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NIRSPEC Electronics Design Note 06.00
Analog "Device" Noise

1. Introduction

Noise can be defined as any part of the unwanted interference or obscuration of the desired signal. The interference can come from external sources to the system and may result from electrostatic or electromagnetic coupling between the circuit and the external sources. Some of sources of interferences can be 60Hz power lines, radio transmitter, fluorescent lights, cross talk between adjacent circuits, dc power supplies. Or microphonics caused by the mechanical vibration of components. Most of these types of interferences can be often minimized or eliminated by adequate shielding, filtering, proper grounding or the layout of circuit components. These external kinds of noises or interferences will be further discuss in separate design note. The other kind of noise is internal or "device" noises which this design note will cover.

Even if all external noise coupling could be eliminated from a circuit, a theoretical minimum noise level would still exist due to certain "device" noise sources. Device noise is generated within the devices used in data acquisition such as amplifier, transistor, diode and resistor. Although the value of these noise sources can be well defined, the instantaneous amplitude can only be predicted in terms of probability.

The device noise is a basic random-noise generator or spontaneous fluctuations that result from the physics of the devices and materials that make up the electrical device. Thus the thermal noise apparent in all electrical conductors at temperatures above absolute zero is an example of device noise.

Noise limits the resolution of the sensor and dynamic range of a system. The highest signal level that can be processed is limited by the characteristics of the circuit, but the smallest detectable level is set by noise.

Noise is a totally random signal. It consists of frequency components that are random in both amplitude and phase. Although the long-term rms value can be measured and predicted, the exact amplitude at any instant of time cannot be predicted. The noise has a Gaussian or normal distribution of instantaneous amplitudes with time.

The three main types of noise mechanisms are referred to as thermal noise, low-frequency (1/f) noise, and shot noise. Thermal noise is the most often encountered and is considered first.

2. Noise Sources

a) Thermal Noise

Thermal noise comes from thermal agitation of electrons within a conductive material above absolute zero temperature, and it sets a lower limit on the noise present in a circuit. Thermal noise is also referred to as resistance noise or "Johnson noise". The open-circuit rms noise voltage produced by a resistance is

$$e_n = \mathrm{sqrt}(4kTR\Delta f)$$

where

T = Absolute temperature (°K)
Δf = Noise bandwidth (hz)
R = Resistance value (ohm)
k = Boltzmann's constant (1.38×10^{-23} joules/°K)

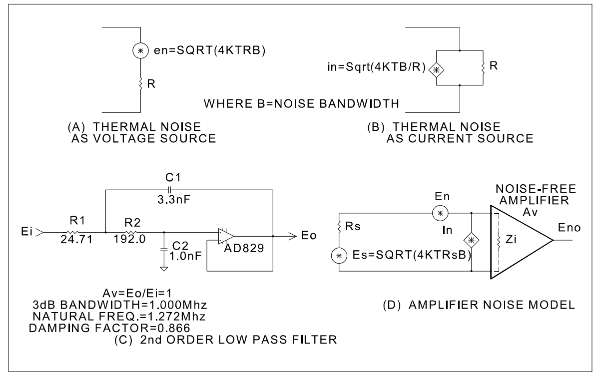

Figure 1 Resistor Noise Models & 2nd Order Bessel LP Filter & Amplifier Noise Model

The thermal noise in a resistor can be represented by adding a thermal noise voltage source e_n in series with the ideal noiseless resistor, as shown in Figure 1A. In some cases, it is preferable to represent the thermal noise by an equivalent rms noise current generator of magnitude

$$i_n = \mathrm{sqrt}(4kT\Delta f/R)$$

in parallel with resistor, as shown in Fig 1B.

As general statement, only dissipating devices could produce thermal noise, like resistor but not capacitor or inductor. As a proof, if a capacitor could be produce thermal noise and apply conservation of energy, since they cannot dissipate energy, their temperature will increase indefinite which is physical impossible.

b) Shot Noise

Shot noise is associated with current flow across a potential barrier. Such a barrier exists at every *pn* junction in semiconductor devices such as in a diode or a transistor junction. In semiconductors, shot noise is due to random diffusion of carriers through the base of a transistor and the random generation and recombination of electron hole pairs. The power density for shot noise is constant with frequency and the amplitude has a Gaussian distribution. The noise is white noise and has the same characteristic as previously described for thermal noise.

$$I_{sh} = \sqrt{2qI_{DC}\Delta f}$$

where q = electron charge (1.6 x 10^{-19} coulombs)
I_{DC} = average DC current (Amp)
Δf = noise bandwidth (Hz)

c) Contact Noise

Contact noise is caused by fluctuating conductivity due to an imperfect contact between two materials. Contact noise is also called by many other names such as "1/f", excess noise, low frequency noise, flicker noise, etc. Due to its unique frequency characteristic, the power density varies as the reciprocal of frequency and the magnitude is Gaussian.

$$I_{1/f} = KI_{DC}\frac{\sqrt{\Delta f}}{\sqrt{f}}$$

where
I_{DC} = average DC current (Amp)
f = frequency (Hz)
Δf = bandwidth centered about the frequency (Hz)
K = a constant that depends on type of material and its geometry

The magnitude of contact noise can become very large at low frequencies due to its 1/f characteristic. Due to its frequency characteristics, contact noise is usually the most important noise source in low-frequency circuits.

d) Popcorn Noise

Popcorn noise, also called burst noise, is due to a manufacturing defect and it can be eliminated by improved manufacturing processes. This noise is caused by a defect in the junction, usually a metallic impurity, of a semiconductor device. Popcorn noise occurs in bursts and causes a discrete change in level. The width of the noise bursts varies from microsecond to seconds. The repetition rate, which is not periodic, varies from several hundred pulses per second to less than one pulse per minute. However, for any particular device, the amplitude is fixed since it is a function of the characteristics of the junction defect. The noise is a current-related phenomenon . Therefore, the popcorn noise voltage is greatest in a high-impedance circuit such as the input circuit of an operational amplifier.

