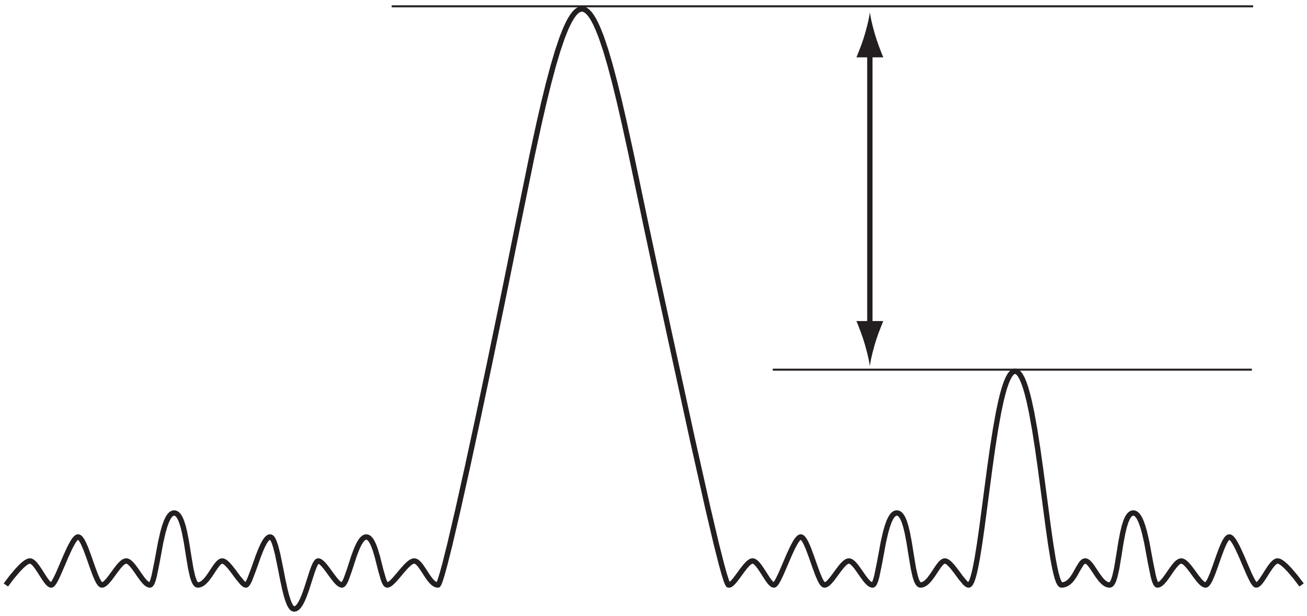
Agilent AN 1315

Optimizing RF and Microwave Spectrum Analyzer Dynamic Range

Application Note



Agilent Technologies

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1. Introduction

What is dynamic range?

The dynamic range of a spectrum analyzer is traditionally defined as the ratio, in dB, of the largest to the smallest signals simultaneously present at the input of the spectrum analyzer that allows measurement of the smaller to a given degree of uncertainty. The signals of interest can either be harmonically or nonharmonically related.

Why is dynamic range important?

The dynamic range specification determines whether or not low-level signals will be visible in the presence of large signals and therefore is one of the most important performance figures for a spectrum analyzer. It is often misunderstood and misinterpreted, since the display range, measurement range, noise floor, phase noise, and spurious response of the instrument all play important roles in determining dynamic range. By understanding which dynamic range interpretation applies to a specific measurement, you can make more accurate, reliable, and repeatable spectrum analyzer measurements.

