How gain impacts ADC FSR, noise, and dynamic range

TIPL 4256
TI Precision Labs – ADCs

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ADC full-scale range (FSR)

ADC w/ no integrated gain

ADS8900B FSR (20-bit SAR ADC)

PARAMETER		MIN	TYP	MAX	UNIT
ANALOG INPUT					
FSR	Full-scale input range (AINP – AINM)	$-V_{REF}$		V_{REF}	V

ADCs w/ integrated gain

ADS8691 FSR (18-bit SAR ADC)

PARAMETER	TEST CONDITIONS	MIN	MAX	UNIT
ANALOG INPUTS				
Full-scale input span (AIN_P to AIN_GND)	Input range = ±3 × V_{REF}	–12.288	12.288	V
	Input range = ±2.5 × V_{REF}	–10.24	10.24	
	Input range = ±1.5 × V_{REF}	–6.144	6.144	
	Input range = ±1.25 × V_{REF}	–5.12	5.12	
	Input range = ±0.625 × V_{REF}	–2.56	2.56	
	Input range = 3 × V_{REF}	0	12.288	
	Input range = 2.5 × V_{REF}	0	10.24	
	Input range = 1.5 × V_{REF}	0	6.144	
	Input range = 1.25 × V_{REF}	0	5.12	

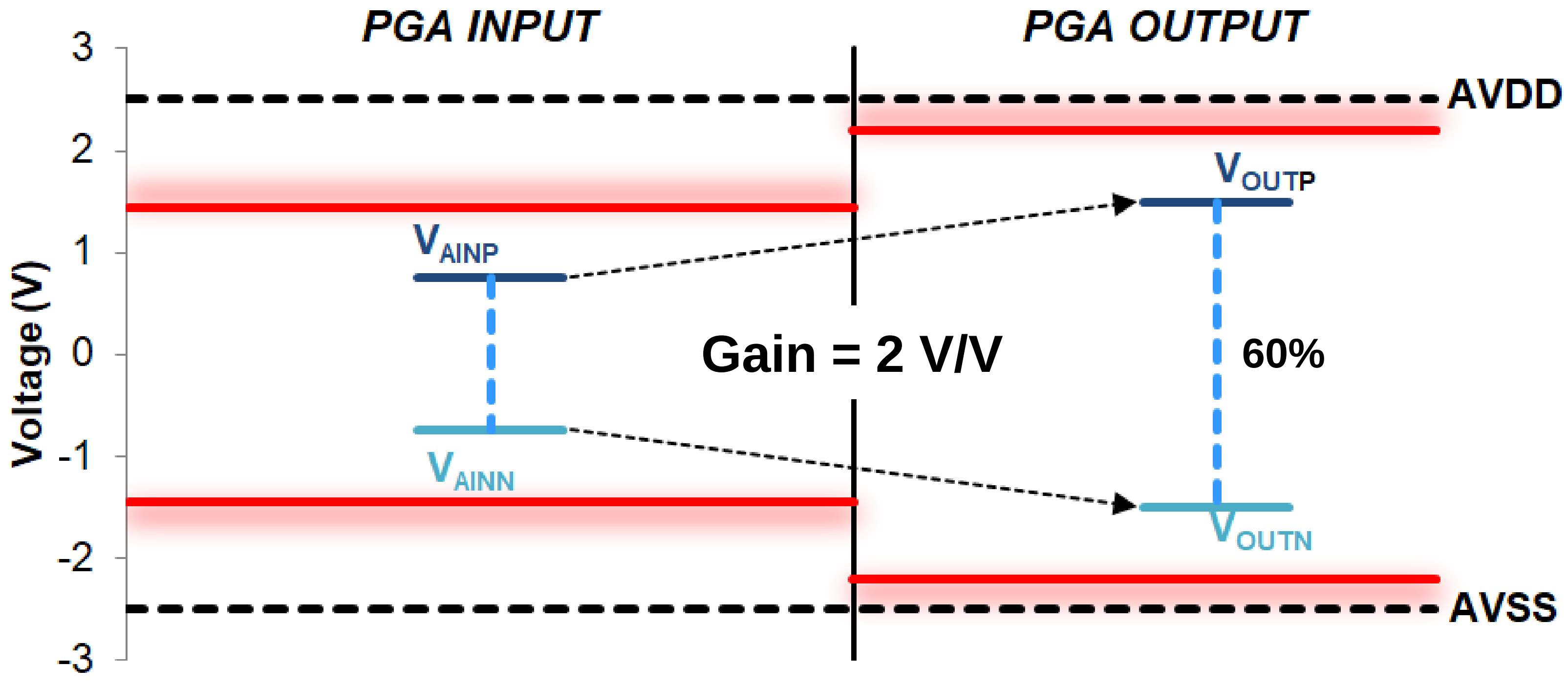
ADS124S08 FSR (24-bit delta-sigma ADC)

