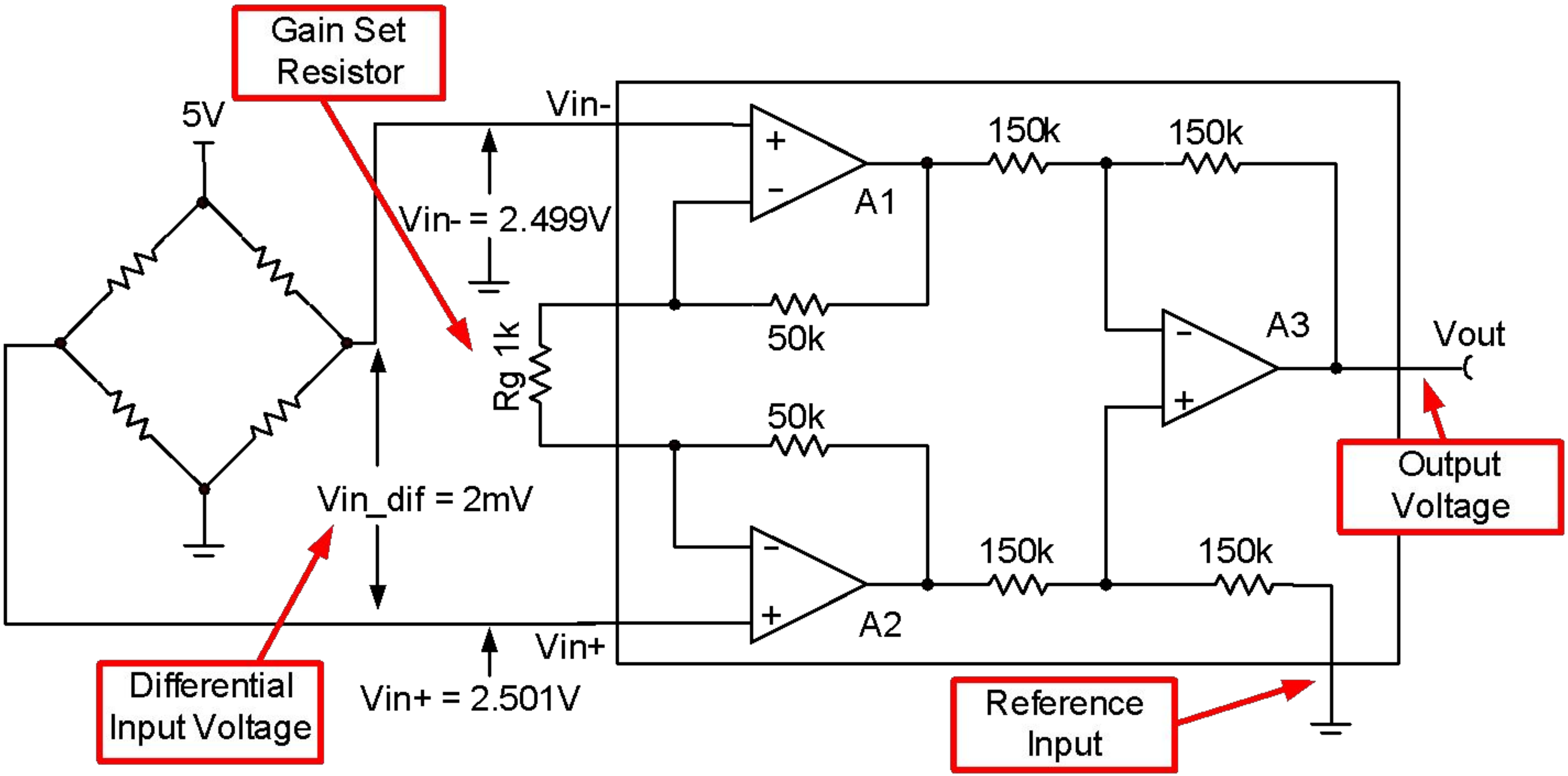
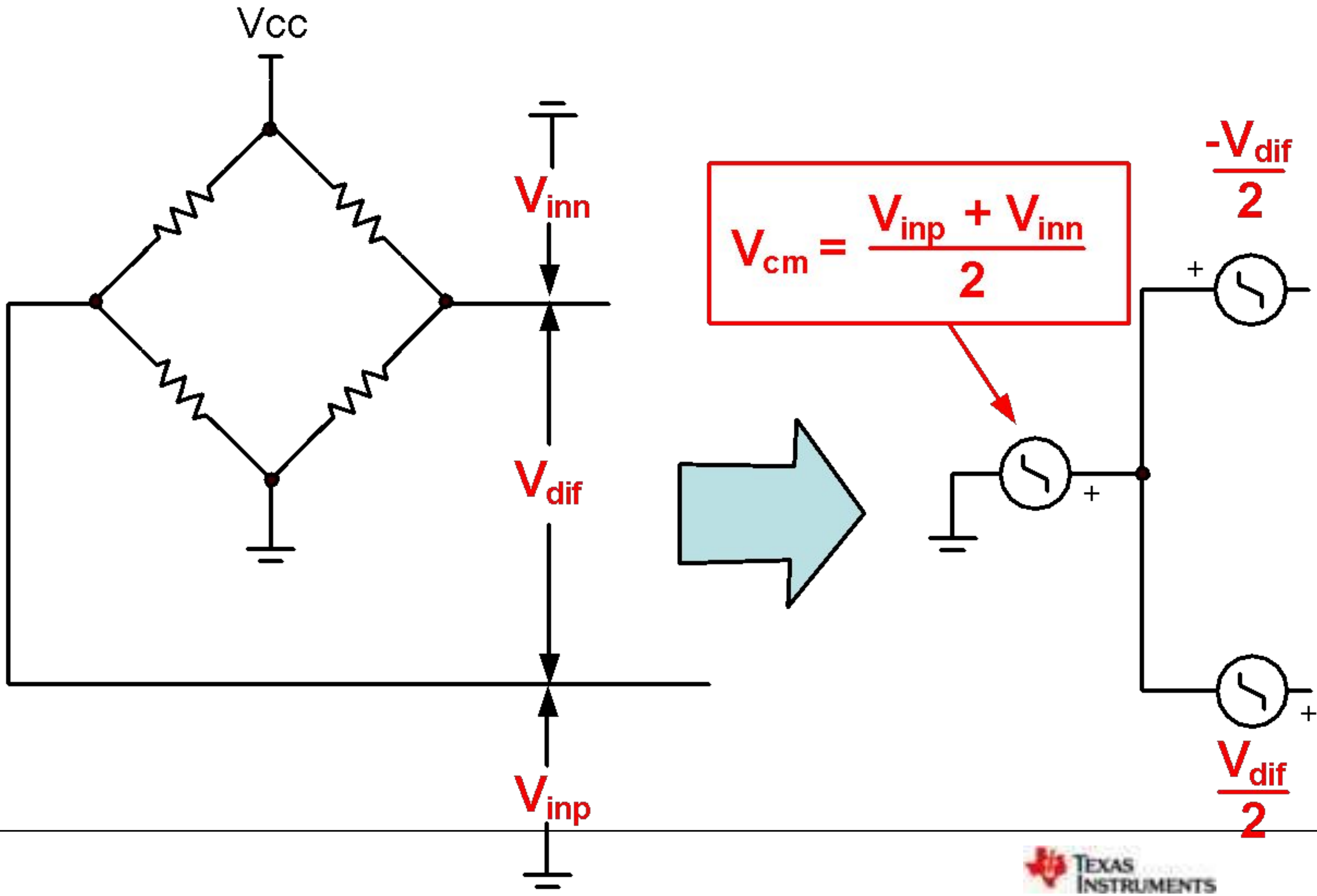
Instrumentation Amplifier Noise Analysis