3. Addition of Noise Voltages

Noise voltage, or currents, produced independently with no relationships between each other are uncorrelated. When uncorrected noise sources are added together, the total power is equal to the sum of the individual powers. For example, adding two noise voltage generators, e_{n1} and e_{n2}, together on a power basis, gives

$$e^2_n(\text{total}) = e^2_{n1} + e^2_{n2} \quad \text{or} \quad E^2_n(\text{total}) = E^2_{n1} + E^2_{n2} \text{ or}$$

where e_{n1}; e_{n2} = noise voltage density sources (nVrms/%&&Hz)
E_{n1}; E_{n2} = noise voltage sources (nVrms)

4. The Noise Voltage and Current Model

Any network can be modeled as a noise-free device with two noise generators, E_n and I_n, connected to the input side of a network, as shown in Figure 1D, E_n represents the device noise that exists when Rs equals zero, and I_n represents the additional device noise that occurs when Rs equal open circuit. The use of these two noise generators plus a correlation coefficient completely characterizes the nose performance of any network. Although E_n and I_n are normally correlated to some degree, values for the correlation coefficient are seldom given on manufacturer data sheets. Therefore, it is common practice to assume the correlation coefficient is equal to zero.

An amplifier noise is represented completely by a zero impedance voltage generator E_n in series with the input port, an infinite impedance current generator I_n in parallel with the input, and by a complex correlation coefficient C (not shown) as shown in Figure 1D. Each of these terms may be frequency dependent. The thermal noise of the signal source resistance, R_s is represented by noise generator E_s. By referring all noise to the input port and considering the amplifier to be noise free, it is easier to appreciate the effects of such changes on both signal and noise.

Although we have reduced the number of noise sources to three in the system shown in Figure 1D by using the E_n-I_n model for the electronic circuity, additional simplifications can be performed. Equivalent input noise, E_{ni} will be used to represent all three noise sources. This parameter E_{ni} refers all noise sources to the signal source location. The expression for equivalent input noise is

$$E^2_{ni} = E^2_{nS} + E^2_n + (I_n R_s)^2$$

$$E^2_{no} = (A_v E_{ni})^2$$

This single noise source E_{ni} located at the input can be substituted for all sources of system noise. Amplifier input resistance and capacitance are not present in the equivalent input noise expression.

5. Equivalent Noise Bandwidth

The noise bandwidth (Δf) is not the same as the commonly used "3-db signal" bandwidth (f_{3db}). The "3-db" signal bandwidth of an amplifier is defined as the frequency of the half-power point.

The half-power point is value on the frequency axis where the signal has been reduced by 3db from the reference value. A 3-db reduction represents a loss of 50% in power level and corresponds to a voltage level equal to 1/%& of the voltage at the frequency reference. Figure 1C shows a unity gain low pass filter circuit called Sallen-Key. The frequency response for any 2nd order unity gain low pass filter can be expressed as shown in Equation 1. The relationship between the f_{-3dB} point and natural frequency f_o, can be solved by solving equation 1 for f_{-3dB}. The natural frequency f_o and damping factor ζ, as function of circuit component values, are given by Equation 1 below:

$$A_v(s) = \frac{f_o^2}{s^2 + 2\zeta f_o s + f_o^2} \Rightarrow |A_v(f_{-3db})| = \left| \frac{f_o^2}{(f_o^2 - f_{-3dB}^2) + j2\zeta f_o^2 f_{-3dB}^2} \right| = \frac{1}{\sqrt{2}}$$

$$where\ \zeta = \frac{1}{2Q} = \frac{R1+R2}{2}\sqrt{\frac{C_2}{R_1 R_2 C_1}}; \quad f_o = \frac{1}{2\pi\sqrt{R_1 C_1 R_2 C_2}}$$

Equation 1 General 2nd Order Low Pass Filter

The component values shown in Figure 1C are for a unity gain, 1Mhz Bessel low pass filter. The damping factor (ζ) and "f_{-3dB} vs f_o" for Bessel low pass filter are defined as follows:

$$\zeta \equiv \frac{\sqrt{3}}{2} = 0.866 \ ; \ f_o = 1.272Mhz \ ; \ f_{-3dB} = \sqrt{\frac{-1+\sqrt{5}}{2}} f_o = 0.786 f_o = 1Mhz$$

Equation 2 Bessel Low Pass Filter

The noise bandwidth, Δf is the frequency of a rectangularly shaped power gain curve equal in area to the area of the actual power gain versus frequency curve. Since power gain is proportional to the voltage gain squared, (P%V^2) the equivalent noise bandwidth can also be written as follows:

$$\Delta f = \frac{1}{P_o}\int_0^\infty P(f)df = \frac{1}{A^2_{vo}}\int_0^\infty [A^2 v(f)]df$$

Equation 3 Equivalent noise Bandwidth

where

Δf = Noise bandwidth (hz)
P(f)=Power Gain as a function of frequency,
A_v(f)= voltage gain as function of frequency and
A_{vo}=pass band gain.

Since, practical circuits do not have these ideal characteristics but have responses that roll-off at some rate likes 12dB/octave starting at f_{-3dB} point for 2nd order filter. The problem then is to find an equivalent noise bandwidth, Δf that can be used in equations to give the same results as the actual nonideal bandwidth. A general second order low pass filter, noise bandwidth can

be written as follows:

$$\nabla f = f_o \int_0^{\infty} \frac{f_o^4 df / f_o}{(f_o^2 - f^2)^2 + (2\zeta f f_o)^2} = f_o \int_0^{\infty} \frac{dx}{(1-x^2)^2 + (2\zeta x)^2};\ where\ x = \frac{f}{f_o}\ ,\ \zeta = damping\ factor$$

Equation 4 2nd Order Low Pass Filter, Noise Bandwidth

Using a calculator with integration function and substituting x=tan θ, the integration for Δf becomes very simple.

$$\nabla f = f_o \int_0^{\frac{\pi}{2}} \frac{\sec^2\theta\, d\theta}{(1-\tan^2\theta)^2 + (2\zeta \tan\theta)^2}$$

Equation 5 Noise Bandwidth

For the special case of a 2nd Order Bessel Low Pass Filter where ζ / 0.8660, the equivalent noise bandwidth as function of f_{-3dB} is as follows:

$$\nabla f = f_o \int_0^{\frac{\pi}{2}} \frac{d\theta}{1 + (\tan\theta \sin\theta)^2} = 1.2720 f_{-3dB} \int_0^{\frac{\pi}{2}} \frac{d\theta}{1 + (\tan\theta \sin\theta)^2} = 1.2720 f_{-3db} * 0.9068 = 1.154 f_{-3dB}$$

Equation 6 Equivalent Noise Bandwidth - Bessel Low Pass Filter

Table 1, summary the noise bandwidth (Δf) as function of the 3-db bandwidth (f_{-3dB}) for various types of filter circuits. Also listed is relationship between the 3-dB bandwidth and the natural bandwidth. The natural bandwidth for lst order is fo=1/(2πRC) and 2nd order is fo=1/(2π%&&&&&&&&&).