		NOM	UNIT
ANALOG INPUTS			
V_{IN}	$V_{IN} = V_{AINp} - V_{AINn}$	$\pm V_{REF}$ / Gain	V

ADS124S08 PGA input and output range

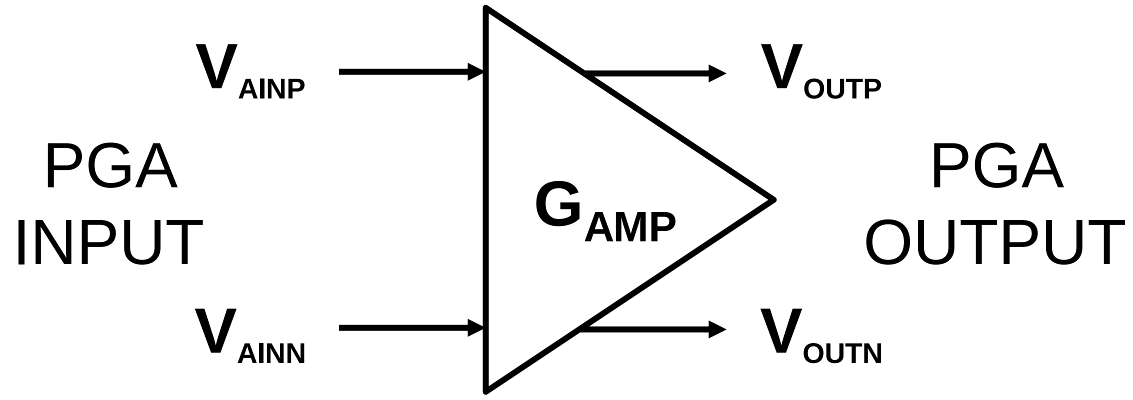
$$FSR_{ADS124S08} = \frac{\pm V_{REF}}{Gain}$$

$V_{SIG\_IN} = \pm 0.75$ V
$FSR_{IN} = \pm 1.25$ V



$V_{REF} = 2.5$ V
$V_{SIG\_OUT} = \pm 1.5$ V
$FSR_{OUT} = \pm 2.5$ V

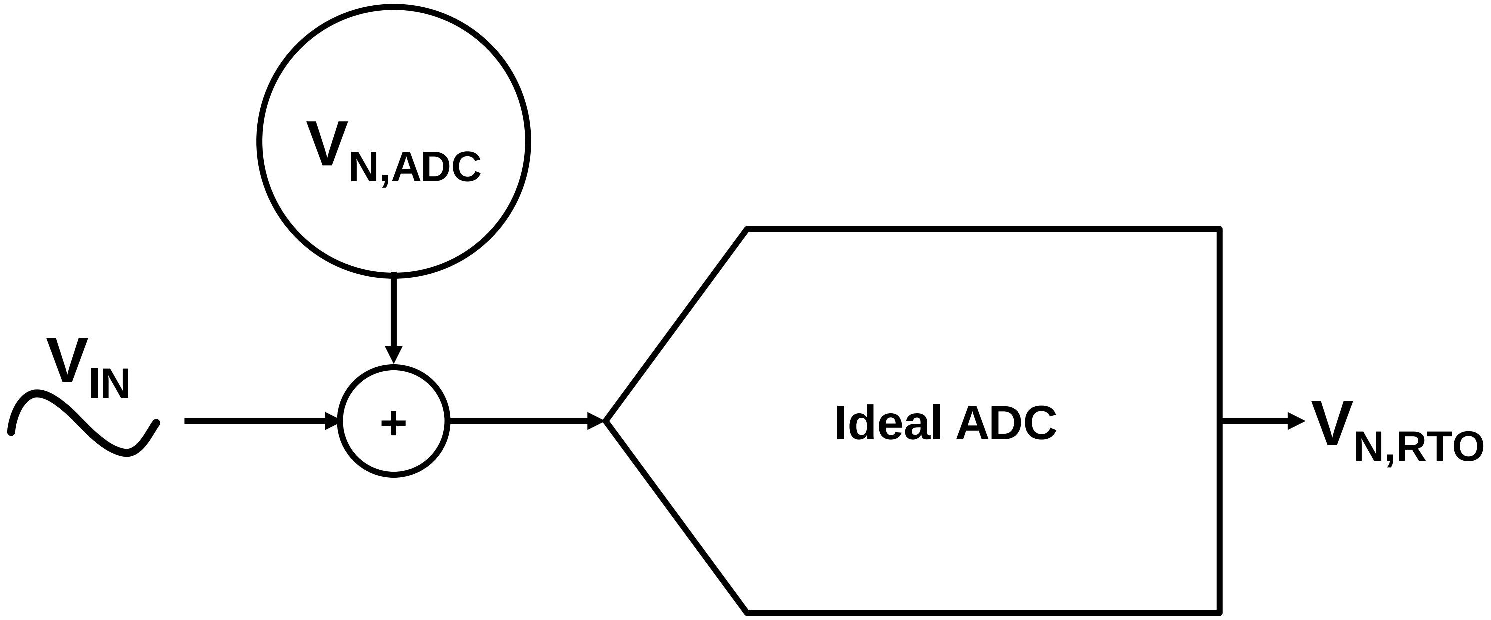
Refer both signal *and* noise to the input



