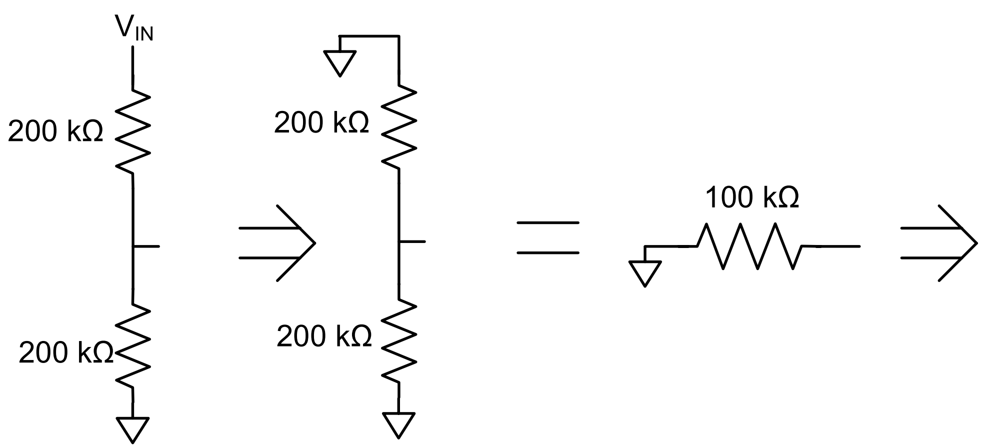
- 4 kΩ→ (2)(4) nV/√(Hz) = 8 nV/√(Hz)
- 9 kΩ → (3)(4) nV/√(Hz) = 12 nV/√(Hz)
- 16 kΩ → (4)(4) nV/√(Hz) = 16 nV/√(Hz)
- 100 kΩ → (10)(4) nV/√(Hz) = 40 nV/√(Hz)

Common Resistor Circuits: Resistor Divider

Theory:



Example:

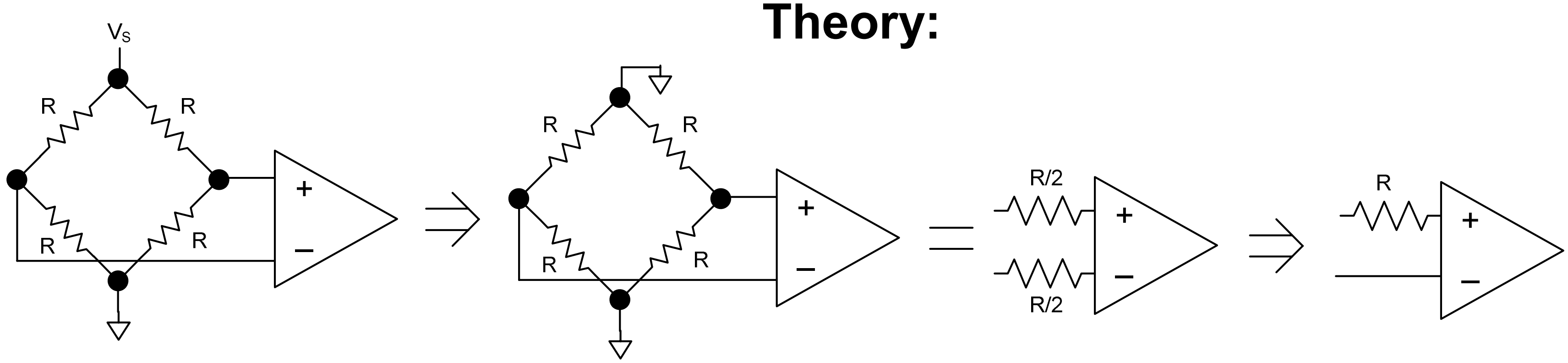


$\sqrt{(100)} * 4\ nV / \sqrt{(Hz)} =$

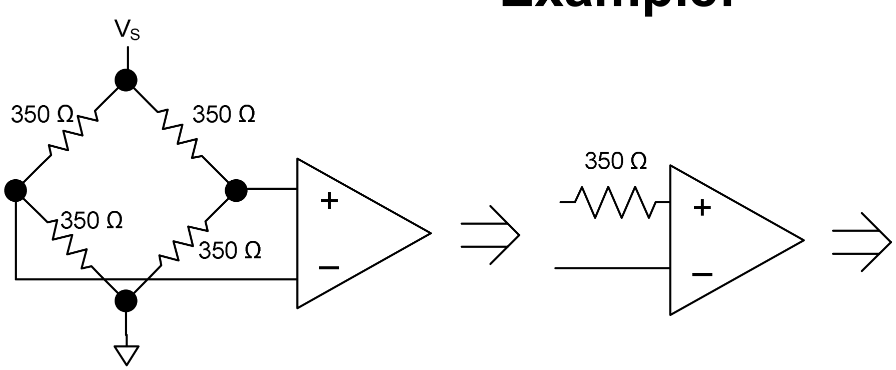
$40\ nV / \sqrt{(Hz)}$

Common Resistor Circuits – Bridge

Theory:



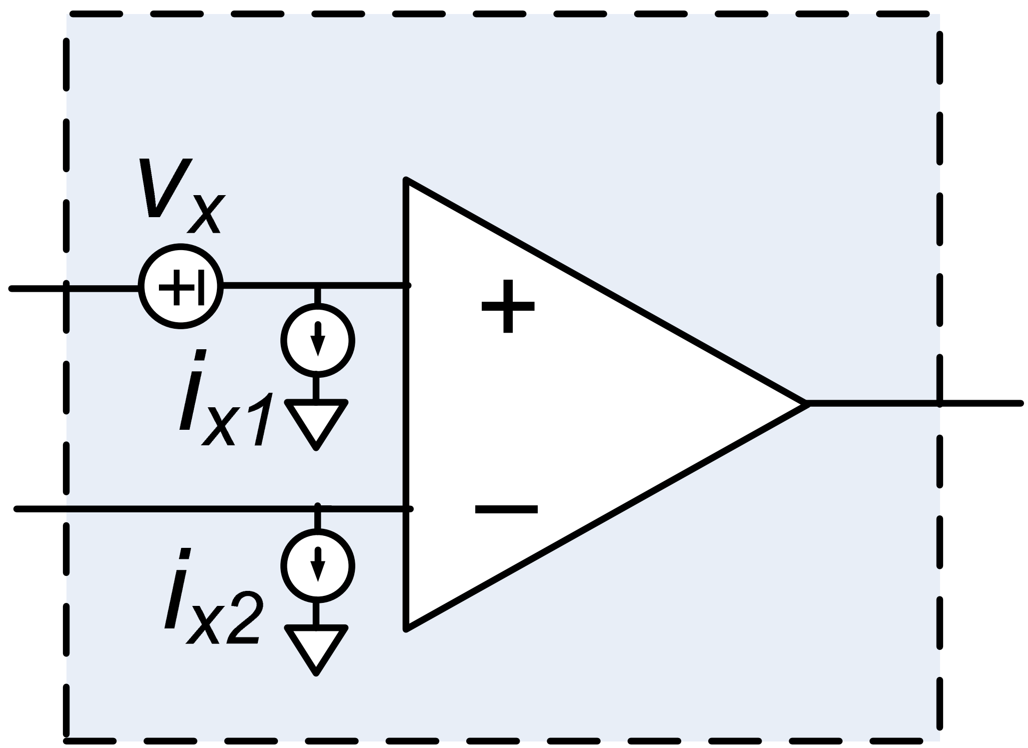
Example:



$\sqrt{(0.35)} * 4\ \text{nV}/\sqrt{(\text{Hz})} =$

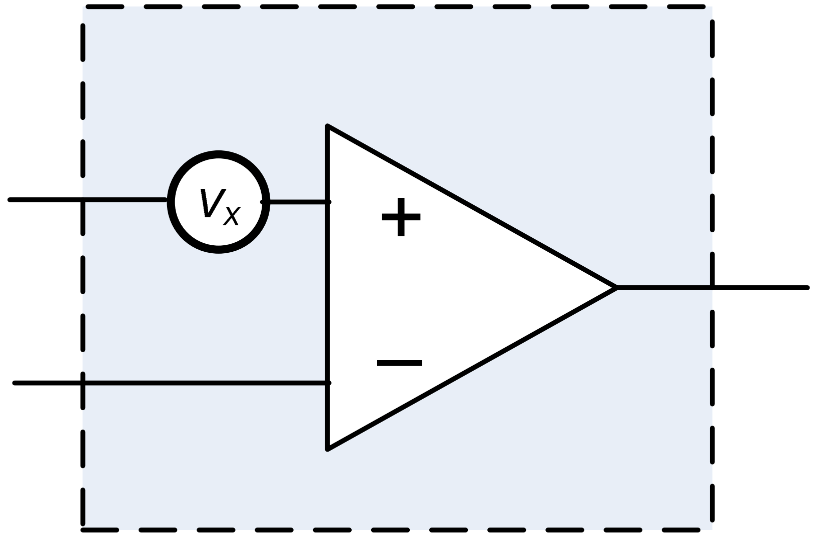
$$\mathbf{2.4\ nV/\sqrt{(Hz)}}$$

Amplifier Noise



Amplifier Voltage Noise

- **Units:**
  - **nV/√(Hz)**
  - **μVrms**
  - **μV p-p**

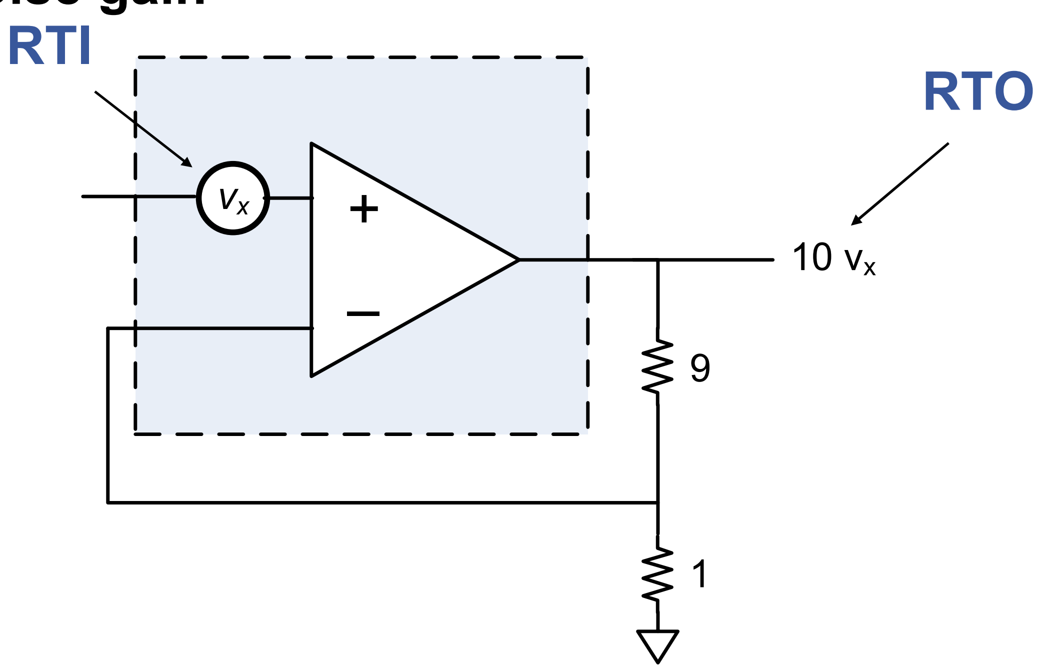


example from AD8295 datasheet:

Voltage Noise Density		40	nV/√Hz
Voltage Noise	f = 0.1 Hz to 10 Hz	2.2	μV p-p

Amplifier Voltage Noise: Referred to What?

- Options
  - Referred to Input (RTI)
  - Referred to Output (RTO)
- If not stated, referred to Input
- Multiply by "noise gain"



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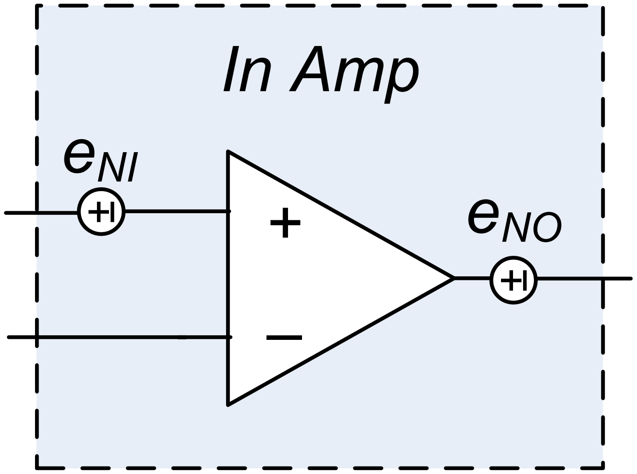
Instrumentation Amplifiers are Different

- **Op Amps**
  - All noise dependent on gain
- **In Amps**
  - Some noise dependent on gain (e_{NI})
  - Some noise independent of gain (e_{NO})
- **Total In Amp Noise, referred to input**
  - $\sqrt{(e_{NI}^2 + (e_{NO}/G)^2)}$