Table 1 Equivalent Noise Bandwidth (Δf)

Order	Identical Poles	Bessell ζ=0.8660	Butterworth ζ=0.7071	Roll-Off (dB/Octave)
1	$\Delta f=1.571*f_{-3dB}$ $f_{-3dB} = f_o$	n/a	n/a	6
2	$\Delta f=1.220*f_{-3dB}$ $f_{-3dB}=0.6436*f_o$	$\Delta f=1.154*f_{-3dB}$ $f_{-3dB}=0.7862*f_o$	$\Delta f=1.112*f_{-3dB}$ $f_{-3dB} = f_o$	12
3	$\Delta f=1.155*f_{-3dB}$ $f_{-3dB}=0.5098*f_o$	Not Computed	Not Computed	18

7. Noise Calculation

The complete analog signal processor circuit is shown in Figure 2. It contains five basic stages: preamplifier, post-amplifier, low pass filter, buffer and A/D converter. The first stage is the preamplifier where the detector signal is amplifier and its offset removed. The output from the preamplifier is feed into post-amplifier which the signal is further amplifier. The second stage postamp has four gain settings which is control by software. Next the post-amplifier signal is feed into the four independent low pass Bessell filters. Again the software will select which low pass filter will feed into the buffer stage. The buffer stage will drive the A/D converter.

Figure 3 through 7 are noise models for each different stage of the analog signal processor. With these noise models, we can generate Table 2 using a Lotus spreadsheet. Table 3 and 4 listed important summary of calculation from spreadsheet under different parameter conditions.

Before we begin to calculate the noise data, we will define some of convention used in this report. Small letter "e" or "i" is used to indicate voltage (nV/%&I&) or current noise density (pA/%&I&). Capital letter "E" is used to indicate voltage level (µVrms). The "+" and "-" are inputs to opAmp. They are non-inverting ("+") and inverting ("-") inputs respectively. Listed below is the common used symbols for noise calculation:

Nomenclature:

e_n(Rx) = voltage noise due to resistor Rx
e_{n+}@Ux = voltage noise at non-inverting input of opAmp Ux due to opAmp Ux
e_{n-}@Ux = voltage noise at inverting input of opAmp Ux due to opAmp Ux
i_{n-}@Ux = current noise at inverting input of opAmp Ux due to opAmp Ux
i_{n+}@Ux = current noise at non-inverting input of opAmp Ux due to opAmp Ux
e_{no}(Equiv)@U2 = voltage noise at output of opAmp U2
i_{n-}@U1*R5 = current noise at inverting input of opAmp U1 multiply by R5 value
i_n(CC)*R_{oCCD} = current noise output constant current FET Q2 multiply by R_{oCCD} value

R_{oCCD} = source resistance of CCD source follower
e_n(CCD-FET) = voltage noise due to output impedance of CCD FET.
$_{o1}$@U1 = voltage noise at output of opAmp U1 due to preamp circuit
e_{o2}@U3 = voltage noise at output of opAmp U3 due to post-amp circuit
e_{o3}@U7 = voltage noise at output of opAmp U7 due to filter circuit
e_{o4}@U10 = voltage noise at output of opAmp U10 due to buffer circuit