Short Review of 3 Amp INA

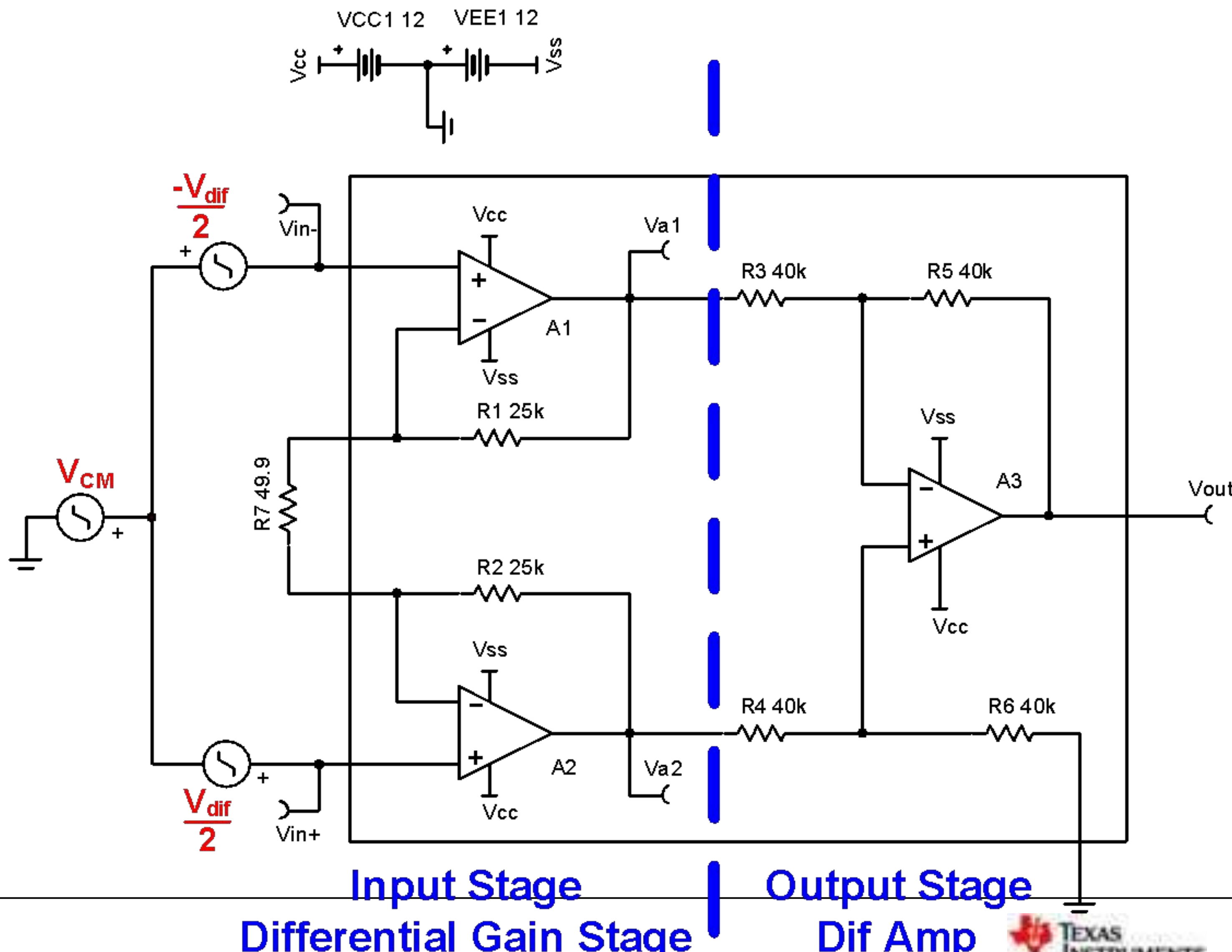
Three Stage IA



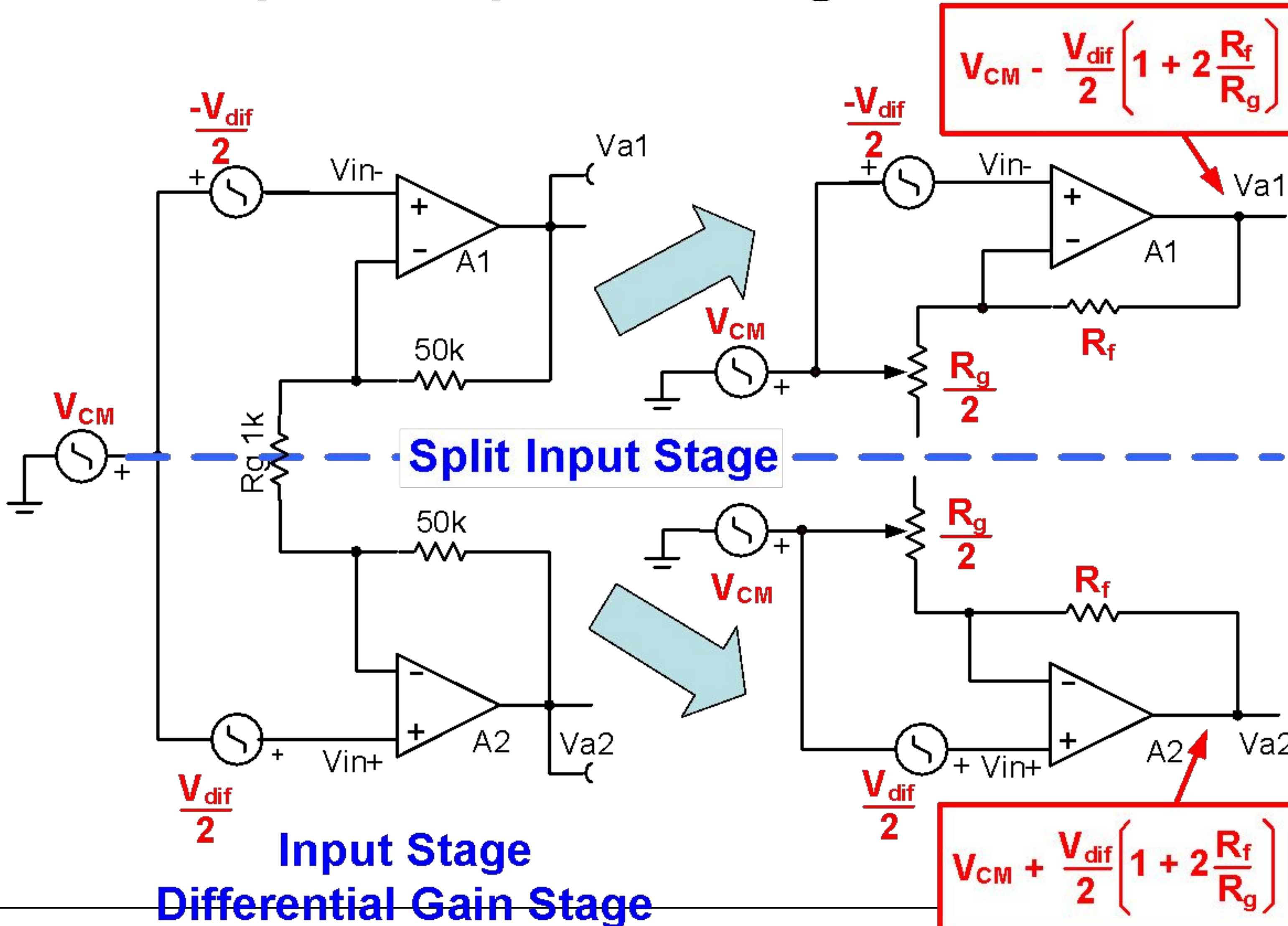
Real World Input to Mathematical Model



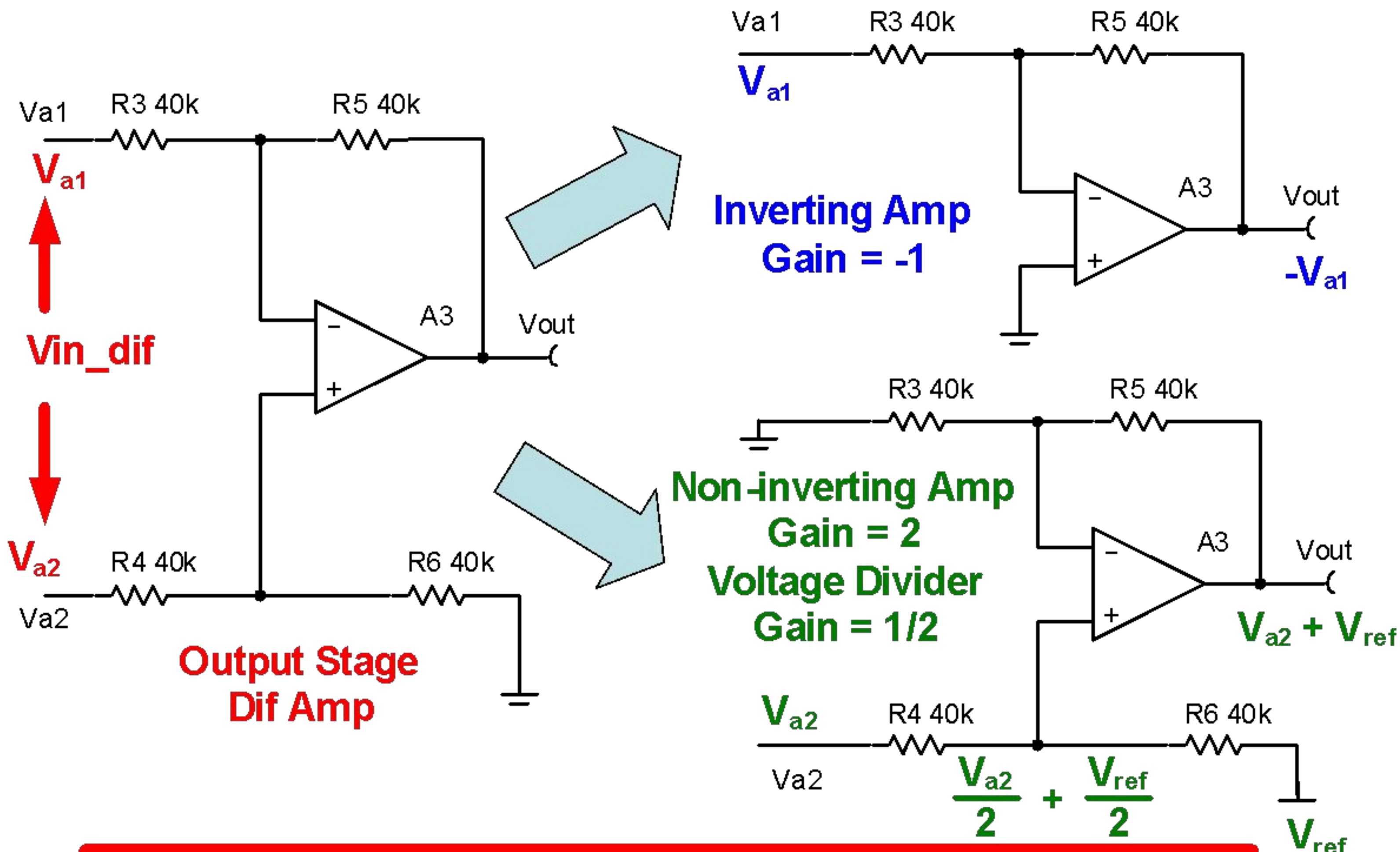
Analyze the Input and Output Separately



Split Input Stage in Half



Use Superposition on Output Amp



Find Vout Through Superposition

$$V_{out} = V_{a2} - V_{a1} + V_{ref}$$

Gain For Three Amp IA

$$V_{a1} = V_{cm} - \frac{V_{dif}}{2} \cdot \left(1 + 2\frac{R_f}{R_g}\right)$$

[1] Input Stage Top Half

$$V_{a2} = V_{cm} + \frac{V_{dif}}{2} \cdot \left(1 + 2\frac{R_f}{R_g}\right)$$

[2] Input Stage Bottom Half

$$V_{out} = V_{a2} - V_{a1} + V_{ref}$$

[3] Output Stage

$$V_{out} = \left[V_{cm} + \frac{V_{dif}}{2} \cdot \left(1 + 2\frac{R_f}{R_g}\right)\right] - \left[V_{cm} - \frac{V_{dif}}{2} \cdot \left(1 + 2\frac{R_f}{R_g}\right)\right] + V_{ref}$$

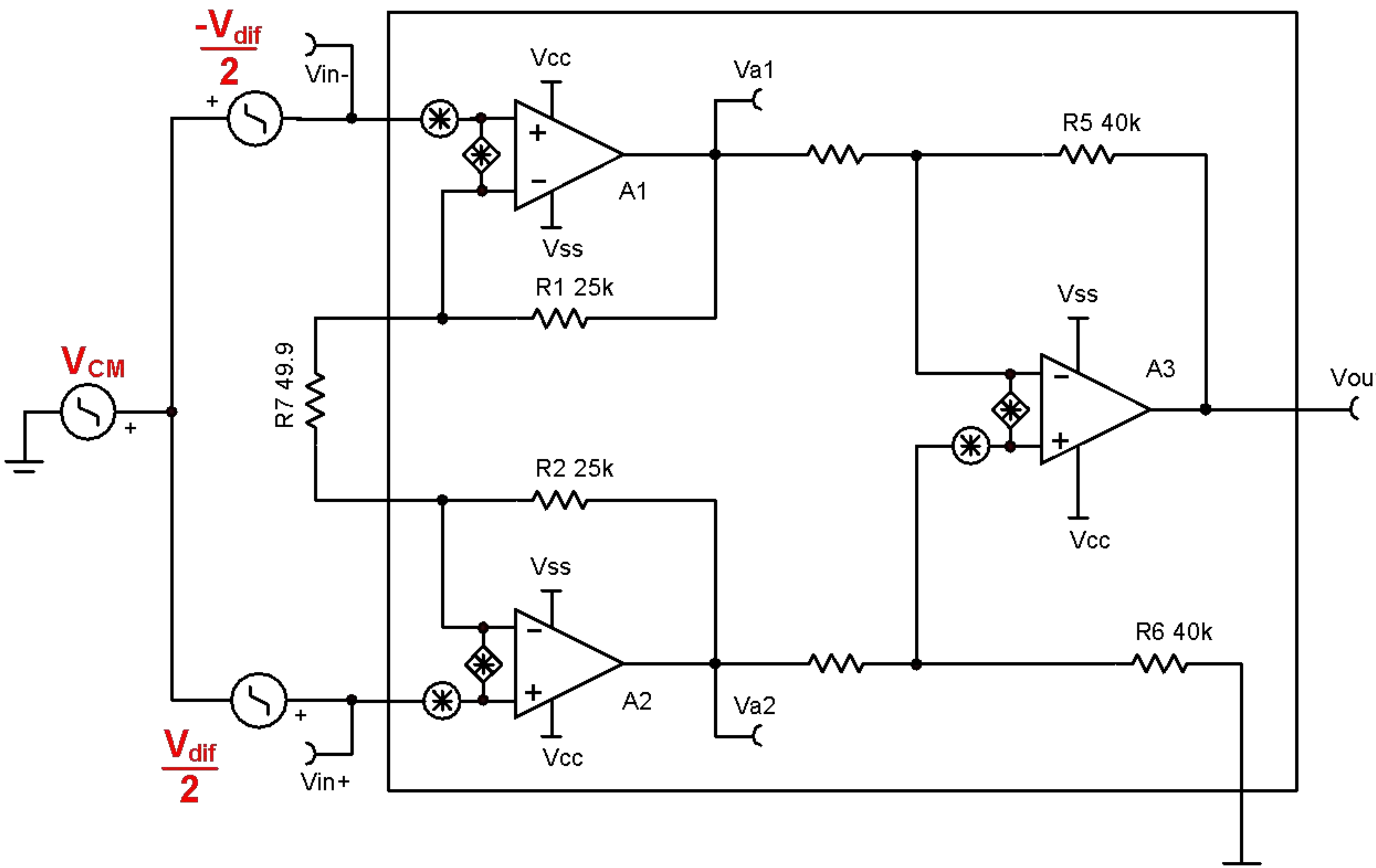
Substitute [1] and [2] into [3]

