Analysis and Measurement of Intrinsic Noise in Op Amp Circuits
Part VIII: Popcorn Noise

by Art Kay, Senior Applications Engineer, Texas Instruments Incorporated

This TechNote discusses how to measure and identify popcorn noise; the magnitude as compared to 1/f and broadband noise; and applications that are especially susceptible to popcorn noise.

Review of 1/f and Broadband Noise

Before looking at popcorn noise, it is useful to review the time domain and statistical representation of broadband and 1/f noise. Both 1/f and broadband noise have Gaussian distributions. Furthermore, these noise types are consistent and predictable for a given design. Thus far in this article series, we have learned how to predict noise levels through calculations and simulations (Figs. 1 & 2). However, these methods cannot be used to measure popcorn noise.

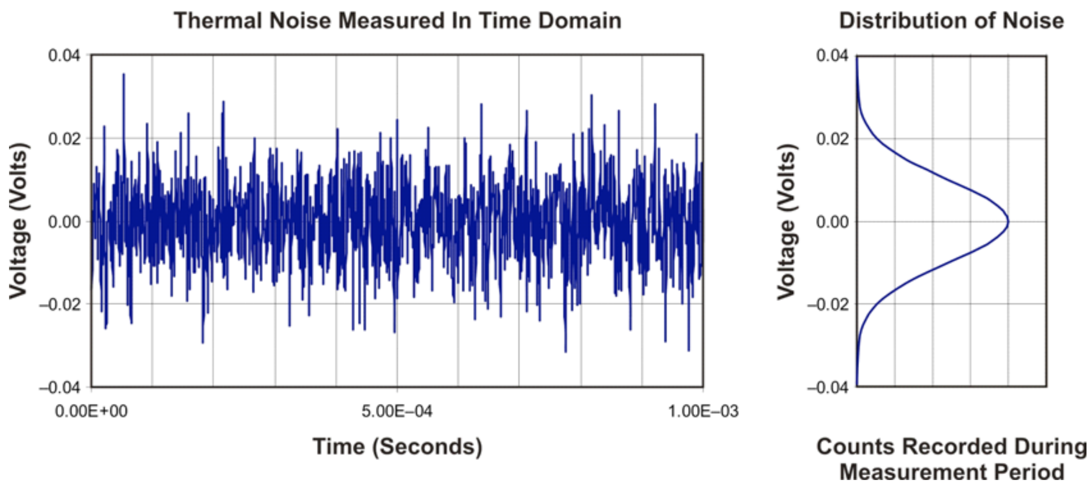

Fig. 8.1: Broadband Noise: Time Domain and Histogram

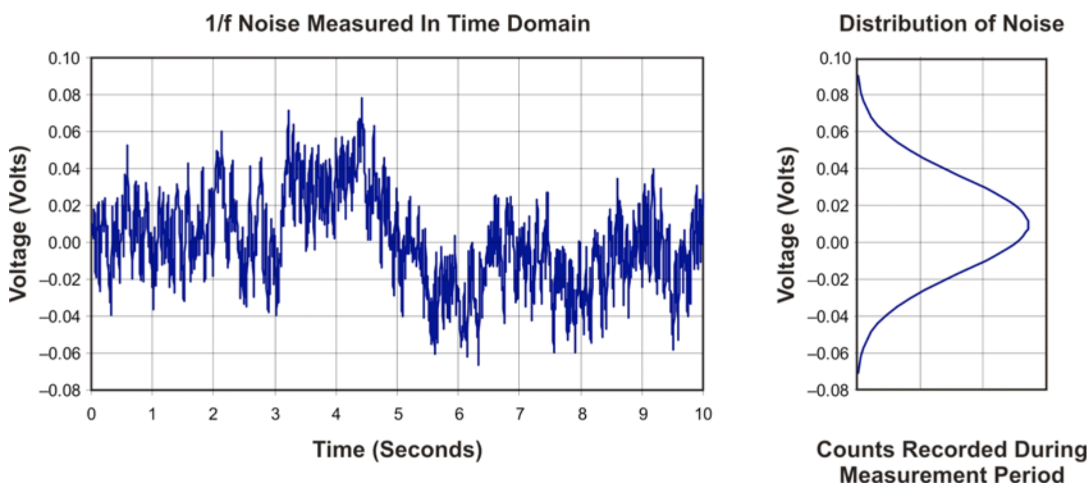

Fig. 8.2: 1/f Noise: Time Domain and Histogram

What is Popcorn Noise?

Popcorn noise is a sudden step, or jump, in base current on bipolar transistors, or a step in threshold voltage on an FET. It got this name because the sound it makes when played over a speaker resembles the sound of popcorn popping. This noise is also called burst noise and random telegraph signals (RTS). Popcorn noise occurs at low frequency (typically f < 1 kHz). Bursts can happen several times a second or, in some rare cases, may take minutes to occur.

Fig. 8.3 shows popcorn noise in the time domain and its associated statistical distribution. Note the distinctive jumps in noise level correspond to peaks in the distribution. Clearly, the distribution associated with popcorn noise in not Gaussian. In fact, the distribution shown in this example is three Gaussian curves placed on top of each other (tri-model distribution). This happens because the popcorn noise in this example has three discrete levels. The noise in between bursts is a combination of broadband and 1/f noise. Thus, the noise consists of three different Gaussian distributions from 1/f and broadband noise that are shifted to different levels by popcorn noise.

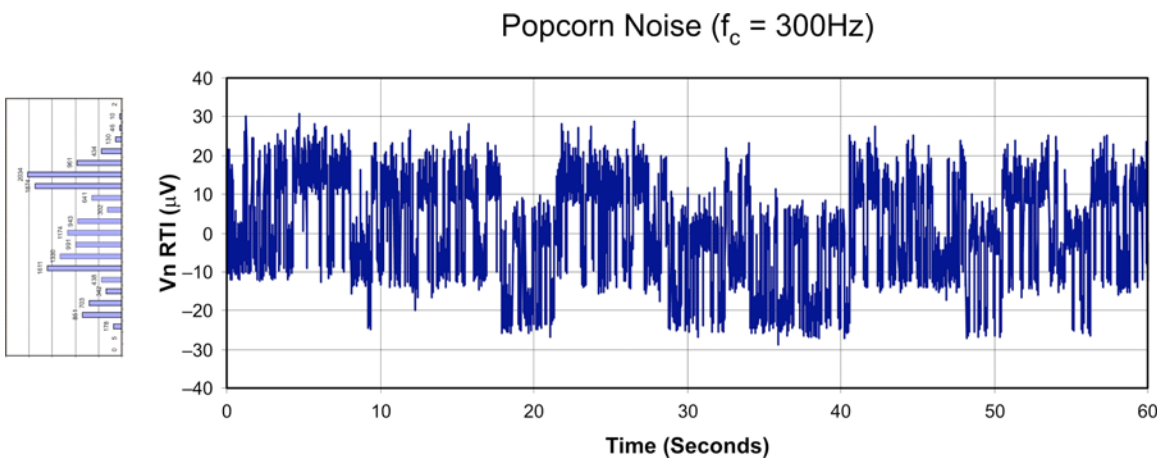

Fig. 8.3: Popcorn Noise: Time Domain and Histogram

What Causes Popcorn Noise?

Popcorn noise is believed to be caused by charge traps or microscopic defects in the semiconductor material. Heavy metal atom contaminates are known to cause popcorn noise. Devices with excessive popcorn noise are often closely examined by experts in the field of failure analysis. Failure analysis searches for microscopic faults that could cause popcorn noise.

Fig. 8.4 shows how a normal transistor compares to one with a crystalline defect.

