# Op Amp Noise

OP AMP INPUT VOLTAGE NOISE

This tutorial discusses the noise generated within op amps, not the external noise which they may pick up due to magnetic and electric coupling. Minimizing this external noise is also important, but in this section we are concerned solely with op amp internal noise.

There are a number of noise sources within an op amp (resistor noise, current noise, KT/C noise, etc.), but it is customary to model them externally as a voltage noise which appears differentially across the two inputs and two current noise sources, one in each input. These three noise sources are shown externally to the ideal "noiseless" op amp. The simple voltage noise op amp model is shown in Figure 1 below. The three noise sources are effectively uncorrelated (independent of each other). There is a slight correlation between the two noise currents, but it is too small to need consideration in practical noise analyses. In addition to these three internal noise sources, it is necessary to consider the Johnson noise of the external gain setting resistors that are used with the op amp.
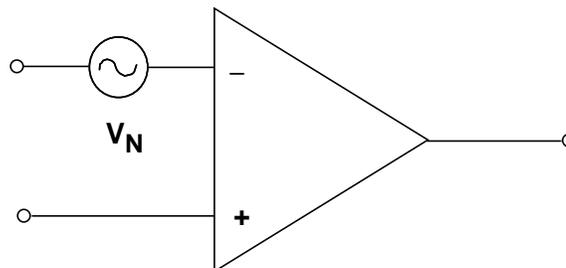
◆ **Input Voltage Noise is bandwidth dependent and measured in nV/√Hz (noise spectral density)**

◆ **Normal Ranges are 1nV/√ Hz to 20nV/√Hz**

Figure 1: Input Voltage Noise

The voltage noise of different op amps may vary from under 1 nV/√Hz to 20 nV√Hz, or even more. Bipolar op amps tend to have lower voltage noise than JFET ones, although it is possible to make JFET op amps with low voltage noise (such as the AD743/AD745), at the cost of large input devices, and hence large input capacitance. Voltage noise is specified on the data sheet, and it isn't possible to predict it from other parameters.

RESISTOR NOISE

Before discussing op amp current noise, it is important to understand that practical op amp circuits require external resistors, and all resistors have a Johnson noise of $\sqrt{(4kTBR)}$, where k is Boltzmann's Constant (1.38×10^{-23}J/K), T is the absolute temperature, B is the bandwidth, and R is the resistance. Note that this is an intrinsic property—it is not possible to obtain resistors that do not have Johnson noise. The simple model is shown in Figure 2 below.


- ◆ **ALL resistors have a voltage noise of $V_{NR} = \sqrt{(4kTBR)}$**

- ◆ **T = Absolute Temperature = T(°C) + 273.15**

- ◆ **B = Bandwidth (Hz)**

- ◆ **k = Boltzmann's Constant (1.38×10^{-23}J/K)**

- ◆ **A 1000Ω resistor generates 4nV / √Hz @ 25°C**

Figure 2: Johnson Noise of Resistors

OP AMP INPUT CURRENT NOISE

Current noise can vary much more widely than voltage noise, dependent upon the input structure. It ranges from around 0.1 fA/√Hz (in JFET electrometer op amps) to several pA/√Hz (in high speed bipolar op amps). It isn't always specified on data sheets, but may be calculated in cases like simple BJT or JFETs, where all the bias current flows in the input junction, because in these cases it is simply the Schottky (or shot) noise of the bias current.

