Analysis and Measurement of Intrinsic Noise in Op Amp Circuits
Part V: Introduction to Noise Measurement
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In Part IV we used TINA SPICE to analyze noise in op amp circuits. The example circuit used for TINA SPICE analysis was also used in the hand analysis example from Part III. The result from hand analysis and TINA SPICE closely matched each other. Here in Part V, we introduce the different types of equipment used for measuring noise with specifications and modes of operation pertinent to noise measurement discussed. Although specific models of equipment are considered, the concepts can be applied to most equipment. In Part VI we will show real-world examples of how the equipment is used to measure the circuits described in Parts III and IV.

Equipment for Measuring Noise: True Rms DMM

There are three categories of test equipment used in measuring noise: true root-mean-square (rms) meter, oscilloscope, and spectrum analyzer. The true rms meter measures the rms voltage for an ac signal regardless of the waveform shape, sinusoidal or non-sinusoidal. Many meters compute the rms value by detecting the peak voltage and multiplying the peak value by 0.707. Meters using this method are not true rms meters because they assume the wave shape is sinusoidal.

Many precision digital multimeters (DMM) have true rms capability. Typically, the meter does this by digitizing the input voltage, collecting thousands of samples, and mathematically computing the rms value. A DMM generally has two configurations for making this measurement: **ac** and **ac+dc**. In the ac configuration, the DMM input voltage is ac-coupled to the digitizer with the dc component striped off. This is the preferred mode of operation (see Fig. 5.1) for broadband noise measurements, because the result is mathematically equivalent to the standard deviation of the noise. In the ac+dc mode, the input signal is directly digitized and the rms value is computed, and this mode should not be used for broadband noise measurements.

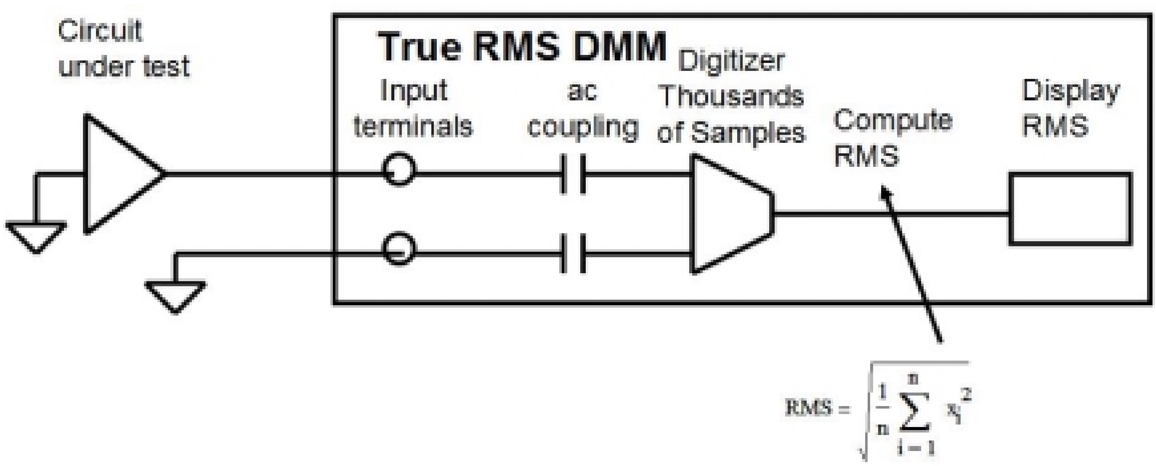


Fig. 5.1: Example Of Typical True Rms DMM

When using a true rms DMM to measure noise you must consider its specifications (see Fig. 5.2) as well as its different modes of operation. Some have a special mode of operation optimized for making broadband noise measurements, when the DMM is in a true rms, ac-coupled mode that measures broadband noise from 20 Hz to 10 MHz. Also, 20 µVrms is a typical noise floor for a precision DMM -- the noise floor can be measured by simply connecting a short across the DMMs input.

Multiple true rms modes: read specifications to select the best mode for noise measurements
Specified bandwidth (BW = 20 Hz to 10 MHz)
Accuracy 0.1% for specified bandwidth
Noise floor 20 µVrms (on 10 mV range)
Ranges: 10 mV, 100 mV . . . 1000 V

Fig. 5.2: Summary: Typical Precision Meter Specifications

Equipment for Measuring Noise: Oscilloscope

One disadvantage to using a true rms meter for measuring noise is that the meter does not help you know the nature of the noise. For example, it cannot tell the difference between noise pickup at a specific frequency and broadband noise. The oscilloscope, on the other hand, allows you to observe the time domain noise waveform; as most different types of noise have a distinctive shape, so you can determine what type of noise dominates.