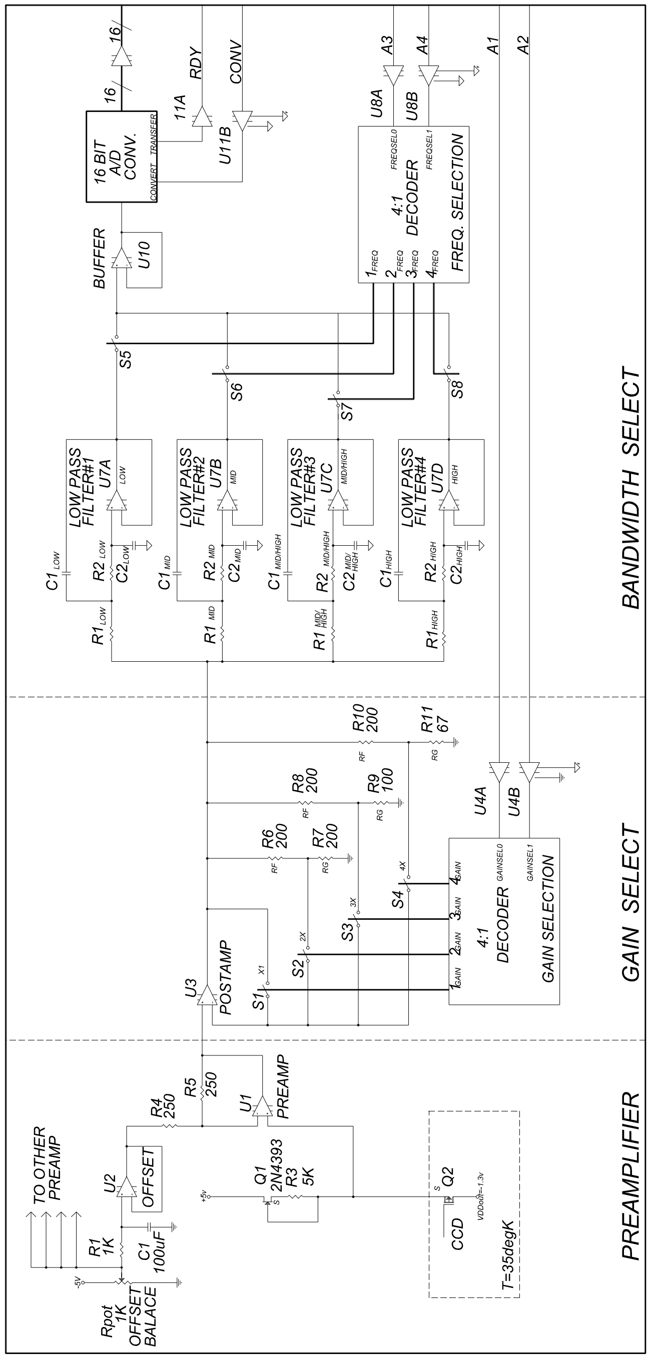

Figure 2 Analog Signal Processor Circuit

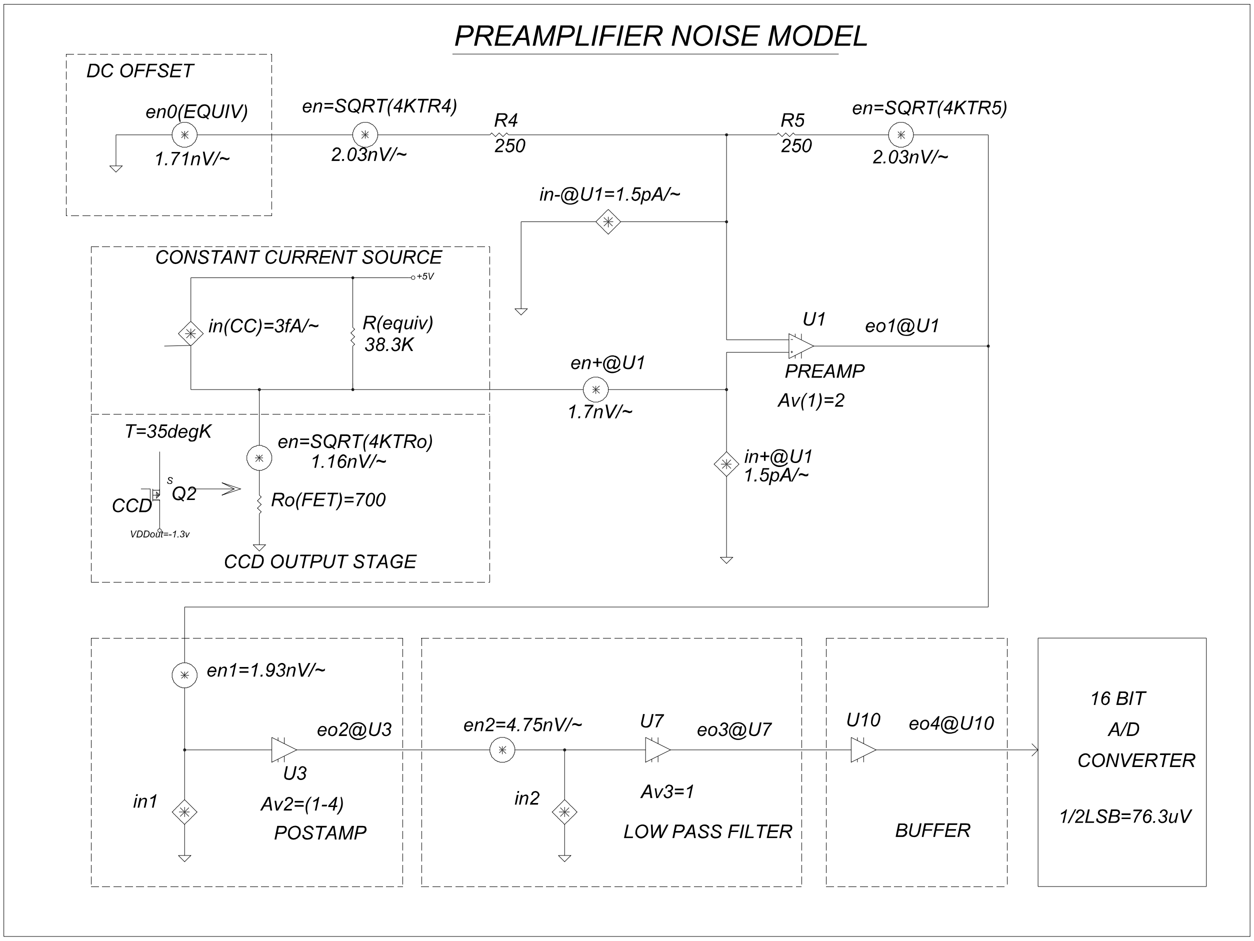

Figure 3 Preamplifier Noise Model

a) Noise Budget

We want the system performance to meet or exceed the signal-to-noise specification of a 16 bit A/D converter. Therefore, the noise budget is determined from the noise constraint in the final signal to A/D converter which is defined to be less than ½ bit. To achieve less than ½ bit of noise, the final noise at the A/D input must be less than 76μVrms as show below in equation 7:

$$En = \frac{10\ volts}{2^{16} bits}\ x\ \tfrac{1}{2} bit = 76.294\,\mu Vrms \qquad \textbf{Equation 7}$$

The dynamic range is defined by equation 8:

$$Vn = 20\log(\frac{1}{2^{16}}) = 96.33\,dB \qquad \textbf{Equation 8}$$

b) Circuit Component Selection

Passive components located in the low-signal level portions of the circuit also can be major contributors of noise. Carbon resistor has more 1/f noise than metal film or wirewound. So it is very important to used only wirewound or metal film resistor only. Zener especially avalanche type also has very large noise. Therefore, any zener voltage reference used in preamplifier should be always filter.

Selecting a low noise opAmp that also has low 1/f frequency corner such as AD829 from Analog Devices. It has low voltage and current noise specification. Further AD829 has a very low 1/f frequency cutoff, below 100Hz, which is very important when operating at low frequency.