$$V_{out} = V_{dif}\left(1 + 2\frac{R_f}{R_g}\right) + V_{ref}$$

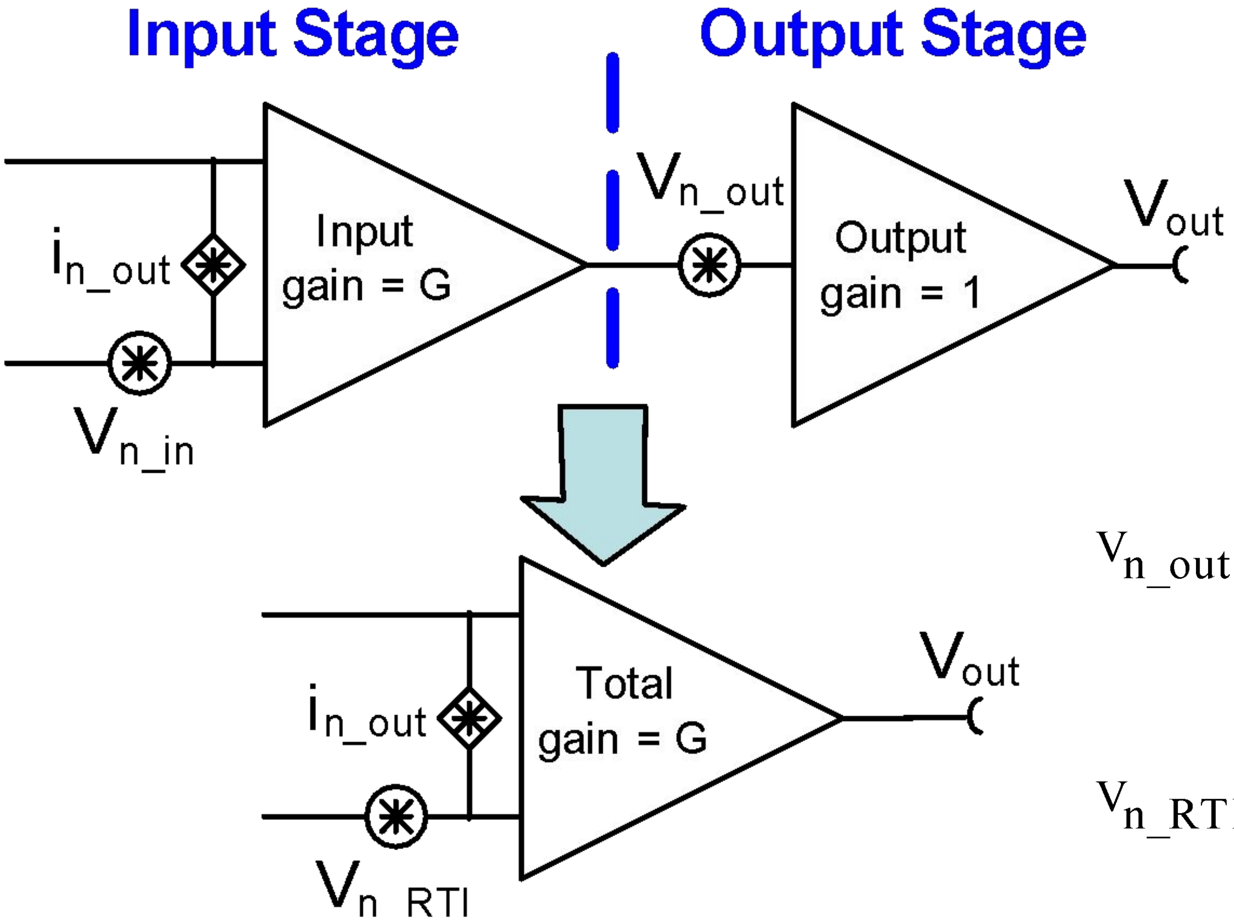
[4] Simplify

Noise Model of 3 Amp INA

Complex Noise Model



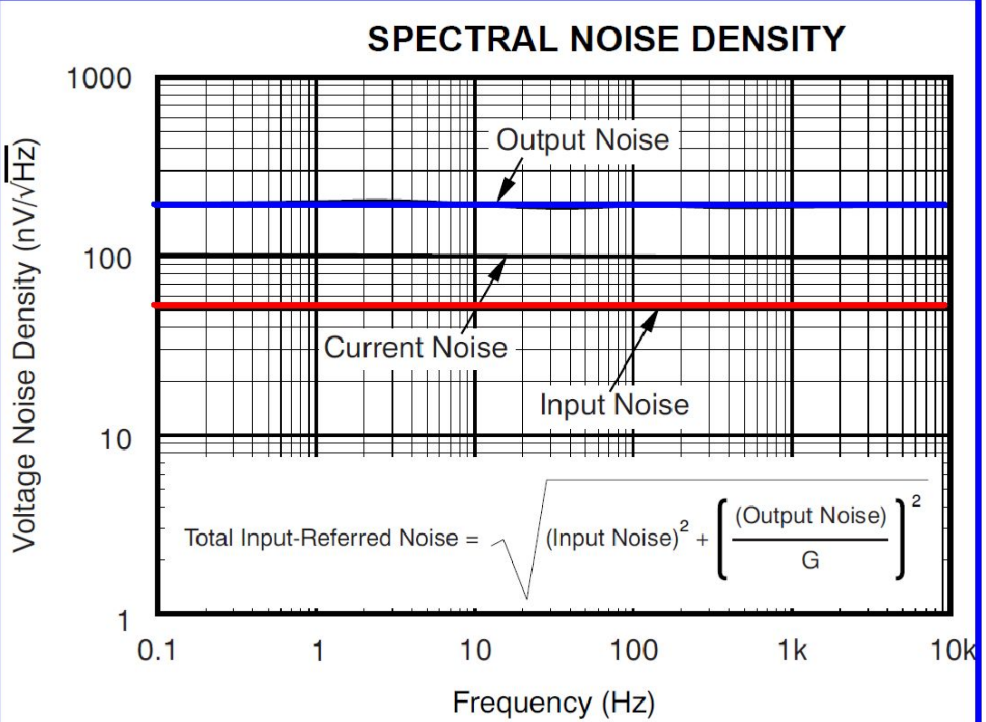
The Complex Model is Simplified



$$V_{n\_out} = \sqrt{\left(V_{n\_out}\right)^2 + \left(V_{n\_in} \cdot G\right)^2}$$

$$V_{n\_RTI} = \sqrt{\left(\frac{V_{n\_out}}{G}\right)^2 + \left(V_{n\_in}\right)^2}$$

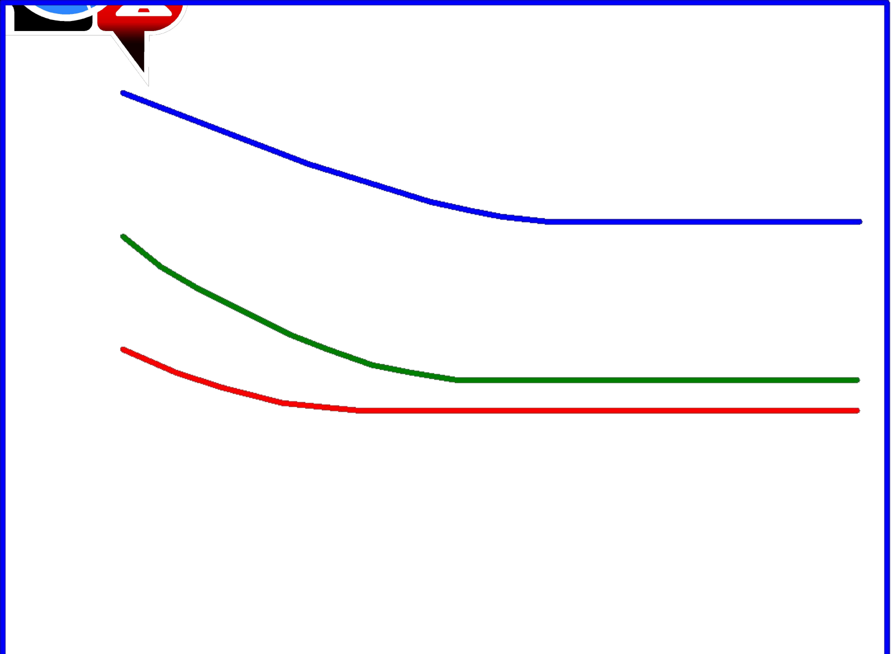
The Input amplifier dominates at High Gain



From INA333 Data Sheet

G	Total Input-Referred Noise (nV/rtHz)	Total Output Noise (nV/rtHz)
1	206.2	206.2
2	111.8	223.6
5	64	320
10	53.9	539
100	50	5000
1000	50	50,000

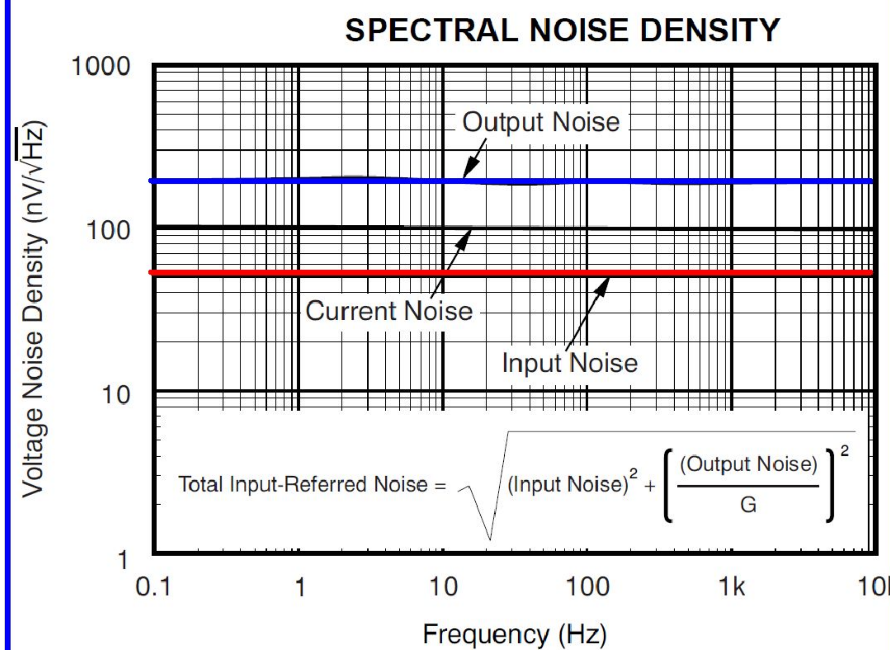
Two Ways to represent INA Spectral Density



