Measuring Noise Figure with a Spectrum Analyzer

Application Note 1439

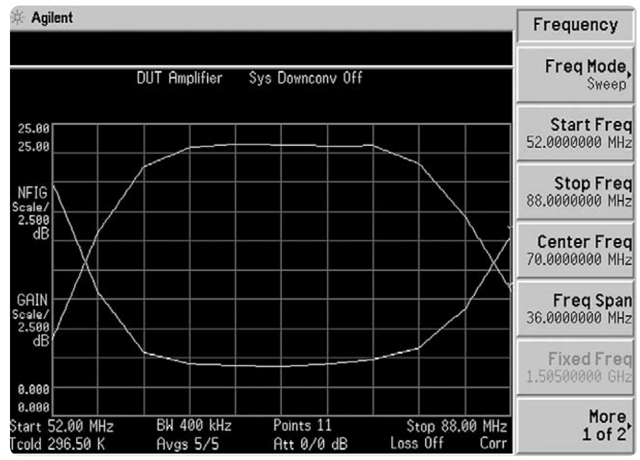


Table of Contents

Chapter 1. Introduction

Using spectrum analyzers for noise figure measurements

Anyone involved with RF and microwave communications will be familiar with noise figure, either as a specification or as a characteristic of components and systems. The widespread use of spectrum analyzers in RF and microwave communications has created an interest in measuring noise figure using a spectrum analyzer rather than a noise figure analyzer. In some cases spectrum analyzers may permit production facilities to reduce the different types of test instruments used, yet still allow a wide range of tests to be performed.

While using spectrum analyzers for noise figure testing is not new, practical implementation can prove complex, and only rarely has measurement accuracy been treated rigorously.

The use of automated measurement routines implemented as "personalities" in modern spectrum analyzers can provide practical and accurate noise figure measurements in addition to traditional spectrum measurements. These personalities automate many aspects of noise figure measurements, making them more convenient and faster, as well as reducing errors due to instrument setup or data manipulation. Since noise figure measurements are often paired with amplifier gain measurements, the personalities can automate these measurements as well, and perform them with the noise figure measurements.

Measurement personalities can also improve the utility of noise figure measurements and the insight they provide by formatting numerical results in a variety of ways such as tables and composite graphical displays.

Option E444xA-219 for the Agilent PSA Series spectrum analyzers

Option E444xA-219 is a measurement personality for the PSA Series spectrum analyzers, providing fast, one-button measurements of gain and noise figure parameters. The spectrum analyzer is used with a noise source such as the Agilent 346 Series (Figure 1.1), available separately. The noise source is powered and controlled by the spectrum analyzer, while the personality controls the spectrum analyzer itself to make measurements and display the results.

The Agilent PSA Series high-performance spectrum analyzers are ideal platforms for noise figure and gain measurements, at frequencies to 3 GHz. Important PSA Series features for noise figure measurements include:

Low internal noise and built-in low-noise preamplifier - Low instrument noise is vital for accurate measurements and the internal low-noise preamplifier (Option E444xA-1DS) eliminates the need for external amplifiers at frequencies below 3 GHz.

All-digital IF and digital log amplifier - The PSA's digital IF provides 160 precise, stable, fast-sweeping RBW filters. The digital log amplifier virtually eliminates a significant source of measurement uncertainty. This combination provides faster and more accurate measurements than traditional spectrum analyzers.

RMS detection, fast averaging - The most accurate noise measurements are made with true RMS detection. Flexible averaging algorithms reduce measurement variance quickly, for more repeatable results in less time.

Computing and communications features - Whether measurements are made in R&D or manufacturing, the PSA's fast processing, PC-compatible files, floppy disk drive, plus GPIB and LAN connectivity quickly provide results in the right format wherever they are needed. Productivity and measurement confidence are enhanced with built-in limit lines and an internal noise figure uncertainty calculator.