Both digital and analog oscilloscopes can be used to measure noise. Since noise is random in nature, analog scopes cannot trigger on the noise signal. Analog scopes can only trigger on repetitive waveforms. Nevertheless, analog scopes display distinctive patterns when connected to sources of noise. Fig. 5.3 shows the result of a broadband measurement using an analog scope. Note that analog scopes tend to create an average or smeared waveform because of the phosphorescent quality of the display and the inability of the timebase to trigger on noise. One disadvantage of most standard analog scopes is that they are not able to capture low-frequency noise (1/f noise).

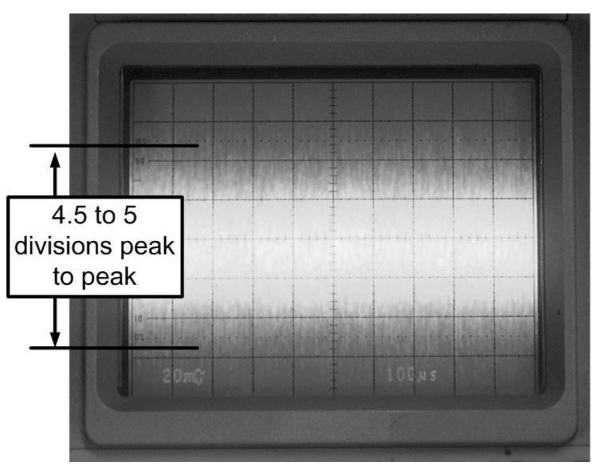


Fig. 5.3: White Noise On Analog Scope

Digital scopes have some convenient features that help with measuring noise. Digital scopes can capture low-frequency noise waveforms (1/f noise). Digital scopes also have the ability to mathematically compute rms. Fig. 5.4 shows the same noise source in Fig. 5.3 captured using a digital scope.

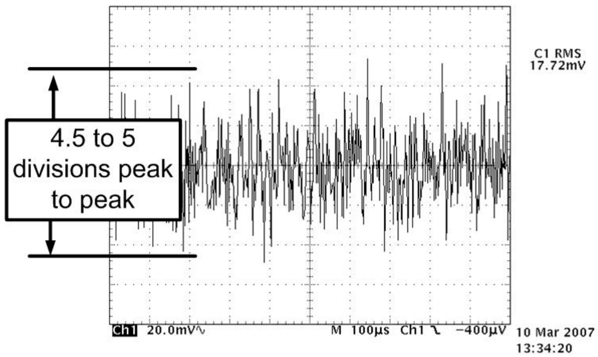


Fig. 5.4: White Noise On Digital Scope

There are some general guidelines that should be followed when using an scope for noise measurements. First of all, it is important to check the noise floor of your scope before measuring your noise signal. This can be done with a BNC shorting cap across the scope high-impedance input, or by shorting the scope lead to the ground lead if a 1x probe is being used: an important consideration because the measurement range is ten times lower when using a 1x probe. Most good scopes have a 1 mV/division range with a 1x scope probe, or direct BNC connection, and a 10 mV/division noise floor with a 10x probe.

Note that a direct BNC connection is preferred over a 1x scope probe because the ground lead connection can pick up RFI/EMI interference (see Fig. 5.5). One way to avoid this issue is to remove the scope probe ground lead and top cover, and use the ground on the side of the probe (see Fig. 5.6). Fig. 5.7 shows a BNC shorting cap.