From INA128 Data Sheet

G	Input-Referred Noise (nV/rtHz)
1	110
10	12
100	8
1000	8

Taken directly from the graph



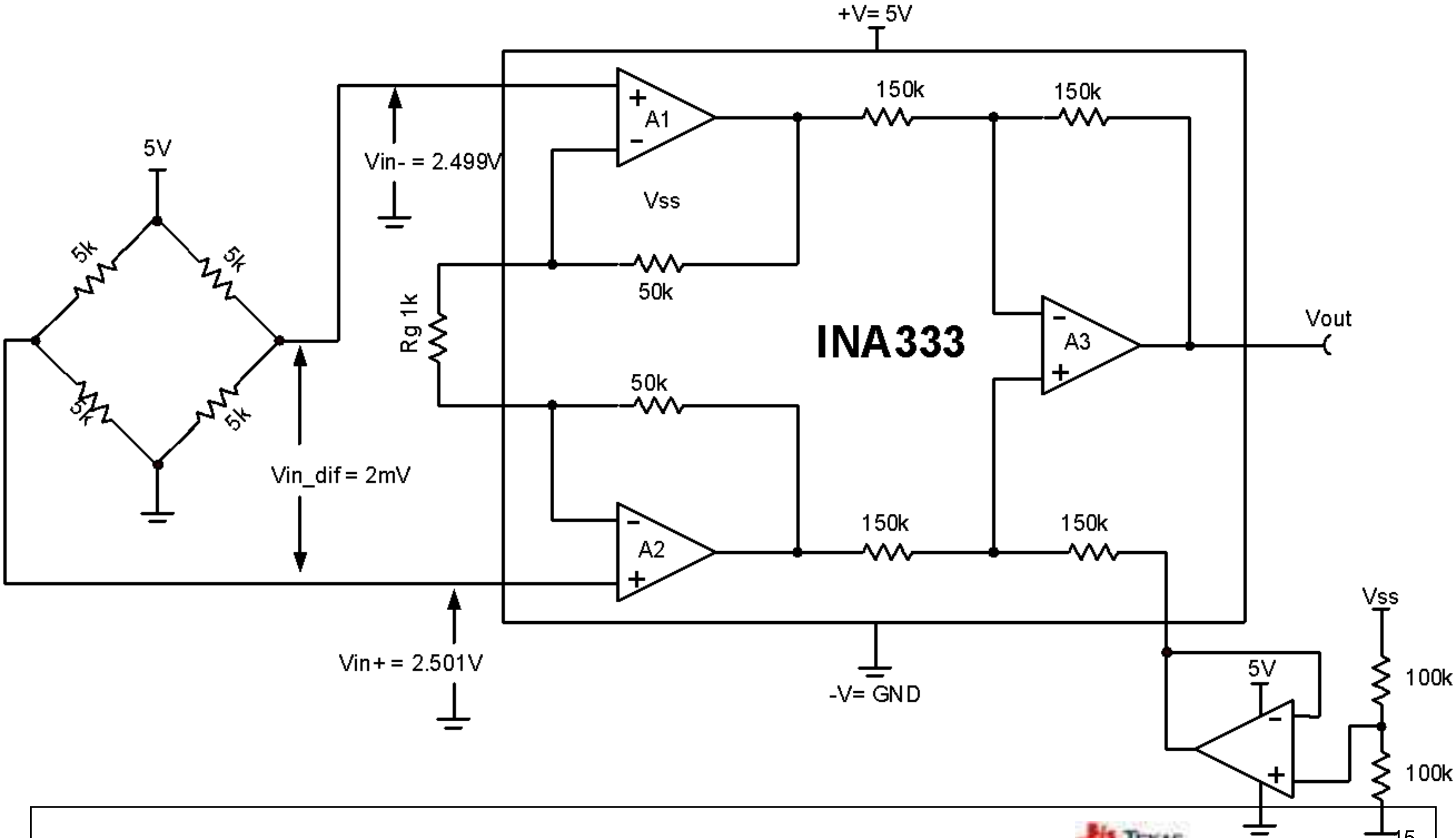
From INA333 Data Sheet

G	Input-Referred Noise (nV/rtHz)
1	206.2
10	53.9
100	50
1000	50

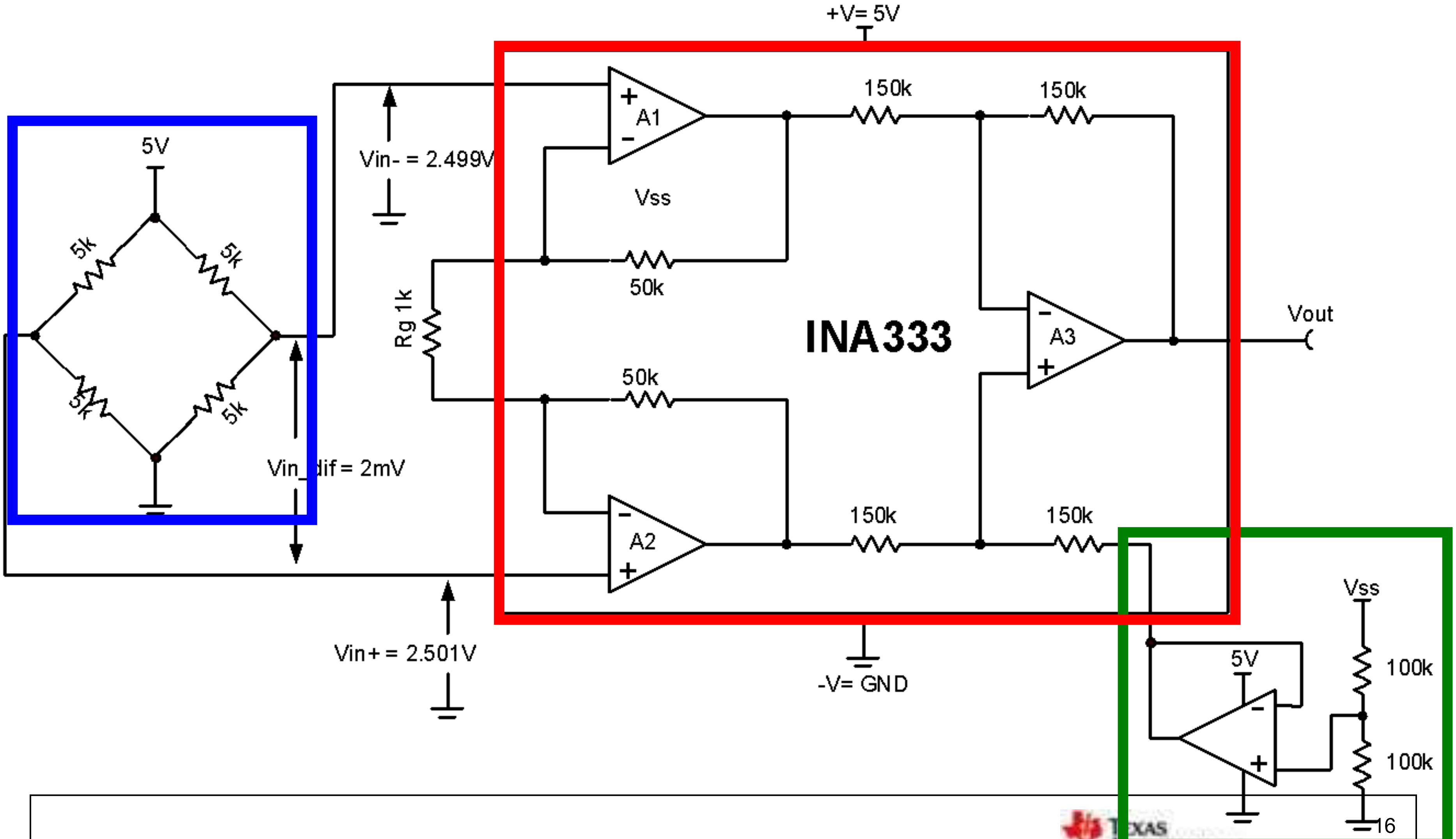
Calculated using graphs and formula

Hand Analysis of 3 Amp INA

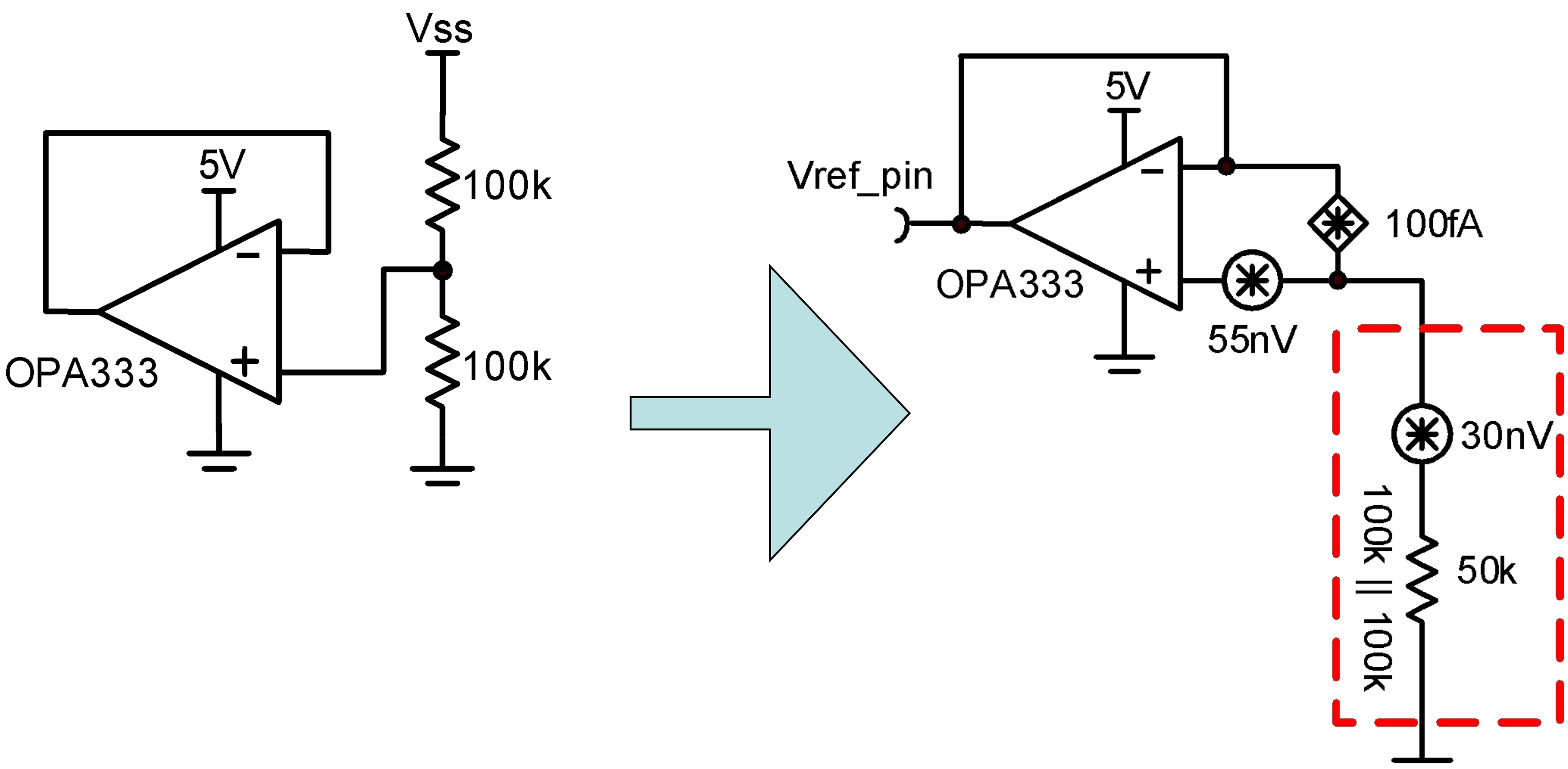
Find the total RMS Noise Voltage at the Output



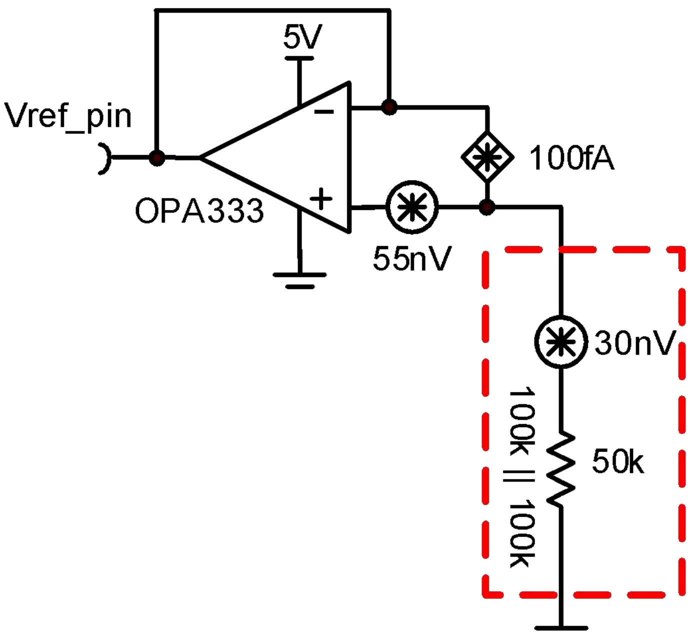
Look at Noise Sources: Bridge, INA333, Reference Buffer



Noise Equivalent Model for Reference Pin Buffer



Reference buffer



$k_n = 1.38 \cdot 10^{-23}$ Boltzmann's constant

$T_k = 273 + 25$ Temperature in Kelvin

$R_{eq} = 50k\Omega$ Input resistance (parallel combination of voltage divider)

$e_{n\_r} = \sqrt{4k_n \cdot T_n \cdot R_{eq}} = 28.7 \frac{nV}{\sqrt{Hz}}$ Thermal Noise from input resistor

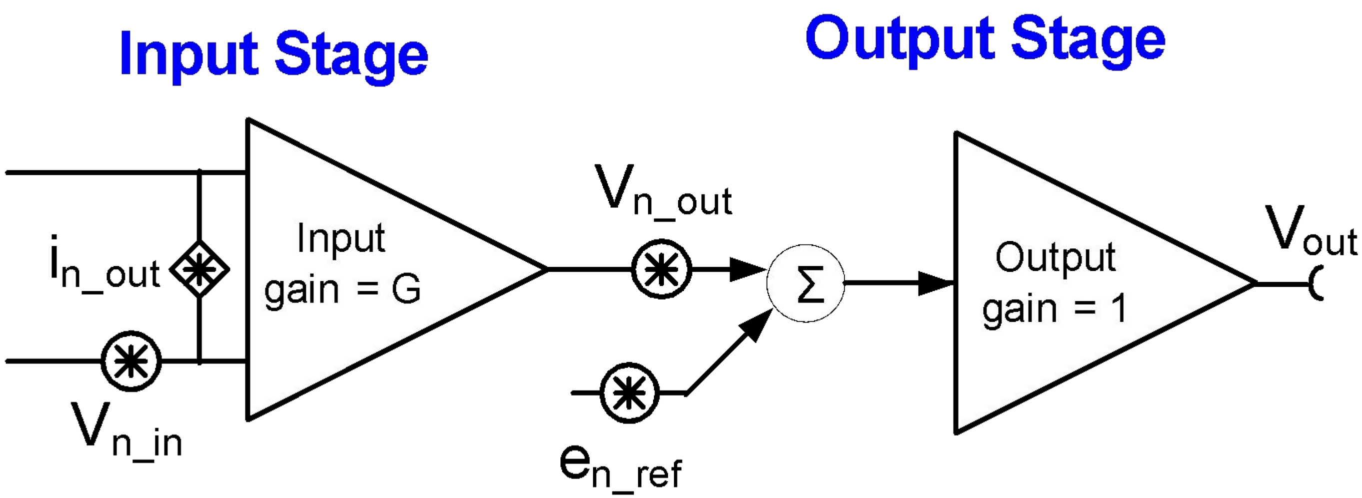
$i_n = 100fA$ Current noise from OPA333

$e_{n\_i} = i_n \cdot R_{eq} = 5 \frac{nV}{\sqrt{Hz}}$ Voltage Noise from current noise

$e_{n\_opa} = 55 \frac{nV}{\sqrt{Hz}}$ Voltage noise from OPA333

$e_{n\_ref} = \sqrt{e_{n\_opa}^2 + e_{n\_r}^2 + e_{n\_i}^2} = 62.2 \frac{nV}{\sqrt{Hz}}$ Total rms noise from reference driver circuit

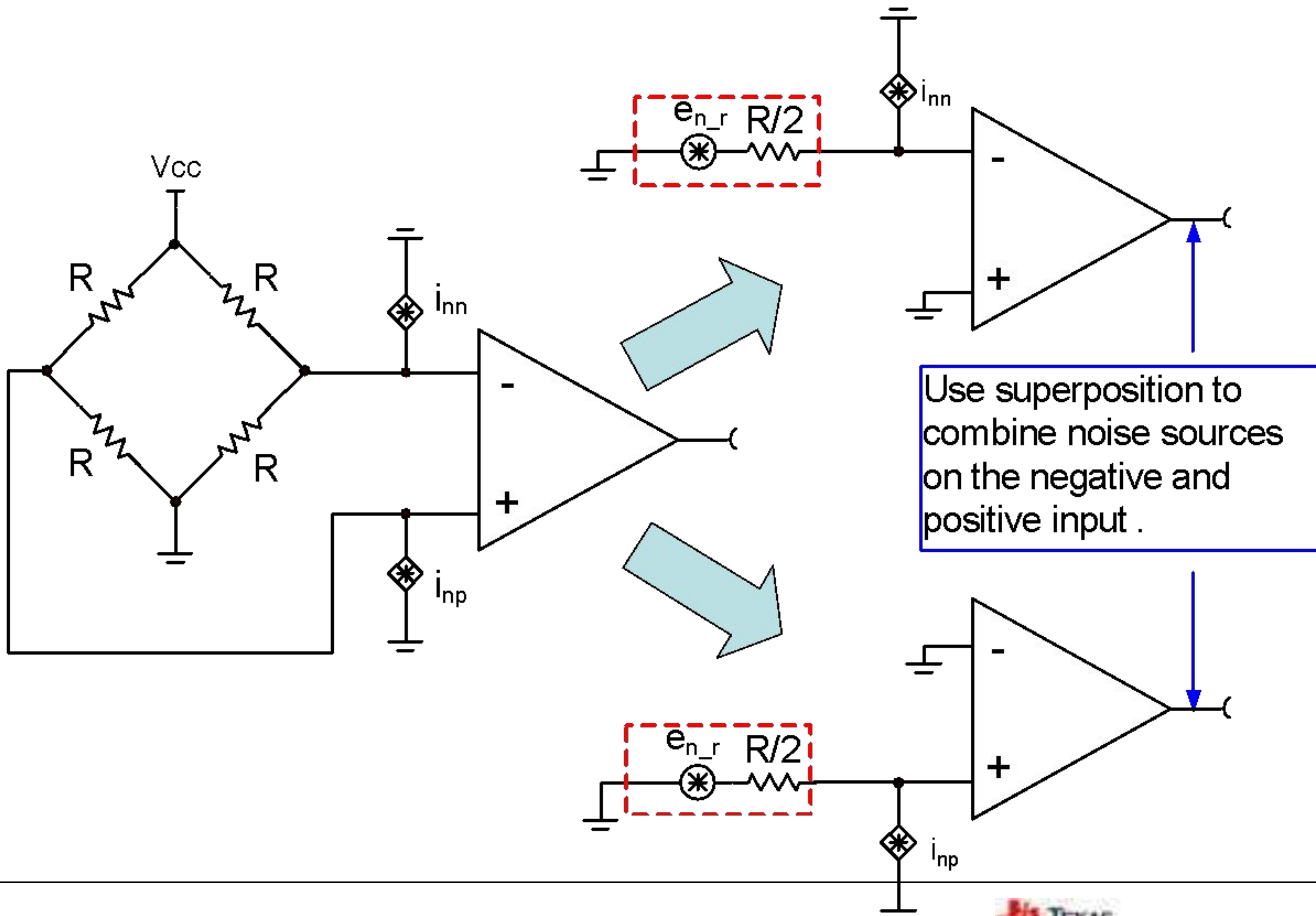
The reference voltage directly adds to the output noise



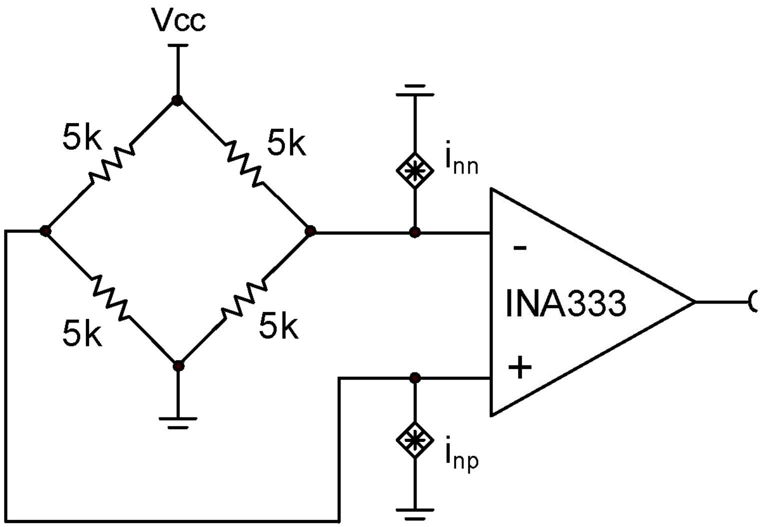
$$e_{n\_ref} := 62.2 \cdot 10^{-9} \qquad V_{n\_out} := 200 \cdot 10^{-9}$$

$$Output\_Stage\_Noise := \sqrt{e_{n\_ref}^{2} + V_{n\_out}^{2}} = 209.449 \times 10^{-9}$$