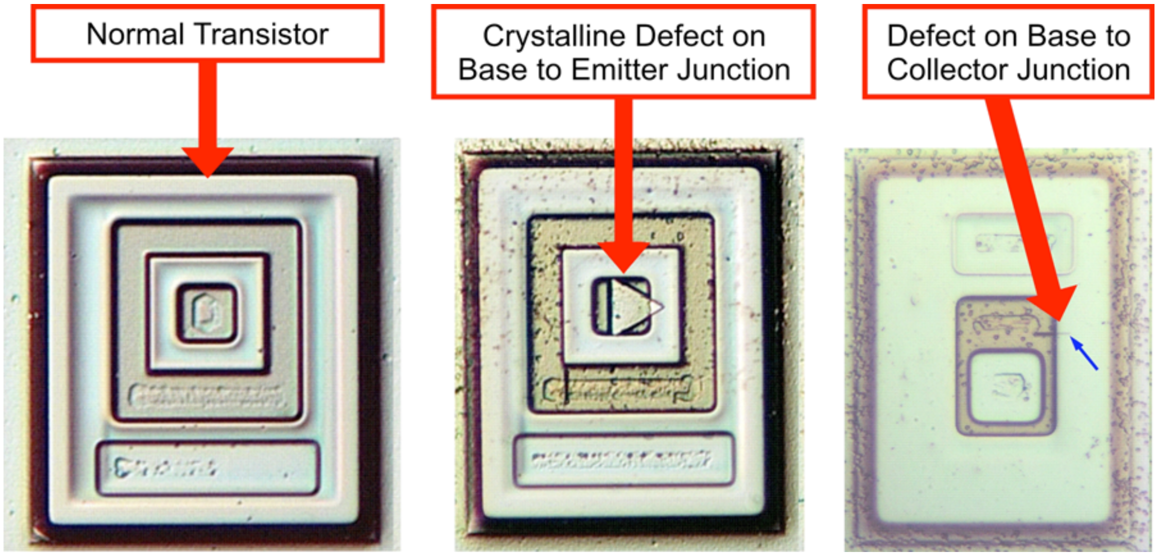

Fig. 8.4: Normal Transistor vs. Transistor with Crystalline Defect

How Common is the Problem?

Popcorn noise is related to problems that occur during semiconductor fabrication. For many modern processes the occurrence of popcorn noise can be relatively small. Generally, there is a *lot-to-lot* dependency; ie, some lots will have no popcorn noise while other lots may have a small percentage of contamination. A particularly bad semiconductor lot could have 5% of the devices with popcorn noise. In some cases it is possible to identify the fabrication issue that caused the popcorn noise.

Popcorn Noise : Current or Voltage Noise?

On bipolar transistors popcorn noise shows up as a step change in base current. So, bipolar op amp popcorn noise typically will show up as bias current noise. For this reason, popcorn noise in bipolar amplifiers may only show up in applications with high source impedances.

On bipolar op amps with JFET input amplifiers, bias current noise generally is not a problem. In some cases, a bipolar transistor on an internal stage will generate popcorn noise. This popcorn noise shows up as a voltage noise.

In general, MOSFET amplifiers tend to be less prone to popcorn noise. Popcorn noise in MOSFET transistors shows up as a step in the threshold voltage. This would show up as voltage noise in an op amp.

Bench and Production Test for Voltage Popcorn Noise

In this TechNote we discuss how to implement a bench test and a production test for popcorn noise. A bench test is a test setup in an engineering laboratory used for testing a small sample of devices. A production test is one that uses automated test equipment to test large quantities of devices. The fundamental difference between the two is that the production test needs to have a short test time (typically $t \leq 1$ s). Production testing times need to be short because production test time is very expensive. In many cases test costs are comparable to the cost of the semiconductor die.

Fig. 8.5 shows the bench setup for measuring an op amp (U1) voltage popcorn noise. Note that the non-inverting input of the amplifier is grounded, so the amplifier noise and dc output is the offset multiplied by the gain. The noise is further amplified by U2. Note that gains of U1 and U2 are both set to 100; ie, the total gain is 100 x 100 = 10,000. This is a typical gain setting for popcorn noise measurements; however, you may need to adjust this for your application.

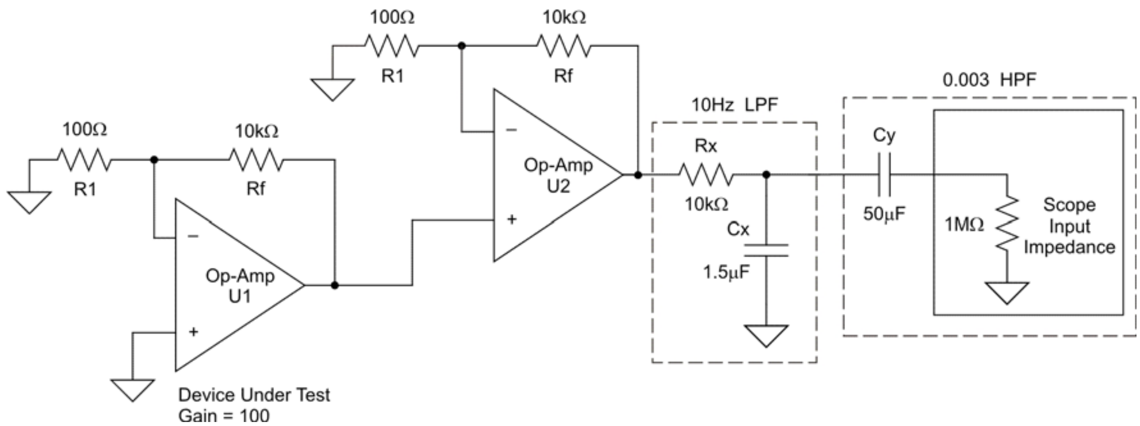

Fig. 8.5: Bench Test for Measuring Op Amp Voltage Popcorn Noise

The low-pass filter at the output of U2 limits the bandwidth to 100 Hz. The filter eliminates the higher frequency noise and reveals popcorn noise (or 1/f noise, if there is no popcorn noise). This filter could be adjusted over the range of 10 Hz to 1000 Hz, depending on the application. A 10 Hz low-pass filter has the advantage of somewhat attenuating the 60 Hz, or 50 Hz, line pick-up. However, it has the disadvantage of obscuring some of the higher-frequency bursts. A 1000 Hz low-pass filter will capture higher-frequency bursts, but will also begin to include significant broadband noise. The 100 Hz filter is a good compromise between 10 Hz and the 1000 Hz filter. However, you may want to experiment to see what produces the best results for your measurements.

Following U2 is a 0.003Hz HPF. The filter is built using a ceramic capacitor and the input impedance of the oscilloscope. Note that a number of small ceramic capacitors in parallel can be used to build the large ceramic capacitor (eg, 10 x 5 μF). The high-pass filter is used to eliminate the dc offset. This offset will likely be significantly larger than the noise being measured. Using this filter allows the noise signal to be measured using the optimal range on the oscilloscope. In this example, the dc output offset is approximately 2 V and the noise has a 340 mVpp magnitude. The 0.003 Hz HPF removes the 2 V dc component and allows you to observe the 340 mVpp signal on the 200 mV/div oscilloscope scale.

You can easily estimate the possible output offset by taking the input offset and multiplying it by the total gain. Fig. 8.6 shows this calculation. Be careful that the output offset does not drive the amplifier into the power supply rail (±15 V for this example). If the output offset approaches the power supply rails, you will need to either reduce the gain or ac couple between U1 and U2. Also note that the filter capacitor, Cy, will need to be charged to the output offset voltage when the circuit is initially powered up. This will take a significant amount of time (approximately 5 min). Fig. 8.6 also gives the charge time calculation.