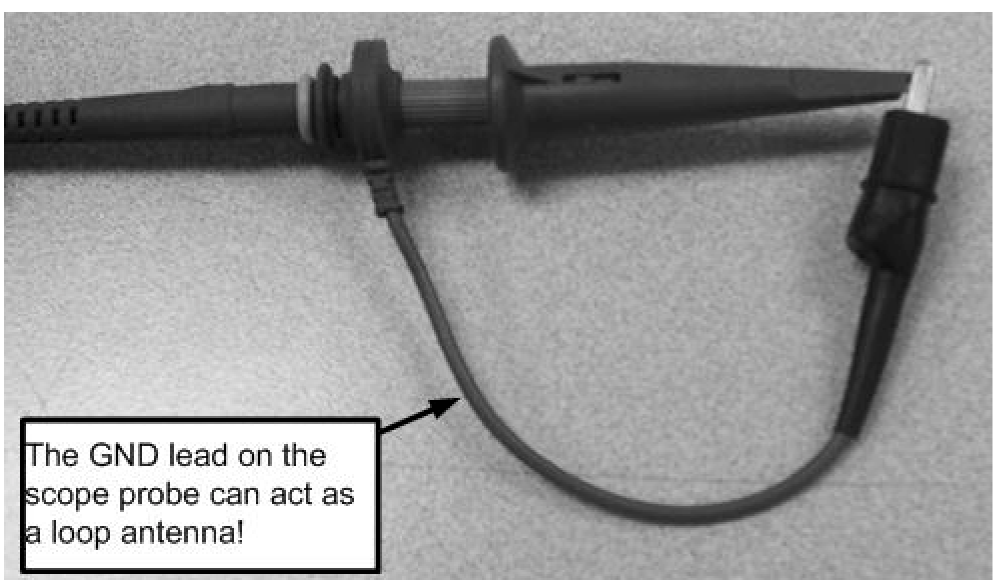


Fig. 5.5: Ground Lead Can Pick Up RFI/EMI

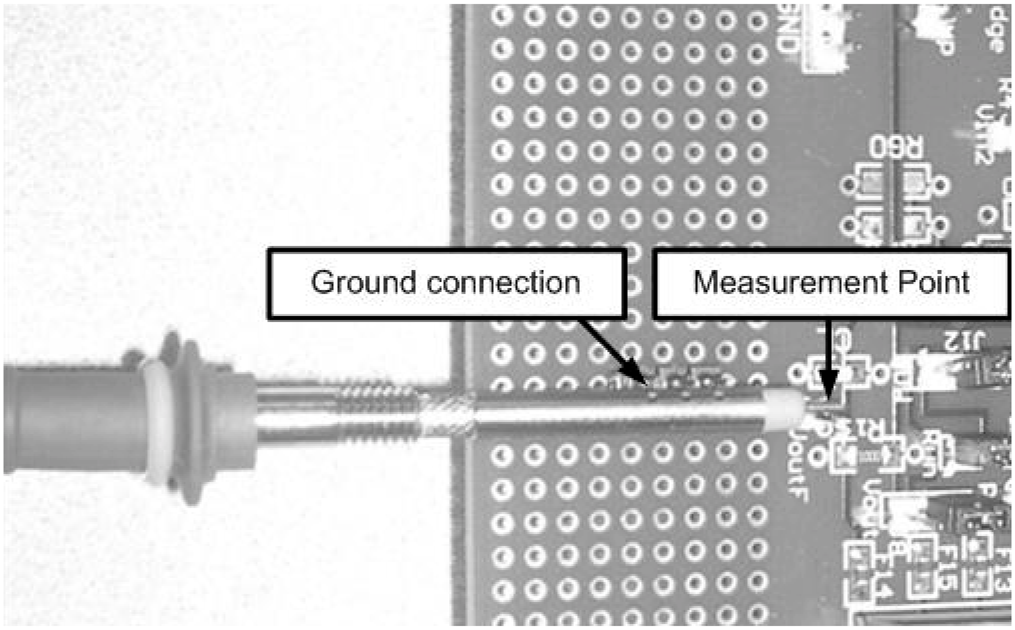


Fig. 5.6: Scope Probe With Ground Lead Removed

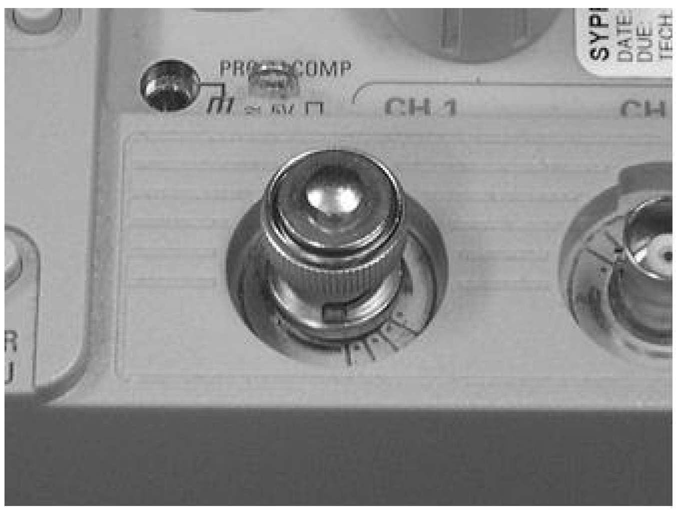


Fig. 5.7: BNC Shorting Cap

Most scopes have a bandwidth limiting feature. To accurately measure the noise of the scopes, bandwidth must be greater then the noise bandwidth of the circuit that you are measuring. However, for best measurement results, the scope bandwidth should be limited to some value above the noise bandwidth. For example, assume that a scope has a full bandwidth of 400 MHz, and a bandwidth of 20 MHz when the limiting feature is turned on. If you are measuring the noise of a circuit with a noise bandwidth of 100 kHz, then it makes sense to turn on the bandwidth limit feature. For this example, the noise floor is lower because the RFI/EMI interference outside the bandwidth of interest will be eliminated. Figs. 5.8 and 5.9 shows the noise floor of a typical digitizing oscilloscope with and without bandwidth limiting. Fig. 5.10 shows that the noise floor is substantially higher with a 10x probe.

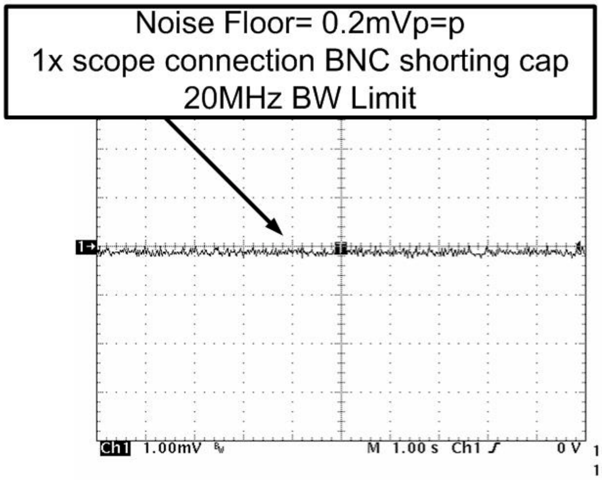