To access this calculator, navigate to the ADS124S08's product folder on TI.com

Output- versus input-referred noise

Equivalent ADC Noise Model:



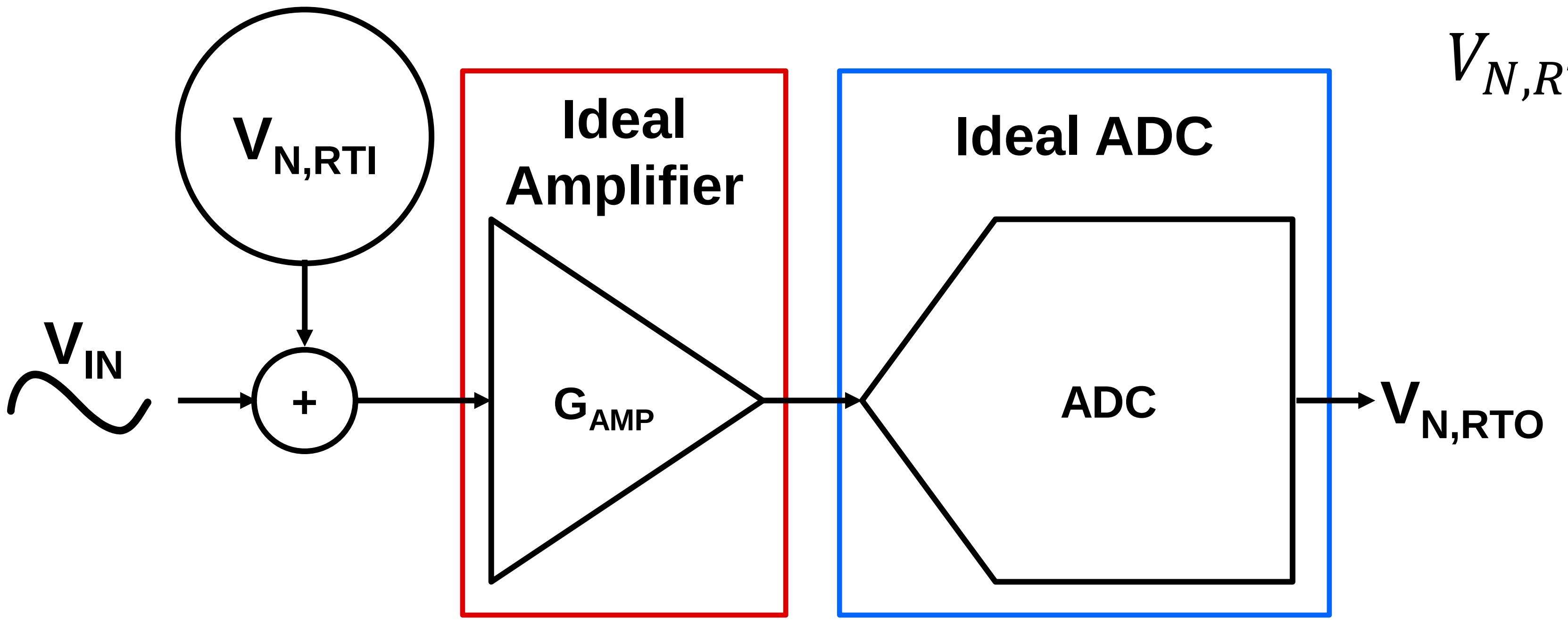
For ADC w/ no gain, $V_{N,RTO} = V_{N,RTI} = V_{N,ADC}$

$V_{N,RTI}$ is the system's input resolution:

- If $V_{IN} < V_{N,RTI}$, the signal is below the noise floor
- Else if $V_{IN} > V_{N,RTI}$, the signal can be observed

Input-referred noise for amp + ADC

Equivalent Amp + ADC Noise Model:



$$V_{N,RTO} = \sqrt{(V_{N,AMP(RTI)} * \boxed{G_{AMP}})^2 + (V_{N,ADC})^2}$$

$$V_{N,RTI} = \sqrt{(V_{N,AMP(RTI)})^2 + (\cancel{V_{N,ADC}/\boxed{G_{AMP}}})^2}$$