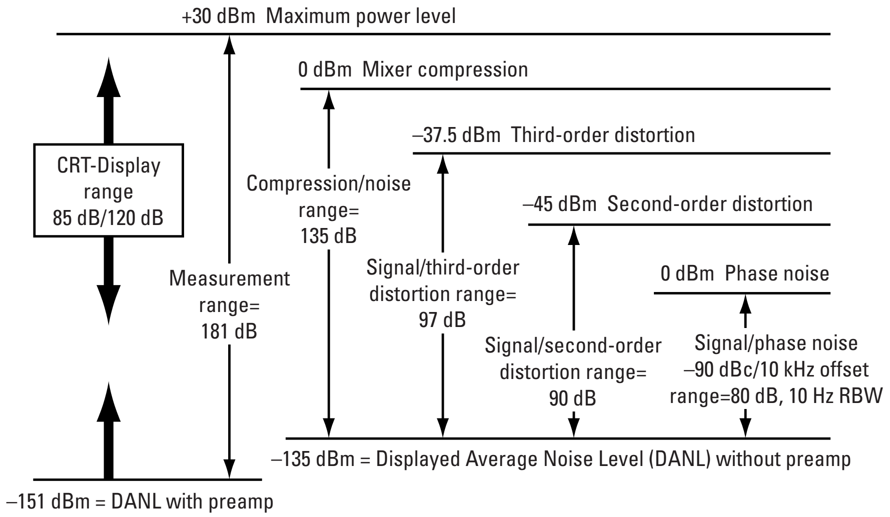

Figure 1. Dynamic range interpretations

2. Dynamic Range Interpretations

Figure 1 shows several different interpretations for dynamic range. In this chapter we will explain each interpretation.

Measurement range

The measurement range is the difference between the largest and smallest signals that can be measured on a spectrum analyzer, allowing for different instrument settings. Usually, the maximum power level that can be applied to the input of the analyzer without damaging the front-end hardware dictates the largest signal; this is +30 dBm (1 watt) for most analyzers. The noise floor of the instrument determines the lower limit of the measurement range; signals below the noise level are not visible on screen. Note that the lowest noise level cannot be achieved with the same input attenuator setting used for a 1 watt measurement.

Display range

The display range is the calibrated amplitude range of the display. If an analyzer display has 10 vertical divisions, it is usually assumed that in the 10 dB/ division logarithmic display mode the analyzer is able to display signals 100 dB apart. However, the log amplifier often limits the range. For example, if we have an 85 dB log amplifier and 10 divisions on our screen, we only have 8.5 calibrated divisions. An analyzer's reference level setting positions the display range anywhere within the measurement range.

In some spectrum analyzers, the narrow resolution bandwidths are implemented with digital filters. The log amplifier in this case is bypassed and the limitation now comes from the digital-to-analog converter plus any auto-ranging. A calibrated display range in this case can be as much as 120 dB.

Hint: ***optimize using reference level***
If small signals need to be measured in the presence of larger signals, the larger signals can often be moved above the upper limit of the display by up to 10 dB by changing the reference level, to place the small signals in the calibrated display range. This will have little effect on the accuracy of measuring the smaller signal; however, mixer compression must be avoided.

Mixer compression

The mixer compression level is the maximum power level that we can put into the analyzer without compromising the accuracy of the displayed signal. When the signal level at the mixer is well below the compression point, the level of the desired mixing product (IF signal) is a linear function of the input and little energy is diverted to distortion. As the mixer level increases, the transfer function becomes nonlinear because significant energy is lost to the distortion products. At this point the mixer is considered to be in compression, and the displayed signal level is below the actual signal level.

The mixer compression specification describes the total mixer input power level below which the analyzer compresses the displayed signal less than 1 dB. Keep in mind that the input level at the mixer is the sum of the input power at all frequencies, even if all the input signals cannot be seen on the display. There are three different ways to evaluate compression: CW compression, two-tone compression, and pulse compression. Each is a different compression mechanism with its own compression threshold **[1]**.

Hint: *limit the mixer level*

For accurate measurements of high-level signals, it is important to determine the input attenuation setting that will prevent compression by limiting the power that reaches the mixer. In Agilent ESA spectrum analyzers the maximum mixer level can be set. The attenuator setting will then change automatically to keep power levels equal to or less than the selected level at the input mixer, for any signal that is displayed on-screen. The default and maximum setting is –10 dBm.

Internal Distortion

Internal distortion is one of the factors that determines the dynamic range when measuring distortion products, such as harmonic distortion from a single tone or the intermodulation distortion from two or more tones. The internally generated intermodulation and harmonic distortions are a function of the input signal amplitude at the mixer. To understand these effects, it is helpful to look at how our input mixer behaves.

Most analyzers use diode mixers, which are nonlinear devices and behave according to the ideal diode equation **[1]**. Using the Taylor Series expansion, it can be shown that in nonlinear devices a 1 dB change in the fundamental signal power at the input results in a 2 dB change in second-order (for example, second-harmonic) distortion and a 3 dB change in third-order (for example, third-harmonic) distortion at the output (see Figure 2). We can equate the dynamic range to the differences between the fundamental tone or tones and the internally generated distortion. We find that for a 1 dB change in the fundamental power, the second-harmonic distortion product changes by 1 dBc (dB relative to the carrier or fundamental), and the third-order product changes by 2 dBc.

