- **Presented by Dan Seslar**
  - **20+ years of Mixed Signal Instrumentation Experience**
  - **TI Boston Based Technical Resource**
  - **Customer Design Support and Troubleshooting**
  - Design Calculators
  - **TI Factory Contacts**
  - **Roadmap / Future Part Updates**
  - **Part Selection Assistance**

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Texas Instruments Incorporated
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Waltham, Massachusetts 02451

Agenda

- **Designing with ADC and Opamp Specs**
  - **Summary of ADC Specs**
  - **Noise Sources**
  - **Output Noise and Distortion by Opamp Configuration**
  - **Settling Time and BW**
  - **Noise Calculations / Examples**
  - **Using Tina to Calculate Total Integrated Noise**
  - **Design Guidelines**
- **DAC and Opamp Circuit Considerations**
  - **Summary of DAC Specs**
  - **Tradeoffs by DAC architecture**
  - **Noise Sources**
  - **DAC Glitch Energy**
  - MDAC Linearity with Opamp Errors
- **Conclusions**

TEXAS INSTRUMENTS

ADC Specs

- Signal-to-Noise Ratio (SNR)

  SNR is the ratio of the RMS value of the actual input signal to the RMS sum of all other spectral
  components below the Nyquist frequency, excluding harmonics and dc. The value for SNR is
  expressed in dB. SNR = 20 * log (Signal RMS / Noise and Spurious RMS)

- Signal-to-Noise and Distortion (SINAD)

  SINAD is the ratio of the RMS value of the actual input signal to the RMS sum of all other
  Spectral components below the Nyquist frequency, including harmonics but excluding dc.
  SINAD = 20 * log (Signal RMS / Noise and Spurious RMS)

- Total Harmonic Distortion (THD)

  THD is the ratio of the RMS summation of the first five harmonic components (HD2 to HD6)
  to the RMS value of a full-scale input signal. The value for THD is expressed in dB.
  THD = 20 * log (sqrt(HD2^2 + HD3^2…) / Signal RMS)

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ADC Specs

$$ENOB = \frac{SINAD - 1.761}{6.0206}$$

What does this mean?!

ADC Specs

- Ideal Quantization Noise
  - Quantization of a continuous signal to discrete values looses up to +/- ½ LSB of information.
  - Quantization Error = Original Signal – Quantized Signal
  - Quantization Error for a large input signal (many LSBs) is a Saw tooth waveform with an RMS value of sqrt(2/3) of an LSB

$$SNR = 1.761 + 6.0206 \cdot Q$$

$$SNR = 20 \cdot LOG\sqrt{\frac{3}{2}} + 20 \cdot LOG(2^{Q})$$

$$V_{noise} = \frac{1}{\sqrt{\frac{3}{2}} \cdot 2^{Q}}$$

(dB) SNR	Resolution	(Vrms) Noise
49.926	8	3.189E-03
55.946	9	1.595E-03
61.967	10	7.974E-04
67.988	11	3.987E-04
74.008	12	1.993E-04
80.029	13	9.967E-05
86.049	14	4.983E-05
92.070	15	2.492E-05
98.091	16	1.246E-05
104.111	17	6.229E-06
110.132	18	3.115E-06
116.152	19	1.557E-06
122.173	20	7.787E-07
128.194	21	3.893E-07
134.214	22	1.947E-07
140.235	23	9.733E-08
146.255	24	4.867E-08
152.276	25	2.433E-08
158.297	26	1.217E-08

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ADC Specs

- Effective Number of Bits (ENOB)

  Effective Number of Bits is the useable resolution of a converter compared to the quantization noise of an ideal converter:

$$ENOB = \frac{SINAD - 1.761}{6.0206}$$

$$ENOB = \log_2\left(\frac{\sqrt{\frac{2}{3}}}{N+D}\right)$$

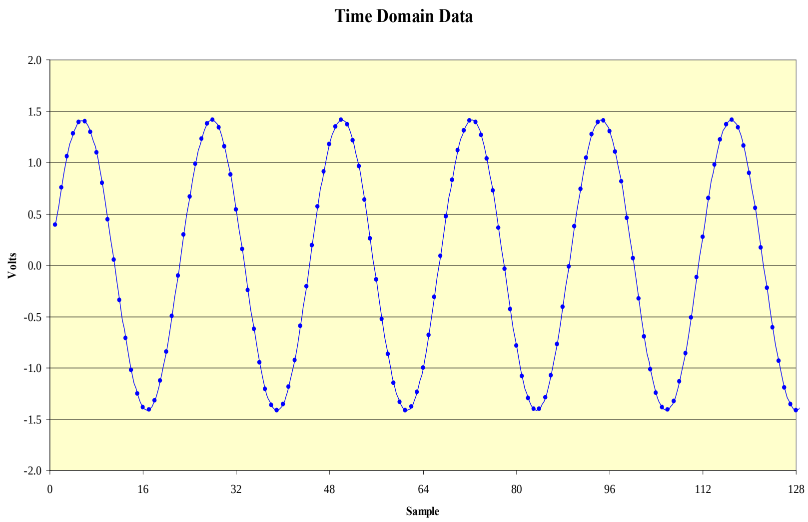
$$Noise + Distortion = \frac{\sqrt{\frac{2}{3}}}{2^{(ENOB)}}$$

(dB) SINAD	(Vrms) Noise+Distortion	Effective Resolution
50.000	3.162E-03	8.012
56.000	1.585E-03	9.009
62.000	7.943E-04	10.005
68.000	3.981E-04	11.002
74.000	1.995E-04	11.999
80.000	1.000E-04	12.995
86.000	5.012E-05	13.992
92.000	2.512E-05	14.988
98.000	1.259E-05	15.985
104.000	6.310E-06	16.982
110.000	3.162E-06	17.978
116.000	1.585E-06	18.975
122.000	7.943E-07	19.971

ADC Spec Calculations

- Excel Workbook for *ENOB Calculation*
  - Filename: Ideal Quantization Noise.xls

ADC Spec Calculations



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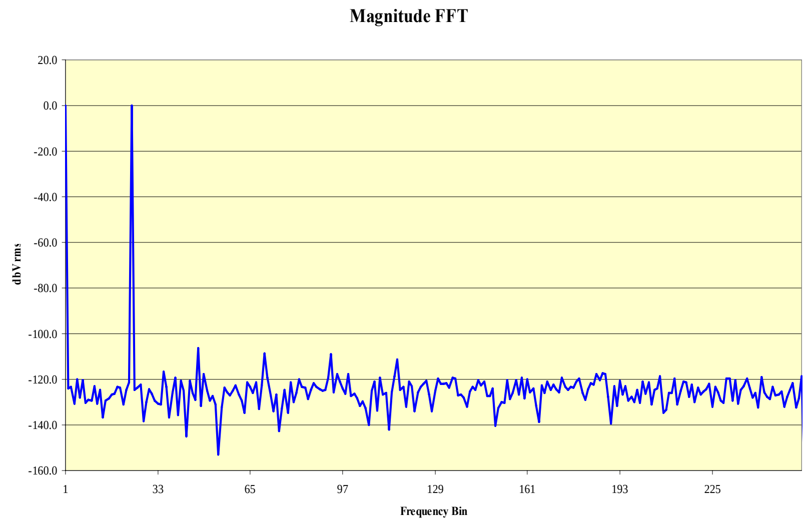
ADC Spec Calculations