Fig. 5.8: Scope Noise Floor With 1x Probe/Bandwidth Limiting

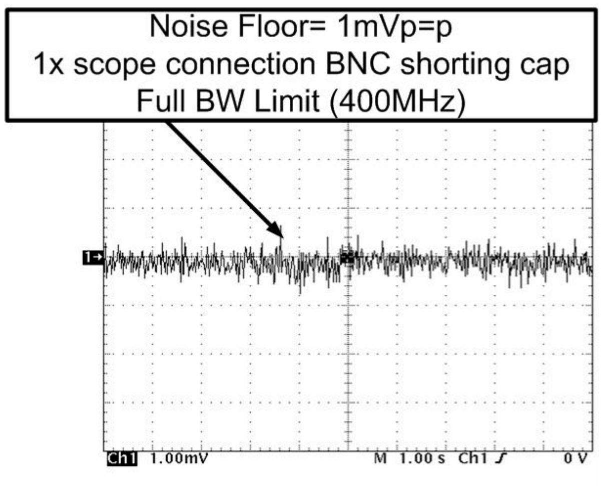


Fig. 5.9: Scope Noise Floor With 1x Probe/No Bandwidth Limiting

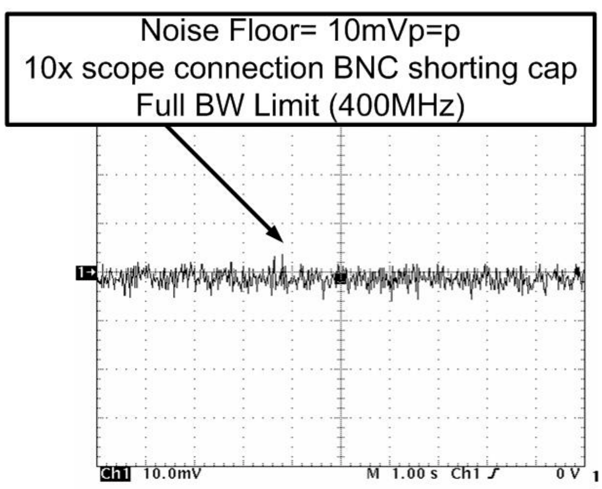


Fig. 5.10: Scope Noise Floor With 10x Probe/No Bandwidth Limiting

The coupling mode for the scope must also be considered when making noise measurements. Ac-coupling should be used with broadband measurements because the noise signal generally rides upon a larger dc voltage. For example, a 1 mVpp noise signal may ride on a 2 V dc signal. Thus, in the ac-coupling mode, the dc signal is eliminated, allowing for the highest gain. However, it is important to note that the ac-coupling mode should not be used to measure 1/f noise. This is because the bandwidth in ac-coupling mode generally has a lower cutoff frequency, of approximately 10 Hz. Of course, this number will vary for different models, but the point is that the lower cutoff frequency is too high for most 1/f noise measurements, typically from 0.1 Hz to 10 Hz. So for 1/f measurements, dc coupling with an external bandpass filter is generally used. Figure 5.11 summarizes the general guidelines for noise measurements with oscilloscopes.