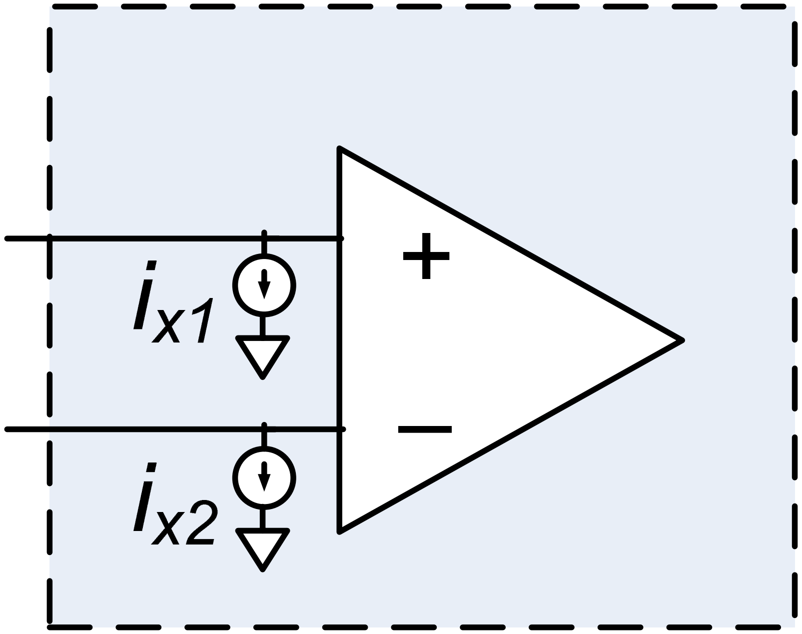


example from AD8221 datasheet:

Voltage Noise, 1 kHz	RTI Noise = $\sqrt{(e_{NI}^2 + (e_{NO}/G)^2)}$		
Input Voltage Noise, e_{NI}	V_{IN+}, V_{IN-}, V_{REF} = 0 V	8	nV/√Hz
Output Voltage Noise, e_{NO}	V_{IN+}, V_{IN-}, V_{REF} = 0 V	75	nV/√Hz

Amplifier Current Noise

- **Units:**
  - **fA/√(Hz)**
  - **pArms**
  - **pA p-p**

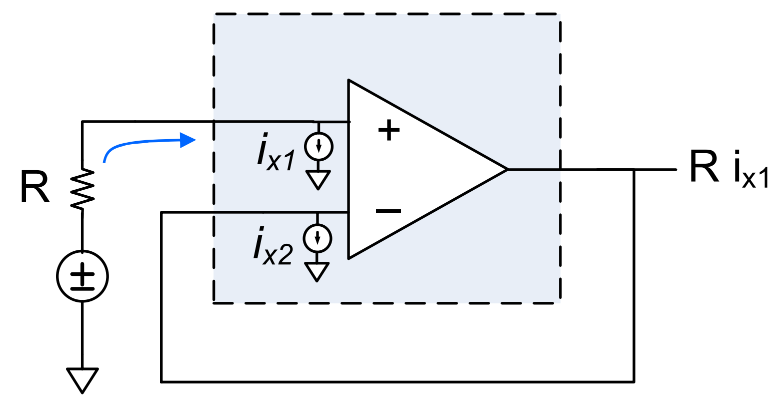


example from AD8295 datasheet:

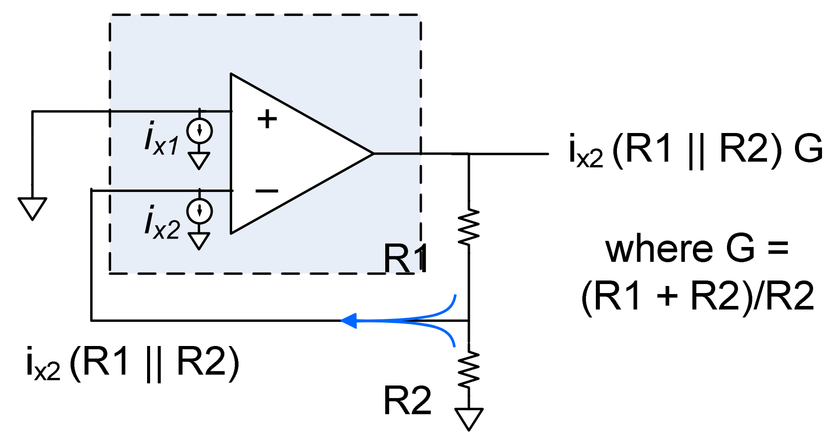
Current Noise	f = 1 kHz	40	fA/√Hz
	f = 0.1 Hz to 10 Hz	6	pA p-p

Amplifier Current Noise: Effect depends on resistance

- Source resistance



- Feedback network



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ADC Noise:

- Sometimes voltage units provided:

Table 6. RMS Noise (nV) vs. Gain and Output Data Rate

Filter Word (Decimal)	Output Data Rate (Hz)	Settling Time (ms)	Gain of					
			1	8	16	32	64	128
1023	4.7	852.5	340	53	34	18	12	11
640	7.5	533	410	67	40	24	14	13
480	10	400	430	76	45	28	16	15

- But most of the time, signal to noise ratio (SNR)
  - With distortion: SINAD

Signal-to-Noise Ratio, SNR	f_{IN} = 20 kHz, V_{REF} = 4.096 V, internal reference	87.0	88.5	dB
	f_{IN} = 20 kHz, V_{REF} = 5.0 V, external reference	89.0	90.0	dB

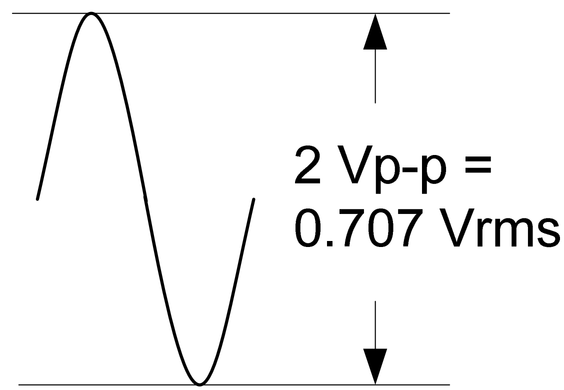
- In emergency use ideal equation
  - SNR = 6.02 * Bits + 1.76
  - Gives better performance than reality

ADC Noise – Converting SNR to µVrms

Conversion Equation:

$$\frac{\text{Full Scale Voltage in } \mu\text{Vrms}}{10^{\frac{SNR}{20}}} = \text{ADC noise in } \mu\text{Vrms}$$

Key Point: Use RMS value for full scale range!



Example:

- **2 V ADC input range**
- **69 dB SNR**

$$\frac{(2 \times 10^{6}\ \mu V)(0.5)(.707)}{10^{\frac{69}{20}}} = 251\ \mu\text{Vrms}$$

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Why so many units?