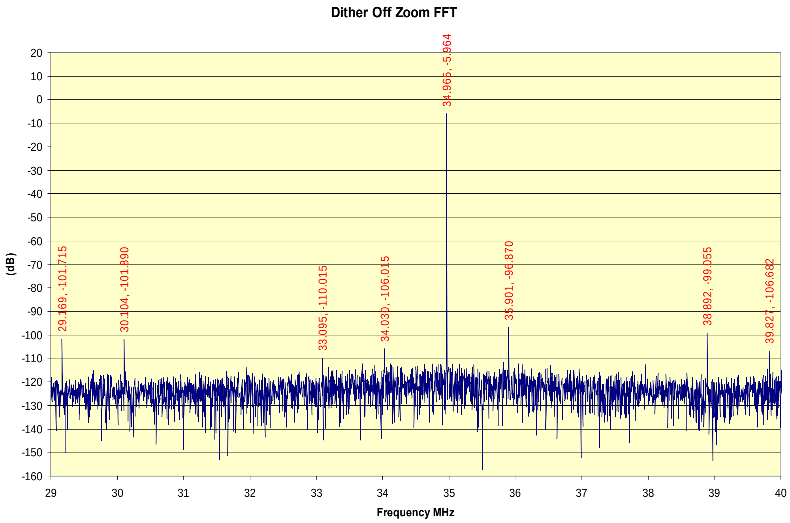
ADC Spec Calculations

					Zero						
Sample Size	**Sample**	**Time Data**	**Fund**	**N + D**	**Mean**		**Reverse dB Calc**		Notes:		
512	1	0.393923	0.393886	0.000037	0.000020		-102	dBVrms	Enter Values in Shaded Cells		
	2	0.756626	0.756601	0.000025	0.000008		7.94328E-06	Vrms	Type CTRL+"t" to update the FFT		
Cycles	3	1.059459	1.059439	0.000020	0.000003						
23	4	1.278437	1.278434	0.000004	-0.000013		**SNR**				
	5	1.396252	1.396255	-0.000003	-0.000020		1.000000	Vrms	Signal		
(Vrms)	6	1.403604	1.403578	0.000026	0.000009		0.000010	Vrms	Noise		
Noise	7	1.299834	1.299823	0.000010	-0.000007		100.0	dB			
0.000010	8	1.093199	1.093202	-0.000003	-0.000020						
	9	0.800066	0.800066	0.000000	-0.000017		**SINAD**			**SINAD**	
(Vrms)	10	0.443616	0.443613	0.000003	-0.000014		1.000000	Vrms	Signal	1.000000	Vrms
Amplitude	11	0.052071	0.052053	0.000018	0.000001		0.000013	Vrms	Noise and Distortion	0.000013	Vrms
1.000000	12	-0.343599	-0.343626	0.000027	0.000010		97.7	dB		97.5	dB
	13	-0.712102	-0.712111	0.000009	-0.000008						
(Vrms)	14	-1.024218	-1.024240	0.000023	0.000006		**ENOB**				
Harmonics	15	-1.255297	-1.255312	0.000015	-0.000002		15.9	bits			
0.000006	16	-1.387010	-1.387040	0.000030	0.000013		15.9	bits			
0.000004	17	-1.408993	-1.408999	0.000006	-0.000011						
0.000004	18	-1.319442	-1.319451	0.000009	-0.000008		**THD**				
0.000003	19	-1.125477	-1.125483	0.000006	-0.000011		1.000000	Vrms	Fundamental		
	20	-0.842450	-0.842446	-0.000004	-0.000021		0.000008	Vrms	Harmonics		
	21	-0.492742	-0.492738	-0.000004	-0.000021		101.7	dB			
	22	-0.104013	-0.104036	0.000023	0.000006						
	23	0.292923	0.292900	0.000023	0.000006		**Mean Value**				
	24	0.666703	0.666656	0.000048	0.000031		1.70648E-05	Vrms	Combined		
	25	0.987673	0.987653	0.000020	0.000003		2.42216E-17	Vrms	Fundamental		
	26	1.230522	1.230489	0.000033	0.000016		1.70257E-05	Vrms	N + D		
	27	1.375962	1.375945	0.000017	0.000000						
	28	1.412522	1.412510	0.000012	-0.000005						
	29	1.337306	1.337291	0.000015	-0.000002						
	30	1.156268	1.156240	0.000028	0.000011						

ADC Spec Calculations

- Excel Workbook for *ADC Spec Calculations*
  - Filename: FFT Analysis3.xls
  - Backward and Forward
  - Frequency and Time Domain