SCPI programmable, code compatible with NFA Series - Whether you choose the PSA Series spectrum analyzers or one of Agilent's dedicated NFA series noise figure analyzers (see more information about choosing an analyzer below), programming is simplified with SCPI commands that are compatible with both platforms.

Choosing a measurement tool: Spectrum analyzers and dedicated noise figure analyzers

Both the PSA Series spectrum analyzers and NFA Series noise figure analyzers automatically measure noise figure and gain, along with Y-factor, Teffective, Phot and Pcold. They both display results in table, meter, and graph formats, and have multiple markers and limit lines. Both series of analyzers use the same compatible set of SCPI commands, and the specifications for both series of analyzers are pre-entered in Agilent's Web-based uncertainty calculator.

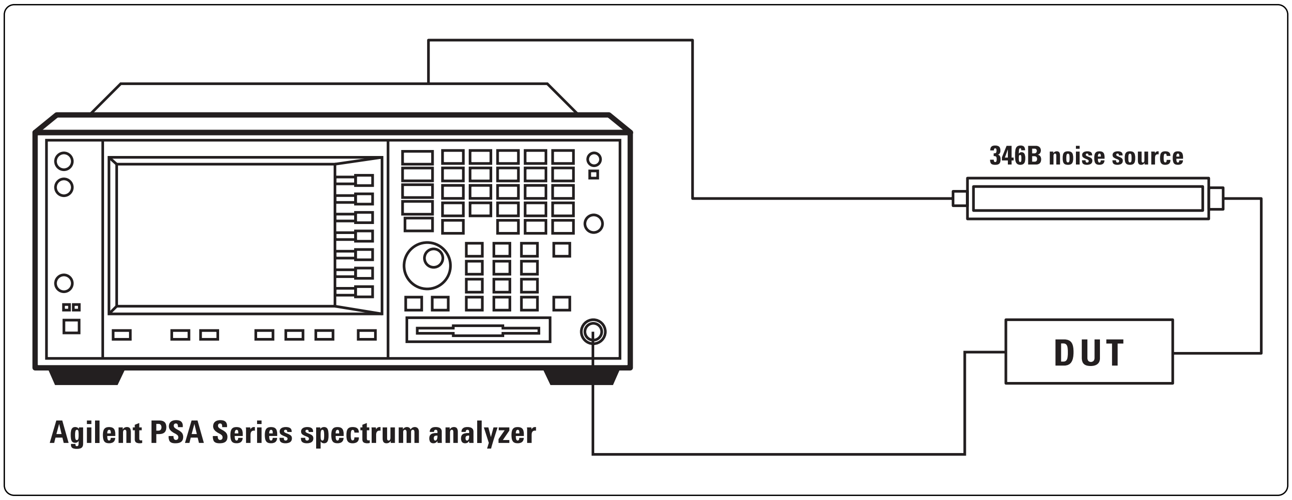


Figure 1.1. The PSA Series Option E444xA-219 Noise Figure Measurement Personality operates in the measurement system shown here. The spectrum analyzer is used as the measurement receiver, and also provides bias power to switch the noise source on and off during measurements.

The following paragraphs describe the features and characteristics of each family of solutions, which can help you choose the best one for a specific application.

The PSA Series spectrum analyzers

Flexibility for multiple measurements - Spectrum analyzers can make many different types of measurements, and adding a noise figure measurement personality may be a more cost-effective solution if a spectrum analyzer is already required in an application. Spectrum analyzers are also useful for troubleshooting noise figure measurements because of their ability to identify sources of signals or interference that could increase uncertainty.

Low frequency measurements - PSA Series spectrum analyzers measure noise figure at lower frequencies (200 kHz vs. 10 MHz) than the NFA Series noise figure analyzers. These frequencies are also covered by the PSA's internal preamplifier (Option E444xA-1DS).

Wider selection of RBWs - Measurement bandwidth for noise figure should be narrower than the bandwidth of the DUT, and the PSA Series has 160 RBWs, from 1 Hz to 8 MHz. For DUTs with a very narrow bandwidth this may be an advantage.