General Guidelines for Noise Measurements with Oscilloscopes:
Do NOT use 10x probes for low noise measurements
Use direct BNC connection (10 times better noise floor)
Use BNC shorting cap to measure noise floor
Use bandwidth limiting, if appropriate
Use digital scope in dc coupling for 1/f noise measurements (ac coupling has a 10 Hz cutoff)
Use ac coupling for broadband measurements, if necessary

Fig. 5.11: General Guidelines For Noise Measurement With Oscilloscopes

Equipment for Measuring Noise: Spectrum Analyzer

The spectrum analyzer is a powerful instrument for measuring noise. Typically, it displays power (or voltage) versus frequency, similar to noise spectral density curves: in fact, some spectrum analyzers have special modes of operation that allow the measured results to be displayed directly in spectral density units (ie nV/√Hz). In other cases, the results must be multiplied by a correction factor to convert the units into spectral density.

Spectrum analyzers, like oscilloscopes, may be either digital or analog. One way analog instruments generate a spectral curve is to frequency sweep a bandpass filter and plot the measured output of the filter. Another way is to use a superhet technique where a local oscillator is frequency swept. Digital analyzers use the fast Fourier transform (FFT) (often in conjunction with a superhet technique) to generate the frequency spectrum.

Regardless of the type of spectrum analyzer used some key parameters need to be considered. The start and stop frequencies indicate the sweep range of the bandpass filter. The resolution bandwidth is the sweep frequency range of the bandpass filter. Decreasing the resolution bandwidth increases the ability of the spectrum analyzer to resolve signals at discrete frequencies, and will lengthen the sweep time. Fig. 5.13 illustrates the swept filter operation. In the Fig. 5.14 measurement, the resolution bandwidth is set small enough to allow proper resolving of discrete frequency components (150 Hz). On the other hand, in the Fig. 5.15 measurement the resolution bandwidth is set too wide to allow proper resolution of the frequency components (1200 Hz).