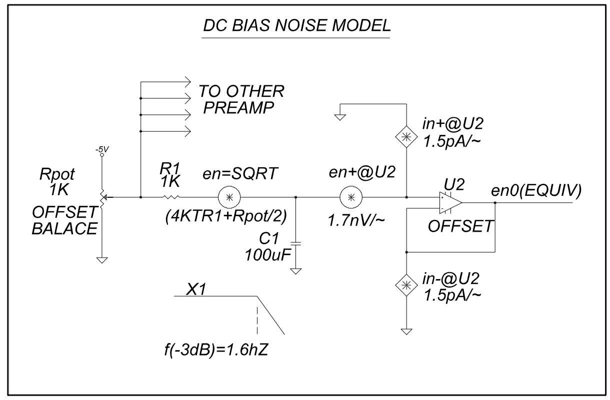

Figure 4 DC Offset Bias Noise Model

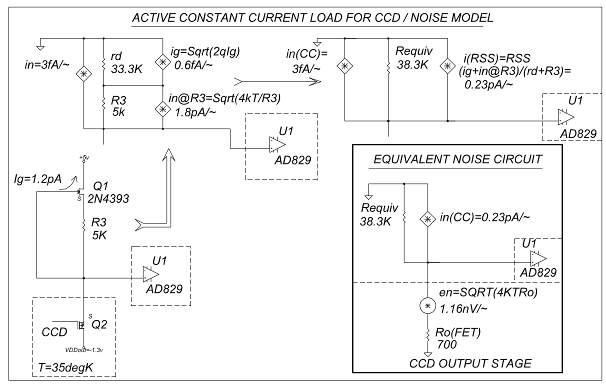

Figure 5 Constant Current Noise Model

c) Spreadsheet

Table 2, analog noise calculation spreadsheet, was generated by combining all noise models from Figure 3 through 7 into spreadsheet format. With this spreadsheet, it is very simple to change parameter values and observed the noise result.

Column (a) of spreadsheet is description of noise component. Column (b) is voltage noise and column (c) is the gain multiply factor. Since the noise added as power, we needed to square noise voltage of column (d) to give column (e). At bottom of each sub-spreadsheet, the power noise is added and takes the square root of it which it will be output noise for this stage. This output noise is feed into the next section. For example, the preamplifier noise output voltage, eo1 (Table 2a) is the input to postamplfier (Table 2c). Finally the output eo4 (Table 2e) is the input to A/D converter.

Column (f) listed the noise contribution from each noise element with respect to the total system noise. As you can see from Table 2a, the preamplifier contributes 95% of noise, of which 41% from voltage noise at non-inverting input of opAmp U1 due to opAmp U1. Next 20% from detector source resistance and 17% from current noise at non-inverting input of opAmp U1 due to opAmp U1 times output resistance of detector.

Since most of the noise comes from preamplifier, it is very important to design low noise circuit configuration and select low noise component.

Table 3 is summary from calculation of Table 2 spreasheet. It shows various parameter values vs noise. Below is some of conclusion, we can stated:

a) Double DetTemp from 35ºK to 70ºK; output noise increases from 45.5 to 49.7µVrms.

b) Double Detector Source Resistance from 700Ω to 1400Ω; output noise increases from 45.5 to 58.9µVrms.

c) Double resistance in Preamp Gain Ratio from 750/250 to 1500Ω/500Ω; output noise increases from 45.5 to 49.5µVrms.

d) Double resistance in PostAmp Gain Ratio from 300/100 to 600Ω/200Ω; output noise increases from 45.5 to 45.8µVrms. Notice: the amount of change is smaller than (c) above.

e) 1/f noise calculation for f_{-3dB} =100Hz; Quadruple the noise voltage and current density from 1.7 to 6.8nV/%&1& and noise current density from 1.5 to 6pA/%&1&; output noise increases from 0.5 to 1.5µVrms. Note: This is a very small portion of our total noise of 1Mhz system which is 45.5µVrms. See Table 4 & 5.

d) Conclusion

The design shown in Figure 3, will meet the ½bit accuracy with gain up to 24 at 1Mhz bandwidth. The maximum system gain required, asuume C_{cell} . 0.06pF, is 12. If the bandwidth could be reduced further, then the gain can be even higher. However, a very important consideration has not discussed. It is grounding and shielding noise which will be discuss further in another engineer design note.

I have assumed that the input noise voltage and current to be flat for the opAmp. This is strictly not true as seen in any of the noise curves in data sheets such as AD829 opAmp. The bend usually occurs at a few thousand Hz, except AD829 which occurs below 100Hz. This introduces an error amount at low frequency noise calculation. But inspecting table 5, we see the noise below 100Hz only add less than 3% to the total noise or less 0.05 % increase from the 1Mhz noise amount. Therefore, we can neglect the 1/f noise, if the system bandwidth is 100 times above 1/f corner. Since, for AD829 where 1/f corner frequency is 100Hz, we can ignore the 1/f for the system having a bandwidth greater than 10Khz.

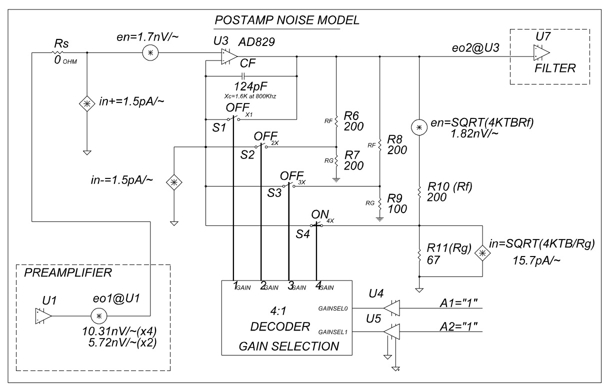

Figure 6 POSTAMPLIFIER NOISE

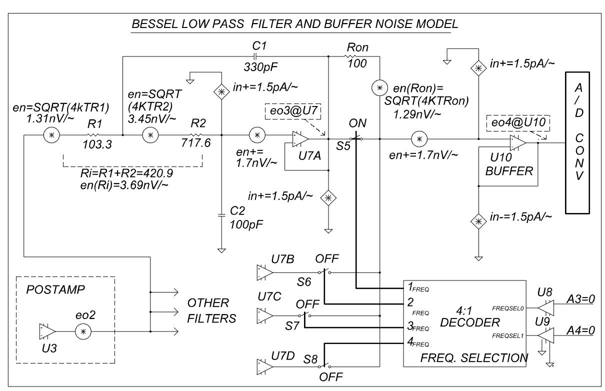

Figure 7 Bessel Low Pass Filter Noise

TABLE 2. Analog Noise Calculation

Summary:

eo4 (to A/D) = 42.37 nV/%&&

Signal Bandwidth (f-3dB) = 1,000 Khz

Noise Bandwidth ()f) = 1,154 Khz

Eo4 (to A/D) = 45.52 :Vrms = 1.1 e~ (electron noise), assume Cc=0.06pF

Equivalent Bits: 0.30 (1:16 LSB)