Internal uncertainty calculator - In addition to Agilent's Web-based uncertainty calculator, the measurement personality for the PSA Series also includes an internal uncertainty calculator which incorporates the analyzer's own specifications.

The NFA Series noise figure analyzers

Highest instrument accuracy and lowest uncertainty - The NFA Series offers the industry's most accurate and reliable noise figure measurements.

Coverage from 10 MHz to 110 GHz – Both the PSA Series and NFA Series cover frequencies to 3 GHz, but the NFA Series also directly covers frequencies to 26.5 GHz, and includes an internal preamplifier to cover this frequency range. The NFA Series also supports external mixing to cover the frequency range of 26.5 to 110 GHz. While the PSA Series measurement personality covers frequencies to 26.5 GHz, no internal preamplifier is provided, and measurement performance is most appropriate for high-gain (20 dB or more) devices.

Automatic download of ENR data from SNS Series smart noise sources – While the PSA Series and NFA Series both support the Agilent 346A/B/C noise sources, the NFA also supports the SNS Series noise sources. When plugged into the NFA Series, these noise sources automatically download their excess noise ratio (ENR) data, speeding measurement setup and eliminating a major cause of user measurement error. In addition, the SNS Series noise sources automatically measure temperature, and the operator can use these readings to make the most accurate measurements possible.

Faster measurements where mode switching is required - In manufacturing applications where a spectrum analyzer is also making other measurements such as distortion or power, the time required to switch modes to the noise figure personality may be significant. A dedicated noise figure solution, such as the NFA, will provide measurements immediately.

Control of external sources - The Agilent NFA Series has the ability to control external signal sources for making variable LO mixer measurements.

Cost-effective solution for noise figure only - While a spectrum analyzer with a noise figure personality may be more cost effective when other measurements are required, dedicated noise figure analyzers are less expensive than high performance RF and microwave spectrum analyzers as a solution for measuring noise figure specifically.

Chapter 2. Factors Affecting Noise Figure Measurement Accuracy

Because noise figure is an extremely sensitive, low-level measurement, many more factors affect its accuracy than are found in other higher-level measurements.

People measuring noise figure often make the mistake of considering one, two, or only a few factors when estimating measurement accuracy. Most often, considering only a few factors is not adequate to obtain true accuracy.

This chapter discusses many error sources in noise figure measurements. These error sources can be divided into sources of error that can be eliminated or sources of error that cannot be eliminated.

Error sources that good practices can reduce or eliminate include the following:

- Dirty or faulty connectors, which cause mismatch uncertainty (and make the measurement susceptible to stray signals)
- Electromagnetic (EM) susceptibility (Stray signals are measured as noise power.)
- Noise source impedance change between “on” and “off”
- Mismatch effects at system preamplifier input
- Jitter (the random nature of noise causes successive noise readings to differ)
- Finite bandwidth of device (This problem arises with narrow bandwidth devices.)
- Errors associated with frequency converters
- Loss compensation uncertainty
- Compression effects
- Ambient temperature
- Error from AGC in receivers

Sources of error that cannot be eliminated are combined and determine the overall accuracy of a noise figure measurement when the above errors have been eliminated. The actual contribution of these non-removable errors is a function of device gain, device noise figure, measurement system noise figure, and noise source excess noise ratio (ENR). Errors that cannot be eliminated include the following:

- Mismatch uncertainty
- ENR uncertainty of noise source
- Measurement system uncertainty

Sources of error that can be reduced or eliminated

Before modern noise figure measurement systems became available, eliminating some sources of error was difficult. Quite often, they were ignored and the errors were accepted. With the Agilent PSA Series Option E444xA-219, many of these errors are eliminated. Some sources of error, however, can only be reduced or eliminated using good measurement practice. Descriptions of these error sources follow.

Dirty or faulty connectors

Only a small amount of dirt on a connector can cause insufficient contact and allow extraneous signals to couple into the measurement. (And it only takes one dirty connector to spread dirt to many.)