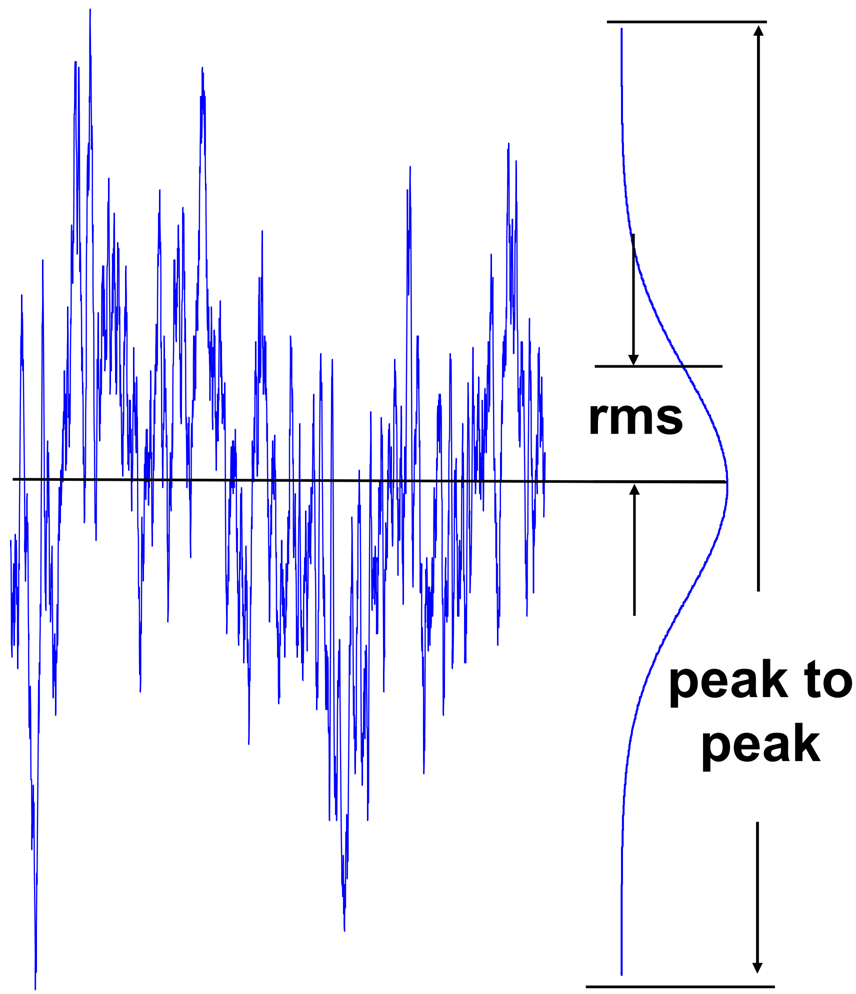
- μVrms, μVp-p, nV/√Hz
- RMS, peak to peak, spectral density
- converting between units

Peak to Peak and RMS noise

- **Peak to peak noise**
  - **Distance from min and max points on waveform**
  - **Depends on only two points**
    - Less accurate
      - Variable
      - Measure longer -> bigger result
    - Easy to compute
      - Max - Min

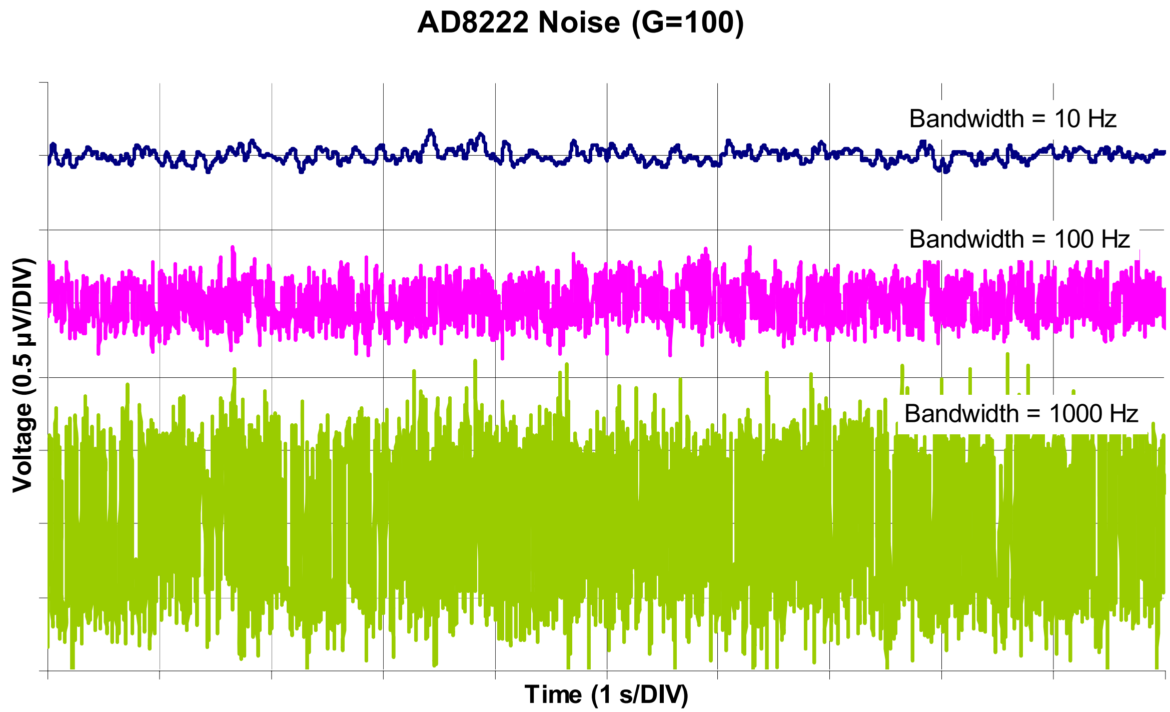
- **RMS noise**
  - **One standard deviation**
    - (mean is zero)
  - **Depends on all points**
    - More accurate
      - Repeatable
      - Measure longer -> more accurate result
    - Lengthy to compute

$$\sqrt{\frac{x_1^2 + x_2^2 + \ldots + x_n^2}{n}}$$



RMS and Peak to Peak: Dependent on Bandwidth

- **When measuring:**
  - Circuit bandwidth
  - Measurement instrument bandwidth
- **When specifying**
  - Bandwidth must be noted