Identifying Spurs



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Identifying Spurs

- Excel Workbook to

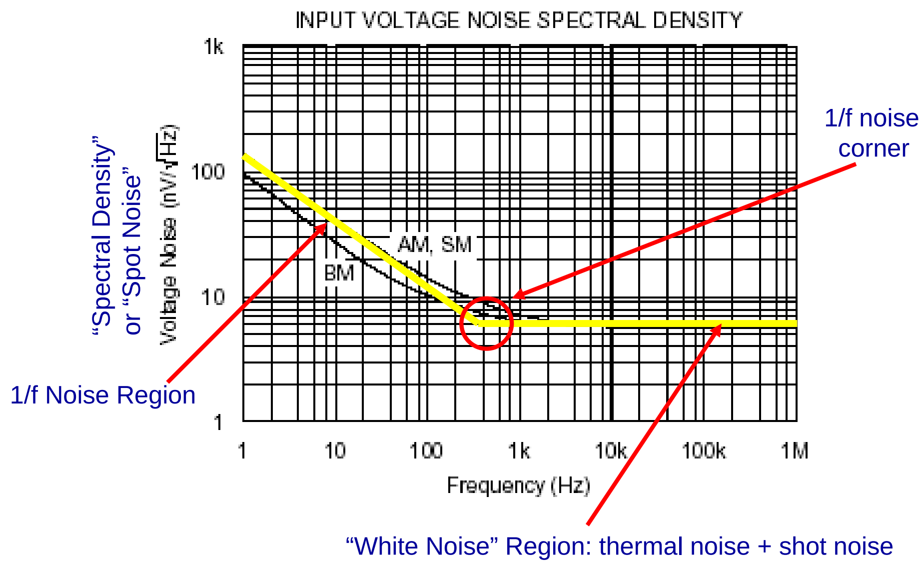
  Calculate Aliased Harmonic Frequencies

  – Filename: Harmonic Calculator.xls
  – Surprisingly high order harmonics may be present!
  – Enter sample rate and Fin
  – *Paste special* calculation table as *values*
  – Sort by Aliased Frequency
  – Change your sample rate and real signals will stay put

Total Instrument Noise

- Types of Noise
- ADC Noise
- Signal Conditioning Noise
  - Noise Sources
  - Equivalent Noise Bandwidth
- Combined Capture System Noise

Noise Regions



White Thermal Noise

$$\text{Power} = 4kT\Delta f$$

- Noise Power is independent of frequency in white noise.
- Noise Power is independent of resistance (R).
- Noise Power is independent of the electronic charge (q).

It can be shown that the thermal noise power in any resistor at 290ºK is:

-114 dBm/MHz or -174 dBm/Hz

Reference: AILTech Noise Slide- Rule

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Thermal Noise Reference

- Excel Workbook to *Calculate Thermal Noise*
  - Filename: Thermal Noise2.xls

(J/°K)
k
1.38E-23

(°K)	(°K)
T_{ROOM}	**T_{HIGH}**
298	**368**

(Ω)	*(nV/rtHz)*	*(nV/rtHz)*
R_S	***NTE_{RS}***	***NTE_{RS}***
50	*0.907*	*1.008*
60	*0.993*	*1.104*
70	*1.073*	*1.192*
80	*1.147*	*1.275*
90	*1.217*	*1.352*
100	*1.283*	*1.425*

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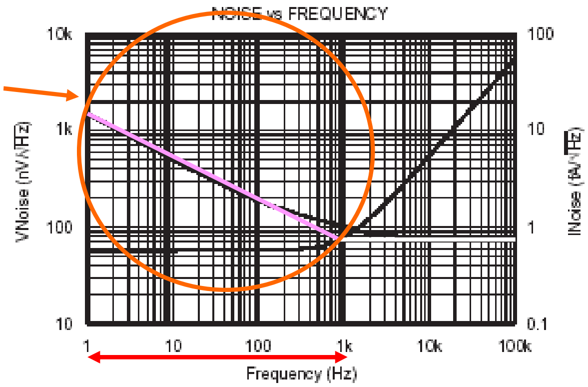
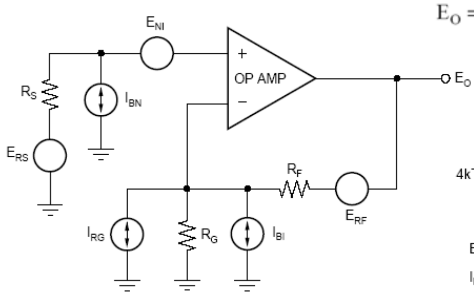
The Dreaded 1/F Region

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



Because in the 1/f noise region the noise density increases at the same rate that you reduce the bandwidth!