½bit Accuracy: 76 :Vrms @ A/D Input

Av(Total) = 16 = (4 * 4 * 1) = Av1 * Av2 * Av3

(a) Noise Calculation for Preamplifier Stage

eo1 @Preamp = 10.33 nV/%&&; Eo1 @Preamp = 11.09 :Vrms

T(CCD-FET) = 35`°K
Ro(CCD-FET) = 700 ohm;
en(CCD) = 1.16 nV/%&&
Room Temp = 300`°K = 80.6°F
R5 = (Rf) = 750 Ohm;
en(R5) = 3.52 nV/%&&
R4 = (Rs) = 250 Ohm;
en(R4) = 2.03 nV/%&&
in(CC) = 230 `fA/%&&
R equiv(CC) = 38.3 `Kohm;
Av1=+(1+R5/R4) = 4.0 unit (Pre-Amplifier)
Av2=(1+R10/R11) = 4.0 unit (Post-Amplifier)
Av3 = 1.0 `unit (2nd Order Bessell Low Pass Filter)
Av(Total) = 16 = Av1*Av2*Av3
Signal BW (f-3dB) = 1,000 `Khz; Noise bandwidth ()f) = 1,154 Khz.

OpAmp "U1" AD829
en+@U1= 1.7 nV/%&&
in+@U1= 1.5 pA/%&&
in-@U1= 1.5 pA/%&&

Noise Elements eo1 @ U1 Preamplifier	WideBand Noise nV/%&&	Gain	Noise Voltage: en0x nV/%&&	Noise Power: $(en0x)^2$ nV^2/Hz	Noise Power Contribution to Overall Noise
(a)	(b)	(c)	(d)	(e)	(f)
en(R5)	3.52	1	3.52	12.42	11.07%
{en0(Equiv)}@U2 from Table (b)	1.71	1	1.71	2.91	2.59%
{en(R4)}	2.03	1	2.03	4.14	3.69%
{in-@U1}*R5	1.13	1	1.13	1.27	1.13%
{in+@U1}*(RoCCD)	1.05	4	4.20	17.64	15.72%
{in(CC)}*(RoCCD)	0.1610	4	0.64	0.41	0.37%
{en+@U1}	1.70	4	6.80	46.24	41.20%
{en(CCD-FET)}	1.16	4	4.65	21.64	19.28%
eo1 @ U1 = 10.33 nV/%&& = %E&&			Ge= 106.67nV^2/Hz		95.0%<=Total

(b) Noise Calculation for DC Offset Bias Stage

eo @U2 = en0(equiv) = 1.71 nV/%&&; Eo @U2 = 1.84 :Vrms

R1 = 1000 'ohm	OpAmp "U2" AD829
en(R1) = 4.069 nV/%&&	en+ @U3= 1.7 nV/%&&
Av = 1.0 unit	in+ @U3= 1.5 pA/%&&
Compute for fx = 50 `Hz	in- @U3= 1.5 pA/%&&
Xc (@fx) = 31.83 ohm	
R1//Xc = 30.85 ohm	

Noise Elements eo @U2=en0(EQUIV) Offset Bias (a)	WideBand Noise nV/%&& (b)	Gain at fx(Hz) (v/v) (c)	Noise Voltage: en0x nV/%&& (d)	Noise Power: (en0x)^2 nV^2/Hz (e)	Noise Power Contribution to Overall Noise (f)
en(R1) at fx = 50 Hz	4.07	Xc/(Xc+R1) 0.03	0.13	0.02	0.014%
{en+ @U2}	1.70	1.0	1.70	2.89	2.575%
{in+}*{R1//Xc1}	0.05	1.0	0.05	0.00	0.002%
en0(EQUIV) = 1.71 nV/%&& = %E&&			Ee=2.91 nV^2/Hz		2.6%

(c) Noise Calculation for Post Amplifier Gain Stage//Including Preamplifier

eo2 @U3 = 42.11 nV/%&&; Eo2 @U3 = 45.23 :Vrms

R10 = Rf = 300 ohm	OpAmp "U3" AD829
en(Rf) = 2.229 nV/%&&	en+ @U3= 1.7 nV/%&&
R11 = Rg = 100.00 ohm; or	in+ @U3= 1.5 pA/%&&
in(Rg) = 12.869 pA/%&&	in- @U3= 1.5 pA/%&&
Av2=(+1+Rf/Ri) = 4.0 unit	

i_{n-}(total) = Sqrt{ $i^2_{n(Rg)}$ + $i^2_{n(@U3)}$ } = 12.956 pA/%&& (Eq A)

Noise Elements eo2 @ U3 PostAmplifier (a)	WideBand Noise nV/%&& (b)	Gain (v/v) (c)	Noise Voltage: en0x nV/%&& (d)	Noise Power: (en0x)^2 nV^2/Hz (e)	Noise Power Contribution to Overall Noise (f)
eo1 @U1 (Preamp) from Table (a)	10.33	4.0	41.31	1706.67	
{en(R10)}	2.23	1.0	2.23	4.97	0.28%
{en+@U3}	1.70	4.0	6.80	46.24	2.58%
{i_{n-}(total)}*Rf from Eq A	3.89	1.0	3.89	15.11	0.84%
eo2 @U3= 42.11 nV/ %&& = %E&&			Ee=1772.98nV^2/Hz		3.7%<=Total