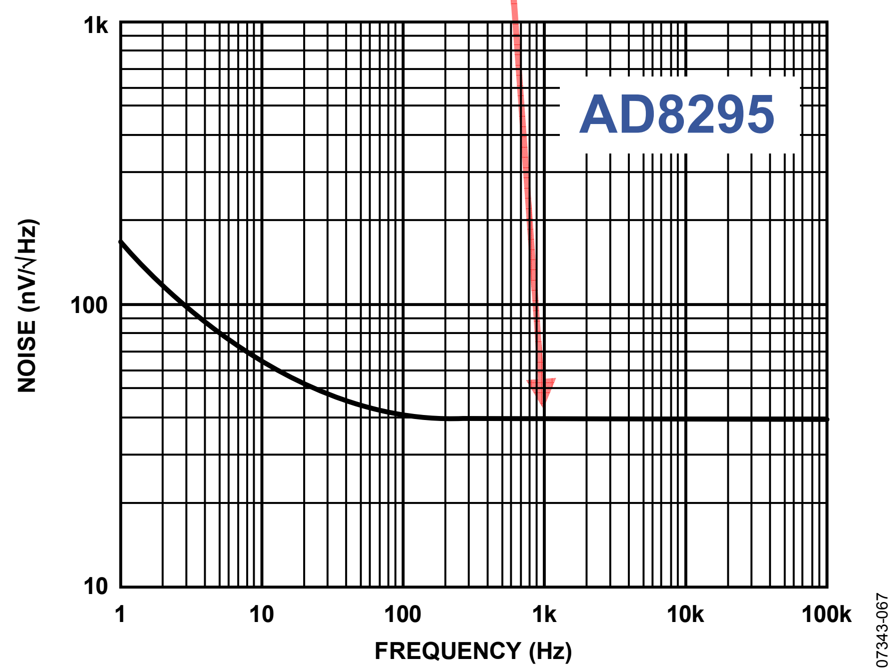


NOISE			
RTI	f = 0.1 Hz to 10 Hz		
G = 100 to 1000		0.25	µV p-p

Spectral Noise Density

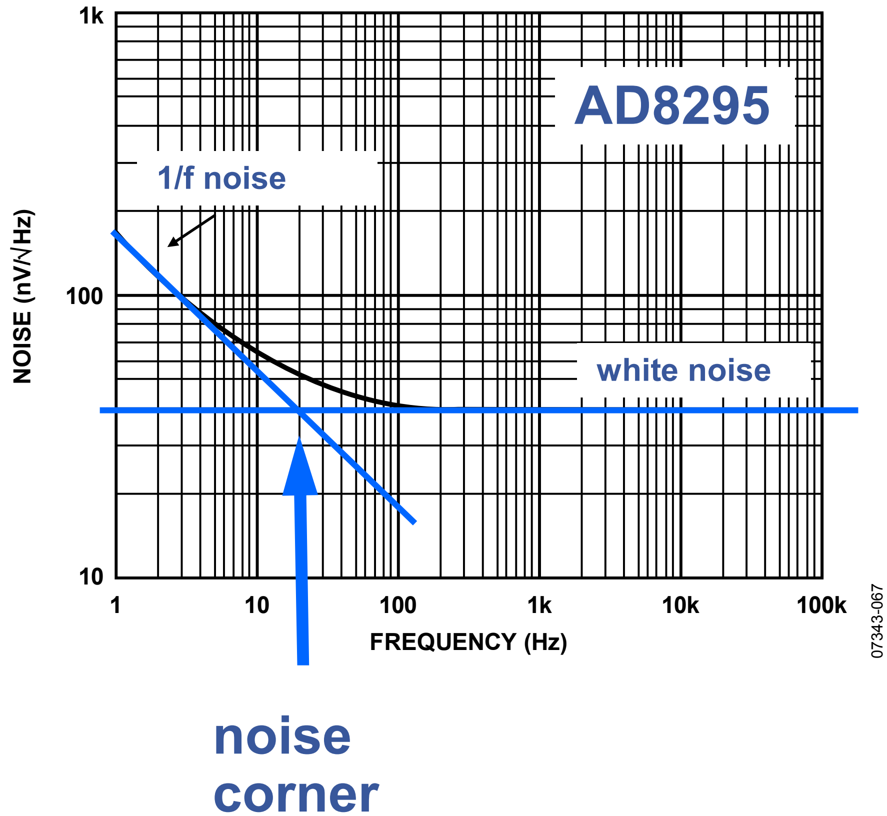
Voltage Noise Density	f = 1 kHz	40	nV/√Hz
Voltage Noise	f = 0.1 Hz to 10 Hz	2.2	µV p-p

- **Frequency Domain**
  - **Noise density at specific frequency**
- **Units**
  - **nV/√Hz**
  - **fA/√Hz**
- **Includes many, many points**
  - **Datasheet figure has lots of averaging**



Spectral Noise Density – 1/f corner

- **1/f noise**
  - Noise density increases at low frequencies
- **White noise**
  - Noise density flat at high frequencies
- **1/f corner**
  - Where 1/f noise and white noise trendlines intersect



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How to convert

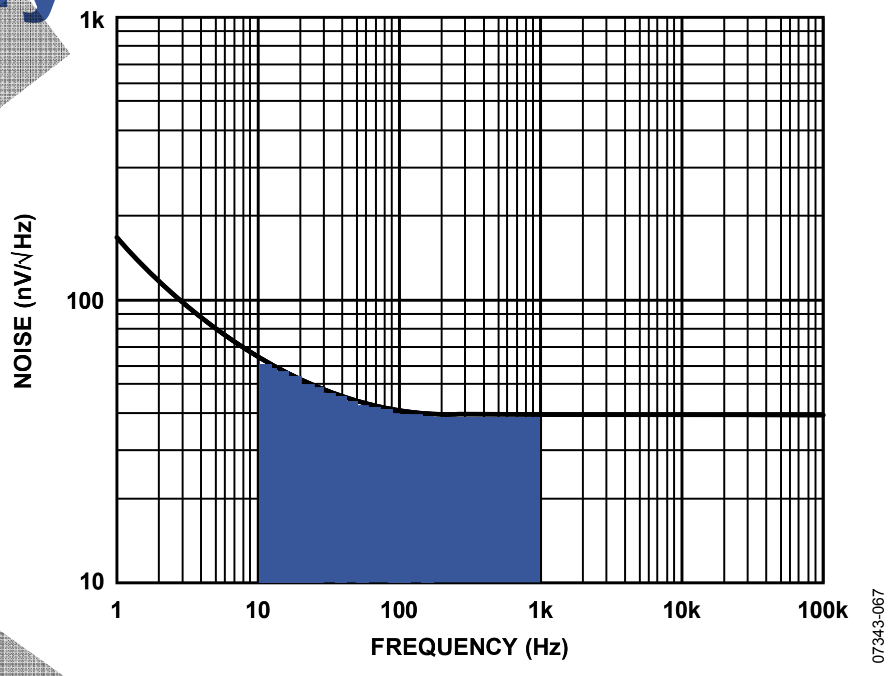
- **Conversion process**
  - **nV/√(Hz) → µVrms**
  - **µVrms → µVp-p**

nV/√(Hz) -> μVrms: theory

- **Theoretical Equation**

$$Noise_{RMS} = \sqrt{\int_{f_{LOW}}^{f_{HIGH}} (SD_f)^2 \, df}$$

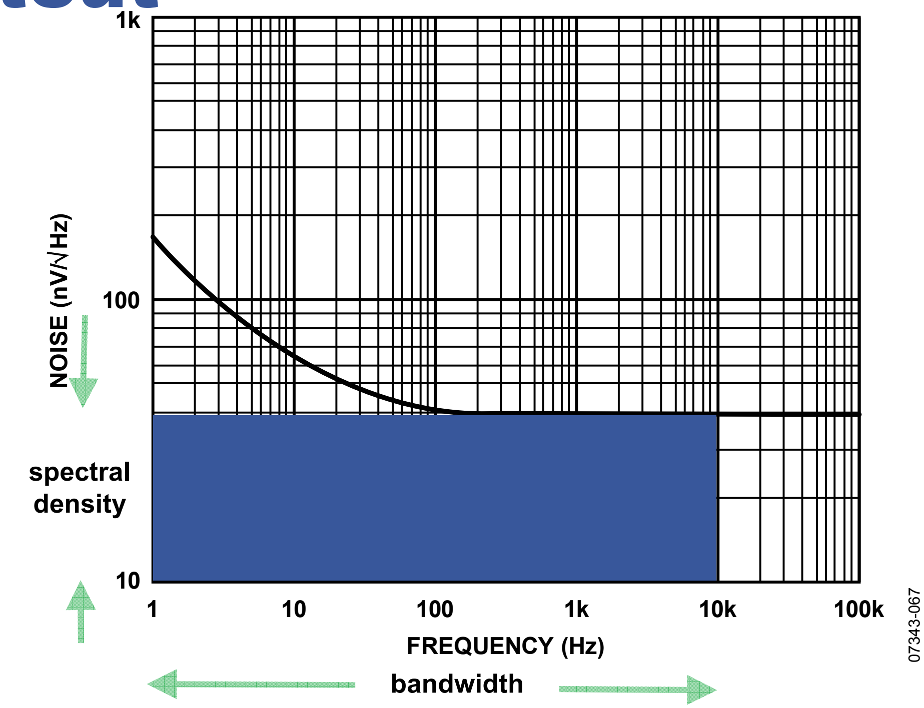
- **Where**
  - SD_f: spectral density at frequency f
  - f_{LOW}: low frequency cutoff
  - f_{HIGH}: high frequency cutoff