The bridge generates: thermal noise, i_n x R_bridge



Noise From Bridge / Current Sources



$i_{nn} \cdot \frac{R}{2}$ Voltage noise from current noise

$e_{n\_rb} = \sqrt{4k_n \cdot T_n \cdot \frac{R}{2}}$ Resistor Noise

Use superposition to add the noise from the input resistance and both current noise sources

$$e_{in\_i} = \sqrt{\left(i_{nn} \cdot \frac{R}{2}\right)^2 + \left(e_{n\_rb}\right)^2 + \left(i_{np} \cdot \frac{R}{2}\right)^2 + \left(e_{n\_rb}\right)^2}$$

Assume $\left|i_{nn}\right| = \left|i_{np}\right|$

Note that these sources are uncorrelated

$$e_{in\_i} = \sqrt{2\left(i_n \cdot \frac{R}{2}\right)^2 + 2\left(e_{n\_rb}\right)^2}$$ Total Noise from input resistors and current source

For this example (R=5kO, in = 100fA/rtHz)

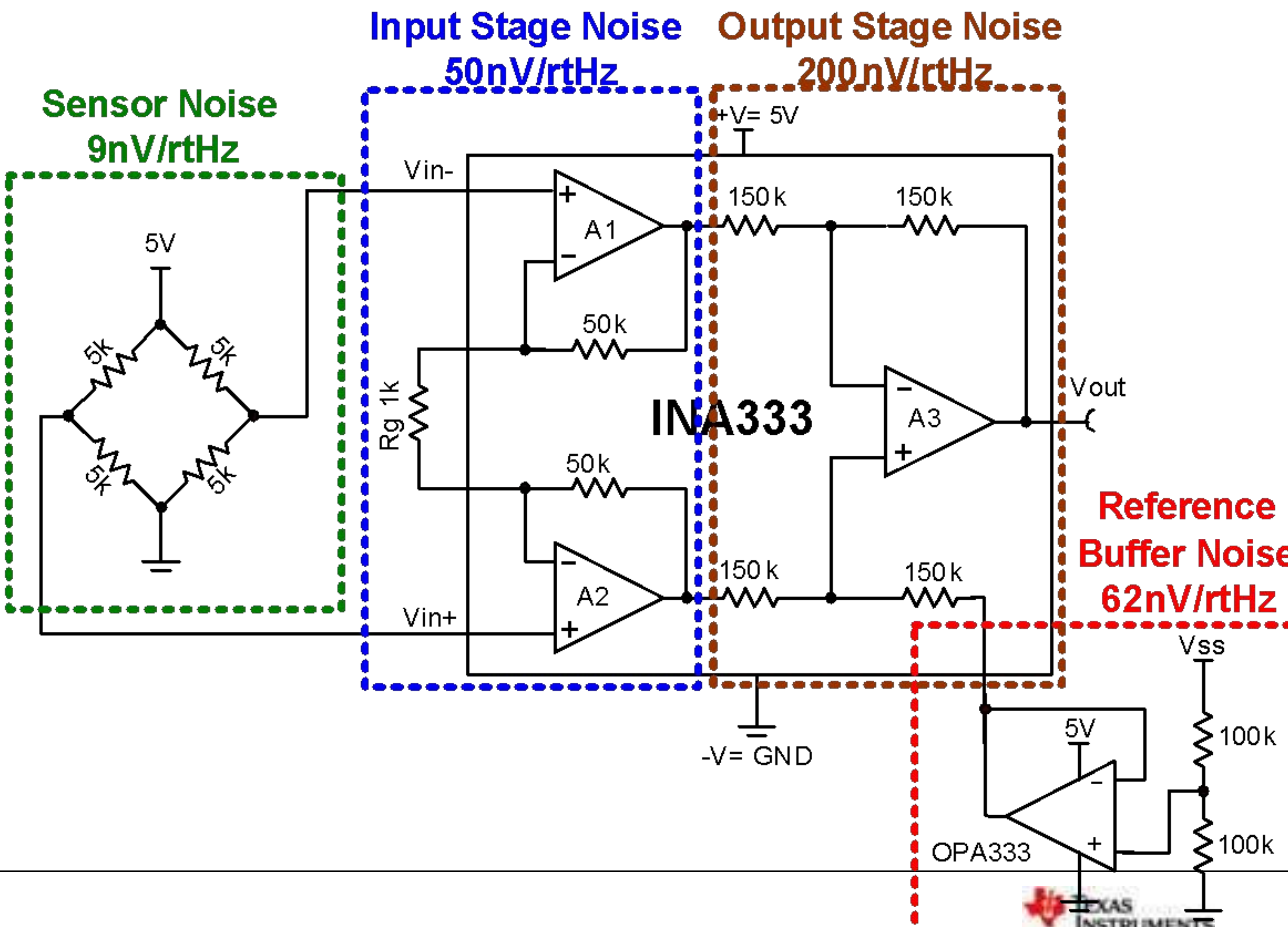
$e_{n\_rb} = 6.4 \frac{nV}{\sqrt{Hz}}$ Resistor noise

$i_{nn} \cdot \frac{R}{2} = 0.25 \frac{nV}{\sqrt{Hz}}$ Voltage noise from current noise

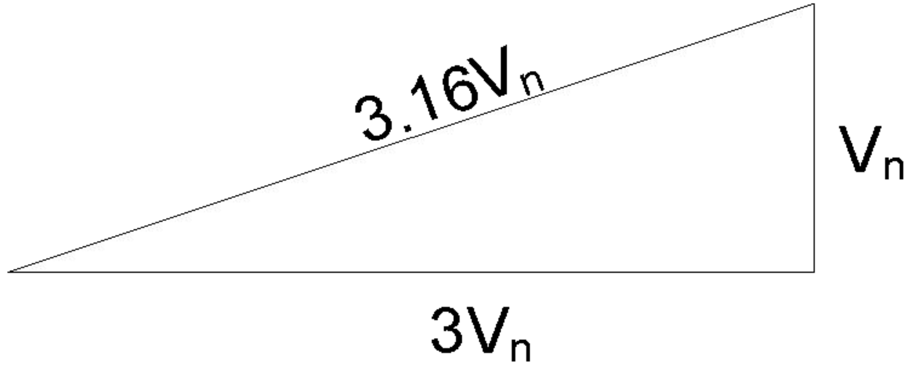
$e_{in\_i} = \sqrt{2(0.5)^2 + 2(9.1)^2} = 9.1 \frac{nV}{\sqrt{Hz}}$ Total Noise from input resistors and current source

Texas Instruments

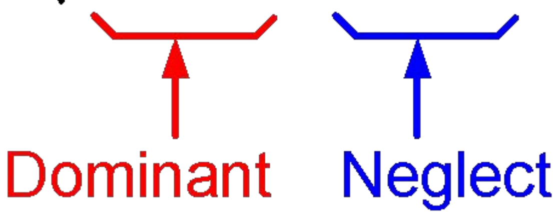
Combine all the noise sources



Rule of 3x



$$\sqrt{(3\cdot V_n)^2 + V_n^{\,2}} = \sqrt{9\cdot V_n^{\,2} + V_n^{\,2}} = 3.16V_n$$



When adding two uncorrelated noise terms , the larger term will dominate if it is 3 times larger then the smaller term . You can neglect the smaller term with a relatively small error (i.e. 6%).

For this example compute noise spectral density refered to the input

$$\text{Noise\_Spec\_Den\_RTI} = \sqrt{V_{n\_in\_stage}{}^{2} + V_{n\_bridge}{}^{2} + \left(\frac{V_{n\_out\_stage}}{G}\right)^{2} + \left(\frac{V_{n\_ref\_buf}}{G}\right)^{2}}$$

$$\text{Noise\_Spec\_Den\_RTI} = \sqrt{(50)^{2} + (9)^{2} + \left(\frac{200}{100}\right)^{2} + \left(\frac{62}{100}\right)^{2}} = 50.847\frac{\text{nV}}{\sqrt{\text{Hz}}}$$

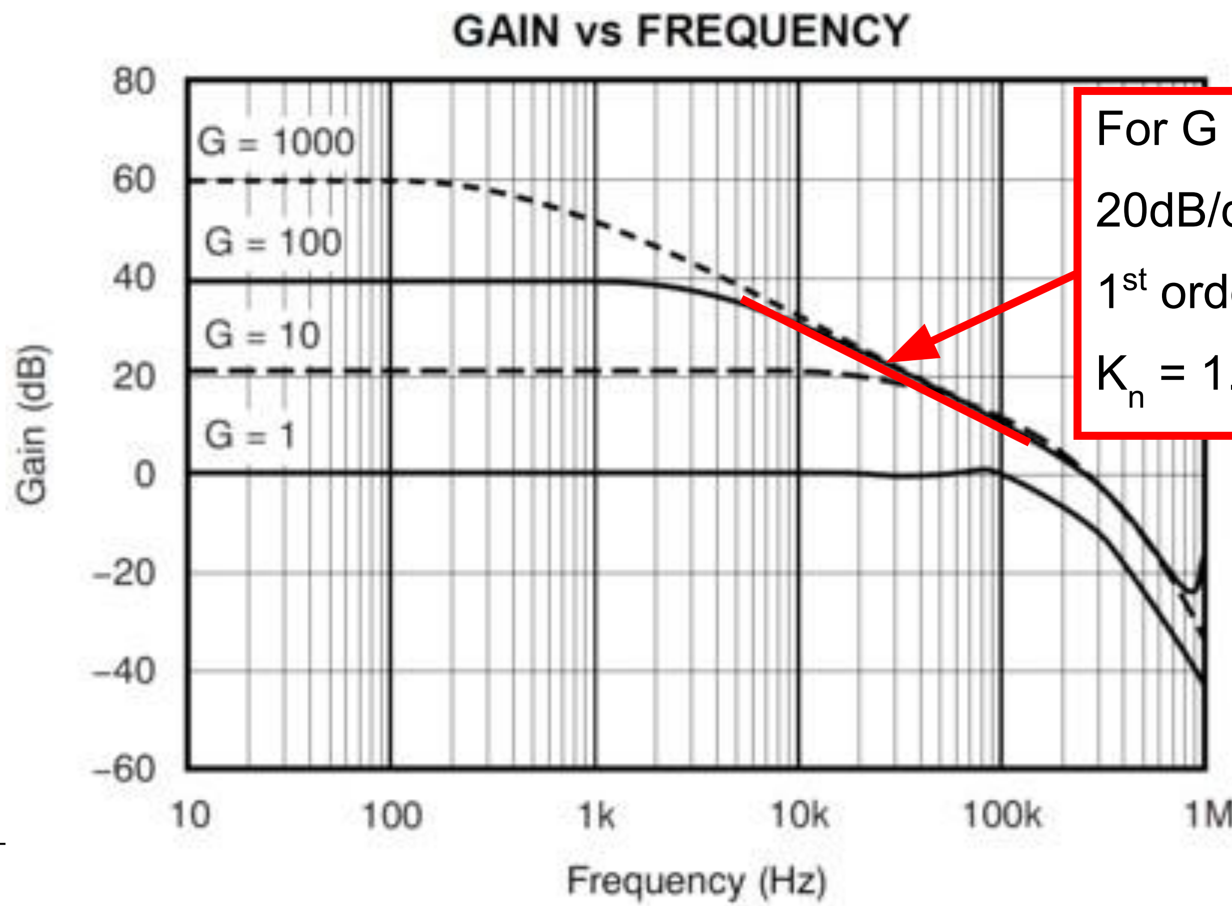
Dominant: $(50)^2$

Neglect: $(9)^2 + \left(\frac{200}{100}\right)^2 + \left(\frac{62}{100}\right)^2$

Approximately equal to the dominant term: $50.847\frac{\text{nV}}{\sqrt{\text{Hz}}}$

PARAMETER	INA333			UNIT
	MIN	TYP	MAX	
FREQUENCY RESPONSE				
Bandwidth, –3dB				
G = 1		150		kHz
G = 10		35		kHz
G = 100		3.5		kHz
G = 1000		350		Hz