Opamp Noise Calculations



$$E_O = \sqrt{E_{NI}^2 G_N^2 + 2(I_B R_F)^2 + 2(4kTR_F G_N)}$$

$(1+R_F/R_G) = G_N$ = Noise Gain

$4kT = 1.6E-20J \bullet \frac{T}{290°K}$, T is the Temperature in Kelvin

E_{NI} = Op Amp Input Noise Voltage

I_{BN} = Op Amp Non-Inverting Input Noise Current

I_{BI} = Op Amp Inverting Noise Current

E_{RS} = Source Resistor Noise Voltage = $\sqrt{4kTR_S}$

E_{RF} = Feedback Resistor Noise Voltage = $\sqrt{4kTR_F}$

I_{RG} = Gain Setting Resistor Noise Current = $\sqrt{\frac{4kT}{R_G}}$

$$E_N = \sqrt{E_{NI}^2 + (I_{BN} R_S)^2 + 4kTR_S + \left(\frac{I_{BI} R_F}{G_N}\right)^2 + \frac{4kTR_F}{G_N}}$$

http://focus.ti.com/docs/apps/catalog/resources/appnoteabstract.jhtml?abstractName=sboa066

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Opamp Noise Calculations

Noise Term	Gain
E_{NI}	G_N
I_{BN}	$R_S \bullet G_N$
E_{RS}	G_N
I_{BI}	R_F
E_{RF}	1
I_{RG}	R_F

$4kT = 1.6E-20J \bullet \frac{T}{290^{\circ}K}$, T is the Temperature in Kelvin

E_{NI} = Op Amp Input Noise Voltage

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I_{RG} = Gain Setting Resistor Noise Current = $\sqrt{\frac{4kT}{R_G}}$

http://focus.ti.com/docs/apps/catalog/resources/appnoteabstract.jhtml?abstractName=sboa066

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Opamp Noise Calculations

Excel Noise Calculator

Add Noise Terms from Data Sheet

Add Circuit Values

(V/V)		(nV/rtHz)	(pA/rtHz)	(pA/rtHz)	(Ω)	(Ω)	(Ω)	(V/V)
A_V	Opamp	E_{NI}	I_{BN}	I_{BI}	R_S	R_G	R_F	Noise Gain
2	**OPA627**	**4.5**	**0.0016**	**0.0016**	**0**	**1000**	**1000**	**2.0**
-2	**OPA627**	**4.5**	**0.0016**	**0.0016**	**0**	**1000**	**2000**	**3.0**

TEXAS INSTRUMENTS

Opamp Noise Calculations

Excel Noise Calculator

- Individual Noise Terms, Output and Input Referred Noise are Calculated
- Identify Dominant Noise Term
- Reduce The Dominant Term to Reduce Noise

							Input
	Output Referred					Output	Referred
	Individual Noise Term Contributions					Noise	Noise
(V/V)	(V/rtHz)	(V/rtHz)	(V/rtHz)	(V/rtHz)	(V/rtHz)	(nV/rtHz)	(nV/rtHz)
Noise Gain	***NTE_{NI}***	***NTI_{BN}***	***NTE_{RS}***	***NTI_{BI}***	***NTE_{RF}***	**E_O**	**E_N**
2.0	***9.00E-09***	*0.00E+00*	*0.00E+00*	*1.60E-12*	*0.00E+00*	**9.00**	**4.50**
3.0	***1.35E-08***	*0.00E+00*	*0.00E+00*	*3.20E-12*	*0.00E+00*	**13.50**	**6.75**