Compute the output offset for Figure 8.5

$$V_{out\_offset} = \left[V_{in\_offset1} \times (\text{Gain}1) + V_{in\_offset2}\right] \times \text{Gain}2$$

$$V_{out\_offset} = \left[0.2\text{mV} \times (100) + 0.3\text{mV}\right] \times 100$$

$$V_{out\_offset} = 2.03\text{V}$$

Compute the delay required to charge the HPF of Figure 8.5

$$\tau = R \times C$$

$$\tau = \left(1 \times 10^{6}\right) \times \left(50 \times 10^{-6}\right) = 50\,\text{sec}$$

$$5\tau = 5 \times (50) = 250\,\text{sec}$$

for 99.3% settling

Compute the delay required to charge the LPF of Figure 8.5

$$\tau = R \times C$$

$$\tau = \left(1.5 \times 10^{-6}\right) \times \left(10 \times 10^{3}\right) = 0.015\,\text{sec}$$

$$5\tau = 5 \times (0.015) = 0.075\,\text{sec}$$

for 99.3% settling

Fig. 8.6: Calculations Associated with Op Amp Voltage Popcorn Noise Bench Test

Fig. 8.7 shows the production setup for measuring voltage popcorn noise of an op amp (U1). The main difference between the bench setup and the production setup is that digital filters are used in the production test. Digital filters use mathematics to filter the digitized data. Consequently, they do not have the long charge time associated with analog filters. This keeps the test time short (ie, low cost). In this example, the tester uses a programmable gain amplifier (PGA) to amplify the noise to a level that is easy to measure. The pedestal DAC can be used to cancel the output offset. The final test resources are typical of many production test systems. However, the resources will vary from system to system.

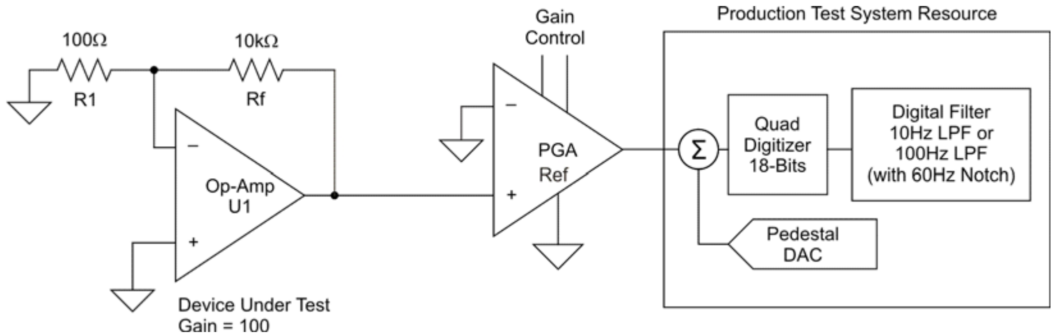

Fig. 8.7: Production Setup for Measuring Popcorn Voltage Noise

Bench and Production Test for Current Popcorn Noise

Fig. 8.8 shows the bench setup for measuring current popcorn noise of an op amp (U1). Note that a 1 MΩ resistor is in series with both inputs. The 1 MΩ resistors amplify the current noise so that it is the dominant noise at the output. Note that this configuration will look for popcorn noise on both inputs. This is important because the noise may be associated with either input. Consequently, both inputs must be checked. Fig. 8.9 illustrates the fact that current noise increases linearly with input resistance, and thermal noise increases with the square root of input resistance. Thus, if you increase the input resistance enough, you can always make current noise dominate. Fig. 8.10 gives equations to help select an input resistance that will make current noise dominate.

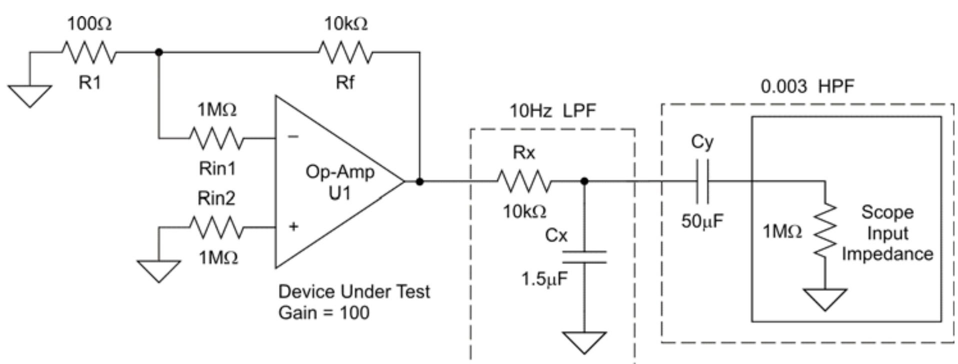

Fig. 8.8: Bench Test for Measuring Instrumentation-Amp Current Popcorn Noise

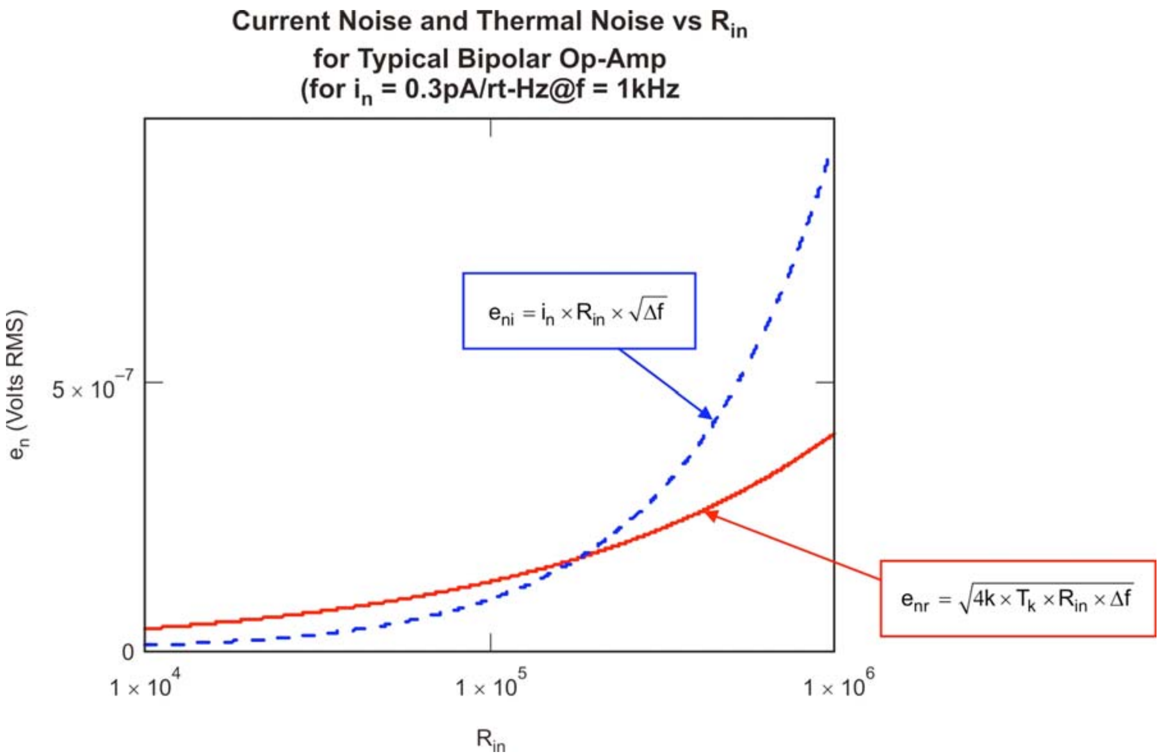

Fig. 8.9: Noise Increases Linearly with Input Resistance

$$e_{nr} = \sqrt{4k \times T_k \times R_{in} \times \Delta f}$$

$$e_{ni} = i_n \times R_{in} \times \sqrt{\Delta f}$$

If the magnitude of the current noise must be at least 3× the thermal noise to dominate. Below is the equation for R_{in} that 3× and 5×