Shot noise spectral density is simply $\sqrt{(2I_B q)}$/√Hz, where I_B is the bias current (in amps) and q is the charge on an electron (1.6×10^{-19} C). It can't be calculated for bias-compensated or current feedback op amps, where the external bias current is the *difference* of two internal currents. A simple current noise model is shown in Figure 3 below.
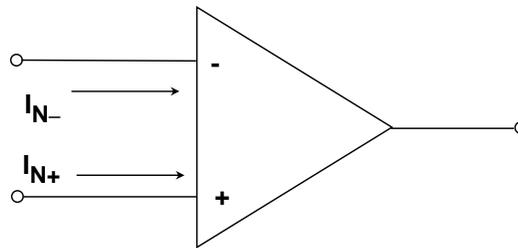
- **Normal Ranges: 0.1fA/√ Hz to 10pA/√Hz**
- **In Voltage Feedback op amps the current noise in the inverting and non-inverting inputs is uncorrelated (effectively) but roughly equal in magnitude.**
- **In simple BJT and JFET input stages, the current noise is the shot noise of the bias current and may be calculated from the bias current.**
- **In bias-compensated input stages and in current feedback op amps, the current noise cannot be calculated.**
- **The current noise in the two inputs of a current feedback op amp may be quite different. They may not even have the same 1/f corner.**

Figure 3: Input Current Noise

Current noise is only important when it flows in an impedance, and thus generates a noise voltage. Maintaining relatively low impedances at the input of an op amp circuit contributes markedly to minimizing the effects of current noise (just as doing the same thing also aids in minimizing offset voltage).
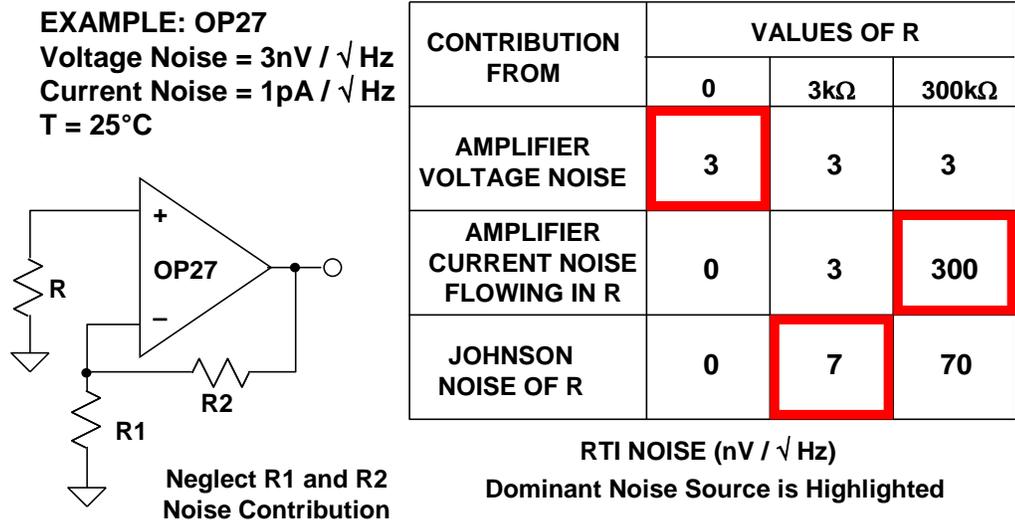
It is logical therefore, that the optimum choice of a low noise op amp depends on the impedances around it. This will be illustrated with the aid of some impedance examples, immediately below.

COMBINING NOISE SOURCES

Uncorrelated noise voltages add in a "root-sum-of-squares" manner; i.e., rms noise voltages V_1, V_2, V_3 give a summed result of $\sqrt{(V_1^2 + V_2^2 + V_3^2)}$. Noise powers, of course, add normally. Thus, any noise voltage that is more than 3 to 5 times any of the others is dominant, and the others may generally be ignored. This simplifies noise assessment in complex circuits.

DETERMINING THE DOMINANT NOISE SOURCE

Consider for example an OP27, an op amp with low voltage noise (3 nV/√Hz), but quite high current noise (1 pA/√Hz). With zero source impedance, the voltage noise will dominate as shown in Figure 4 below (left column). With a source resistance of 3 kΩ (center column), the current noise of 1 pA/√Hz flowing in 3 kΩ will equal the voltage noise, but the Johnson noise of the 3 kΩ resistor is 7 nV/√Hz and is dominant. With a source resistance of 300 kΩ (right column), the current noise portion increases 100× to 300 nV/√Hz, voltage noise continues unchanged, and the Johnson noise (which is proportional to the resistance *square root*) increases tenfold. Current noise dominates.