If dirt is visible on connectors, they should be cleaned with a cotton swab and isopropyl alcohol.

Connectors do not last forever; they wear. Connectors with worn plating on the inner or outer conductors should be replaced to prevent loose, intermittent connections.

To learn more about proper connector care, ask your sales representative about Agilent courses (H7215A/B/C #160). These courses on connector care are available in-person or through Agilent e-learning channels.

EM susceptance

Noise figure measurements are often performed in environments where stray signals are present. Since screen rooms are a luxury not available to many testers, stray signals often get coupled into the measurement. Signals emitted from computers and other instruments, fluorescent lights, local broadcast stations, wireless networks, and other sources can get coupled into a measurement through non-threaded connectors, poorly shielded cables, or directly into the device being tested.

Stray signals can be identified easily with the PSA by selecting the spectrum analyzer mode and searching for signals present over the frequency range of interest. (A narrow resolution bandwidth and 0 dB attenuation may be useful, along with the built-in preamplifier Option E444xA-1DS.)

How are problems with stray signals avoided? First, threaded connectors should be used in the signal path whenever possible. (Non-threaded connectors, like BNC, are very susceptible to stray signals.) Second, double-shielded cables should be used. Third, the device being measured should be enclosed in a shielding container. (This is especially important when measuring noise figure on an open PC board.)

If all else fails, it is possible through judicious use of bandwidth and number of points to “miss” the interfering signal. This is possible because Option E444xA-219 actually measures at discreet frequency points and interpolates the trace between them. These points are equally spaced and are indicated on the trace during system calibration.

Impedance change between noise source “on” state and “off” state

During a noise figure measurement, the noise source is turned on and off automatically under instrument control. When a noise source turns on, the noise generating diode appears as one impedance. When off, it appears as another, different impedance. With some noise sources, especially high ENR models (> 20 dB ENR) this impedance difference is significant. Most 13 to 16 dB ENR models, such as the 346B, have an internal attenuator that reduces this difference to an acceptable amount (change in reflection coefficient of about 0.05 or less). Use of models with an internal attenuator is suggested with the Agilent PSA’s Option E444xA-219. Low ENR noise sources (< 10 dB ENR) are available that have additional internal attenuation. Generally, they are only used when the device to be tested is sensitive to changes in match. For some measurements, a low ENR noise source may actually increase the measurement error. High noise figure devices are most affected as shown in Figure 2.3.

Mismatch effects at system preamplifier input

During system calibration, the preamplifier/spectrum analyzer noise figure is measured. This noise figure is then used during measurement as a correction (second stage contribution) to overall noise figure. If the device to be tested presents an output impedance different from the noise source impedance, the internal noise generation mechanisms within the system preamplifier may be affected between calibration and measurement, resulting in a deviation in the second-stage contribution. With high-gain devices and devices with good output match, this error is generally negligible. When testing low-gain devices having a poor output match, an isolator can be used at the system preamplifier input to provide a constant impedance to the preamplifier.

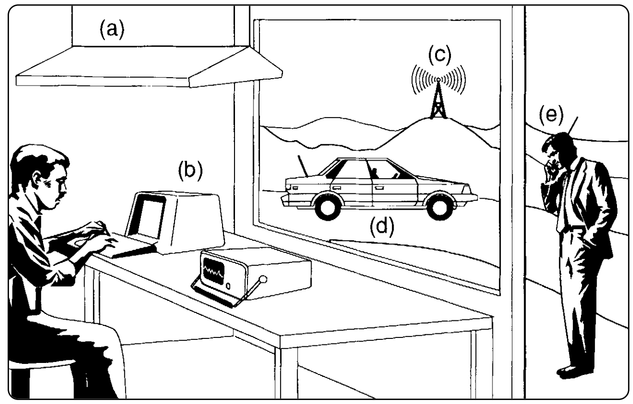


Figure 2.1. Signals can get coupled into a noise figure measurement from many different sources (a) fluorescent lights (b) computers and other instruments (c) local tv/radio stations (d) mobile radio (e) portable two-way radio or phone.

