

Rarely Asked Questions—Issue 138 This Noise Will Keep You Up at Night

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Question:

What is the smallest voltage I can measure?



Answer:

My first project as an engineer was to measure the settling time of what was going to be a 6½ digit DMM. It didn't seem like a big deal, I just had to figure out the final settled value and work my way backward to the smallest detectable change. I got everything set up, shorted the inputs, and started increasing the aperture time! As expected, the noise would come down ... until it didn't. The baseline just kept moving. I had eliminated extrinsic noise sources, thermal EMF, and even drafts from the ac vents. These random fluctuations were coming from the intrinsic noise of the circuit. But after eliminating most of the broadband noise, there was this other noise that would not go away. Anyone who has tried this would have noticed the same limitation. To the contrary, we may find more noise than if we had stopped sooner! We know that we are in the 1/f noise region when that happens.

This so-called 1/f noise (or flicker noise) is the most pervasive limitation for precision measurements. The name comes from the fact that its power spectral density is inversely proportional to frequency, as expressed by:

Noise_Power
$$(f) = \left(\frac{k}{f^{\alpha}}\right)$$

Where k is a magnitude coefficient and α is an exponent that will take values greater than 0, but the canonical form is for $\alpha = 1$. This noise eventually becomes smaller than broadband noise, producing a corner as shown in Figure 1. Evidence of this type of noise has been found outside of electronic circuits, including the rotation of the Earth, economic indicators, and biological systems, to name a few. While the fundamental cause keeps eluding the most brilliant scientists, we must understand how to mitigate it if we want to perform low level measurements.



Figure 1. Typical noise spectral density plot for a low noise electronic component.

Let's start with off-the-shelf components. The highest sensitivity ADC you will find these days in an IC is AD7177-2, and that is 200 nV p-p at 5 SPS. But we can do better than that by adding some gain before the ADC. We need an amplifier that is both low noise and with a low 1/f corner. The easiest is to look up the 0.1 Hz to 10 Hz noise specification on the data sheet, which is equivalent to recording measurements for 10 seconds with 10 Hz bandwidth.

If you have been paying attention, you may have read about the AD797 op amp being used in the LIGO experiment to detect gravitational waves for the first time in human history. The AD797 has a noise specification of 50 nV p-p (8 nV rms) from 0.1 Hz to 10 Hz. The AD8428, the lowest noise instrumentation amplifier is only 40 nV p-p (7 nV rms). Because these amplifiers are built in bipolar processes, their current noise can be significant if used with large source resistance (including gain resistors), and current noise also has a 1/f corner! And don't forget that resistors themselves can show current-dependent excess noise due to their construction. Metal foil and wirewound resistors tend to have the lowest noise indices.

A neat trick to avoid 1/f noise is to modulate the signal to a region where there is no 1/f noise and then demodulate it. This trick, known as chopper stabilization, has been used for decades to shift the 1/f noise to a different frequency band, where it can be easily filtered out. Zero-drift op amps like the ADA4528-1 and ADA4522-1 take advantage of this (and other tricks) to get about 100 nV p-p (16 nV rms) from 0.1 Hz to 10 Hz, mostly due to white noise. A simpler alternative is to parallel multiple amplifiers to reach lower noise levels, since this is equivalent to averaging uncorrelated noise sources.

The bottom line is that with off-the-shelf components, you can detect signals just below the 10 nV mark, and paralleling amplifiers will get you close to the 1 nV level. Anything below that will require special (and perhaps pricy) techniques. But no matter what you do, 1/f will always find a way to resurface.

So, what if we were to record several measurements for a really long time? Would 1/f noise make this an impossible task? Let us bring some perspective: if we had recorded the AD797 noise from the moment of the big bang until the time of reading this article," it would only be three times larger than if we had measured it for the last 10 seconds," so I wouldn't lose any sleep over that.

References

- ¹The aperture time in a DMM is the interval during which the signal gets integrated or averaged.
- ^a Assuming 4.32e17 seconds have passed since the Big Bang.
- ^{III} Hypothetically speaking, since there is no evidence 1/f follows this curve for that long. Aging and other factors start to play in at longer measurement intervals.

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