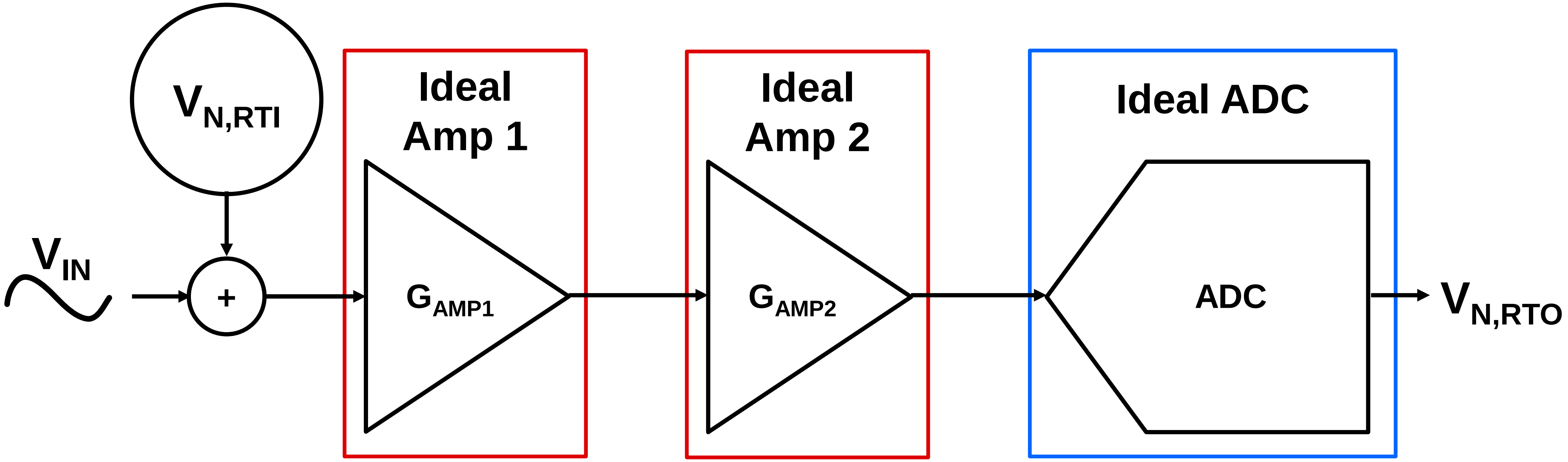
0

For ADC w/ gain, $V_{N,RTO} \neq V_{N,RTI}$

$G_{AMP} * V_{N,AMP(RTI)} >> V_{N,ADC}$

Input-referred noise for 2x amps + ADC

Equivalent 2x Amplifier + ADC Noise Model:

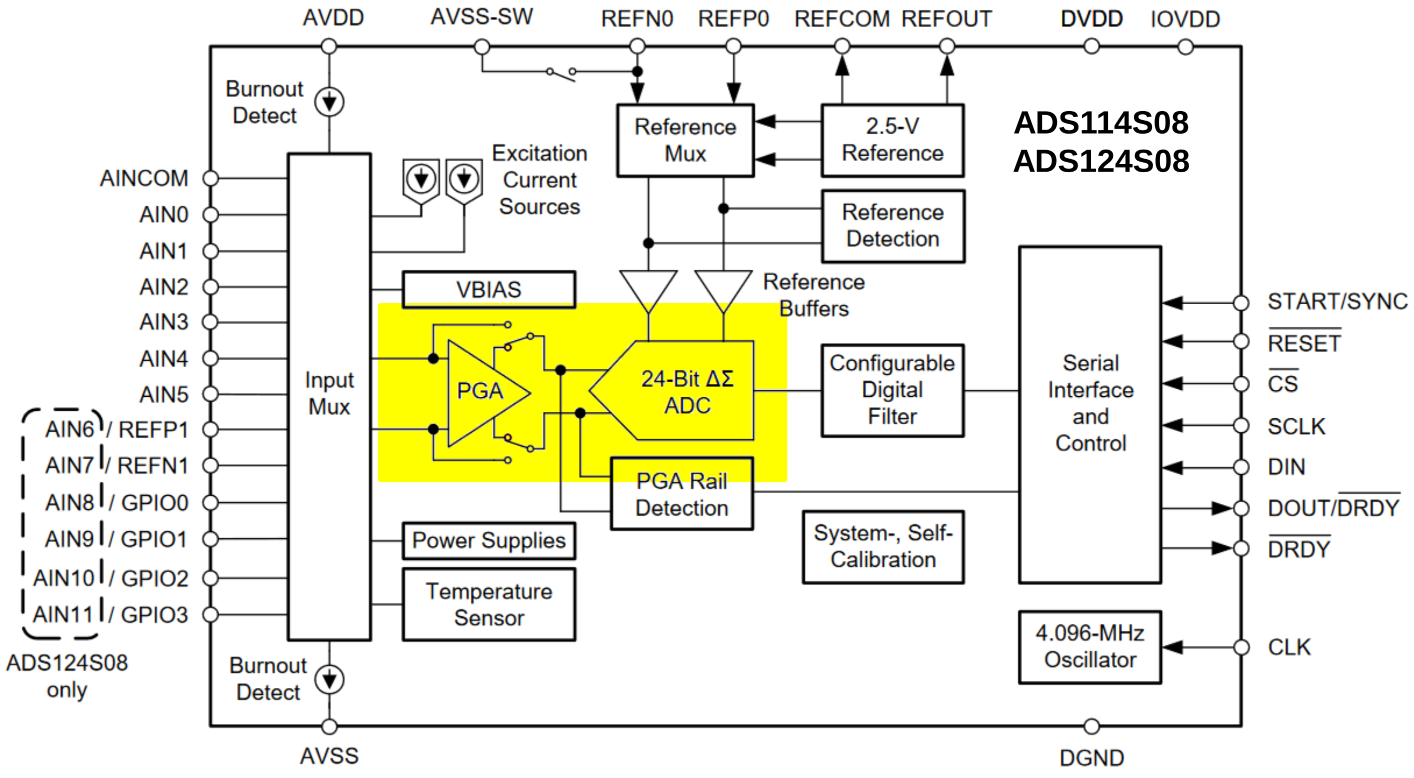


$$V_{N,RTI} = \sqrt{V_{N,AMP1(RTI)}{}^2 + \left(\cancel{\frac{V_{N,AMP2(RTI)}}{G_{AMP1}}}^{\,0}\right)^2 + \left(\cancel{\frac{V_{N,ADC}}{G_{AMP1} * G_{AMP2}}}^{\,0}\right)^2}$$

If G_{AMP1}*G_{AMP2}*$V_{N,AMP1\ (RTI)}$ >> (G_{AMP2}*$V_{N,AMP2\ (RTI)}$)+$V_{N,ADC}$, **then $V_{N,RTI}$ = $V_{N,AMP1(RTI)}$**

Lower vs higher-resolution ADC total noise

ADS1x4S08 block diagram



16-bit ADS114S08

Parameters (Sinc 3, 60 SPS)	Gain 1	2	4	8	16	32	64	128	Units
Noise, RTI	76.3	38.1	19.1	9.5	4.8	2.4	1.2	0.6	μV_{RMS}

$$\frac{V_{N,G=1}}{V_{N,G=2}} = \frac{76.3\ \mu V_{RMS}}{38.1\ \mu V_{RMS}} = 2$$

$$\frac{V_{N,G=64}}{V_{N,G=128}} = \frac{1.2\ \mu V_{RMS}}{0.6\ \mu V_{RMS}} = 2$$

24-bit ADS124S08

Parameters (Sinc 3, 60 SPS)	Gain 1	2	4	8	16	32	64	128	Units
Noise, RTI	1.4	0.7	0.37	0.21	0.12	0.11	0.1	0.089	μV_{RMS}

$$\frac{V_{N,G=1}}{V_{N,G=2}} = \frac{1.4\ \mu V_{RMS}}{0.7\ \mu V_{RMS}} = 2$$

$$\frac{V_{N,G=64}}{V_{N,G=128}} = \frac{0.1\ \mu V_{RMS}}{0.09\ \mu V_{RMS}} = 1.1$$

Applying the input-referred noise equation

$$V_{N,RTI} = \sqrt{\left(V_{N,AMP(RTI)}\right)^2 + \left(V_{N,ADC}/G_{AMP}\right)^2} \quad (nV_{RMS})$$

Lower-resolution ADCs – quantization noise dominates

$G_{AMP} * V_{N,AMP(RTI)} < V_{N,ADC}$

- Use a higher-noise (lower $) amp
- Larger gain if system allows

Higher-resolution ADCs – thermal noise dominates

$G_{AMP} * V_{N,AMP(RTI)} >> V_{N,ADC}$

- Higher gain does not reduce noise
- Use a very low noise amp

How gain affects dynamic range (effective resolution)

$$Dynamic\ range\ (effective\ resolution) = log_2\left(\frac{FSR_{RMS}}{V_{N,RMS}}\right)\ \text{(bits)}$$

16-bit ADS114S08

Parameters (Sinc 3, 60 SPS)	Gain 1	2	4	8	16	32	64	128
Full-scale range (VREF = 2.5 V)	±2.5	±1.25	±0.625	±0.313	±0.156	±0.078	±0.039	±0.019
Noise, RTI (μV_{RMS})	76.3	38.1	19.1	9.5	4.8	2.4	1.2	0.6
Effective resolution (bits)	16	16	16	16	16	16	16	16