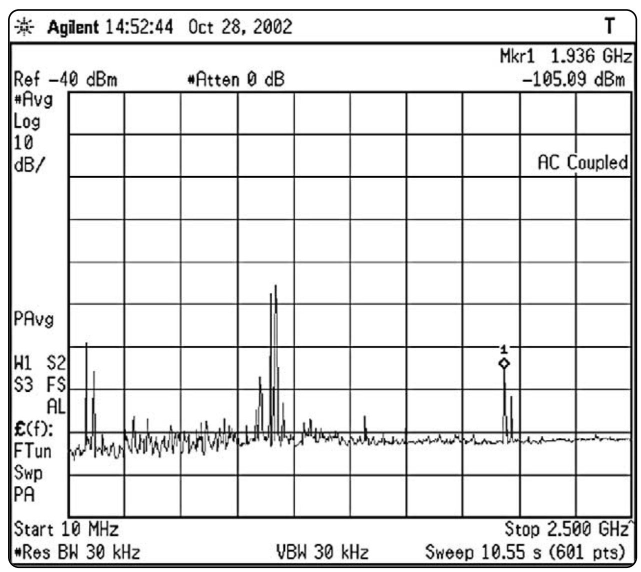


Figure 2.2. Stray signals can be found and measured directly using PSA in its normal spectrum analyzer mode The built-in preamplifier (Option E444xA-1DS) can be used to make these measurements faster and more accurate.

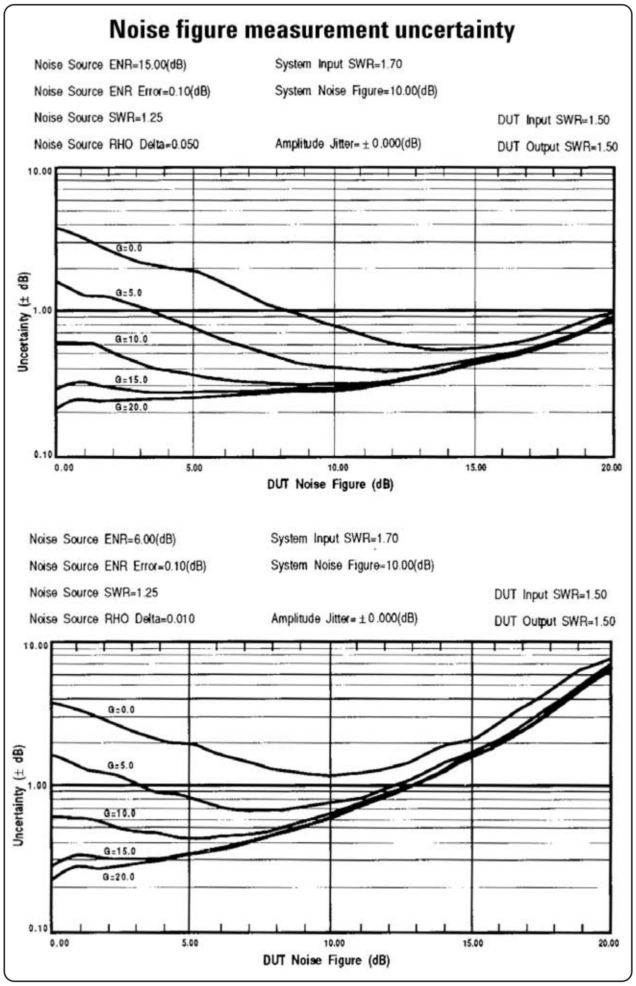


Figure 2.3. The effect of the noise source ENR on noise figure measurement uncertainty

Jitter

All noise measurements exhibit some degree of instability, variance, or jitter, because of the random nature of noise. The resulting repeatability error is a function of the following:

- Device noise figure and gain
- ENR of noise source
- Bandwidth of measurement system
- Averaging time of measurement system

Because the device and the noise source parameters usually cannot be changed, jitter is minimized by using a wide bandwidth and a large amount of averaging. When making narrow bandwidth measurements, increasing the averaging time is generally necessary. How averaging time and measurement bandwidth affect repeatability is discussed in more detail in Chapter 4. PSA Option E444xA-219 has an uncertainty calculator mode that provides a simple way to determine the repeatability due to jitter for a specific measurement. The uncertainty calculator is discussed in Chapter 5.

