AN72

# An Introduction to Op Amp Noise

## INTRODUCTION

Op amp noise is a critical specification in many applications like electron scanning microscopes and test & measurement equipment. Noise introduced by an op amp can result in blurry images for electron scanning microscopes or unreliable data from measurement systems. Many Apex datasheets contain noise characterization data in the input specification table. This data is meant to help designers determine the total amount of noise an op amp will introduce into the system. Unfortunately, noise can be characterized using various methods, which can make it difficult to make direct comparisons between fundamentally similar products. This can result in op amps that offer the same noise performance, having different noise specifications in their respective datasheets.

Great examples of this are the datasheets of the Apex PA98 and PA198. The PA198 is the next-generation version of the PA98, and its design is heavily based on that of the PA98. Despite the similarities between these op amps, the PA198 uses spectral noise density to characterize noise and the PA98 specifies noise across a 100kHz bandwidth. The PA198 has a noise specification of 3nV/√Hz while the PA98's noise specification is 1µVrms over a 100kHz bandwidth. The difference in noise specifications makes it difficult to have an apples-to-apples noise comparison for these op amps.

Electrical noise is a daunting subject, and many have spent their entire careers investigating the various sources and measurement methods. The goal of this application note is *not* to identify the source of op amp noise nor to discuss measurement methods. The goal of this application note is to clearly define the distinct types of noise measurement results and show they can still be used to compare the noise performance of op amps.

## NOISE ORIGIN

To understand the various noise measurement methods, there first needs to be an understanding of the different types of noise. There are five types of electrical noise; shot, thermal, flicker, popcorn, and avalanche noise. Modern op amps are primarily affected by shot, thermal, and flicker noise. Below are definitions of these three types of noise.

### *SHOT NOISE*

Shot noise is the random fluctuation in current caused by charge carriers crossing a potential barrier, such as a PN junction in a diode or transistor. Because electrons and holes arrive independently and unpredictably, this noise is always present whenever there is current flow through the junction. It is a fundamental noise source, proportional to the square root of the DC current, and has a flat (white) frequency spectrum.

### *THERMAL NOISE*

Thermal noise (also called Johnson-Nyquist noise) is the random voltage or current fluctuation caused by the thermal agitation of charge carriers in a conductor or resistor. It occurs because electrons move randomly due to temperature, and this motion creates noise across any resistive element. Thermal noise is always present in resistors and semiconductor channels, even when no current is applied, and its magnitude depends on resistance, temperature, and bandwidth.

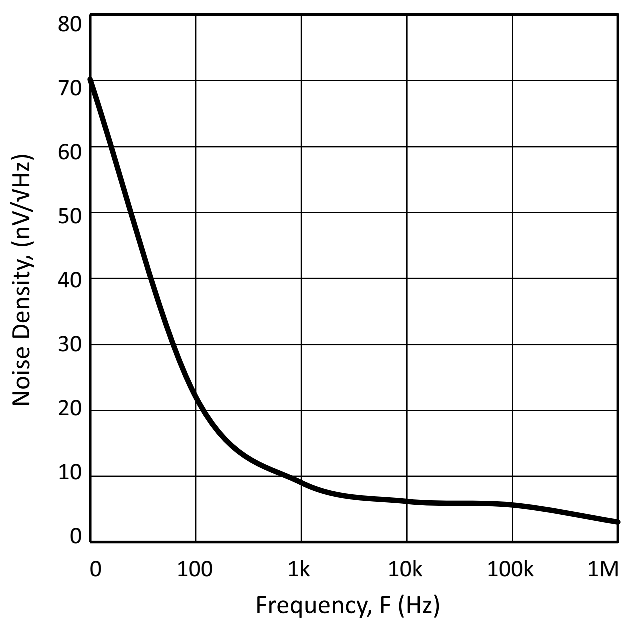
### *FLICKER NOISE*

Flicker noise (also called 1/f noise) is a low-frequency noise that decreases as frequency increases, creating an inverse relationship with frequency. It originates from random trapping/detrapping of charge carriers in semiconductor materials. Flicker noise is most noticeable at low frequencies in active devices like MOSFETs and BJTs and is always present when current flows.

Historically, the first CMOS op amps were affected by popcorn noise and the three previously defined noise types. Thanks to process improvements, popcorn noise is negligible for modern op amps.