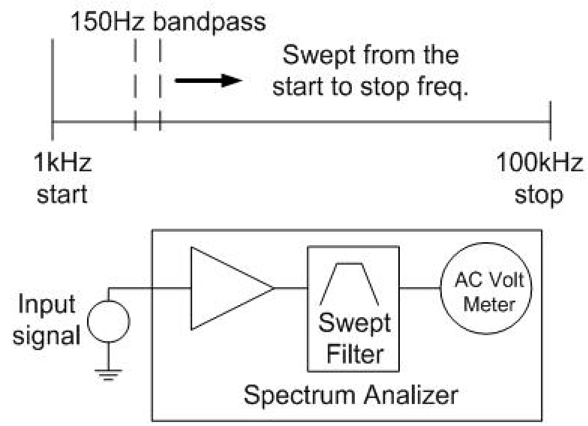


Fig. 5.12: Operation Of Spectrum Analyzer

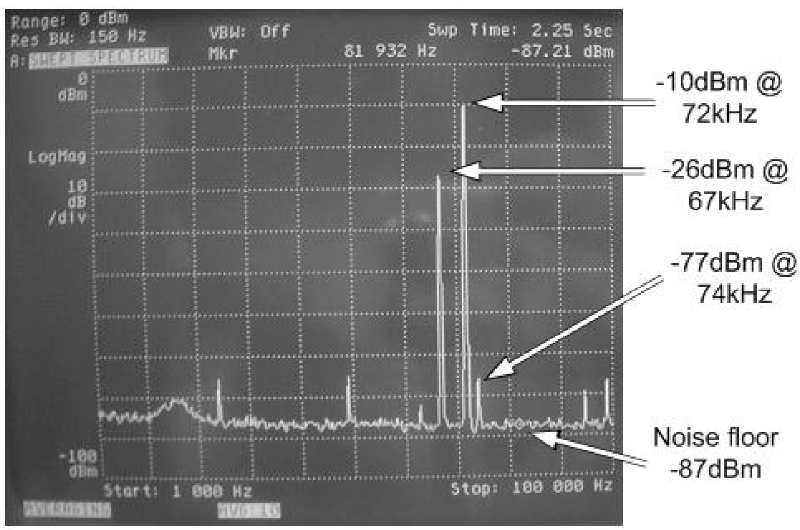


Fig. 5.13: Resolution Bandwidth Selected For Good Signal Resolution

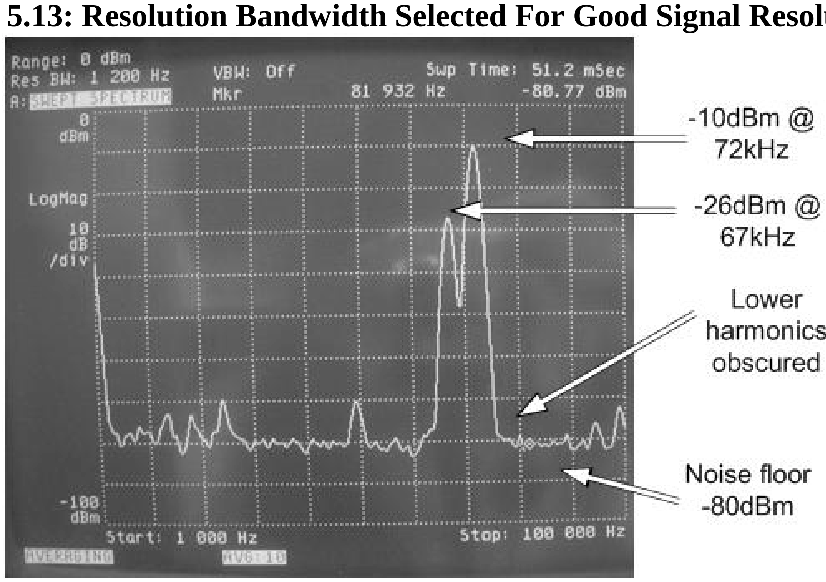


Fig. 5.14: Resolution Bandwidth Selected For Poor Signal Resolution

In Figs. 5.13 and 5.14, the magnitude of the spectrum is given in decibel milliwatts (dBm), a typical unit of measurement. dBm is the power ratio measured in decibels with reference to one milliwatt. For the spectrum analyzer in this example, the dBm numbers also assume a 50 Ω input impedance. For most spectrum analyzers, this is even when the input impedance is set to be 1 MΩ. Fig. 5.15 gives the derivation of the formula for converting dBm to rms voltage. In Fig. 5.16, the formula is used to compute the magnitude of the –10 dBm signal from the measurement illustrated in Figs. 5.13/5.14.

$$NdBm = 10 \cdot \log\left(\frac{P}{1mW}\right) \qquad (5.1)$$

where
NdBm -- decibel milliwatts
P -- Measured power

solve for power

$$P = \left[10^{\left(\frac{NdBm}{10}\right)}\right] \cdot (1mW) \qquad (5.2)$$

power formula for resistors

$$V = \sqrt{P \cdot R} \qquad (5.3)$$

substitute (5.2) into (5.3)

$$V = \sqrt{\left(10^{\frac{NdBm}{10}}\right) \cdot (1mW) \cdot R} \qquad (5.4)$$

Where
R - spectrum analyzer input impedance. Some models will assume R=50 ohm for both 50ohm and 1Mohm input impedance.
NdBm -- decibel milliwatts as displayed on spectrum analyzer

Fig. 5.15: Convert dBm To Rms Voltage

In Figs. 5.13 and 5.14, the noise floor increased from –87 dBm to –80 dBm when the resolution bandwidth was decreased but the magnitude of the signals at 67 kHz and 72 kHz, on the other hand, do not change. The noise floor is affected because it is thermal noise and a wider bandwidth increases the total. The magnitudes are constant because they are sinusoidal and will remain constant inside a bandpass filter, regardless of bandwidth. This distinction is important in noise analysis because it must be understood that discrete signals should not be included in spectral density calculations. For example, when measuring the noise spectral density of an op amp, you may see a discrete signal at 60 Hz (power line pickup) which should not be included.