Noise from i_n 3× thermal noise

$$i_{in} \times R_{in} \times \sqrt{\Delta f} = 3\sqrt{4k \times T_k \times R_{in} \times \Delta f}$$

$$R_{in} = 36 \times k \times \frac{T_k}{i_n^2}$$

Noise from i_n 5× thermal noise

$$i_{in} \times R_{in} \times \sqrt{\Delta f} = 5\sqrt{4k \times T_k \times R_{in} \times \Delta f}$$

$$R_{in} = 100 \times k \times \frac{T_k}{i_n^2}$$

Fig. 8.10: Equations for Selecting Input Resistance

Note that the circuit for measuring current popcorn noise shown in Fig. 8.8 does not require the second stage of gain because the input resistors act as a gain to current noise and bias current. The current noise measurement circuit has the same filters that are used in the voltage noise circuit. The 0.003 Hz high-pass filter eliminates the dc output offset. The dc output offset is generated primarily from the bias current flow through the input resistors. The low-pass filter at the output of U1 limits the bandwidth to 100 Hz. The filter eliminates the higher-frequency noise and reveals popcorn noise (or 1/f noise if there is not any popcorn noise). Fig. 8.11 gives calculations pertinent to the filters for the current popcorn noise measurement circuit shown in Fig. 8.8.

Compute the output offset for Figure 8.8

Typical bipolar values for gain and offset

$$I_{b\_offset1} = 0.5\text{nA} \qquad V_{in\_offset} = 0.3\text{mV} \qquad \text{Gain} = 100$$

$$V_{out\_offset} = \left[I_{b\_offset1} \times (R_{in}) + V_{in\_offset} \right] \times \text{Gain}$$

$$V_{out\_offset} = \left[0.5\text{nA} \times (1\text{M}\Omega) + 0.3\text{mV} \right] \times 100$$

$$V_{out\_offset} = 0.53\text{V}$$

Compute the delay required to charge the HPF of Figure 8.8

$$\tau = R \times C$$

$$\tau = \left(1 \times 10^{6}\right) \times \left(50 \times 10^{-6}\right) = 50\,\text{sec}$$

$$5\tau = 5 \times (50) = 250\,\text{sec}$$

for 99.3% settling

Compute the delay required to charge the LPF of Figure 8.8

$$\tau = R \times C$$

$$\tau = \left(1.5 \times 10^{-6}\right) \times \left(10 \times 10^{3}\right) = 0.015\,\text{sec}$$

$$5\tau = 5 \times (0.015) = 0.075\,\text{sec}$$

for 99.3% settling

Fig. 8.11: Calculations Pertinent to the Filters

Fig. 8.12 shows the production setup for measuring current popcorn noise of an op amp (U1). The main difference between bench and production setup is, again, that digital filters with no long charge times are used in the production test, keeping the test time short.

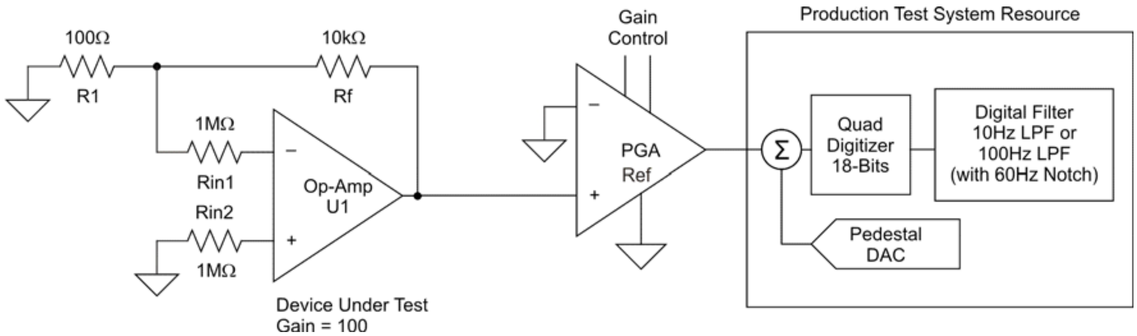

Fig. 8.12: Production Setup for Measuring Popcorn Current Noise

Analyzing the Popcorn Noise Data

In this section we propose several methods for analyzing low-frequency noise and determining if it contains popcorn noise. The analysis techniques are independent of the circuit configuration used to measure the data. Engineers often can inspect an oscilloscope waveform qualitatively and identify that a signal has popcorn noise. We will also propose how to quantitatively identify popcorn noise. Furthermore, we will discuss how to set pass/fail limits for popcorn noise and 1/f noise.

Fig. 8.13 shows a typical time domain noise signal without popcorn noise. The cut frequency for this signal is 300 Hz. Therefore, the noise is a combination of 1/f noise and broadband noise. The histogram to the left of the noise signal is used to emphasize that the noise voltage is Gaussian.

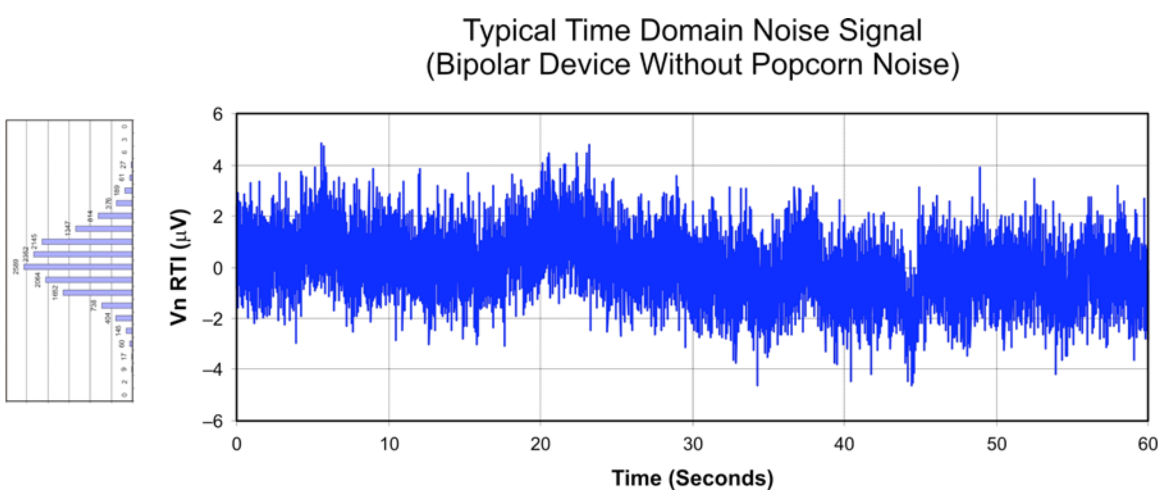

Fig. 8.13: Noise for a Good Unit: 1/f Noise and Broadband Noise

Fig. 8.14 is a more detailed view of the Gaussian distribution of the typical noise.