Too Complicated!

nV/√(Hz) -> µVrms shortcut

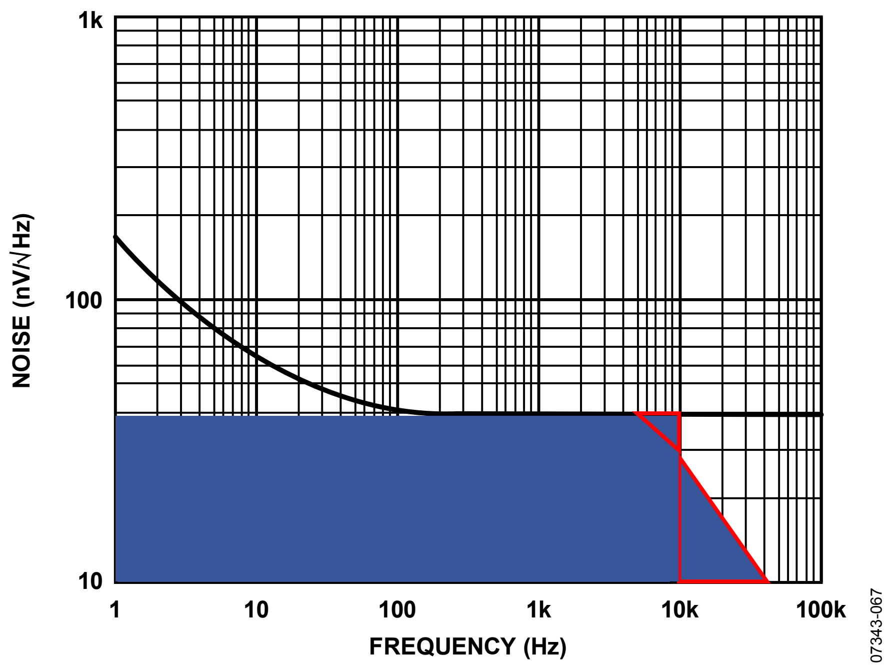
- **Assumption**
  - **Mostly white noise**
    - 1/f corner << bandwidth
- **Equation**
  - **RMS Noise = spectral density * √(bandwidth)**



Equivalent Noise Bandwidth

- **Equivalent Noise bandwidth for Butterworth filters**
  - **1 pole: 1.57**
  - **2 pole: 1.11**
  - **3 pole: 1.05**

- **Example:**
  - **Given:**
    - 40 nV/rt(Hz)
    - 10 kHz 1 pole filter
  - **Answer:**
    - 40 nV/rt(Hz) * sqrt(10 kHz * 1.57) ≈ 5000 nVrms = 5 μVrms



nV/√(Hz) -> µVrms

- **Not mostly white noise?**
  - **1/f corner near bandwidth**

- **Options**
  - **Use theoretical formula?**
  - **Use amplifier with low 1/f corner**
  - **Compare uVp-p numbers**
    - 0.1 to 10 Hz
  - **Autozero/Chopper**