Bandwidth from Data Sheet



For G = 100

20dB/decade

1st order

K_n = 1.57

Calculate RMS Output Noise for INA333 From Voltage Noise

$G = 100$

$V_{in\_RTI} = 50.85 nV/rtHz$ From "Input referred noise" equation

$f_H = 3.5kHz$ From data sheet table for gain = 100

$K_n = 1.57$ For first order function
See Gain vs Frequency in the data sheet

$BW_n = f_H \cdot K_n = 5.495kHz$ Noise Bandwidth

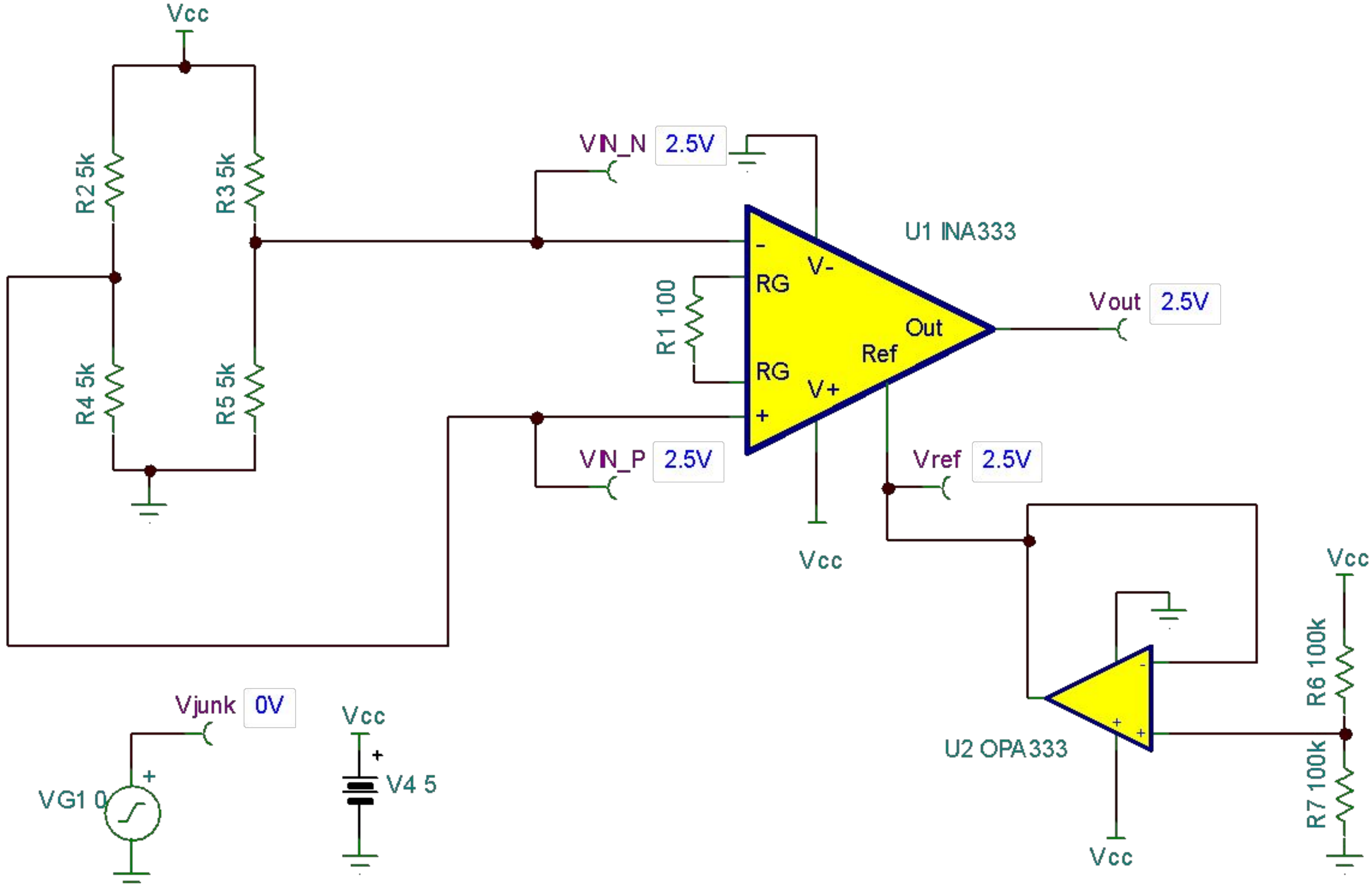
$e_{n\_out} = G \cdot V_{in\_RTI} \sqrt{BW_n} = 376.9 \mu Vrms$ RMS Output Noise