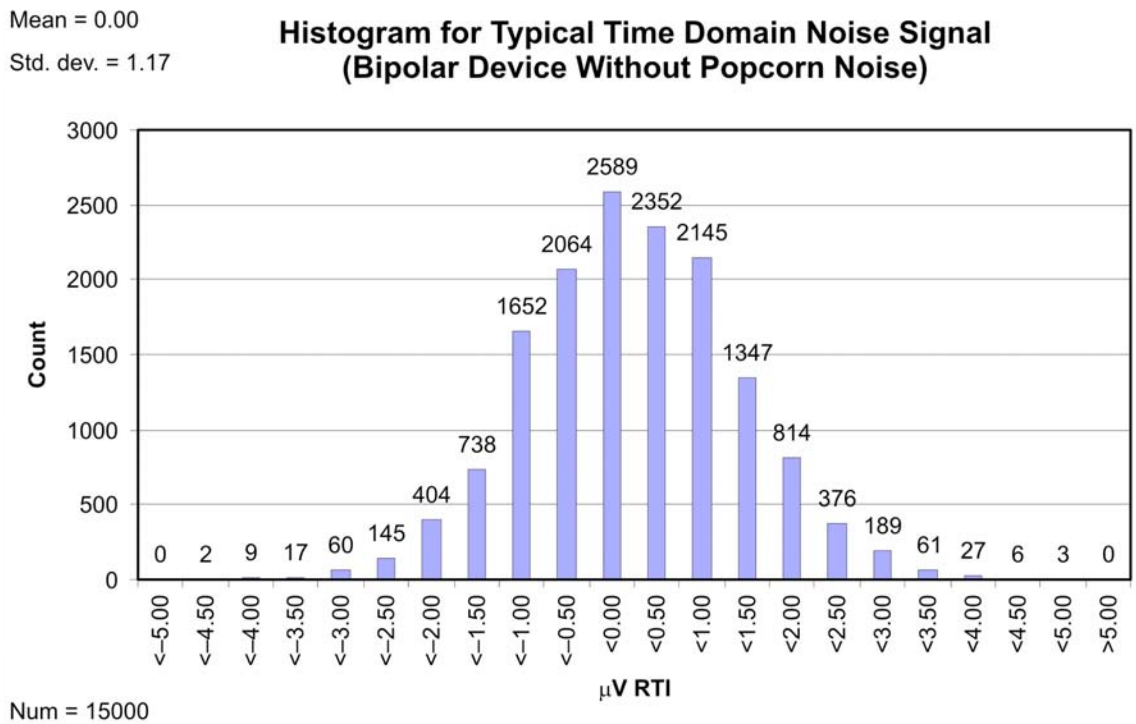

Fig. 8.14: Gaussian Distribution Associated with Noise from Normal Device

Fig. 8.15 shows a typical time domain noise signal with popcorn noise. The cut frequency for this signal is 300 Hz. The histogram to the left of the noise signal is used to emphasize that the noise voltage is non-Gaussian. Fig. 8.16 is the same waveform shown in Fig. 8.15 with circles and arrows used to emphasize the fact that the popcorn noise jumps to discrete modes. For this particular example there appears to be three discrete noise levels that generate three modes in the distribution. See Fig. 8.17 for a more detailed view of the typical non-Gaussian noise distribution.