Referring to the Agilent Technologies E4402B spectrum analyzer's specifications **[4]** for spurious responses, the second-harmonic distortion for this analyzer is –75 dBc for a –30 dBm signal at the mixer input and third-order intermodulation distortion (TOI) is –80 dBc for two –30 dBm signals at the mixer. We can create a graph (Figure 3) for a variety of mixer input levels since we know the relationship between the fundamental and the internally generated second- and third-order distortion products. The slope is one for the plot of the internally generated second harmonic, and two for the plot of the third-order intermodulation distortion. It appears from the graph that, if the mixer level is low enough, there is no need to be concerned about internally generated distortion. This is true, but as our signal gets lower we need to take into account the effects of noise.

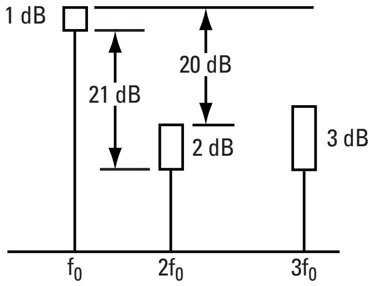

Figure 2. Changes in the relative amplitudes of distortion products with input power level

Noise

Two types of noise contribute to dynamic range: phase noise and sensitivity. Noise is a broadband signal; therefore, as the resolution bandwidth (RBW) filter is widened, more random noise energy is allowed to hit the detector. This increases the level of phase noise as well as the noise floor of the analyzer. Therefore, noise specifications must be referenced to the RBW.

Sensitivity

The sensitivity of the analyzer, also called the Displayed Average Noise Level (DANL) or noise floor, determines the smallest signal we can measure. The lower limit of DANL is theoretically kTB,[1] or –174 dBm, for a noise bandwidth of 1 Hz at room temperature.

Phase noise

While DANL is the key parameter when measuring two signals that are far apart in frequency, phase noise is the key parameter when measuring two signals that are close in frequency (<1 MHz apart). Also called sideband noise, phase noise is caused by the instability of the local oscillator (LO). There is no such thing as a perfect oscillator; all are phase-modulated to some extent by random noise, and any instability in the LO is translated to the displayed signal through the mixer. The more stable the LO, the further down the phase noise will be, assuming a sufficiently stable input signal. For dynamic range considerations, phase noise is like third-order intermodulation distortion in that it matters when the test tones are close to each other.

Second- and third-order dynamic range

To incorporate the effect of noise in the graph of internal distortion levels (Figure 3), we need to consider how signal-to-noise changes with respect to changes in the fundamental level at the mixer input. For every dB that we increase the signal level at the mixer, we gain 1 dB of signal-to-noise ratio.

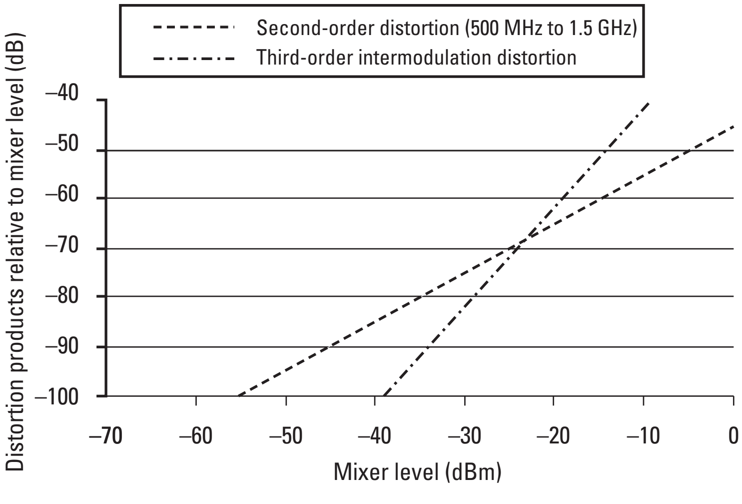

Figure 3. Internally generated second-harmonic and third-order intermodulation distortion levels as a function of mixer input level for the Agilent E4402B

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[1] Where k=Boltzmann's constant, T=absolute temperature in degrees Kelvin, and B=bandwidth in Hertz.