$e_{n\_outPP} = 6 . e_{n\_out} = 2.26 mVpp$ Peak-to-Peak Output

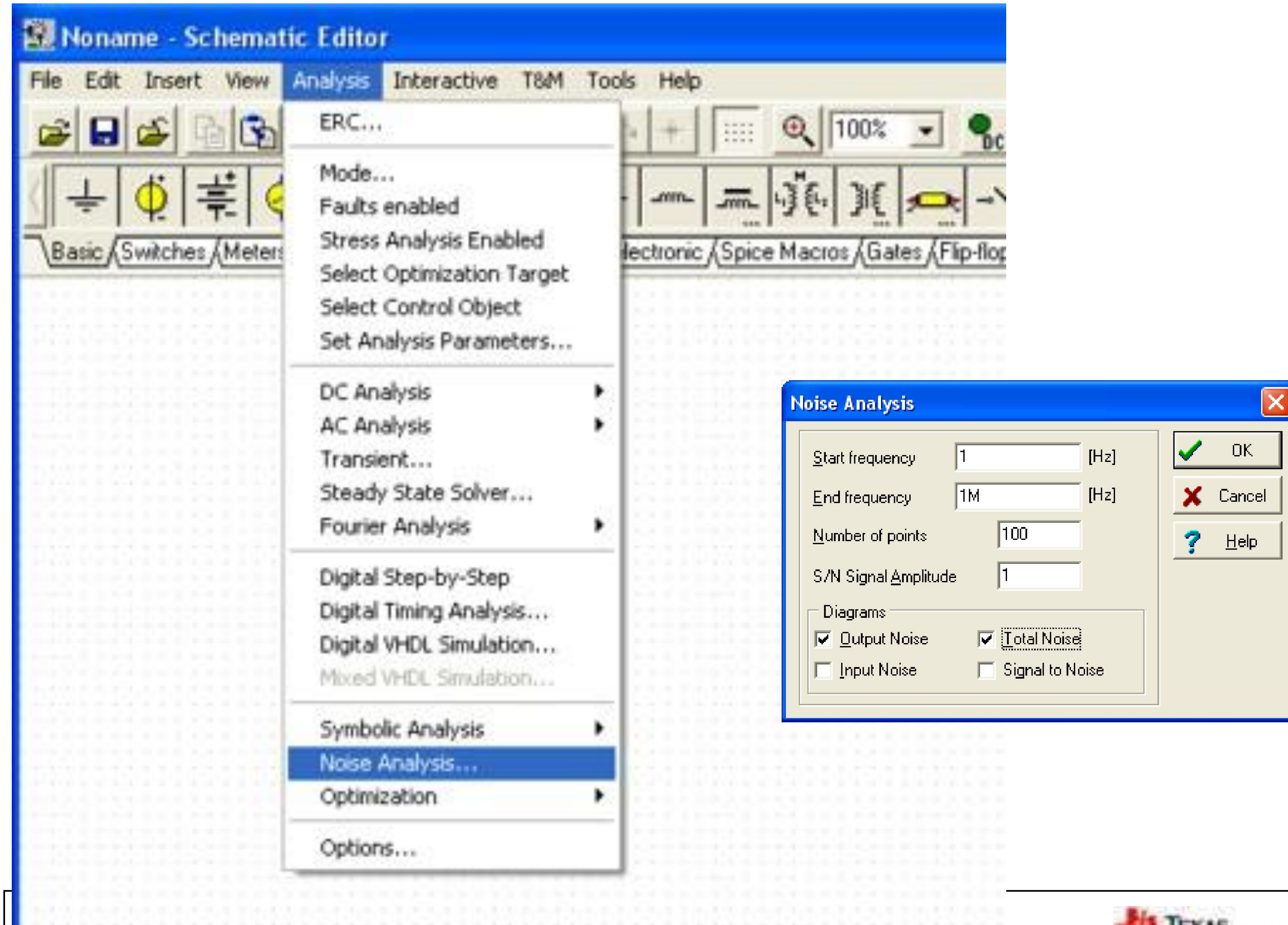
Texas Instruments

Simulation of 3 Amp INA

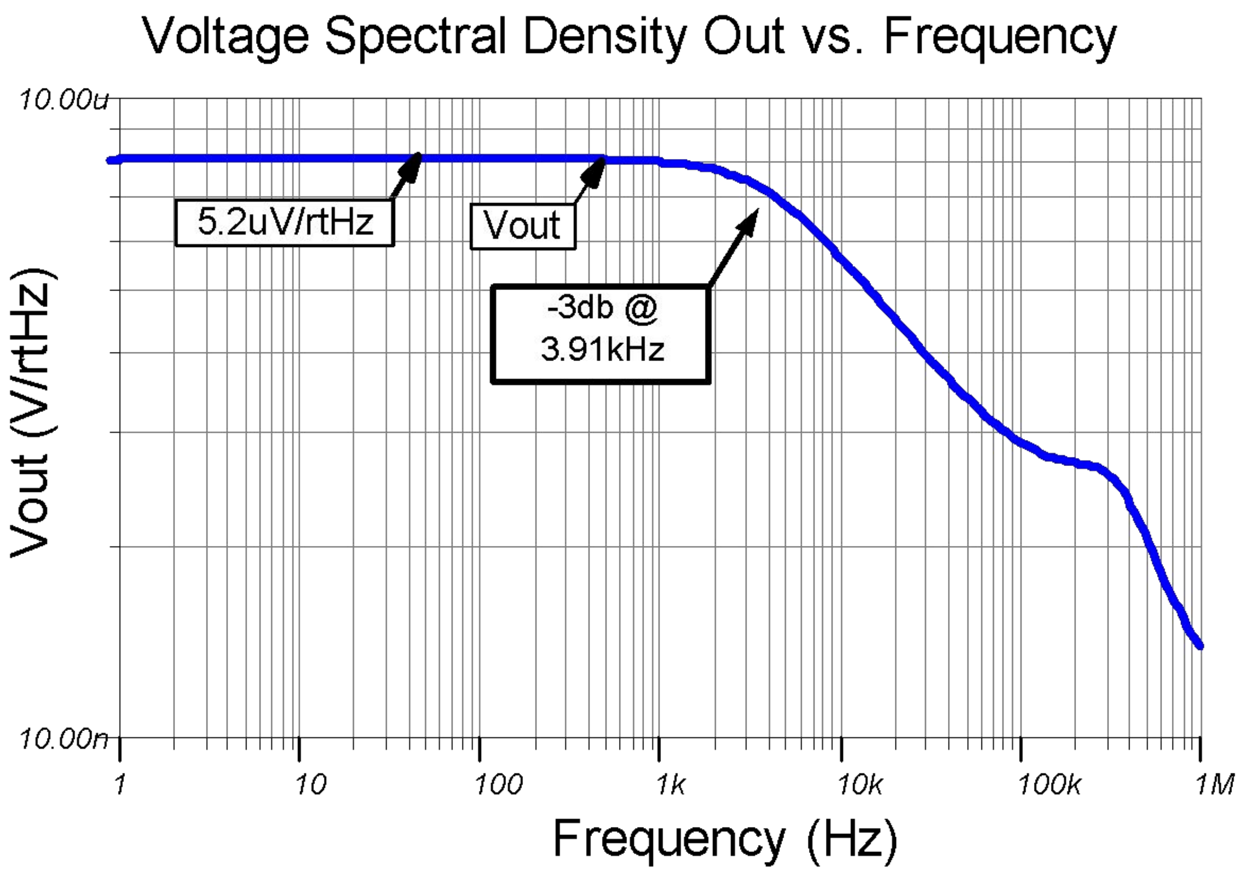
Simulate the Circuit



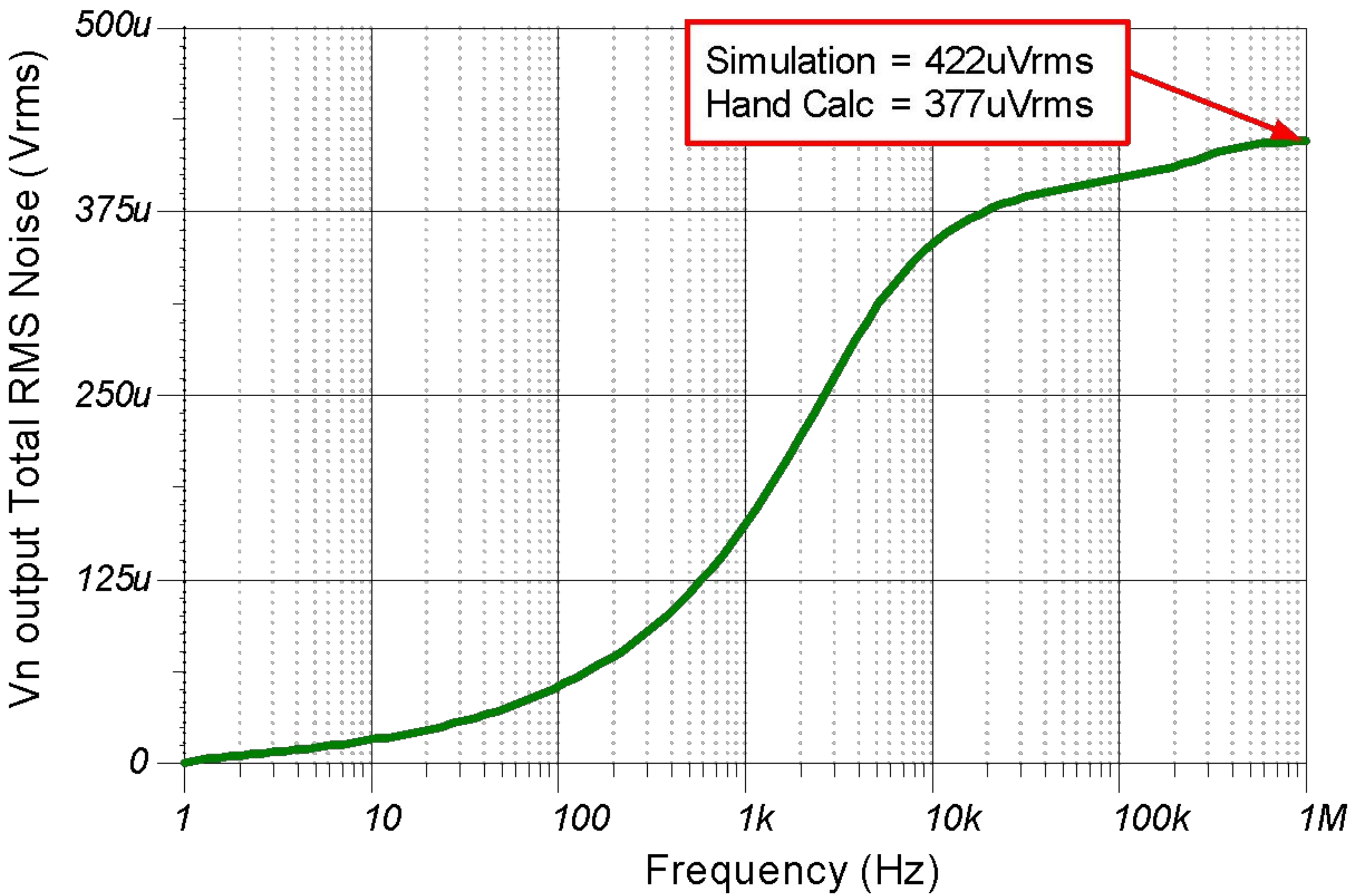
Using Tina Spice



Noise Spectral Density at the Output



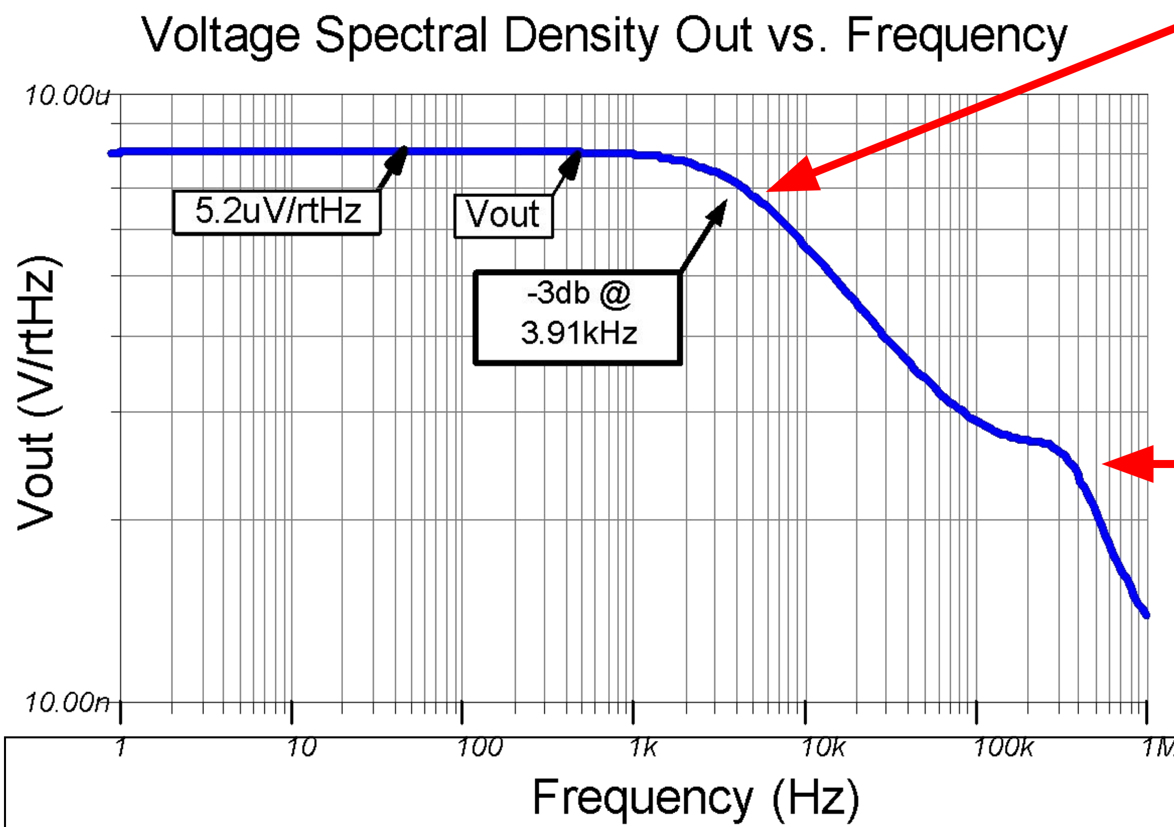
Total RMS Noise at the Output



Why doesn't calculation match simulation exactly?

PARAMETER	INA333 MIN	TYP	MAX	UNIT
FREQUENCY RESPONSE				
Bandwidth, –3dB				
G = 1		150		kHz
G = 10		35		kHz
G = 100		3.5		kHz
G = 1000		350		Hz

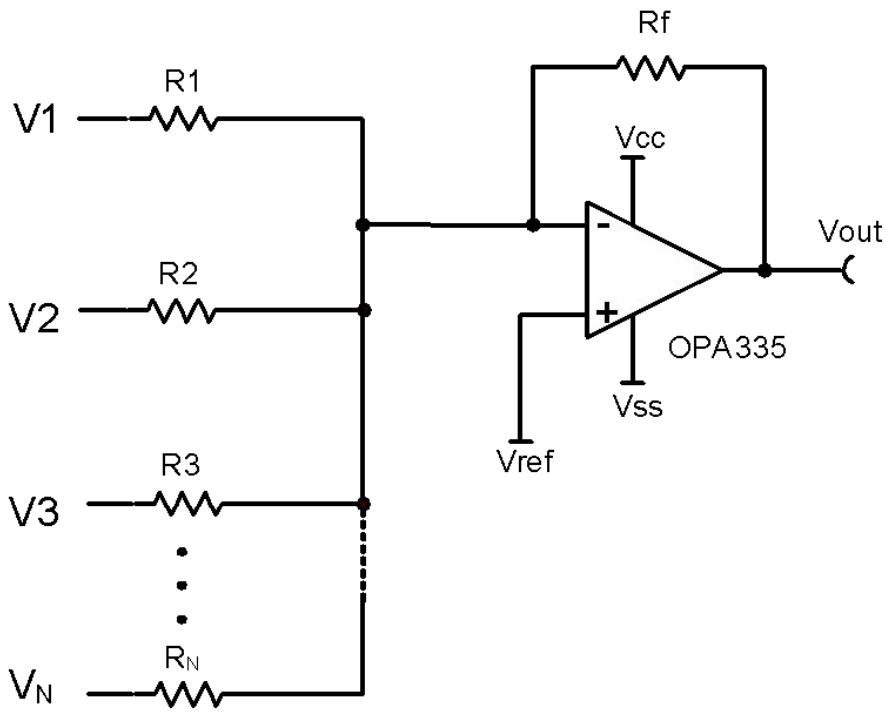
Bandwidth from Data Sheet and simulated bandwidth is different.



The roll-off was approximated as first order in the calculations. Simulation shows that it is not first order.

Reduce Noise Using Averaging Circuit

Averaging Circuit



$$V_{out} = V_{ref} - R_f\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} + \ldots + \frac{V_N}{R_N}\right) \quad [15]$$

For an averaging circuit choose

$R_1 = R_2 = R_3 = \ldots R_N = R$

$R_f = R / N$

$$V_{out} = V_{ref} - \frac{(V_1 + V_2 + V_3 + \ldots + V_N)}{N} \quad [16]$$

Noise in Averaging Circuit

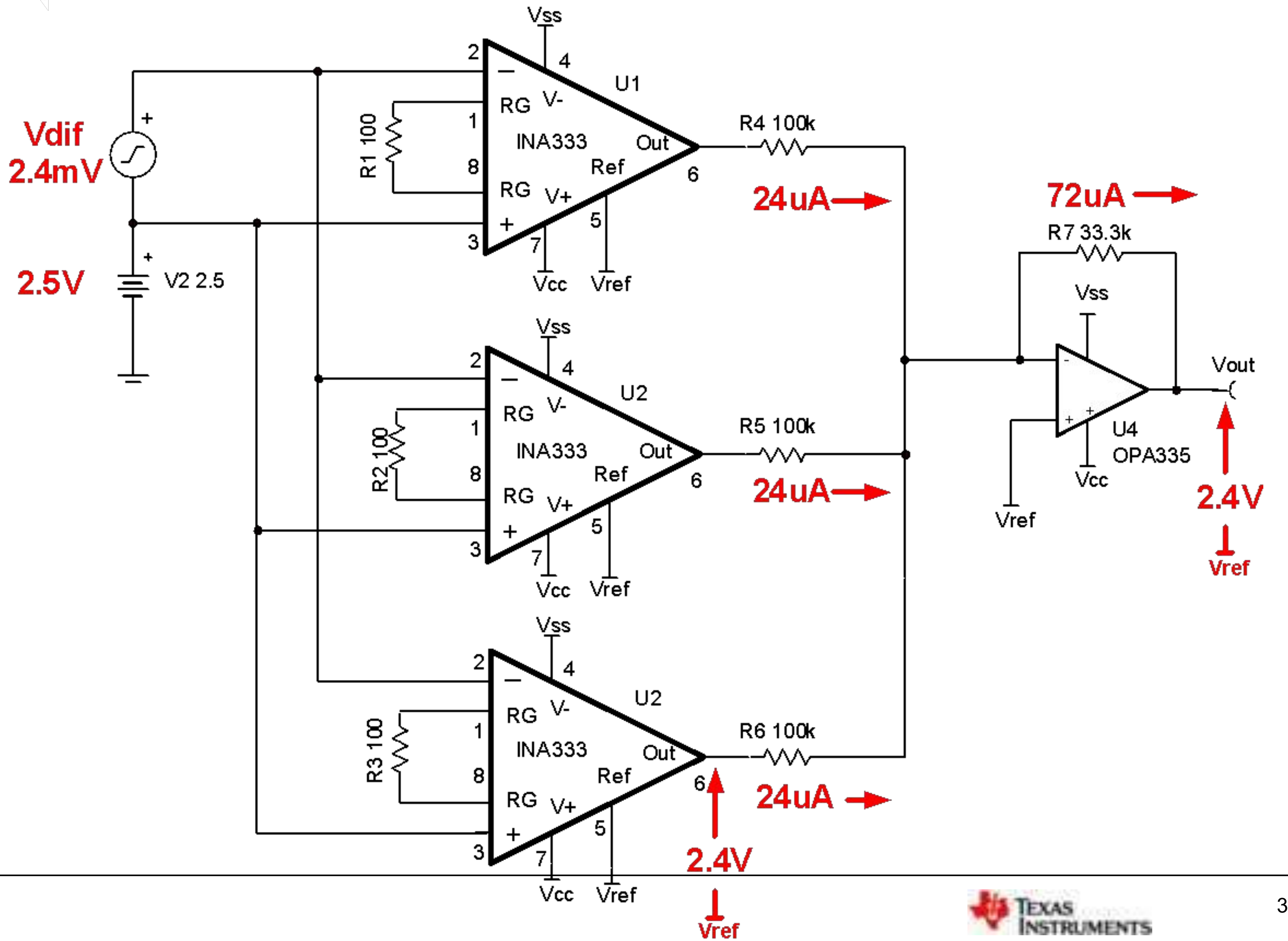
$$v_{noise\_output} = \sqrt{\left(\frac{v_{noise1}}{N}\right)^2 + \left(\frac{v_{noise2}}{N}\right)^2 + \left(\frac{v_{noise3}}{N}\right)^2 + \ldots + \left(\frac{v_{noiseN}}{N}\right)^2}$$

Where v_{noise1}, v_{noise2}, v_{noise3}, … v_{noiseN} are noise sources

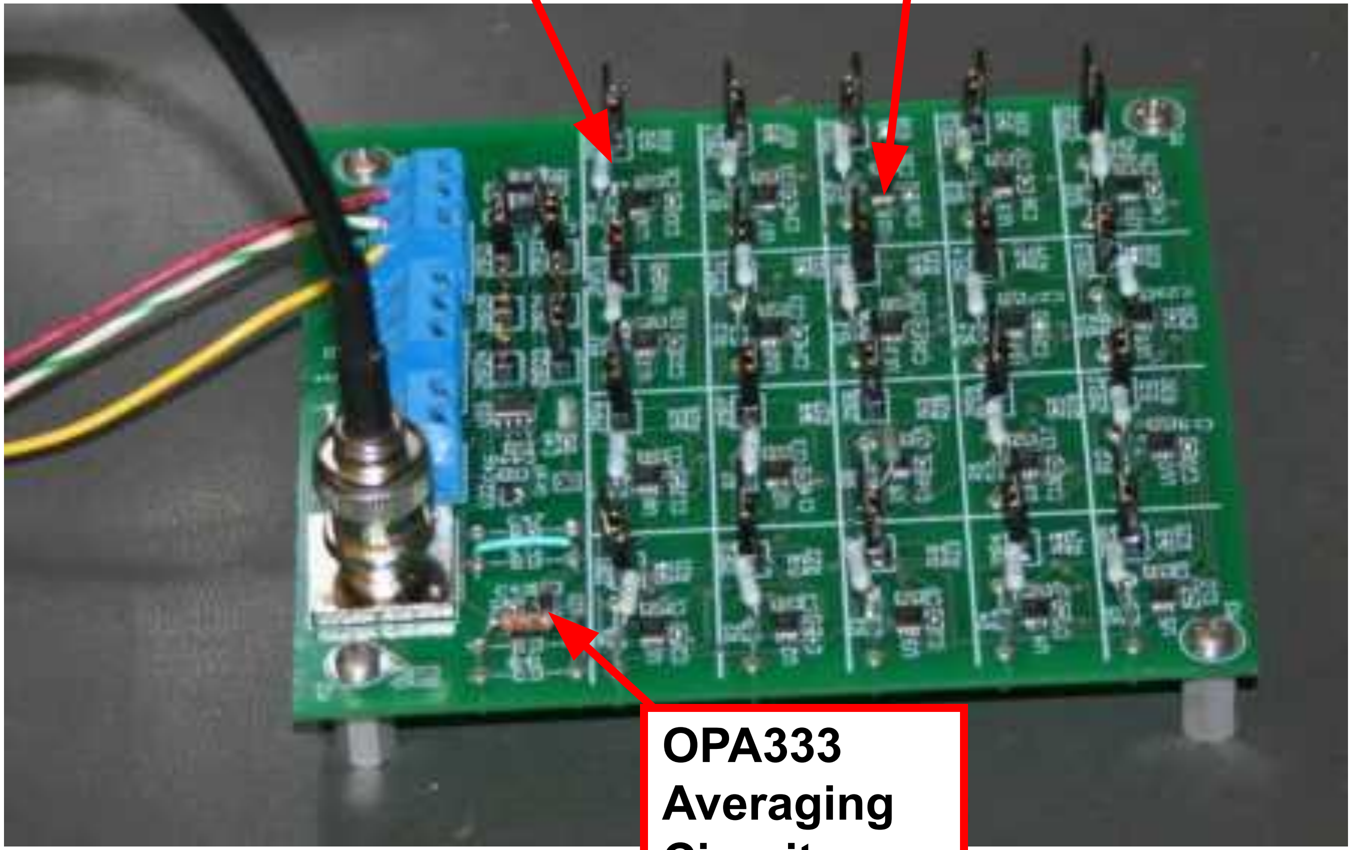
If you assume that v_{noise1}, v_{noise2}, v_{noise3}, … v_{noiseN} are equal uncorrelated noise sources, then

$$v_{noise\_output} = \sqrt{N\left(\frac{v_{noise}}{N}\right)^2} = \sqrt{\frac{v_{noise}^{\;2}}{N}} = \frac{v_{noise}}{\sqrt{N}} \qquad [17]$$