(d)Noise Calculation for Low Pass Bessel Filter//Including Preamp & Post-amp

eo3 @U7 = 42.32 nV/%&&; Eo3= 45.46 :Vrms

R1	= 103.3 `ohm;	OpAmp "U7" AD829	
en(R1)	= 1.31 nV/%&&	en+ @U7=	1.7 nV/%&&
R2	= 717.6 `ohm;	in+ @U7=	1.5 pA/%&&
en(R2)	= 3.45 nV/%&&	in- @U7=	1.5 pA/%&&
Ri=R1+R2	= 821 ohm;	OpAmp "U10" AD829	
en(Ri)	= 3.69 nV/%&&	en+ @U7=	1.7 nV/%&&
Ron	= 100 'ohm;	in+ @U7=	1.5 pA/%&&
en(Ron)	= 1.29 nV/%&&	in- @U7=	1.5 pA/%&&

Noise Elements eo3 @ U7 Low Pass Filter	WideBand Noise nV/%&&	Filter Gain (v/v)	Noise Voltage: en0x nV/%&&	Noise Power: $(en0x)^2$ nV^2/Hz	Noise Power Contribution to Overall Noise
(a)	(b)	(c)	(d)	(e)	(f)
eo2 @U3 (PostAmp) from Table (c)	42.11	1.0	42.11	1772.98	
en(Ri)	3.69	1.0	3.69	13.59	0.76%
{en+}	1.70	1.0	1.70	2.89	0.16%
{in+}*Ri	1.23	1.0	1.23	1.52	0.08%
eo3 @U7 = 42.32 nV/%&& = %E&&				Ee= 1790.98nV²/Hz	1.0%<=Total

(e) Noise Calculation for Buffer Stage//Including Preamp,Postamp,Filter

eo4 (to ADC) = 42.37 nV/%&&; Eo4= 45.52 :Vrms <======Total Noise at ADC Input.

Av(Total) = Av1*Av2*Av3= 4*4*1 = 16

Noise Elements eo @ U10 Buffer	WideBand Noise nV/%&&	Buffer Gain (v/v)	Noise Voltage: en0x nV/%&&	Noise Power: $(en0x)^2$ nV^2/Hz	Noise Power Contribution to Overall Noise
(a)	(b)	(c)	(d)	(e)	(f)
eno3 @U7(Filter) from Table (d)	42.32	1.0	42.32	1790.98	
{en(Ron)}	1.29	1.0	1.29	1.66	0.09%
{en+}	1.70	1.0	1.70	2.89	0.16%
{in+}*Ron	0.15	1.0	0.15	0.02	0.00%
					0.3% <==Total
eo4 @U10 = 42.37nV/%&& = %E&&;				Ee= 1795.55 nV²/Hz;	Sum % = 100.00%

Table 3 Noise Summary with Different Parameter Values (½bit = 76:Vrms)

f_{-3dB} = Signal BW = 1.0 Mhz;)f = Noise BW = 1.154 Mhz; Room Temp = 80.6°F; Detector Temp = 35°K

#	PreAmp R5 (S)	PreAmp R4 (S)	Post-Amp R10 (S)	Post-Amp R11 (S)	Overall Gain (v/v)	Ro (CCD-FET) (S)	Eo4 @A/D in (:Vrms)	Eff Bit 1:16	PreAmplifier Noise Distribution: $en_{+@U1}$ (%)	$+en_{@CCD}$ (%)	$+in_{+@U1}$ (%)	$+en_{@R5}$ (%)	+Misc.	=Total eo1	PostAm eo2	LowPas eo3	Buffer eo4	Equiv e~ Noise
1	750	250	300	100	4 x 4 =16	700	45.5	0.30	41.2%+	19.3%+	15.7%+	11.1%+	7.8%=	95.0%	3.7%	1.0%	0.3%	1.1
					Above Row is the Reference Condition. Gain = 16													
2	750	250	300	100	RefCond=16	1,400	58.9	0.39	24.6%+	23.0%+	37.5%+	6.6%+	5.3%=	97.0%	2.2%	0.6%	0.2%	1.4
3	750	250	300	100	DetTem=70°K	700	49.7	0.33	34.5%+	32.3%+	13.2%+	9.3%+	6.5%=	95.8%	3.1%	0.8%	0.2%	1.2
4	750	250	300	100	RmTemp=32°F	700	45.2	0.30	41.8%+	19.6%+	16.0%+	10.2%+	7.6%=	95.2%	3.6%	0.9%	0.2%	1.1
5	750	250	400	100	4 x 5 =20	700	56.8	0.37	41.4%+	19.4%+	15.8%+	11.1%+	7.8%=	95.4%	3.8%	0.6%	0.2%	1.1
6	750	250	500	100	4 x 6 =24	700	68.1	0.45	41.4%+	19.4%+	15.8%+	11.1%+	7.8%=	95.6%	3.8%	0.4%	0.1%	1.1
7	750	250	600	100	4 x 7 =28	700	~~79.4~~	0.52	41.5%+	19.4%+	15.8%+	11.1%+	7.8%=	95.7%	3.9%	0.3%	0.1%	1.1
8	750	250	700	100	4 x 8 =32	700	~~90.7~~	0.59	41.5%+	19.4%+	15.8%+	11.2%+	7.8%=	95.8%	3.9%	0.3%	0.1%	1.1
9	1000	250	300	100	5 x 4 =20	700	55.3	0.36	43.6%+	20.4%+	16.6%+	10.0%+	6.0%=	96.6%	2.5%	0.7%	0.2%	1.0
10	1250	250	300	100	6 x 4 =24	700	65.2	0.43	45.2%+	21.2%+	17.2%+	9.0%+	5.0%=	97.6%	1.8%	0.5%	0.1%	1.0
11	1500	250	300	100	7 x 4 =28	700	75.1	0.49	46.3%+	21.7%+	17.7%+	8.1%+	4.4%=	98.2%	1.4%	0.4%	0.1%	1.0
12	1750	250	300	100	8 x 4 =32	700	~~85.1~~	0.56	47.2%+	22.1%+	18.0%+	7.4%+	4.0%=	98.6%	1.1%	0.3%	0.1%	1.0
13	750	250	300	100	RefCond=16	700	45.5	0.30	41.2%+	19.3%+	15.7%+	11.1%+	7.8%=	95.0%	3.7%	1.0%	0.3%	1.1
14	250	250	300	100	2 x 4 = 8	700	26.6	0.17	30.1%+	14.1%+	11.5%+	10.8%+	19.0%=	85.5%	10.8%	2.9%	0.7%	1.2
15	750	250	300	100	RefCond=16	700	45.5	0.30	41.2%+	19.3%+	15.7%+	11.1%+	7.8%=	95.0%	3.7%	1.0%	0.3%	1.1
16	750	250	100	100	4 x 2 = 8	700	23.1	0.15	39.9%+	18.6%+	15.2%+	10.7%+	7.5%=	91.9%	3.2%	3.9%	1.0%	1.1
17	750	250	300	100	RefCond=16	700	45.5	0.30	41.2%+	19.3%+	15.7%+	11.1%+	7.8%=	95.0%	3.7%	1.0%	0.3%	1.1
18	750	250	600	200	4 x 4 =16	700	45.8	0.30	40.7%+	19.1%+	15.5%+	10.9%+	7.7%=	94.0%	4.8%	1.0%	0.3%	1.1
19	1500	500	300	100	4 x 4 =16	700	49.5	0.32	34.9%+	16.3%+	13.3%+	18.7%+	12.6%=	95.8%	3.1%	0.8%	0.2%	1.2