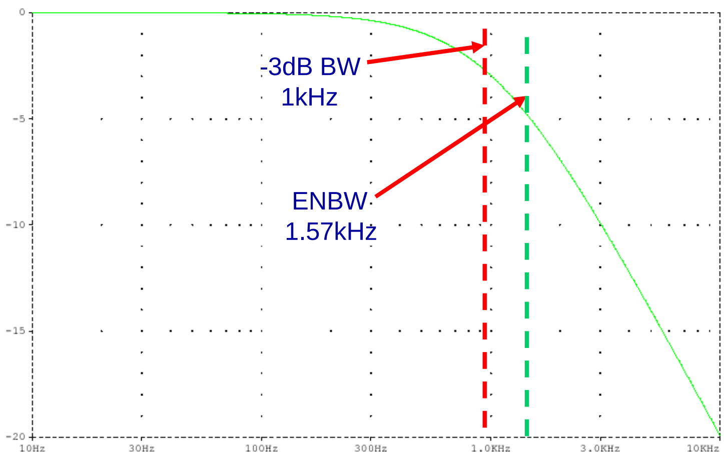
ADC Spec Calculations

- Excel Workbook for *Opamp Noise Calculations*
  - – Filename: Opamp Noise.xls
  - – Identify the dominant noise source!

TEXAS INSTRUMENTS

Equivalent Noise Bandwidth

15.7k & 10nF
RC LPF



Correction factor for 1- pole filter = Pi/2,   1kHz (-3dB BW) * 1.57 = 1.57kHz ENBW

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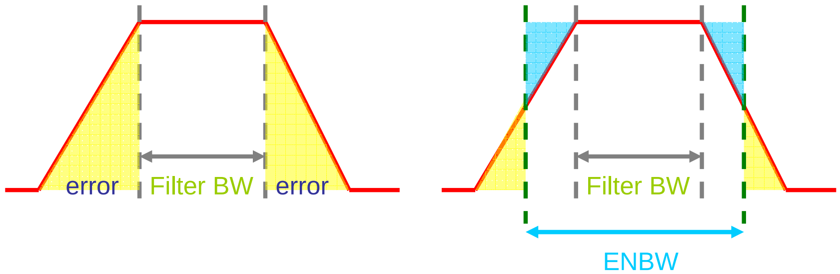
Equivalent Noise Bandwidth

Noise Power is always a function of the measurement bandwidth (Δf).

Unless the filter that defines Δf has a perfect “brick- wall” response, noise will also be contained within the skirts of the filter.



Equivalent Noise Bandwidth (ENBW) is the effective filter bandwidth for white noise filtering, i.e., it is equivalent to a brick- wall filter of that BW.

ENBW by Filter Type

Butterworth (fco = 3 dB)		Chebyshev (fco = ripple)						Bessel (fco = 3 dB)	
Order	EqNBW	Ripple / Order	0.01 dB	0.1 dB	0.25 dB	0.5 dB	1.0 dB	Order	EqNBW
1	1.5708							1	1.57
2	1.1107	2	3.6672	2.1444	1.7449	1.4889	1.2532	2	1.56
3	1.0472	3	1.9642	1.4418	1.2825	1.1666	1.0411	3	1.08
4	1.0262	4	1.5039	1.2326	1.1405	1.0656	0.9735	4	1.04
5	1.0166	5	1.3114	1.1417	1.0780	1.0208	0.9433	5	1.04
6	1.0115	6	1.2120	1.0937	1.0448	0.9970	0.9272	6	1.04
7	1.0084	7	1.1537	1.0653	1.0251	0.9828	0.9175		
8	1.0065	8	1.1166	1.0471	1.0125	0.9736	0.91133		
9	1.0051	9	1.0914	1.0347	1.0038	0.9674	0.9071		
10	1.0041	10	1.0736	1.0258	0.9977	0.9629	0.9041		

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

Integrating Noise Density

Amplifier Noise Calculation		
Signal to Noise (typical)	**(dB)**	**105.00**
Max Signal	**(Vpeak)**	**2.50**
Max Signal	**(Vrms)**	**1.77**
Integrated Noise	**(uVrms)**	**9.94**
-3dB Input Bandwidth	**(MHz)**	**3.39**
Corrected Noise Bandwidth for 1-Pole	**(MHz)**	**5.319**
Corrected Noise Bandwidth for 2-Pole	**(MHz)**	**3.761**
Noise Density with 1-Pole	**nV/rtHz**	**4.31**
Noise Density with 2-Pole	**nV/rtHz**	**5.13**