Increasing gain

Constant effective resolution

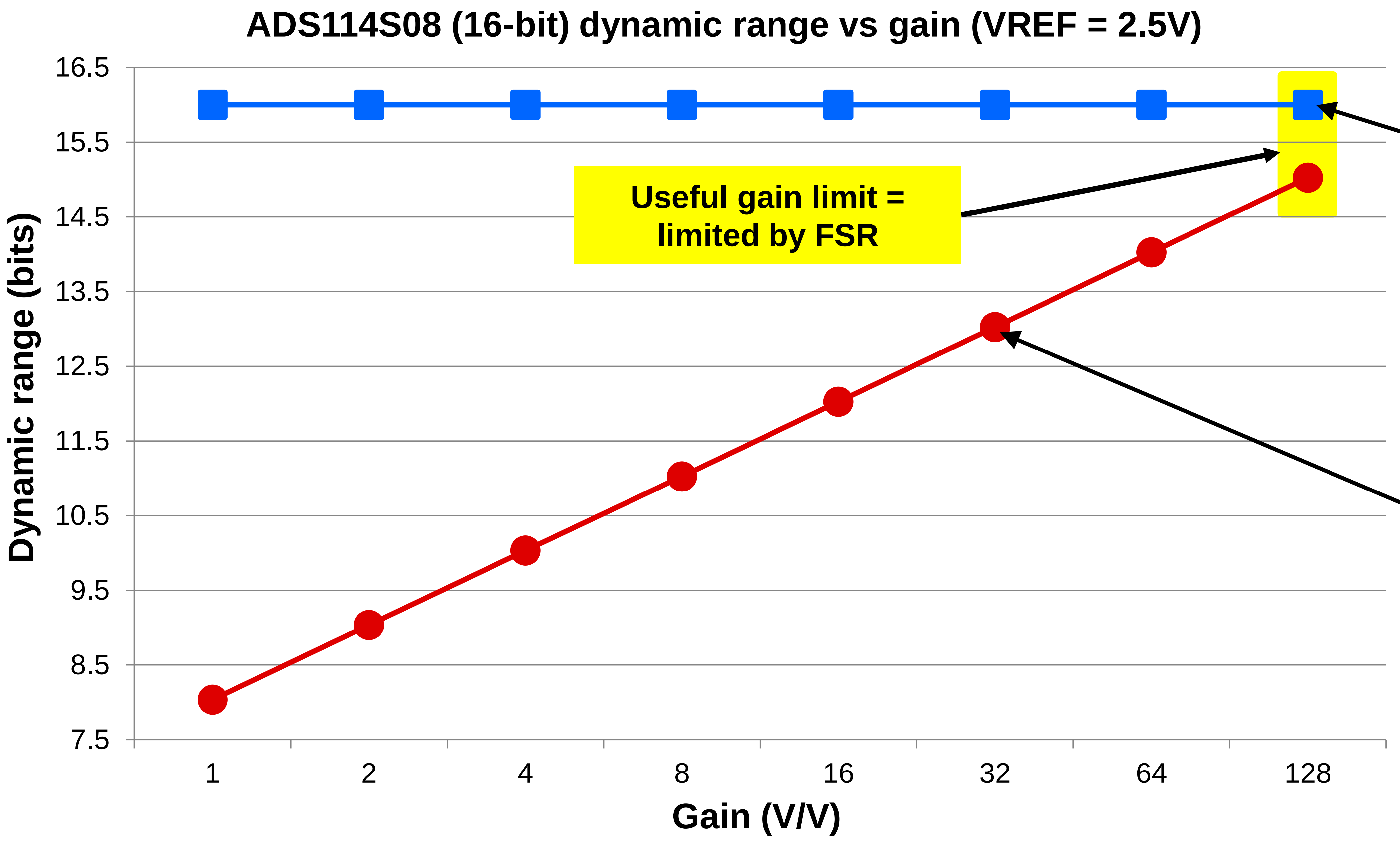
24-bit ADS124S08

Parameters (Sinc 3, 60 SPS)	Gain 1	2	4	8	16	32	64	128
Full-scale range (VREF = 2.5 V)	±2.5	±1.25	±0.625	±0.313	±0.156	±0.078	±0.039	±0.019
Noise, RTI (μV_{RMS})	1.4	0.7	0.37	0.21	0.12	0.11	0.1	0.089
Effective resolution (bits)	21.8	21.8	21.7	21.5	21.3	20.4	19.5	18.7

Increasing gain

Decreasing effective resolution

Dynamic range: max vs system (low resolution ADC)