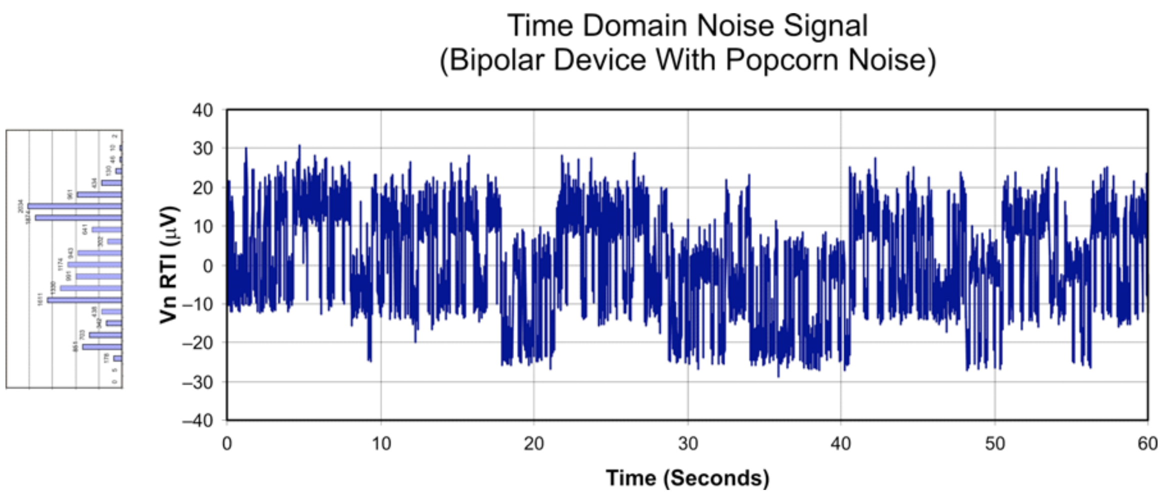

Fig. 8.15: Time Domain Signal of Popcorn Noise

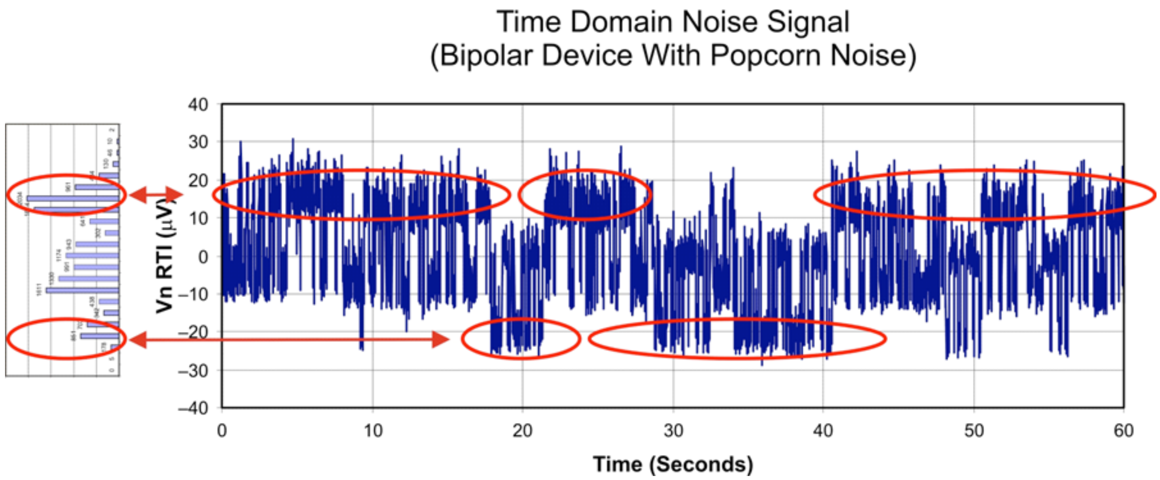

Fig. 8.16: Histogram for Time Domain Popcorn Noise Signal

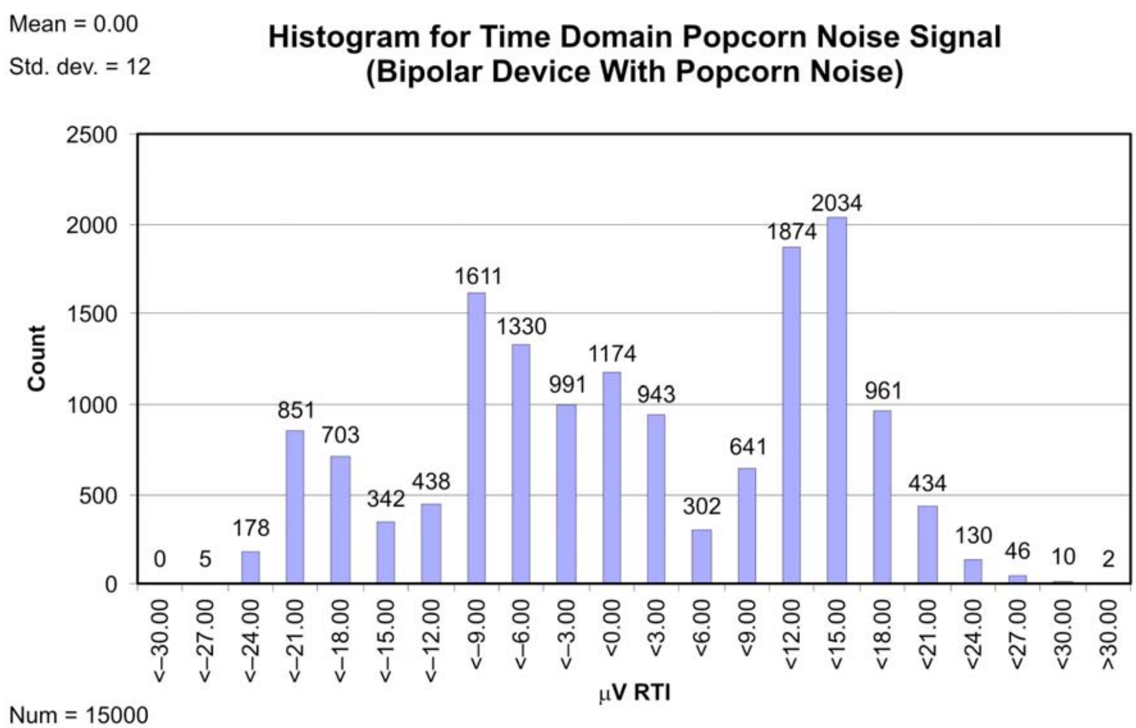

Fig. 8.17: Histogram for Time Domain Popcorn Noise Signal

So, one way to determine if a signal contains popcorn noise is to look for a non-Gaussian distribution. We will not cover the mathematical techniques used to test whether a distribution is Gaussian or non-Gaussian. Instead, we will focus on a technique that looks for the large rapid changes associated with the edges of a noise signal. A common way to look for rapid changes in a signal is to take the derivative of the signal. Fig. 8.18 shows how the derivative of the popcorn noise signal generates large spikes when the popcorn signal makes a transition. Fig. 8.19 shows the derivative of noise from a normal device. The noise in Fig. 8.19 is only broadband and flicker popcorn noise, ie, no popcorn noise. Note that taking the derivative of broadband and flicker noise does not generate the large spikes.

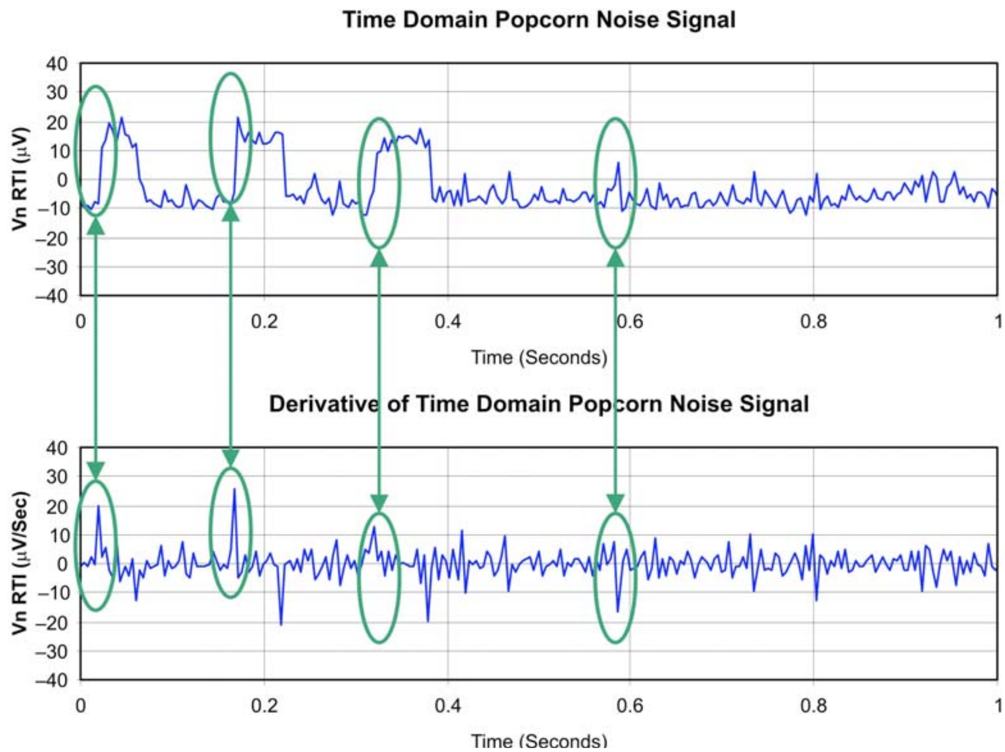

Fig. 8.18: Derivative of Popcorn Noise Signal

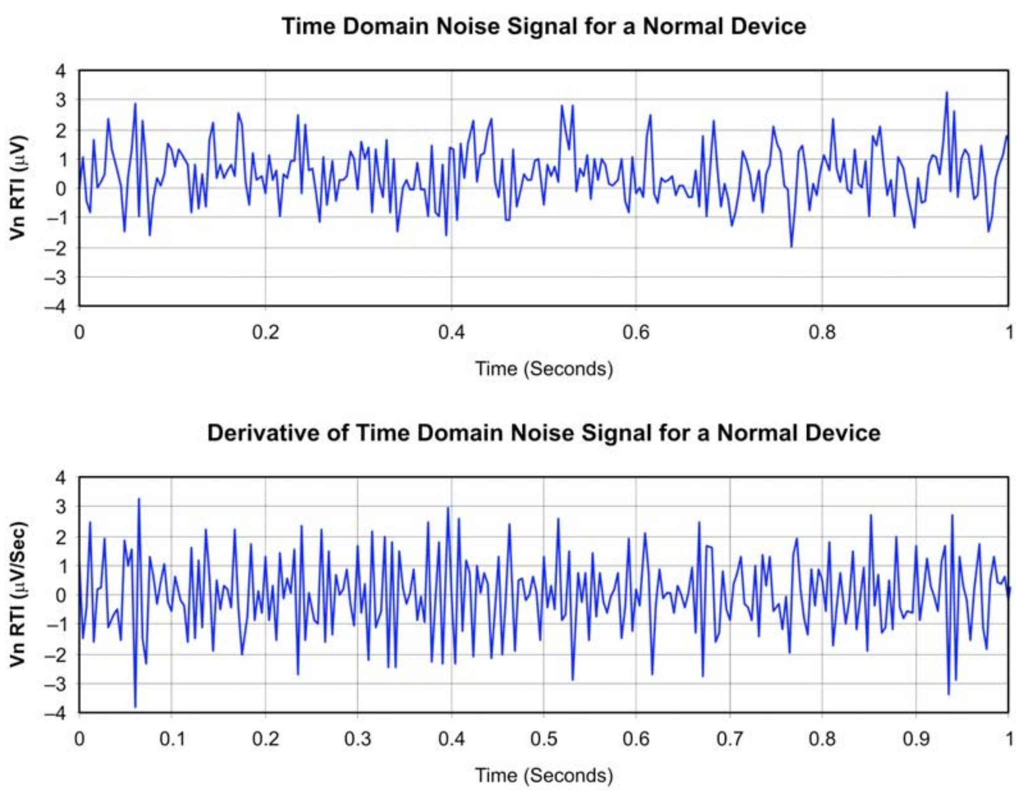

Fig. 8.19: Derivative of Noise from a Normal Device

Fig. 8.20 compares the derivative histogram of the popcorn noise to the derivative histogram of the noise from a normal device. The popcorn noise histogram has a large number of counts in the outlying bins. These outliers correspond to the spikes in the derivative. Note that the histogram from the normal device does not have a significant number of outliers. For this example, we look for outliers in the distribution at ±4σ. The statistical probability of measuring noise outside of ±4 standard deviations is 0.007%. The example histogram shown contains 15000 samples, so we should expect no more then one sample (ie, 15000 x 0.007% = 1.05) outside these limits. Thus, excessive bins outside of the ±4 sigma limits are likely popcorn noise. The limits for this test should be adjusted based on the number of samples in the histogram.