Finite bandwidth of device

A general assumption made when performing noise measurements is that the device to be tested has an amplitude versus frequency characteristic that is constant over the measurement bandwidth. Some noise figure meters (not including the Agilent NFA Series) have a fixed bandwidth of approximately 4 MHz. When the device bandwidth is less than the measurement bandwidth an error is introduced into the system. While most amplifiers and other broadband circuits present no measurement difficulties, many receivers and more complex systems have narrowband circuits and cannot be accurately measured using conventional noise figure meter without performing a bandwidth correction. A bandwidth correction procedure involves characterization of the device noise bandwidth. Care must be taken with this procedure to avoid introducing error.

The PSA Option E444xA-219 simplifies narrowband measurement by providing selectable measurement bandwidths. One must simply select a bandwidth that is narrower than the device to be tested.

When doubt exists as to what the device bandwidth is, it is possible to verify that the measurement bandwidth is narrow enough. The device noise figure is measured, then another measurement is made with a narrower bandwidth. If the resulting device noise figure is the same, the measurement bandwidth was narrow enough. The noise figure should be independent of bandwidth. When using narrow measurement bandwidths, it may be necessary to increase the averaging time.

Errors associated with frequency converters

Frequency converters such as receivers and mixers usually are designed to convert a single RF frequency band to an IF frequency band. Sometimes the desired RF frequency band is not the only band that converts to the IF frequency band. These unwanted frequency band conversions include the image response ($f_{LO} + f_{IF} + f_{LO} - f_{IF}$ depending on the converter), harmonic responses ($2f_{LO} \pm f_{IF}$, $3f_{LO} \pm f_{IF}$, etc.), spurious responses, and IF feedthrough response. Often, particularly in receivers, these responses are negligible due to internal filtering.

With many other devices, especially mixers, one or more of these responses may be present and may convert additional noise from the noise source in these unwanted bands during measurement. This can result in a measurement error showing the noise figure to be worse than the true value.

Mixers having two main responses (f_{LO} + f_{IF} and f_{LO} – f_{IF}) are often termed double sideband (DSB) mixers. One source of error in measuring these mixers involves these two responses. The noise figure measurement system, tuned to the IF, measures the combined noise from the two down-converted bands. Because of this, the noise figure value displayed will be worse by approximately 3 dB. If the device response of the two sidebands is not equal, the error will differ from the 3 dB factor. Also, other responses, although not dominant, may still get averaged into the final noise measurement and, if large enough, will cause additional errors.

Ideally, a filter should be present at the device input to filter out these responses so that the true single-sideband (SSB) noise figure will be measured. Where this is not possible, such as in the case of many microwave mixers with low frequency IF bands, it is possible to correct for the effect of the image response.

If the two main responses are known to be nearly equal and other responses are negligible, an input loss correction of –3 dB can be entered to correct for the additional noise present in the system to give the equivalent SSB noise figure.