System Noise Calculation

ADC + Amp Noise Calculation

RMS 2 Amps Integrated Noise	**(uVrms)**	**14.1**
RMS 2 Amps + ADC Noise	**(uVrms)**	**42.1**
Amps + ADC Signal - to - Noise	**dB**	**-98.5**

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Integrating Noise Density

- Excel Workbook to

  Calculate Amp + ADC System Noise

  – Filename: Noise_Calc6.xls
  – Signal Chain Integrated Noise
  – ADC equivalent noise density
  – *System Integrated Noise and SNR*

TEXAS INSTRUMENTS

ADS1672

High Speed High Resolution 625kSPS, 24 bit ΔΣ ADC

- **Data Rate**
  - ADS1672: 625kSPS
- **Precision Performance**
  - 104dBFS SNR, -115dB THD
  - 4ppm INL
  - 2µV/°C Offset, 2ppm/°C Gain Drift
- **Dual-Path Digital Filter:**
  - Wide Bandwidth (Flat Passband 315kHz)
  - Low Latency (Settles in 5.5µs)
- **350mW Power Dissipation**
- **5V Analog, 3V Digital Supplies**

Applications

- Sonar
- Vibration Analysis
- Automated Test Equipment
- Scientific Instrumentation

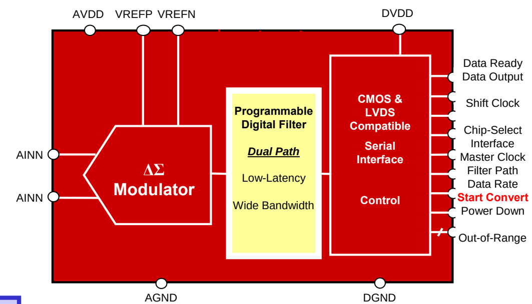
EVM

ADS1672EVM
End of 3Q'08

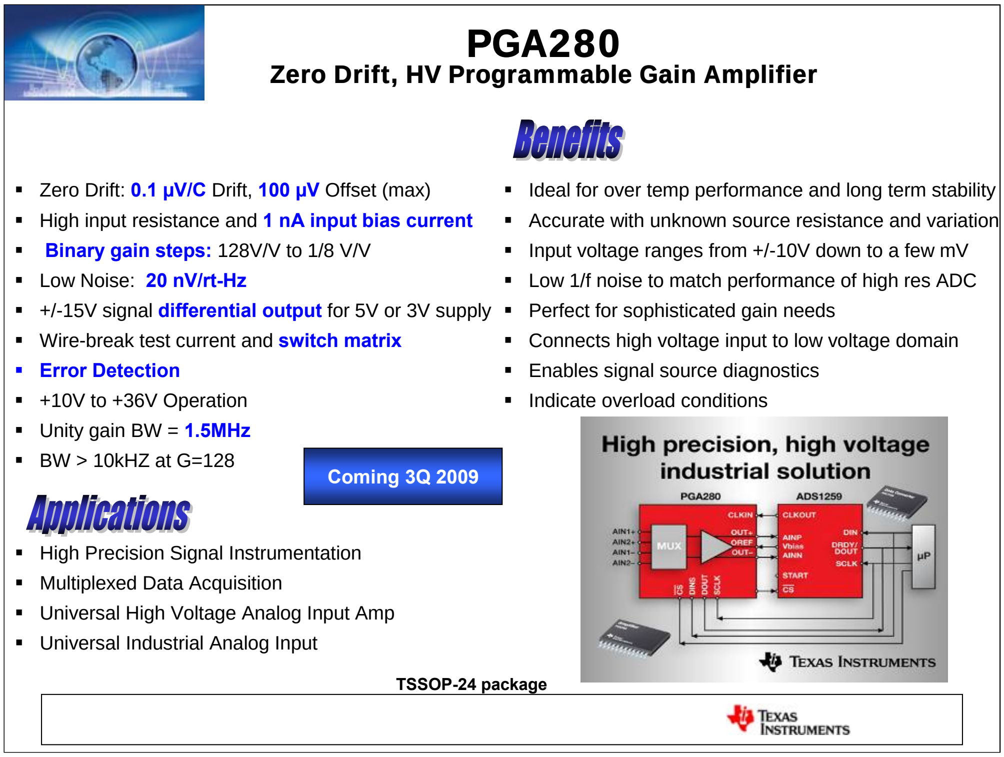
1kU Price = $11.75

Benefits

- Uncompromised Precision with Speed
- Flexible AC and DC Performance for to take applications to the next node
- Selectable Filter for Wide Bandwidth (For AC Apps)
- Low Latency (Ideal for Multiplexing Applications)