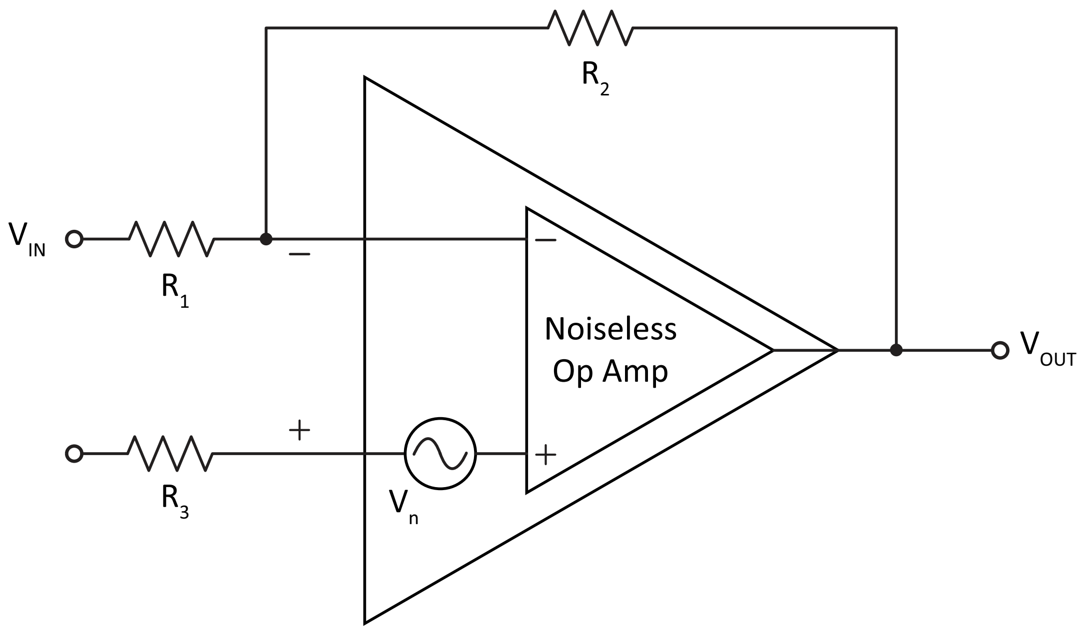
Below is the Input Noise Voltage performance graph from the PA198 datasheet. From DC up to about 1kHz, flicker noise (1/f noise) is the dominant source of noise. Above 1kHz, shot and thermal noise are the dominant noise sources that remain relatively flat across frequencies. These noise sources that are flat across frequencies are often lumped together as white noise.

**Figure 1: PA198 Input Noise Voltage Performance Graph**




It’s important to remember that the noise specification in the datasheet characterizes the internal noise of only the op amp. The noise specification in Apex datasheets is always referred to the input (RTI). This noise source (Vn) can be modeled as being in series with an input pin of a perfect “noiseless” op amp. Figure two is a schematic of this model. By analyzing the model, we can deduce that the op amp noise will be amplified by the op amp’s closed loop gain. Additionally, this noise source does not account for thermal noise generated by the input and feedback resistors. The surrounding circuit and environment, such as lighting and nearby refrigerator compressor, can often introduce more noise than the op amp!

**Figure 2: Internal Noise Source Modeled with a Noiseless Op amp**




## SPECTRAL NOISE DENSITY

Spectral noise density is a common way to characterize noise. It uses the unit of nV/√Hz measured at a specified frequency. Electrical noise is proportional to the square root of the bandwidth and is not linear with frequency. An op amp operating from DC to 20kHz will have the same noise performance if it were operated from 100kHz to 120kHz since the bandwidth is 20kHz in both instances. In this scenario, the dominant effects of flicker noise below 1kHz are ignored.

Spectral noise density assumes a flat noise response across frequency (white noise), which only applies to thermal and shot noise. Flicker noise is not flat; it increases as frequency decreases. Because of this, spectral noise density does not offer much insight into the flicker noise of an op amp. In fact, spectral noise is often measured and specified at frequencies that are unaffected by flicker noise. To obtain a clear understanding of an op amp's flicker noise, a graph like figure one should be consulted.

Fortunately, most applications operate at bandwidths that make the effects of flicker noise negligible. Two op amps, that have a noise density measured at the same frequency, can be quickly compared regardless of operating bandwidth (again ignoring flicker noise).

## NOISE OVER SPECIFIED BANDWIDTH

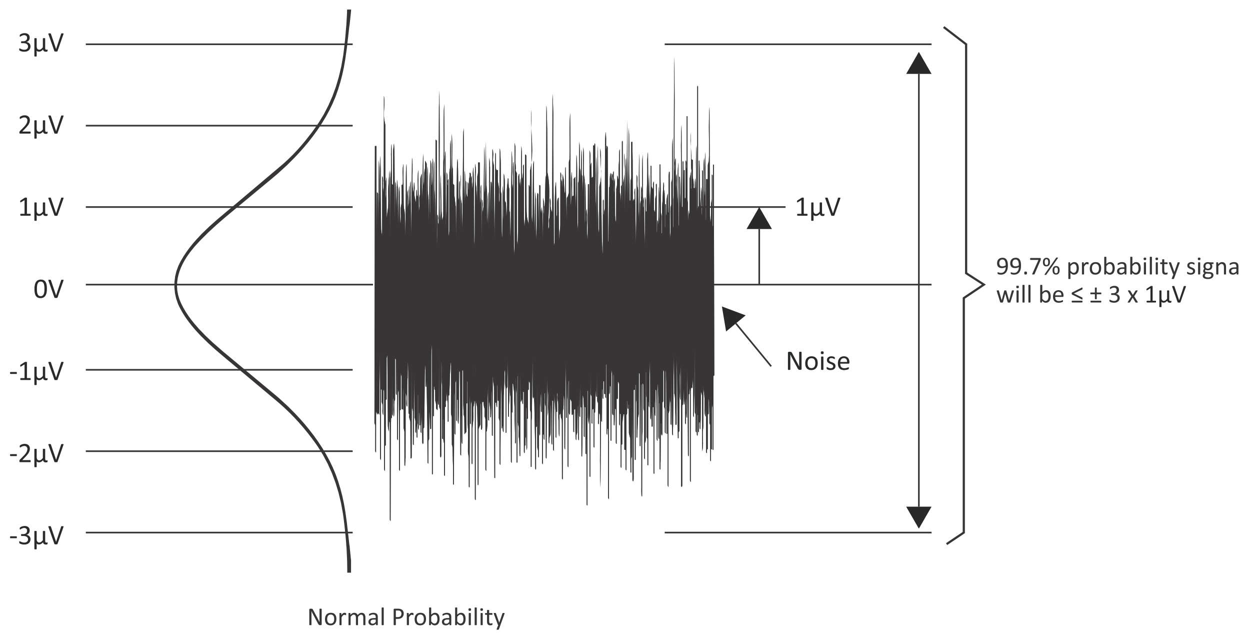
Some datasheets specify noise over a given bandwidth. For example, the PA98 has a noise specification of 1 µVrms across a 100 kHz bandwidth. This means the op amp produces a total integrated noise voltage of 1 µVrms over the 0–100 kHz range. The 1 µVrms value does **not** imply that the amplifier's peak noise is:

$$(2\sqrt{2}) \times 1\mu V$$

because that formula only applies to pure sine waves. RMS is used because it is a measurement of the average noise signal over time.

It's important to remember that electrical noise is random and constantly fluctuating. Measuring noise in Vpp or Vp would be meaningless due to its unpredictability. Using RMS provides a statistical measurement of the average noise voltage introduced by the op amp. In theory, the peak noise could approach infinity, but in practice this does not occur. Noise follows a Gaussian (or normal) distribution. Because noise follows a normal distribution, about 99.7% of all noise values will fall within ±3 × 1µV (±3 standard deviations).

**Figure 3: Voltage Noise Distribution**




It's important to note that flicker noise also follows a normal distribution in the time domain, just like thermal and shot noise. However, the amplitude of the flicker noise is also dependent on frequency, unlike thermal and shot noise that have a flat response across frequency.

## CONVERSION

With a clear understanding of spectral noise density and total integrated noise, it's possible to comprehend the noise performance of an individual op amp. Although, converting between spectral noise density and total integrated noise is required to accurately compare the noise performance of the PA98 vs the PA198. Fortunately, the conversion between the measurements is straightforward and is shown below.

The PA98's total integrated noise is 1µVrms across a 100kHz bandwidth. To convert this measurement to spectral noise density, divide the total integrated noise voltage by the square root of the specified bandwidth (shown below). The spectral noise density of the PA98 is:

$$1\mu V/\sqrt{100kHz} = 3.16nV/\sqrt{Hz}$$

The PA198 has a spectral noise density of 3nV/√Hz. To convert this measurement to total integrated noise across a 100kHz bandwidth, multiply the spectral noise density by the square root of 100kHz (shown below). For the PA198 the total integrated noise across a 100kHz bandwidth is 949nVrms.

$$(3nV/\sqrt{Hz}) \times \sqrt{100kHz} \times 949nVrms$$

The PA198 and PA98 have very similar noise specifications, but this is no coincidence. As mentioned in the introduction, the PA198's design is based on the PA98's design. The input stages of the op amps are nearly identical to one another. Almost all of the op amps internal noise is generated by the input stage, so similar noise specifications are expected.

It is important to note that the PA198's spectral noise density was measured at 1MHz. In other words, the measurement was unaffected by flicker noise. If the spectral noise density were specified at 1kHz, the spectral noise density would be three times larger (see figure one). Using this hypothetical measurement of 9nV/√Hz, and converting it to total integrated noise across the same 100kHz bandwidth would result in the total integrated noise being 2.85µVrms!

In this scenario, the PA198 would appear to be much noisier than the PA98, but in reality it is not. It appears that way because flicker noise was included in the spectral noise density that was used to calculate total integrated noise. Let this serve as a warning to carefully assess the frequency at which the spectral noise is measured and to accurately assess the bandwidth used to calculate total integrated noise.

## CONCLUSION

Noise is a critical op amp specification, but understanding the different types of noise, the various ways to characterize noise, and how to properly compare noise specifications is essential. When evaluating noise, it is important to consider the frequency at which the noise density was measured and the bandwidth used for averaging. Noise density measurements taken at very low frequencies can make an op amp appear noisier. Averaging total noise over a narrow bandwidth can make an op amp appear virtually noiseless.

The key takeaway is that at low frequencies (approximately 0–1 kHz), flicker noise dominates, so DC and low-frequency applications must account for it. Above 1 kHz white noise is the dominant noise source, making it the main concern for higher-frequency applications. For noise sensitive systems with a high-frequency component riding on a variable DC offset, both noise types matter. Flicker noise for the DC portion and white noise for the high-frequency portion.

Ultimately, it is important to consider the frequency/bandwidth that were used to characterize the op amp's noise and the frequency required by the end application.