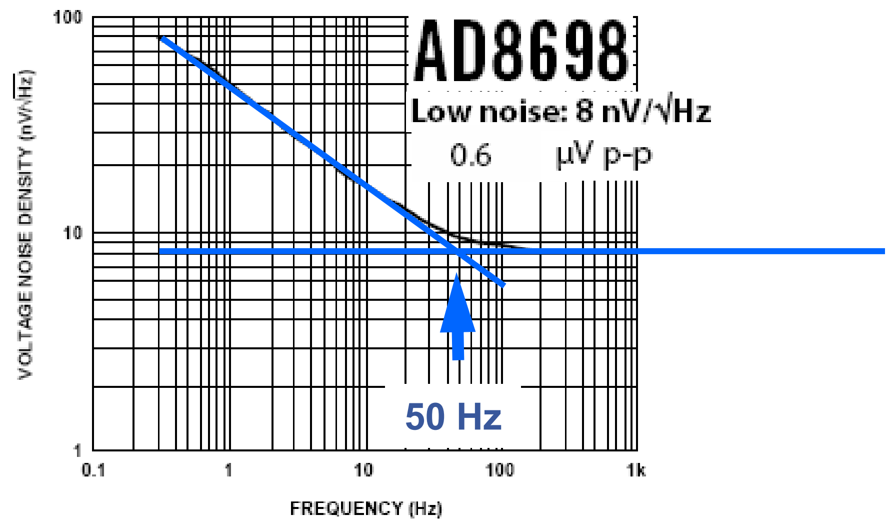


Figure 16. Voltage Noise Density vs. Frequency

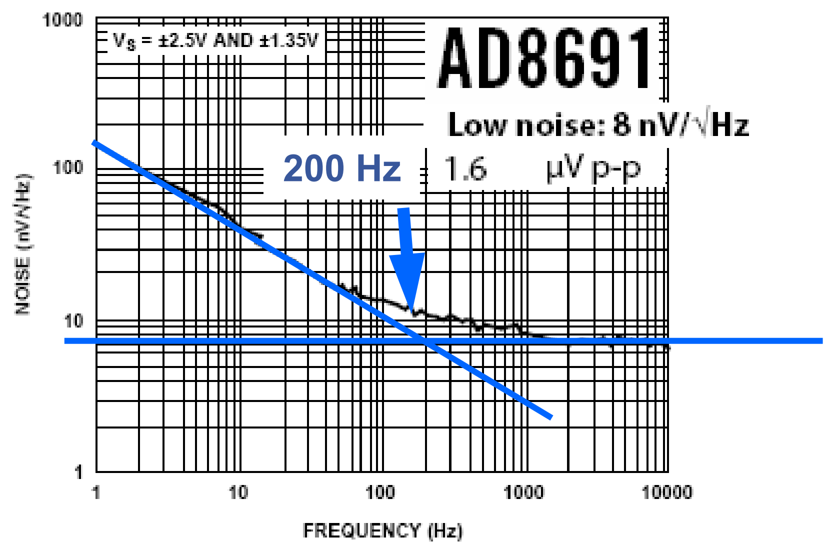
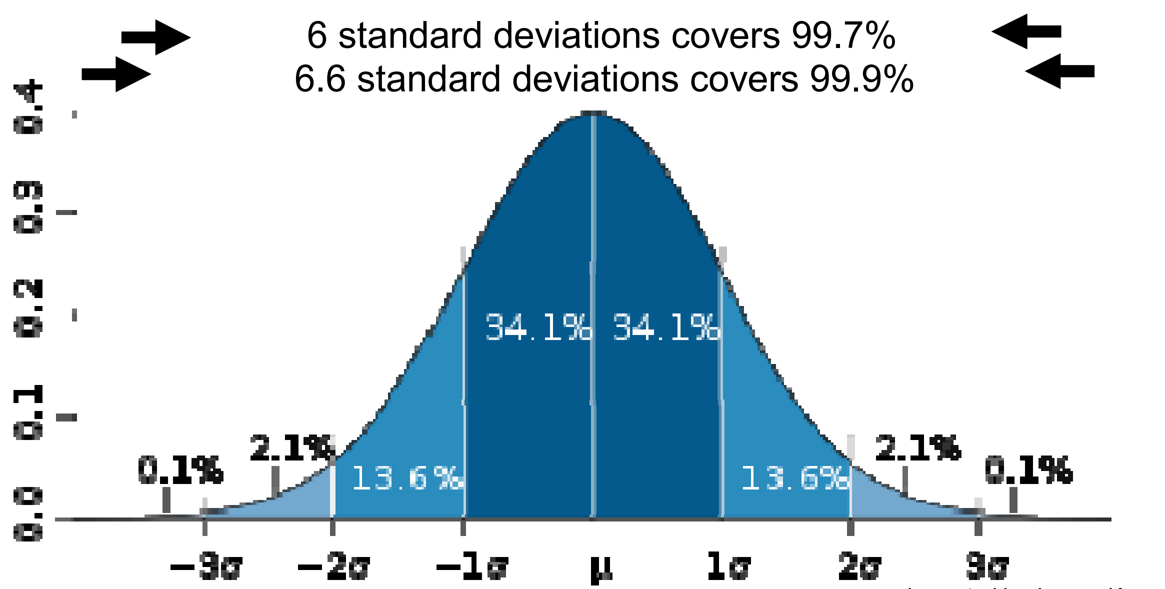


Figure 27. Voltage Noise Density

µVrms -> µVp-p

- **To get peak to peak noise**
  - **In theory: peak to peak noise infinite**
  - **In practice: multiply rms by 6**
    - Multiplier of ‘6’ is rule of thumb: 99.73% of points
- **Examples**
  - **1 µVrms * 6 ≈ 6 µVp-p**
  - **1 µVrms * 6.6 ≈ 6.6 µVp-p**



graph created by Jeremy Kemp

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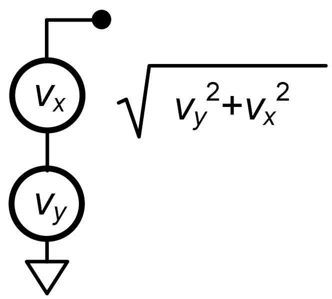
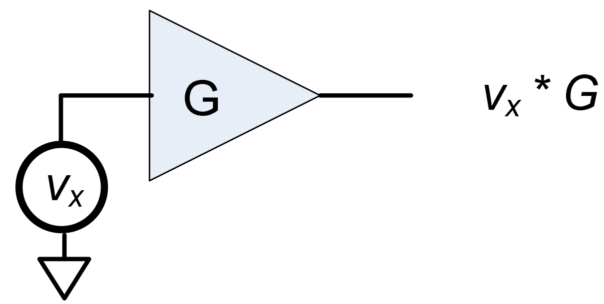
Math and Shortcuts

Noise Math

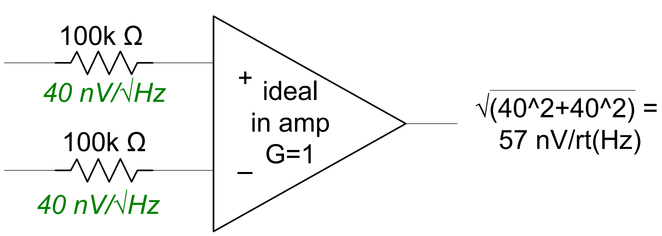
- **Addition**
  - Noise adds as sum of squares



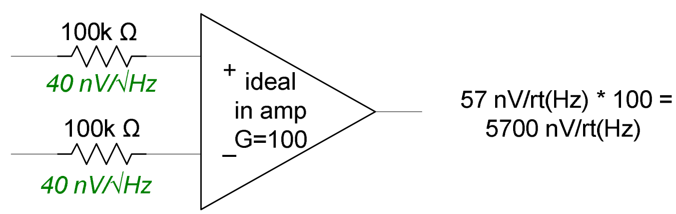
- **Multiplication**
  - Gain and attenuation work just like normal signals



Example



Example



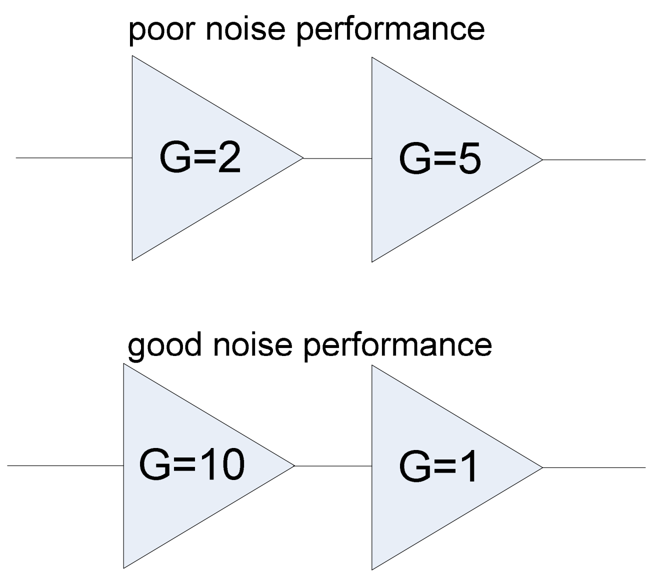
Noise shortcuts

- 1 k Ω resistor -> 4 nV/√Hz
- When adding noise sources, larger sources dominate
  - Sum of squares addition
  - Ignore signals < 1/5th largest signal
- If first stage gain is large
  - Later stages typically have little effect