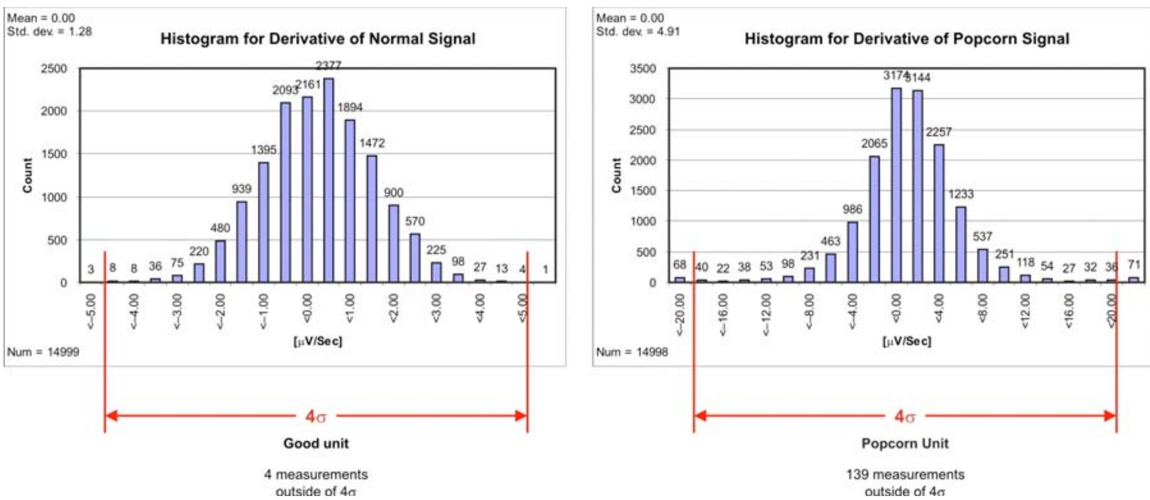

Fig. 8.20: Distribution of the Noise Derivative for Normal and Popcorn Device

Another way to search for devices with popcorn noise is to compare the measured peak-to-peak noise to the expected peak-to-peak noise. Fig. 8.21 compares the distribution of a device with popcorn noise to a normal device.

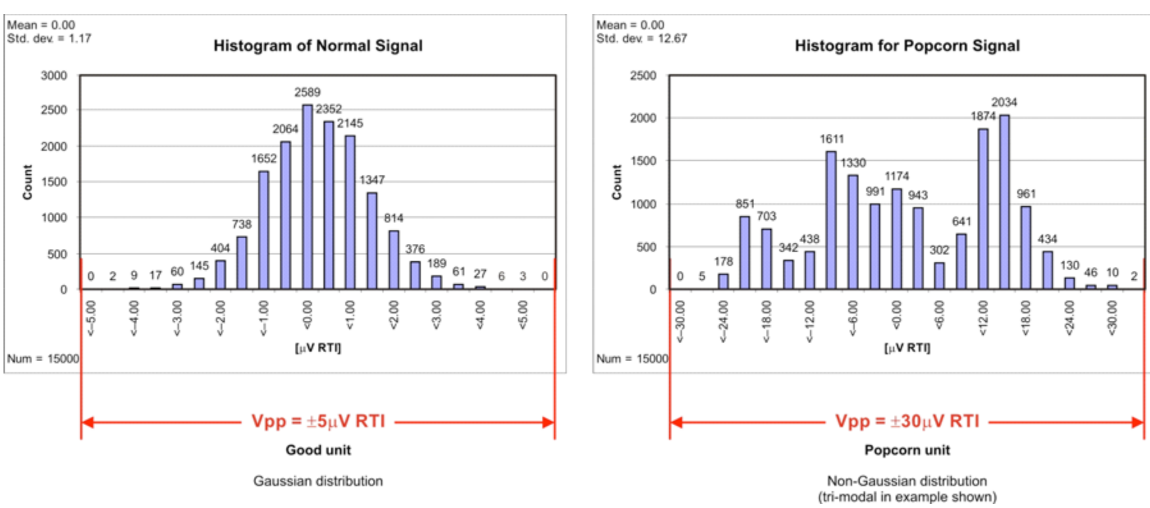

Fig. 8.21: Comparing the Peak-to-Peak Noise of a Normal Vs Popcorn Device

Note that the popcorn noise peak-to-peak is six times larger than the normal unit. Also note that the scale is adjusted so that the non-Gaussian nature of the popcorn noise is emphasized. Keep in mind that abnormally large low-frequency noise is a strong indication of popcorn noise, but it does not necessarily prove the existence of popcorn noise. However, devices that have abnormally high noise levels are problematic, regardless of whether or not they have popcorn noise.

Setting Popcorn Noise Test Limits

This TechNote proposes two methods for screening out popcorn noise. The first involves taking the derivative of the noise signal and searching for outliers in the distribution. The limit proposed for this test is ±4 standard deviations. Thus, if any point in the derivative exceeds ±4 standard deviations, the device is considered a failure.

The second method is to look at peak-to-peak noise. Set the limit for this test using the worst case noise rules from Part VII of this noise series. Fig. 8.22 summarizes these rules graphically. The worst case rule of thumb describes how the spectral density curve can change with process variations. Using the methods described in Parts III - IV and the worst case spectral density curve, you can estimate the worst case expected noise. The worst case expected noise is the maximum noise expected with a normal device. Devices with popcorn noise typically exhibit noise greater than the worst case limit. Thus, set the peak-to-peak noise limits to the worst case estimate. Devices failing these limits will have either popcorn noise or excessively high flicker. In either case they should be considered failures.

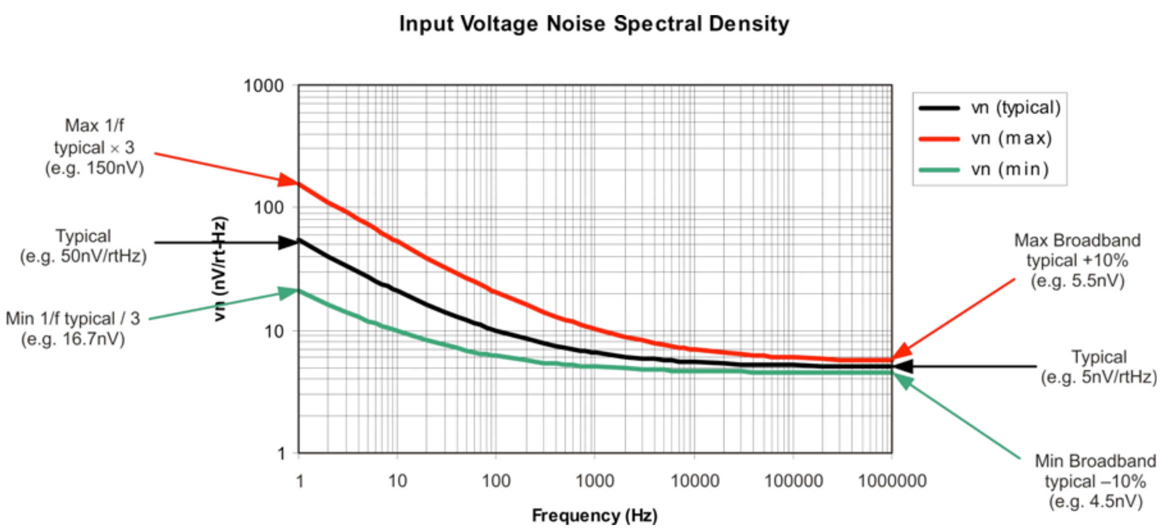

Fig. 8.22: Worst Case Rule of Thumb for Noise

When is Popcorn Noise a Concern?