Note: (1) Shaded cells are value that have been changed with respect the Reference Row (#1) above.
(2) Strikeout cells are noise that exceed ½ bit of a 16 bit A/D converter.

Table 4 1/f Noise Summary up 100Hz (½bit = 76:Vrms)

f_{-3dB} = Signal BW = 100 Hz;)f = Noise BW = 115.4 Hz; Room Temp = 80.6°F; Detector Temp = 35°K

A_{v1}=(1+R5/R4)=(1+750S/250S) = 4 ; A_{v2}=(1+R10/R11)=(1+300S/100S) = 4

Change in **en or in** at 1/f cutoff freq	Overall Gain (v/v)	Ro(CCD-FET) (S)	Eo4 @A/D in (:Vrms)	Eff Bit 1:16	<--- PreAmplifier Noise Distribution ---> $en_{+@U1}$ (%)	$+en_{@CCD}$ (%)	$+in_{+@U1}$ (%)	$+en_{@R5}$ (%)	+Misc.=Total eo1	PostAm eo2	LowPas eo3	Buffer eo4	Equiv e~ Noise
en,in=n.c. f-3db=1Mhz	RefCond=16	700	45.5	0.30	41.2%+	19.3%+	15.7%+	11.1%+	7.8%= 95.0%	3.7%	1.0%	0.3%	1.1
en,in=n.c. f-3db=100Hz	4 x 4 =16	700	14.4	0.09	41.2%+	19.3%+	15.7%+	11.1%+	7.8%= 95.0%	3.7%	1.0%	0.3%	0.3
en=4nV/~; in=n.c.	4 x 4 =16	700	25.4	0.17	73.2%+	6.2%+	5.0%+	3.6%+	6.2%= 94.2%	4.9%	0.6%	0.3%	0.6
en=8nV/~; in=n.c.	4 x 4 =16	700	47.5	0.31	83.9%+	1.8%+	1.4%+	1.0%+	5.7%= 93.9%	5.3%	0.4%	0.3%	1.1
in=2x=3pA/~; en=n.c.	4 x 4 =16	700	17.7	0.12	27.3%+	12.8%+	41.7%+	7.3%+	7.4%= 96.5%	2.5%	0.8%	0.2%	0.4
in=4x=6pA/~; en=n.c.	4 x 4 =16	700	27.1	0.18	11.6%+	5.4%+	71.0%+	3.1%+	7.0%= 98.2%	1.1%	0.6%	0.1%	0.6
in=4x=6pA/~;en=4x=8nV	4 x 4 =16	700	52.7	0.35	68.0%+	1.4%+	18.8%+	0.8%+	5.9%= 95.0%	4.3%	0.4%	0.3%	1.2

Table 5 1/f Noise Summary up to 100Hz (½bit = 76:Vrms)

f_{-3dB} = Signal BW = 100 Hz;)f = Noise BW = 115.4 Hz; Room Temp = 80.6°F; Detector Temp = 35°K

A_{v1}=(1+R5/R4)=(1+750S/250S) = 4 ; A_{v2}=(1+R10/R11)=(1+300S/100S) = 4

Change in **en or in**	Eo4	Eo4^2	Differenc	% Incr	Eo4^2	with	% Incr

at 1/f cutoff frequency		(uV)	(uV^2)	(uV^2)	respect power	Final Val (uV^2)	1/f Eo4 (uV)	respec @1Mhz
f-3db=1Mhz (Full BW)	RefCond= 16	45.5	2072	n/a		2072	45.52	0.00%
f-3db=100Hz	4 x 4 = 16	0.5	0.21	Ref		2072	45.52	0.00%
en=2x=3.4nV/~;in=n.c.	4 x 4 = 16	0.7	0.50	0.29	0.01%	2072	45.53	0.01%
en=n.c.; in=2x=3pA/~	4 x 4 = 16	0.6	0.31	0.11	0.01%	2072	45.52	0.01%
en=2x=3.4nV;in=2x=3pA	4 x 4 = 16	0.8	0.60	0.40	0.02%	2072	45.53	0.01%
en=4x=6.8nV/~; in=n.c.	4 x 4 = 16	1.3	1.66	1.45	0.07%	2073	45.54	0.04%
en=n.c.; in=4x=6pA/~	4 x 4 = 16	0.9	0.73	0.53	0.03%	2072	45.53	0.02%
en=4x=6.8nV;in=4x=6pA	4 x 4 = 16	1.5	2.18	1.98	0.10%	2074	45.54	0.05%