TEXAS INSTRUMENTS



The PGA280 is a universal high voltage instrumentation amplifier with digital gain control. It offers excellent DC precision and long term stability using zero drift topology with internal filters to minimize chopper related noise. The input gain extends from 1/8V/V (attenuation) to 128V/V in binary steps. The signal multiplexor connects two channels with several switches that allows input signal diagnostics such as wire breakage and input disconnect.

The supply voltage of up to +/-18V offers a wide common-mode range with high input impedance that can maintain signal accuracy with unknown source resistance and variations.

The fully differential signal output as well as the very low 1/f noise matches the inputs and performance of modern high resolution and high accuracy data converters.

OPA209

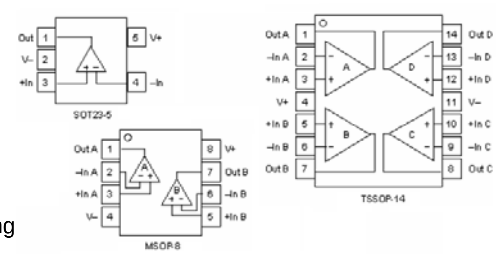
Low Noise, Low Ib Op Amp with RRO in SOT23

- Low Noise : 2.1nV/√Hz (max)
- 100nVp-p Noise, 0.1Hz – 10Hz
- Low Ib: 5nA (max)
- Low Supply Current: 2.5mA (max)
- Low Offset Voltage: 100µV (max)
- Gain Bandwidth Product: 18MHz
- Slew Rate: 6V/µs
- Wide Supply Range ±2.25 To ±18
- Rail-to-Rail Output
- Single - SOT23-5, MSOP-8, SO-8
- Dual – MSOP-8, SO-8
- Quad – TSSOP-14, QFN-16

Benefits

- Improved Dynamic Range
- Lower Power Dissipation
- Space Savings

In Development



Applications

- Pll Loop Filter
- Low Noise, Low Power Signal Processing
- High Performance ADC Driver
- High Performance DAC Output Amplifier.
- Active Filters
- Low Noise Instrumentation Amplifiers

$1.10 in 1k, RTM July 09, Samples March 09

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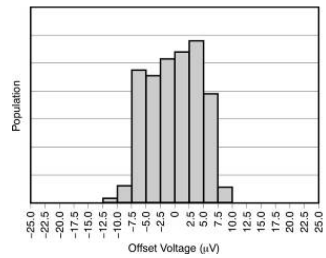
OPAy376

e-Trim Precision Amplifier: Low Offset & Noise

- Low Offset Voltage: 25µV (max)
- Low Noise: 7.5nV/√Hz at 1kHz
- 0.1Hz to 10Hz Noise: 0.8µVPP
- Quiescent Current: 950µA (max)
- Wide Bandwidth: 5.5MHz
- Supply Voltage: 2.2V to 5.5V
- Space Saving Packages:
  - SC70, SOT23, SO, TSSOP, MSOP
- NOW in Wafer Chip Scale Packaging (WCSP) for the DUAL!
- Multi Channel Availability:
  - OPA376 (single) (1KU $0.65)
  - OPA2376 (dual) (1KU $1.00/$0.95 WCSP)
  - OPA4376 (quad) (1KU $1.40)

Benefits

- eTrim combines excellent AC AND DC specifications on <1mA current consumption!
- Low frequency noise (4x lower than nearest competition) benefits dc precision measurement and sensor applications
- Wide bandwidth and low noise density benefit single supply data acquisition systems
- WCSP and low power enable a wide range of opportunity to be used in wireless and handheld, portable equipment



Applications

- Single Supply Data Acquisition Systems
- Sensors and Signal Conditioning
- Wireless Communications
- Medical Instrumentation
- Handheld Test Equipment

1ku Price: $0.65

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