From figure 5.13 the signal at 72kHz has a magnitude of -10dBm
Use (5.4) to convert -10dBm to volts rms.

$$V = \sqrt{\left(10^{\frac{-10\text{dBm}}{10}}\right)\cdot(1\text{mW})\cdot 50\Omega} = 0.071 \quad V_{rms}$$

Fig. 5.16: Convert -10 dBm To Rms Voltage

Some spectrum analyzers display the spectral magnitude as a noise spectral density in nV/√Hz. If this feature is not available, however, the spectral magnitude can be divided by the square root of the resolution noise bandwidth to convert to spectral density. Note that a conversion factor is needed to convert the resolution bandwidth to resolution noise bandwidth. Fig. 5.17 gives the equations for converting a dBm spectrum to a spectral density and also gives a table of conversion factors needed to convert resolution bandwidth to noise bandwidth. Fig. 5.18 shows an example where the spectrum from the example spectrum analyzer is converted to a spectral density.

$$V_{spect\_anal} = \sqrt{\left(10^{\frac{NdBm}{10}}\right)\cdot(1\text{mW})\cdot R} \qquad (5.4)$$

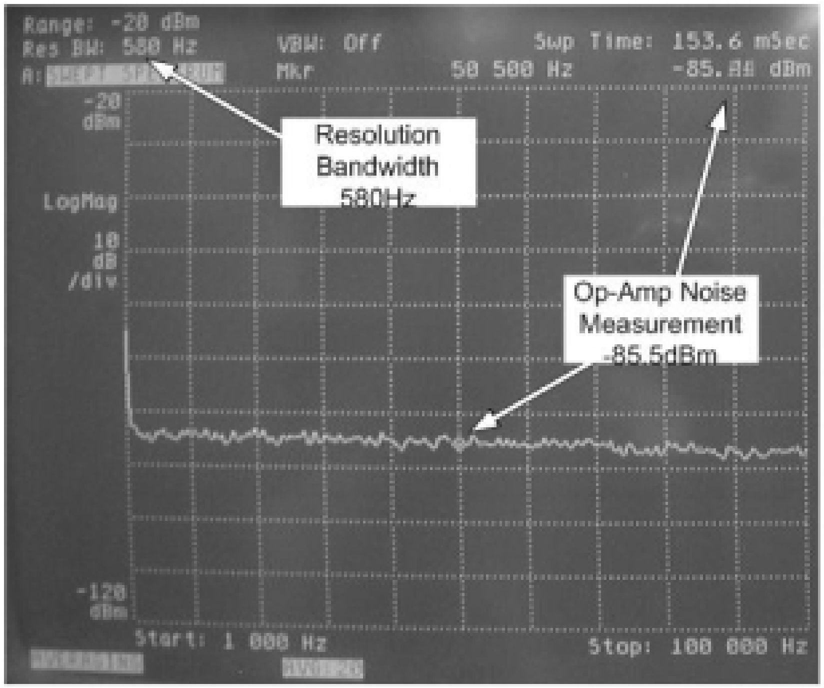
$$V_{spect\_den} = \frac{V_{spect\_anal}}{\sqrt{K_n \cdot RBW}} \qquad (5.5)$$

Where
NdBm -- the noise magnitude in dBm from the spectrum analyzer
R -- the reference impedance used for the dBm calculation
V_{spect_anal} -- noise voltage measured by spectrum analyzer per resolution bandwidth
RBW -- resolution bandwidth setting on spectrum analyzer
V_{spect_den} -- spectral density in (nV/rt-Hz)
K_n -- conversion factor that changes the resolution bandwidth to a noise bandwidth

Fig. 5.17: Formulas For Conversion From dBm To Spectral Density

Filter Type	**Application**	**Kn**
4-pole sync	Most Spectrum Analyzers Analog	1.128
5-pole sync	Some Spectrum Analyzers Analog	1.111
Typical FFT	FFT-based Spectrum Analyzers	1.056

Fig. 5.18: Formulae For Conversion From dBm To Spectral Density[1]



$$V_{spect\_anal} = \sqrt{\left(10^{\frac{-85.5}{10}}\right)\cdot(0.001)\cdot 50} = 11.871\times 10^{-6} \quad V_{rms}$$

$$V_{spect\_den} = \frac{11.871\times 10^{-6}}{\sqrt{1.128\cdot 580}} = 464 \quad \text{nV/rt-Hz}$$

Fig. 5.19: Example Converting Analyzer Measurements To Spectral Density

Most spectrum analyzers also have a feature to average out the measurement variability so that the results are more repeatable. The number of averages is entered via the front panel (typically 1 to 100). Figs. 5.20 - 5.22 show a signal with different averaging.