Therefore, the DANL curve is a straight line having a slope of –1 (see Figure 4). The horizontal line at –80 dB in Figure 4 represents phase noise, rather than DANL, for a 10 kHz offset and 10 Hz RBW. Phase noise is the limiting factor when making measurements close to the carrier (<1 MHz away); for measurements that are far away it can be ignored. Noise affects our ability to minimize internally generated distortion products by limiting how small a signal we can measure.

Second- or third-order dynamic range is limited by three factors: distortion performance of the input mixer, DANL (sensitivity), and phase noise of the local oscillator. It is important that all of these factors are taken into account and optimized for a particular measurement. Figure 4 shows the achievable dynamic range as a function of mixer level for second- and third-order distortion measurements. For maximum distortion-free dynamic range, the power at the mixer should be adjusted so that the DANL and the internally generated distortion are equal.

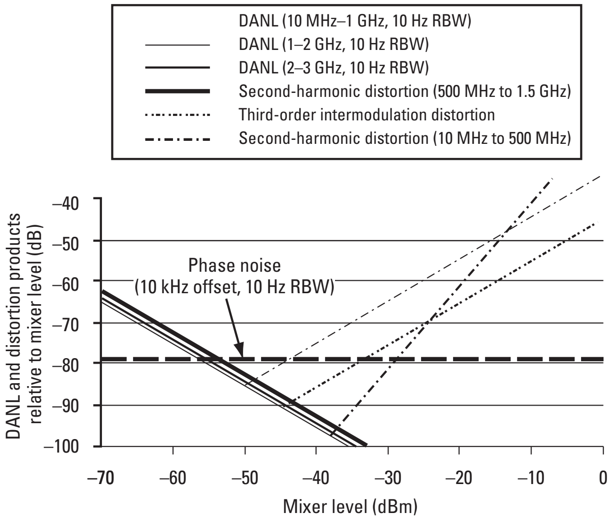

Figure 4. Sensitivity, phase noise, third-order intermodulation, and second-harmonic distortion versus mixer level for the Agilent E4402B

Hint: *determine maximum achievable second- or third-order dynamic range*
Typically, the maximum achievable dynamic range is specified, and refers to the maximum difference in dB between two harmonically related signals without interference from the analyzer's internally generated distortion products. From Figure 4, we see that the maximum dynamic range is achieved when the mixer level corresponds to the intersection of the noise and distortion components. The maximum dynamic range is calculated with the following equations and can be used to determine if your spectrum analyzer has enough dynamic range to make a particular measurement:

Equation 1 Maximum third-order dynamic range = (2/3)(DANL–TOI)

Equation 2 Maximum second-order dynamic range = (1/2) (DANL–SHI)

Where: TOI = mixer level – (1/2) (level of distortion products in dBc)
SHI = mixer level – level of distortion products in dBc.

Summary

A popular use of a spectrum analyzer is to measure harmonic or intermodulation distortion products. Measurement range, display range, and mixer compression do not take into account all of the restrictions encountered when making these types of measurements. Therefore, “dynamic range” is frequently understood to mean either second- or third-order dynamic range. This is the interpretation of dynamic range used in Section 3, which discusses techniques for making better distortion measurements by improving and understanding the effects of dynamic range.

3. Making Harmonic or Intermodulation Distortion Measurements

Measurement uncertainty

Theoretical dynamic range calculations do not account for measurement uncertainties. If internally generated components occur at the same frequencies as the signals that we want measure, as is the case in distortion measurements, our accuracy will be degraded. Depending on the phase relationship of the external and internal distortion products, the measured amplitude can fall anywhere between the sum and the difference of the two. Since we have no way of knowing what the phase relationship is, we can only determine the measurement uncertainty:

Equation 3 $\text{Uncertainty (dB)} = 20 \log (1 \pm 10^{d/20})$

where d = difference in dB between internal and external distortion products (a negative number)