Popcorn noise is a concern for low-frequency applications (fc < 1 kHz) of slow-moving signals. For example, the frequency range and waveforms in medical encephalogram (EEG, brain measurements) would be difficult to discern from popcorn noise. Fig. 8.23 shows typical EEG waveforms. Seismic measurements are also slow-moving dc signals that can be difficult to discern from popcorn noise. In audio applications popcorn noise is considered to be a particularly unpleasant noise.

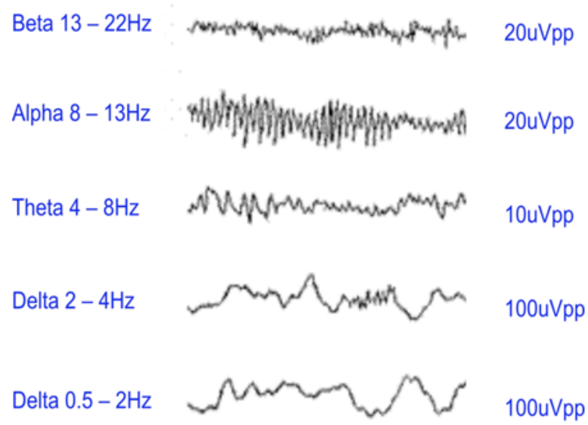

Fig. 8.23: Typical EEG Waveforms

Popcorn noise often shows up as a current noise. Thus, high source impedance applications may be more susceptible to popcorn noise. Fig. 8.24 shows how the magnitude of popcorn noise is affected by input impedance. Keep in mind, however, that in some cases internal current noise is converted to voltage noise inside the device.

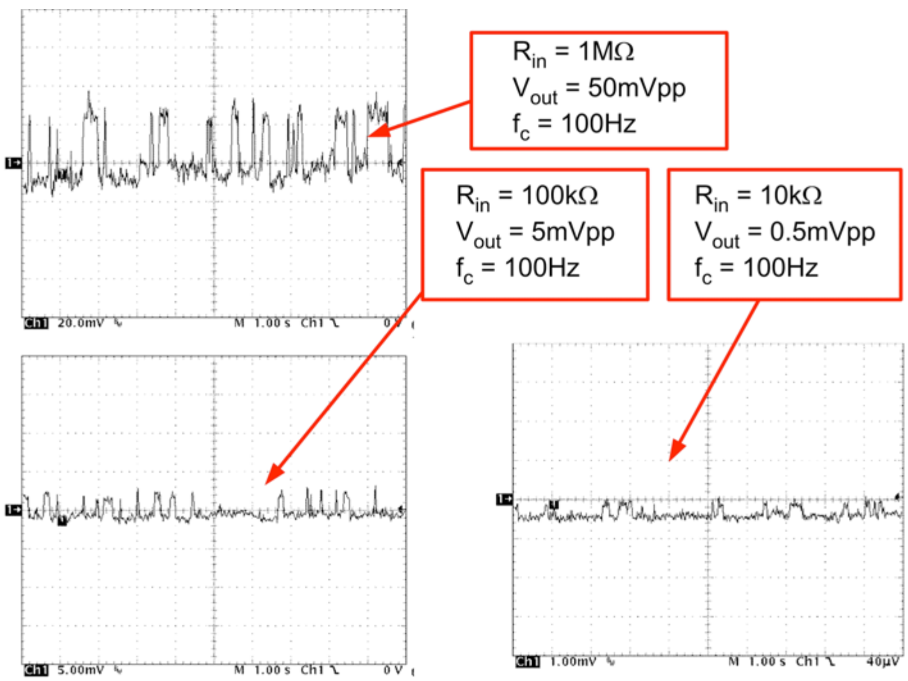

Fig. 8.24: Current Popcorn Noise Affected by Source Impedance

In some cases popcorn noise may be obscured by broadband noise. Fig. 8.25 shows the same device for two different bandwidths. Note that both waveforms in contain popcorn noise, but the popcorn noise in the wide bandwidth case is obscured by white noise.

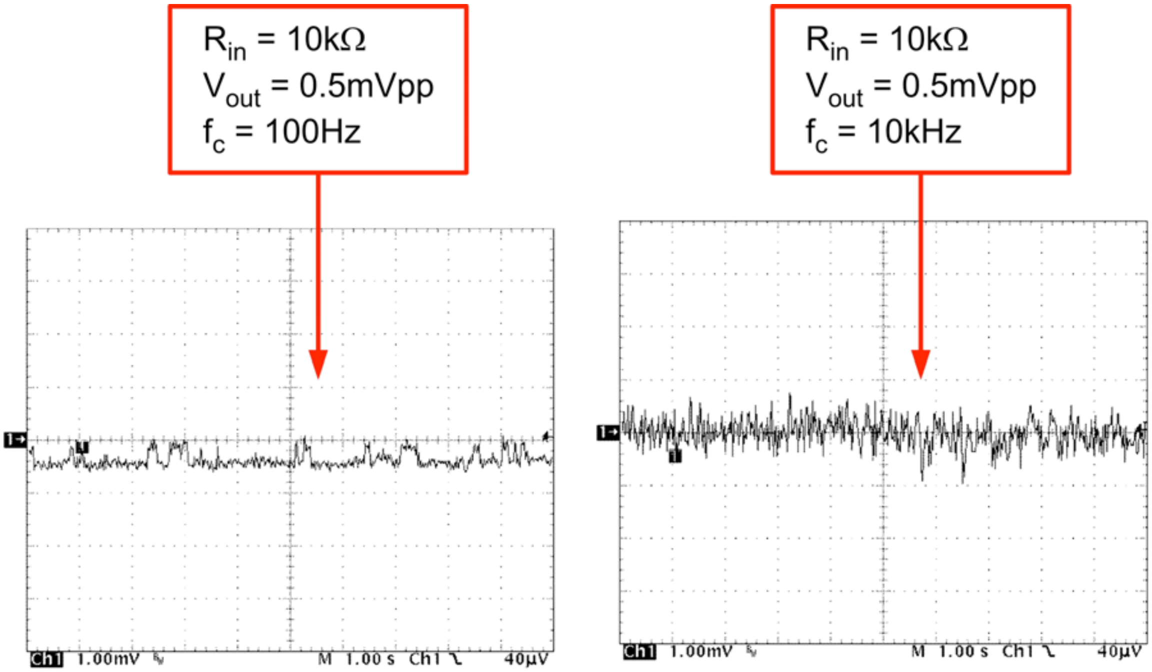

Fig. 8.25: Popcorn Noise Obscured by White Noise at High Bandwidth

Summary and Preview

In this TechNote, we discussed how to measure and analyze popcorn noise. In Part IX we will focus on 1/f noise, and how auto-zero amplifier topology can be used to eliminate it.

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- Tim Green, Applications Engineering Manager
- Scott Gulas, Test Engineering Manager

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About The Author

Arthur Kay is a senior applications engineer at Texas Instruments where he specializes in the support of sensor signal conditioning devices. Prior to TI, he was a semiconductor test engineer for Burr-Brown and Northrop Grumman Corp. He graduated from Georgia Institute of Technology with an MSEE in 1993. Art can be reached at ti_artkay@list.ti.com