Averaging Circuit with INA333



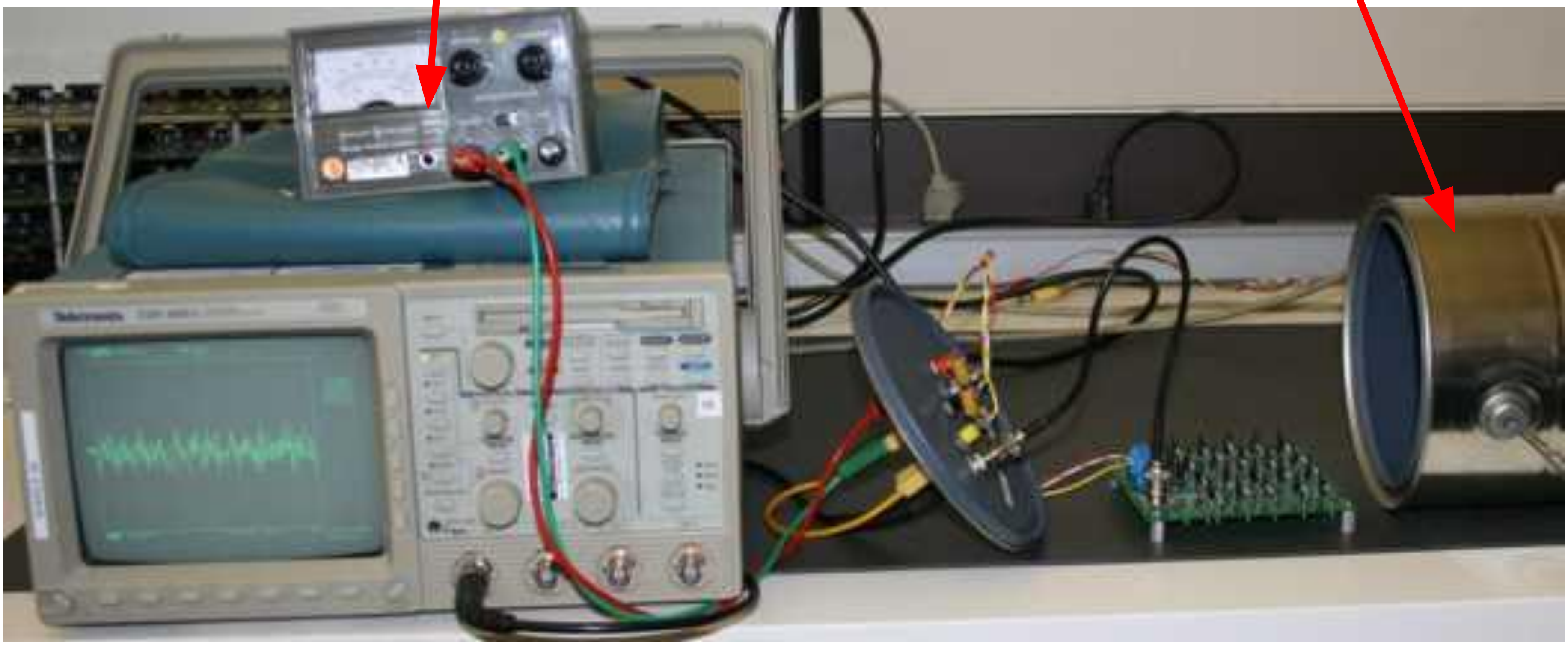
Experiment with 20 Parallel INA333



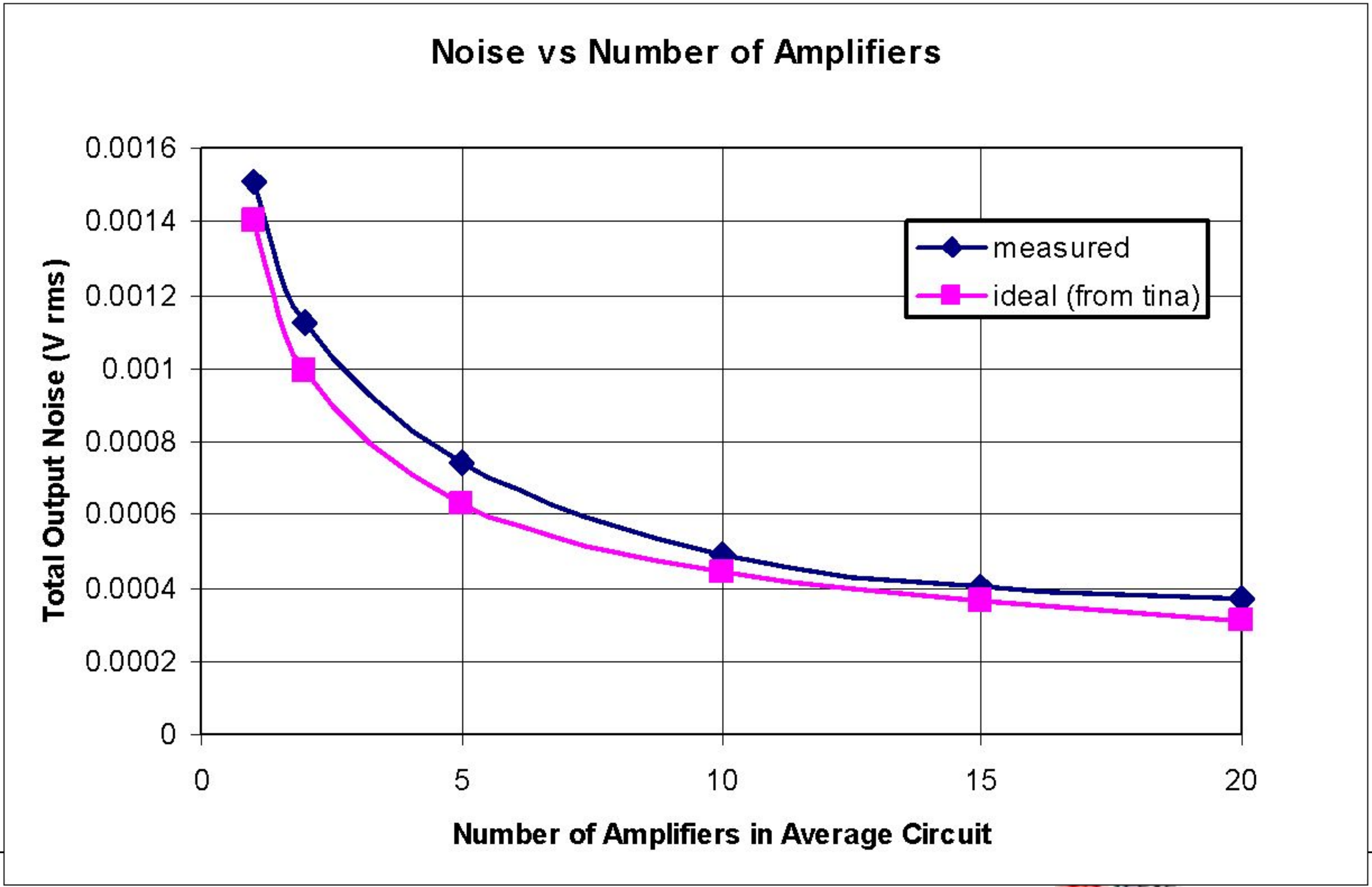
Standard Noise Measurement Precautions

Linear Power Source

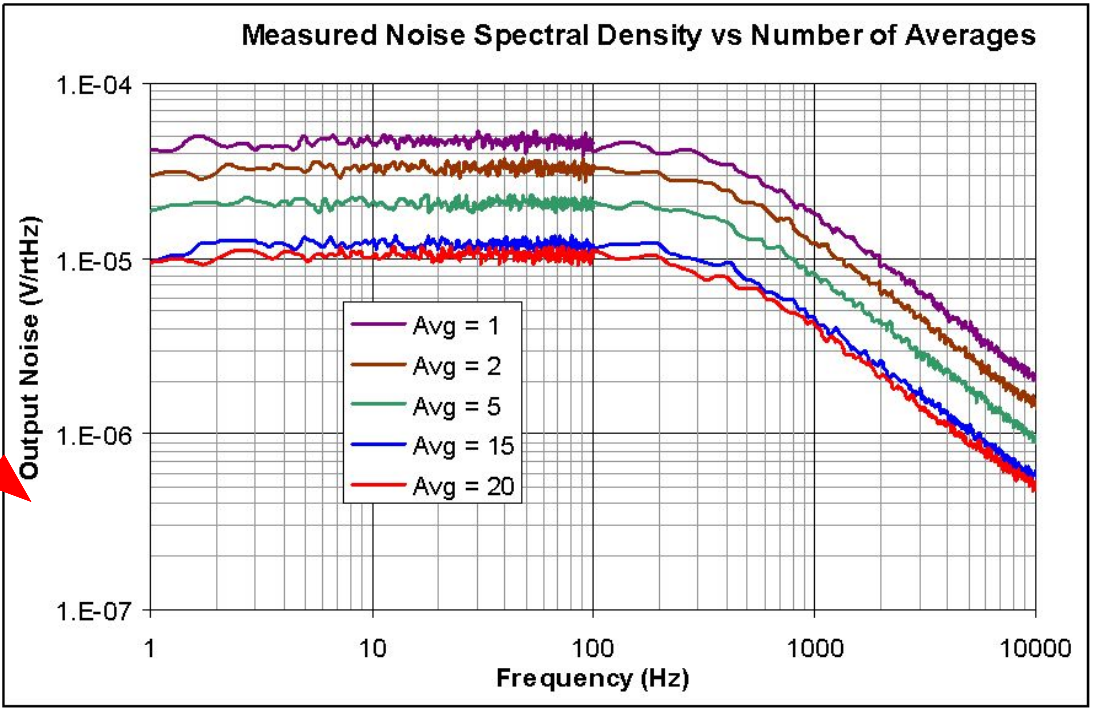
Steel Paint Can for Shielding

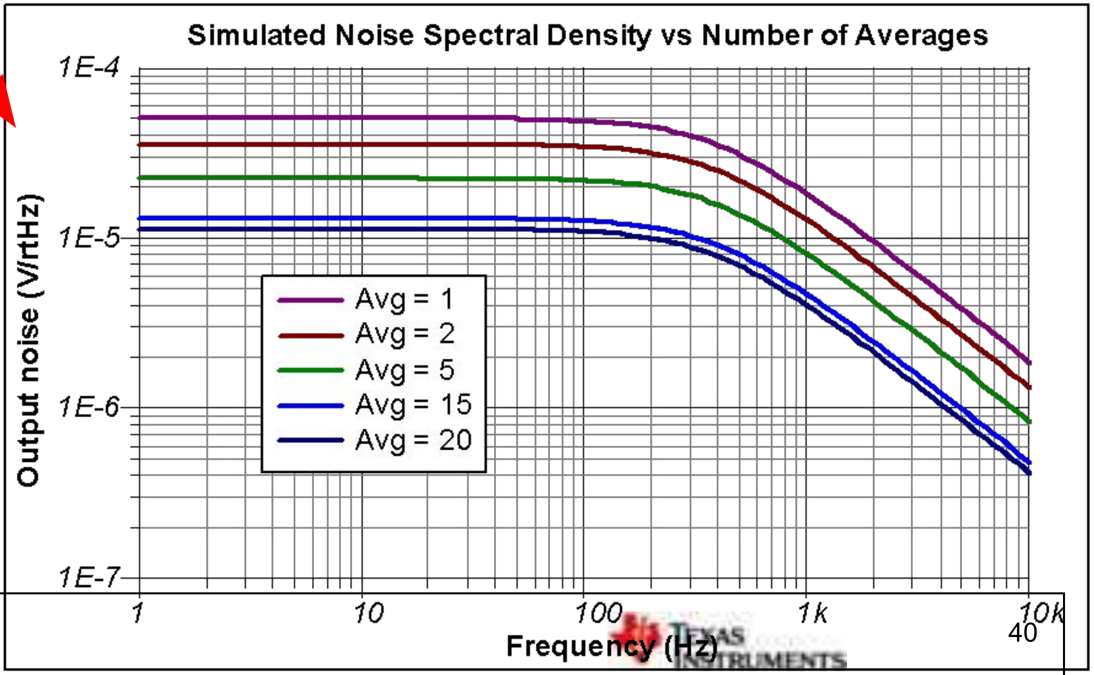


Total Output Noise vs Number of Amplifiers Being Averaged



Measured vs simulated spectral density





References

1. [1] Hann, Gina. "Selecting the right op amp - Electronic Products." Electronic Products Magazine – Component and Technology News. 21 Nov. 2008. Web. 09 Dec. 2009. <http://www2.electronicproducts.com/Selecting_the_right_op_amp-article-facntexas_nov2008-html.aspx>.
2. Henry W. Ott, Noise Reduction Techniques in Electronics Systems, John Wiley and Sons

Acknowledgments:

1. R. Burt, Technique for Computing Noise based on Data Sheet Curves, General Noise Information
2. T. Green, General Information
3. B. Trump, General Information
8. Matt Hann, General INA information and review

Noise Article Series (www.en-genius.net)

http://www.en-genius.net/site/zones/audiovideoZONE/technical_notes/avt_022508

Thank You

for

Your Interest

in

INA Noise – Calculation and Measurement