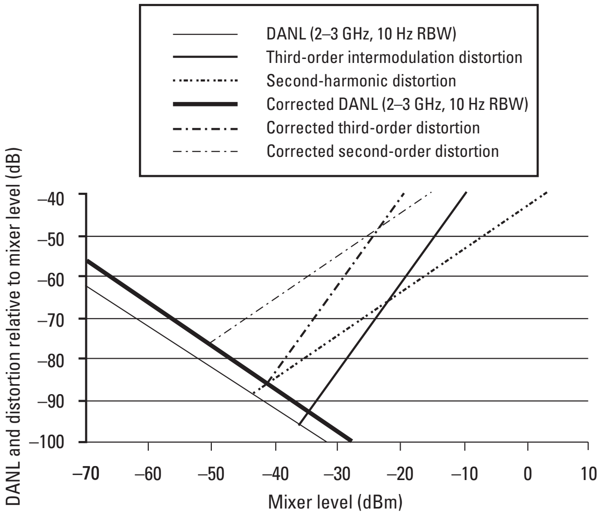

Figure 5. Dynamic range graph corrected for amplitude uncertainty

If we want no more than ±1dB of uncertainty in our measurement, we must be sure that the internally generated distortion product is at least 19 dB below the distortion product that we wish to measure. If we add this 19 dB guardband to the curves, our dynamic range is reduced by 9.5 dB for second order and 12.7 dB for third order, as seen in Figure 5. Notice that we do not lose the full 19 dB that we added for a guardband.

Not only does the instrument's internal distortion play a factor; low distortion-to-noise ratio can contribute to the uncertainty as well. If the distortion components to be measured are at or very close (within a few dB) to the noise level of the spectrum analyzer, the displayed signal level (which is actually the level of signal plus noise) is greater than the actual signal level. A correction factor can be applied to compensate for this measurement error **[3]**. It is common practice to make sure that the signal is at least 5 dB above the displayed noise floor, giving an error in the displayed signal level of less than 0.5 dB.

Optimizing measurements

Preamplifier

A preamplifier is useful when measuring low-level signals. There are two important factors to consider when choosing a preamplifier: gain and noise figure. The noise figure (NF) of the preamplifier must be lower than the NF of the spectrum analyzer (NF_{SA}= DANL + 172 dBm). If the NF plus gain of the preamplifier is less than the NF of the spectrum analyzer, then the preamplifier will reduce the analyzer's DANL (after correcting for the preamplifier gain) by an amount nearly equal to the preamplifier gain. If there is too much gain, the input attenuator can be used to optimize the power level at the mixer.

One of the drawbacks of a preamplifier is that it must be calibrated into the system so its effects can be accounted for in measurement results. In the Agilent ESA-E series spectrum analyzers, there is an optional built-in preamplifier that will lower the noise floor of the system without compromising dynamic range. It is internal to the system and already calibrated for easy use. Figure 6 shows the noise floor without using the internal preamplifier, and Figure 7 shows the approximately 15 dB improvement in noise floor when the internal preamplifier is turned on.

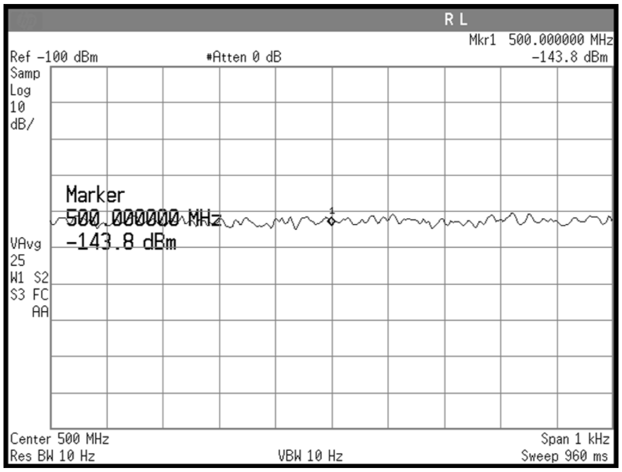

Figure 6. DANL of an Agilent ESA-E series spectrum analyzer without preamplification