Tips

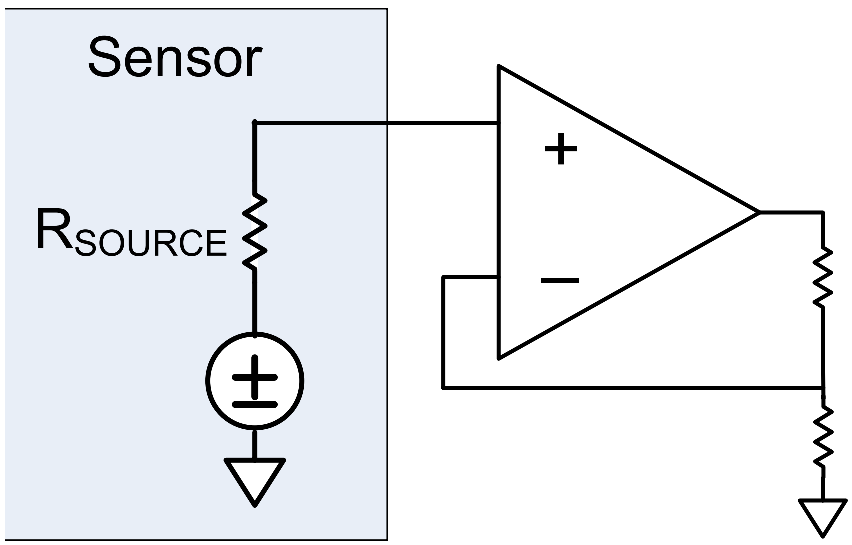
Noise Tip #1: Apply Gain Early

- Noise adds as sum of squares



Noise Tip #2: Watch out for source impedance

- Source Resistance adds noise
- Current noise calculation



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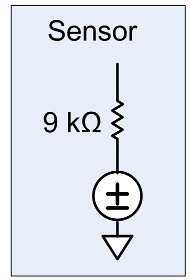
Source impedance example

- Given the following sensor:



Sensor Noise:
√9 x 4 nV/√Hz
= 12 nV/√Hz

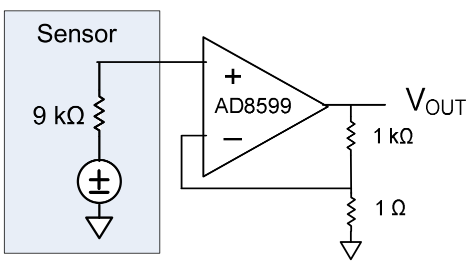
- Which op amp is better?

Ultralow Distortion, Ultralow Noise Op Amp

FEATURES

1.1 nV/√Hz

2.3 pA/√Hz x 9 kΩ = 20.7 nV/rt(Hz)



Noise contributors (RTI):

Sensor noise = 4 x √9 =	12
Amp Voltage noise =	1.1
Amp Current noise = 2.3 x 9 =	20.7

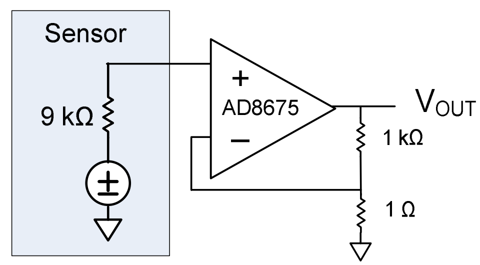
Total Noise = $\sqrt{(12^2+1.1^2 + 20.7^2)}$ = **24 nV/rt(Hz)**

36 V Precision, 2.8 nV/√Hz Rail-to-Rail Output Op Amp

FEATURES

2.8 nV/√Hz

0.3pA/√Hz x 9 kΩ = 2.7 nV/rt(Hz)



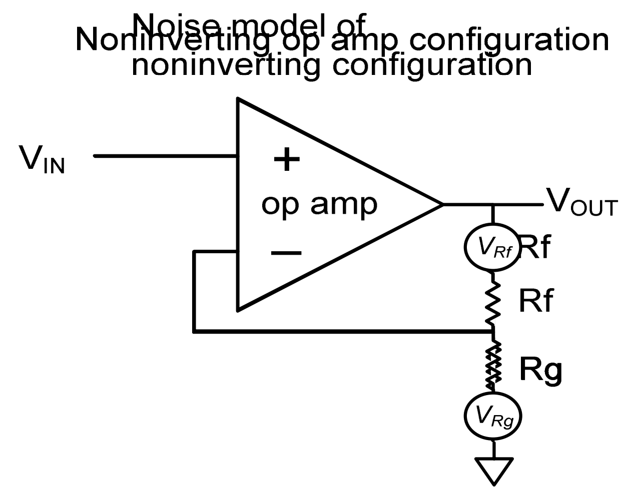
Noise contributors (RTI):

Sensor noise = 4 x √9 =	12
Amp Voltage noise =	2.8
Amp Current noise = 0.3 x 9 =	2.7

Total Noise = $\sqrt{(12^2+2.8^2 + 2.7^2)}$ = **12.3 nV/rt(Hz)**

Noise Tip #3: Watch out for feedback resistors

- Rf acts like voltage source at output
- Rg acts likes inverting configuration voltage source
- What noise dominates?
  - Rf dominates
    - Noninverting config: G<2
    - Inverting configuration: G > -1
  - Rf and Rg noise equal
    - Noninverting config: G=2
    - Inverting config: G = -1
  - Rg dominates
    - Noninverting config: G>2
    - Inverting config: G<-1
- Watch out for current noise

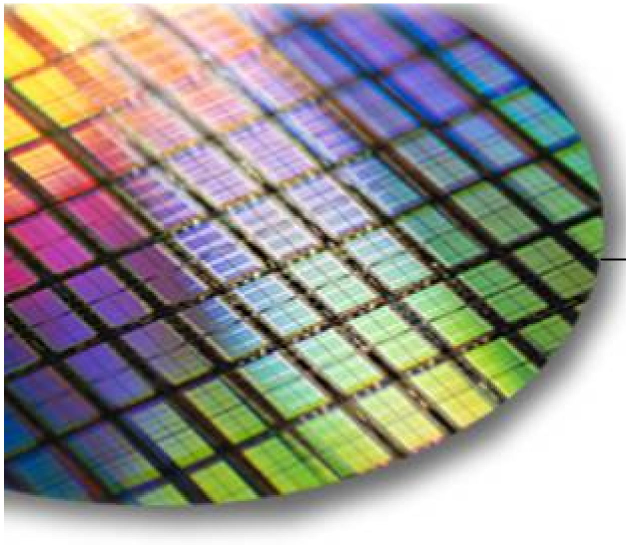


Summary

- Noise
  - Extrinsic
  - Intrinsic
- Three main sources of intrinsic noise
  - Resistance
  - Amplifier
    - Voltage Noise
    - Current Noise
  - ADC
- Why so many units?
  - RMS noise, peak to peak noise, spectral density
  - How to convert between units
- Noise Math & Shortcuts
- Tips
  - Gain Early
  - Source Impedance
  - Feedback resistors

Where to learn more

- **Application Notes**
  - AN-940: Low Noise Amplifier Selection Guide for Optimal Noise Performance
  - AN-358: Noise and Operational Amplifier Circuits
- **Analogue Dialogue**
  - Ask The Applications Engineer -7: What should I know about op-amp noise?
  - Ask The Applications Engineer -8: What is “noise gain”?
- **Webinar**
  - Noise Optimization in Signal Conditioning Circuits (Three part series)
- **Tutorials**
  - MT-047: Op Amp Noise
  - MT-048:Op Amp Noise Relationships: 1/f Noise, RMS Noise,
  - and Equivalent Noise Bandwidth
  - MT-049: Op Amp Total Output Noise Calculations for Single-Pole System
  - MT-050: Op Amp Total Output Noise Calculations for Second-Order System
  - MT-065: In-Amp Noise



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Questions?

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