EXAMPLE: OP27
Voltage Noise = 3nV / √ Hz
Current Noise = 1pA / √ Hz
T = 25°C

CONTRIBUTION FROM	VALUES OF R		
	0	3kΩ	300kΩ
AMPLIFIER VOLTAGE NOISE	3	3	3
AMPLIFIER CURRENT NOISE FLOWING IN R	0	3	300
JOHNSON NOISE OF R	0	7	70

RTI NOISE (nV / √ Hz)
Dominant Noise Source is Highlighted

OP27

R

R2

R1

Neglect R1 and R2 Noise Contribution

Figure 4: Different Noise Sources Dominate at Different Source Impedances

The above example shows that the choice of a low noise op amp depends on the source impedance of the signal, and at high impedances, current noise always dominates.

From Figure 5 below, it should be apparent that different amplifiers are best at different source impedances. For low impedance circuits, low voltage noise amplifiers such as the OP27 will be the obvious choice, since they are inexpensive, and their comparatively large current noise will not affect the application. At medium resistances, the Johnson noise of resistors is dominant, while at very high source resistance, we must choose an op amp with the smallest possible current noise, such as the AD549 or AD795.

Until recently, BiFET amplifiers tended to have comparatively high voltage noise (though very low current noise), and were thus more suitable for low noise applications in high rather than low impedance circuitry. The AD795, AD743, and AD745 have very low values of both voltage and current noise. The AD795 specifications at 10 kHz are 10 nV/√Hz and 0.6 fA/√Hz, and the AD743/AD745 specifications at 10 kHz are 2.9 nV/√Hz and 6.9 fA/√Hz. These make possible the design of low-noise amplifier circuits that have low noise over a wide range of source impedances.
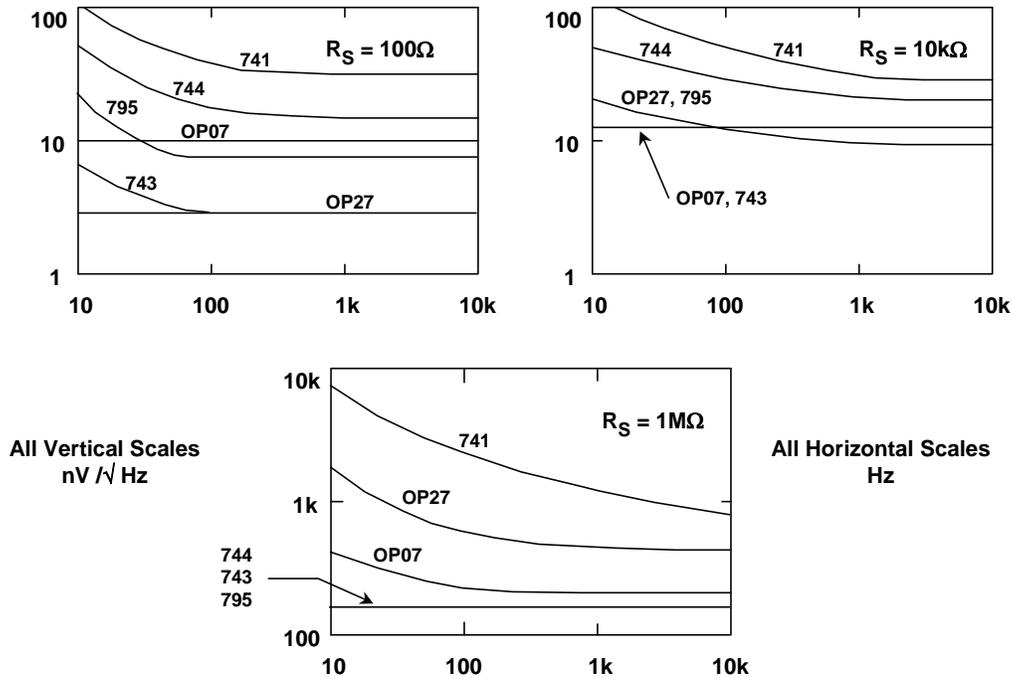
Figure 5: Different Amplifiers are Best at Different Source Impedances