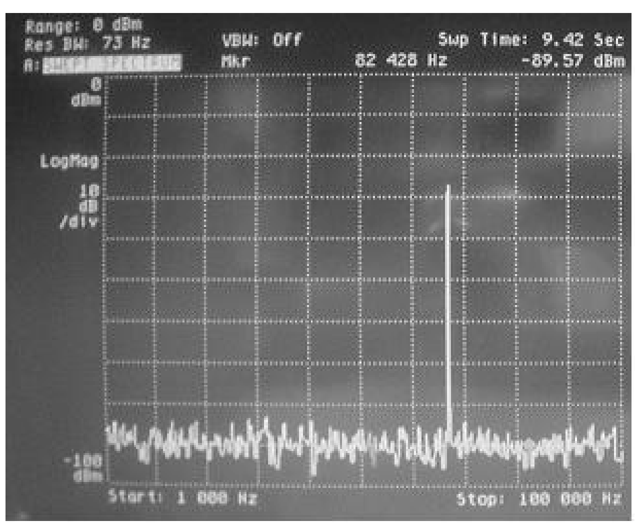


Fig. 5.20: Spectrum Analyzer With Averaging Turned Off

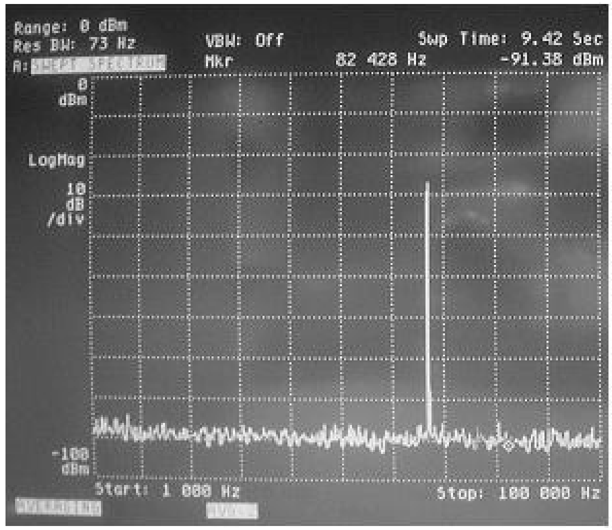


Fig. 5.21: Spectrum Analyzer With Averaging = 2

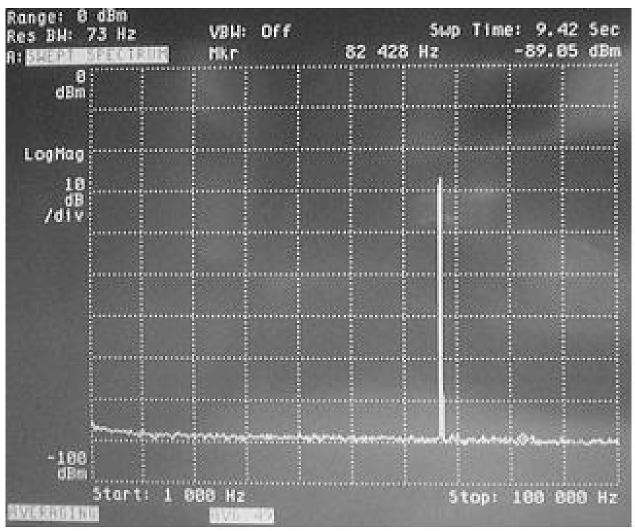


Fig. 5.22: Spectrum Analyzer With Averaging = 49

Noise floor and bandwidth are key specifications that need to be considered when using (or selecting) a spectrum analyzer.

	Typical Digital Spectrum Analyzer	**Typical Analog Spectrum Analyzer**
Noise Floor	20 nV/√Hz	50 nV/√Hz
Bandwidth	0.016 Hz to 120 kHz	10 Hz to 150 MHz
General Comment	This is a modern digital analyzer that uses an FFT to generate the spectrum. It has very low-frequency capability and so, it is appropriate for 1/f measurements	This is an older analog analyzer that uses superhet techniques to generate the spectrum. The cutoff frequency is 10 Hz and so it is not appropriate for typical op amp 1/f measurements

Fig. 5.23: Comparing Specifications For Two Spectrum Analyzers

Summary and Preview

In this TechNote we introduced several different types of equipment for measuring noise. The specifications and key modes of operations that are pertinent to noise are emphasized. Note that although specific models were discussed, the concepts apply to most equipment. This TechNote is meant to help guide you to the key specifications that you should consider when selecting equipment for noise measurements. In Part VI, we will go through real-world examples using this equipment.

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- Tim Green, Applications Engineering Manager
- Michael Steffes, High Speed Market Development Manager

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