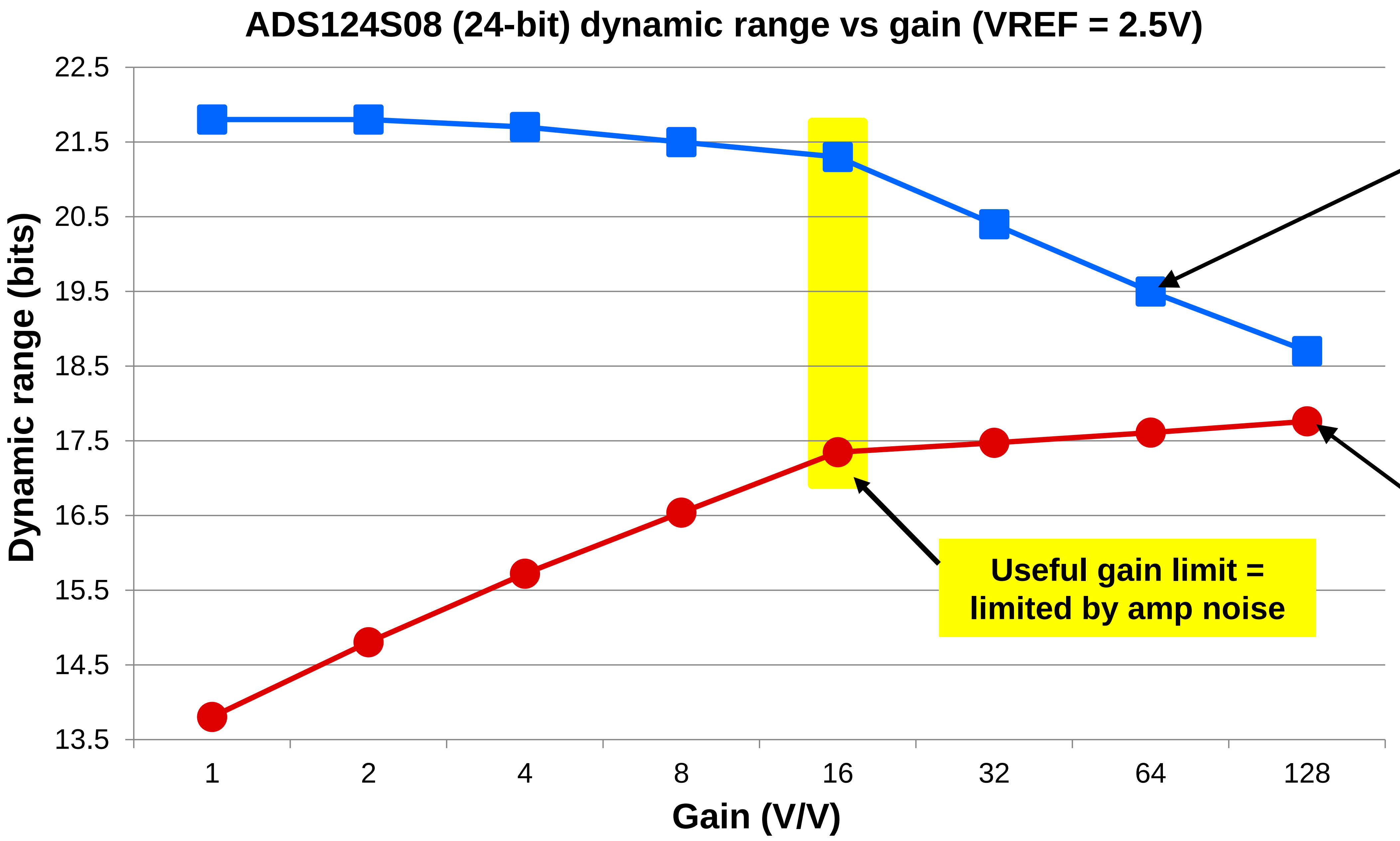
$$V_{IN} = FSR = \frac{\pm V_{REF}}{Gain}$$

$$Maximum\ DR = \log_2\left(\frac{FSR_{RMS}}{V_{N,RMS}}\right) \text{ (bits)}$$

$$V_{IN} = 10\ mV$$

$$System\ DR = \log_2\left(\frac{V_{IN,RMS\ (RTI)}}{V_{N,RMS}}\right) \text{ (bits)}$$

Dynamic range: max vs system (high resolution ADC)