FREQUENCY CHARACTERISTICS OF VOLTAGE AND CURRENT NOISE

So far, we have assumed that noise is *white* (i.e., its spectral density does not vary with frequency). This is true over most of an op amp's frequency range, but at low frequencies the noise spectral density rises at 3 dB/octave, as shown in Figure 6 below. The power spectral density in this region is inversely proportional to frequency, and therefore the voltage noise spectral density is inversely proportional to the square root of the frequency. For this reason, this noise is commonly referred to as *1/f noise*. Note however, that some textbooks still use the older term *flicker noise*.

The frequency at which this noise starts to rise is known as the *1/f corner frequency* (F_C) and is a figure of merit— the lower it is, the better. The 1/f corner frequencies are not necessarily the same for the voltage noise and the current noise of a particular amplifier, and a current feedback op amp may have three 1/f corners: for its voltage noise, its inverting input current noise, and its non-inverting input current noise.
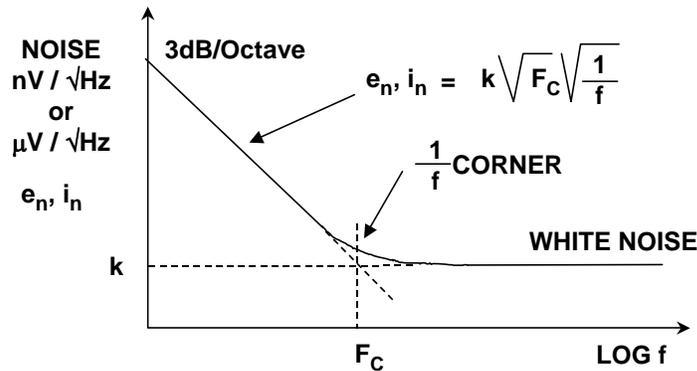
- ◆ **1/f Corner Frequency is a figure of merit for op amp noise performance (the lower the better)**

- ◆ **Typical Ranges: 2Hz to 2kHz**

- ◆ **Voltage Noise and Current Noise do not necessarily have the same 1/f corner frequency**

Figure 6: Frequency Characteristics of Op Amp Noise

The general equation which describes the voltage or current noise spectral density in the 1/f region is

$$e_n, i_n, = k\sqrt{F_C}\sqrt{\frac{1}{f}} ,$$

<div align="right">Eq. 1</div>

where k is the level of the "white" current or voltage noise level, and F_C is the 1/f corner frequency.

The best low frequency low noise amplifiers have corner frequencies in the range 1-10 Hz, while JFET devices and more general purpose op amps have values in the range to 100 Hz. Very fast amplifiers, however, may make compromises in processing to achieve high speed which result in quite poor 1/f corners of several hundred Hz or even 1-2 kHz. This is generally unimportant in the wideband applications for which they were intended, but may affect their use at audio frequencies, particularly for equalized circuits.

POPCORN NOISE

Popcorn noise is so-called because when played through an audio system, it sounds like cooking popcorn. It consists of random step changes of offset voltage that take place at random intervals in the 10+ millisecond timeframe. Such noise results from high levels of contamination and crystal lattice dislocation at the surface of the silicon chip, which in turn results from inappropriate processing techniques or poor quality raw materials.

When monolithic op amps were first introduced in the 1960s, popcorn noise was a dominant noise source. Today, however, the causes of popcorn noise are well understood, raw material purity is high, contamination is low, and production tests for it are reliable so that no op amp manufacturer should have any difficulty in shipping products that are substantially free of popcorn noise. For this reason, it is not even mentioned in most modern op amp textbooks.

REFERENCES

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2. Walter G. Jung, *Op Amp Applications,* Analog Devices, 2002, ISBN 0-916550-26-5, Also available as *Op Amp Applications Handbook*, Elsevier/Newnes, 2005, ISBN 0-7506-7844-5. Chapter 1.