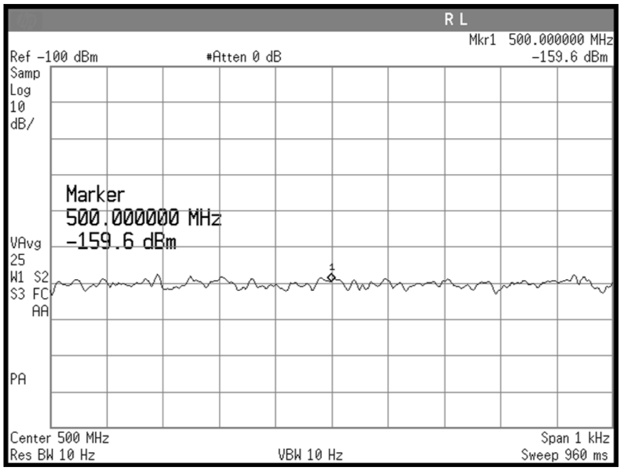

Figure 7. DANL of an Agilent ESA-E series spectrum analyzer with preamplfication

Attenuator

As discussed earlier, when measuring distortion products it may be necessary to adjust the power level at the mixer. If the power level at the mixer is low enough, we can be guaranteed that the distortion products we are seeing are from our Device-Under-Test (DUT). However, if the power is too low, the analyzer's noise floor covers up the distortion products.

There must be enough power at the mixer for the DUT's distortion to be above the DANL, but not so much that the analyzer's distortion masks that of the DUT. The Agilent ESA spectrum analyzers allow you to change the attenuator in 5 dB increments to better approach the optimum balance for a specific measurement.

Attenuator test

While making distortion measurements it is easy to see if the distortion products displayed on the analyzer have been generated internally. The input attenuator attenuates the incoming signal and the analyzer amplifies it again by the same amount after the signal has gone through the mixer. Therefore, if the input attenuation is changed and the distortion products remain the same, the distortion is part of the incoming signal. If the amplitudes of the distortion products change, all or part of the distortion has been internally generated.

External filter

Another way to limit the power reaching the mixer for reduced internally generated distortion products is to attenuate or reject signals that are not of interest. This can be done with an external filter, which acts as a preselector. For example, if we want to test an oscillator for harmonics, we can use a high-pass filter to reject the fundamental but not the harmonic of interest. For closely spaced signals (for example, in an intermodulation test), a high-Q filter may be required.

RBW filter

Since noise is a function of the RBW filter, use caution when interpreting phase noise or DANL specifications.

Phase noise specifications are normalized to a 1 Hz RBW filter even if the analyzer does not have a 1 Hz RBW filter. In order to determine the actual achievable phase noise level, it is necessary to convert from the specified 1 Hz RBW to the actual RBW filter used for the measurement. The correction factor is determined as follows:

Phase noise level correction (dB) = 10 log (actual RBW /1 Hz)

For example, the phase noise specification for the Agilent E4411B at a 10 kHz offset is –90 dBc/Hz, but the minimum RBW setting is 10 Hz. The correction factor for the 10 Hz RBW is:

10 log (10 Hz/1Hz) = 10 dB

Taking this correction factor into account, the actual achievable phase noise is –80 dBc in the analyzer's minimum RBW of 10 Hz.

The DANL is also specified for a particular RBW and must be adjusted if the measurement RBW is different. The same calculation can be used to determine the corrected DANL:

DANL correction (dB) =
10 log (measurement RBW/specified RBW)

The minimum RBW filter is clearly an important factor in determining whether or not the analyzer has enough dynamic range for certain measurements.

Measuring other signals

When comparing small signals (other than second- or third-order distortion) to large signals, the distortion curves that we have been discussing do not apply. In this situation, the distortion products created by the mixer do not affect the measurements. For example, if we are measuring the fourth harmonic, the internally generated distortion is small enough that it can be neglected. For these measurements, phase noise and DANL will be the limiting factors, as long as the total power at the mixer is below mixer compression and there is enough display range.

4. Summary

Dynamic range limits the range of signal amplitudes we can measure with a spectrum analyzer. There are several interpretations of dynamic range, including measurement range, display range, mixer compression, internal distortion, and noise; the applicable interpretation depends on the type of measurement. Second- and third-order dynamic range can be optimized for a particular measurement by controlling various parameters, such as mixer input power and DANL. For maximum distortion-free dynamic range, the power at the mixer should be adjusted so that the DANL and the internally generated distortion are equal.

5. References

	Pub. number
1. *Spectrum Analysis Basics,* Agilent Application Note 150	5952-0292
2. *Effective Spectrum Analysis Testing for Consumer Electronics Production Lines,* Agilent Application Note 130	5966-0367E
3. *Spectrum Analyzer Measurements and Noise,* Agilent Application Note 1303	5966-4008E
4. *Agilent ESA-E Series Spectrum Analyzers,* Data Sheet	5968-3386E

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