$$V_{IN} = FSR = \frac{\pm V_{REF}}{Gain}$$

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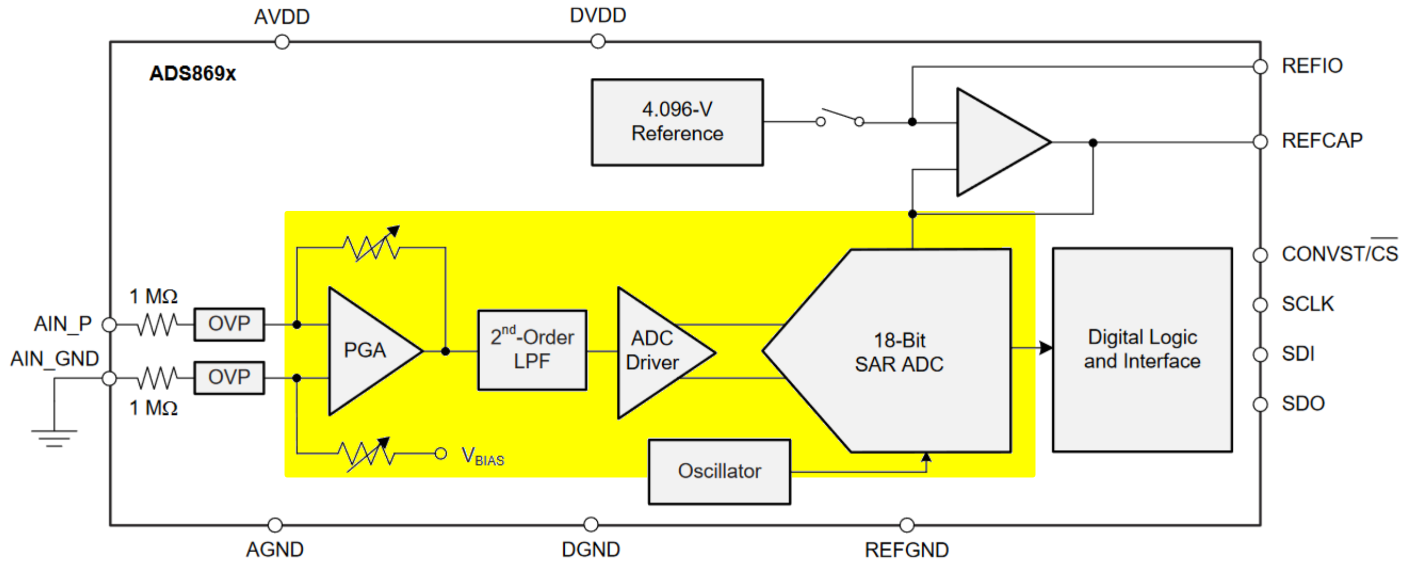
$$V_{IN} = 10\ mV$$

$$System\ DR = \log_2\left(\frac{V_{IN,RMS\ (RTI)}}{V_{N,RMS}}\right) \text{ (bits)}$$

How gain affects dynamic range (SNR)

$$Dynamic\ range\ (SNR) = 20 * log_{10}\left(\frac{FSR_{RMS}}{V_{N,RMS}}\right)\ \text{(dB)}$$

ADS86x1 block diagram



ADS86x1 datasheet SNR values (dB)

Increasing resolution

FSR	ADS8661 (12-bit)	ADS8671 (14-bit)	ADS8681 (16-bit)	ADS8691 (18-bit)
±3 * V_{REF}	73.5	84.5	92	92.5
±2.5 * V_{REF}	73.5	84.5	92	92.5
±1.5 * V_{REF}	73.5	84.25	91.5	91.5
±1.25 * V_{REF}	73.5	84.25	91.5	91.5
±0.625 * V_{REF}	73.5	84	90	90

Increasing gain

Constant SNR

SNR decreases by 0.5 dB

SNR decreases by 2 dB

SNR decreases by 2.5 dB

Thanks for your time! Please try the quiz.

Quiz: How gain impacts ADC FSR, noise & DR

1. When is an external amplifier most effective at improving the system noise performance?
    a) For lower resolution devices
    b) For higher resolution devices
    c) Using an amplifier cannot improve noise performance.

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Quiz: How gain impacts ADC FSR, noise & DR

2. When will increasing the gain of an amplifier driving an ADC cause system noise RTI to decrease?
   a) When amplifier noise is the dominant noise source.
   b) When ADC noise is the dominant noise source.
   c) Increasing gain will always decrease system noise RTI
   d) Increasing gain will never decrease system noise RTI

Quiz: How gain impacts ADC FSR, noise & DR

2. When will increasing the gain of an amplifier driving an ADC cause system noise RTI to decrease?
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Quiz: How gain impacts ADC FSR, noise & DR

3. In the table below, the effective resolution is approximately the same for gains of 1V/V to 16V/V. For gains of 32V/V and higher, the effective resolution drops off quickly. Which of the following statements is not true.
   a) For the low gain ranges the ADC noise is dominant, so the ratio of FSR and noise remain the same.
   b) For higher gain ranges the amplifier noise is dominant, so FSR decreases but noise stays constant.
   c) For higher gain ranges the ADC noise is dominant causing the effective resolution to decrease.

Parameters (Sinc 3, 60 SPS)	Gain 1	2	4	8	16	32	64	128
Full-scale range (VREF = 2.5 V)	±2.5	±1.25	±0.625	±0.313	±0.156	±0.078	±0.039	±0.019
Noise, RTI (μV_{RMS})	1.4	0.7	0.37	0.21	0.12	0.11	0.1	0.089
Effective resolution (bits)	21.8	21.8	21.7	21.5	21.3	20.4	19.5	18.7

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