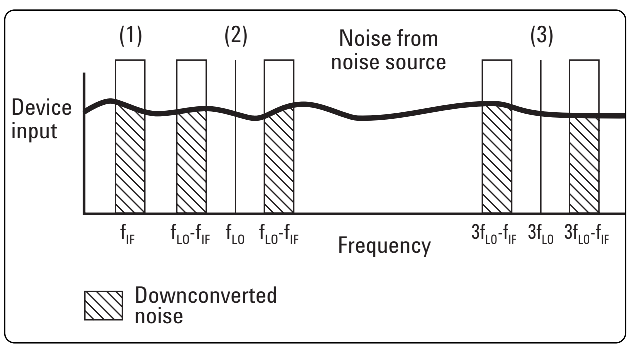


Figure 2.4. Possible noise conversion mechanisms with mixers and converters. (1) IF feedthrough response, (2) double sideband response, (3) harmonic response

Converters used in noise receivers, such as radiometers and radiometric sensors are often designed to make use of both main responses, in which case it is desirable to know the DSB noise figure. In this case, no correction should be made for the additional noise; the resulting noise figure measured will be in DSB terms.

Loss compensation uncertainty

When entering correction factors for losses in the system, the resulting measurement accuracy will depend on the accuracy with which these losses have been specified. When a measurement can be made without cables or other losses, particularly at the device input (noise source output), one should do so. When this is not possible, losses should be accurately measured on a calibrated network analyzer or spectrum analyzer with tracking generator.

Loss compensation should not be used where a reactive mismatch loss is involved, such as when using connectors or adapters. While loss can be associated with connectors, it is generally a reactive mismatch, and the actual loss is dependent on the terminating vector impedance on the transmission line. In this case, it is quite possible that the loss corresponding with the connector would be different in the noise figure system from what was measured on a network analyzer.

Only quality connectors should be used in a noise figure measurement system because mismatch error from a bad connector cannot be easily eliminated.

Compression error

As with any receiver-based system such as a spectrum analyzer, considerations for dynamic range are necessary when performing measurements. Several factors can cause compression errors in the system.

- High gain devices
- Total noise power from broadband devices
- Spurious signals present at system input

High gain devices

When noise levels are too high, as with high-gain devices, compression effects in the spectrum analyzer or in the system preamplifier can introduce error. To maximize measurement range, calibration needs to be performed at low noise levels to allow for level increases when the device to be tested is added to the system.

Generally speaking, the total power at the first mixer should be kept below -20 dBm for high accuracy results using the PSA. This is normally done by using the spectrum analyzer's input attenuator.

Selecting input attenuation range

The PSA noise figure personality cannot automatically set the appropriate input attenuator range, and therefore there is a risk of overdriving the instrument due to the total noise power at its input. In most cases the 0 dB attenuation setting can be used, but other attenuation values may be needed, as shown in Table 1.

For frequencies from 200 kHz to 3 GHz the figures in Table 1 assume the internal PSA preamplifier is on and that a noise source with a 5 dB ENR is being used. For frequencies from three to 26.5 GHz the figures assume a noise source with a 15 dB ENR.

Note: Noise sources are inherently broadband, but if the DUT has a narrower bandwidth than the full 200 kHz to 3 GHz covered by Option E444xA-219 and the internal preamplifier, then the "Approximate DUT Characteristics" described in Table 1 can increase accordingly. For example, if the DUT has a bandwidth of 100 MHz, then the Approximate DUT Characteristics can increase by a factor of 10log (3 GHz - 200 kHz) - 10log (100 MHz) = 15 dB. Therefore for 0 dB attenuation the combined NF and gain of the DUT would now be 35 dB maximum instead of 20 dB.

It is very easy to avoid compression error even for very high gain devices. When measuring devices having noise figure and/or gain in excess of the above guidelines, output attenuation is added to the device and an output loss correction is entered.

Total noise power from broadband devices

Since the preamplifier and spectrum analyzer input circuits often have a very broad bandwidth, the integrated noise power that must be handled by the system can be substantial when broadband devices are to be tested.

This power can be estimated if the gain, noise figure, and noise bandwidth of the device are known:

Equation 2.1

$$P_{noise}\,[\text{dBm}] = 10 * \log_{10}(10^{(ENR/10)} + 10^{(NF/10)}) + \text{gain} + 10 * \log_{10}(bw) - 174$$

where ENR is the noise source ENR in dB
NF is the device noise figure in dB
gain is the device gain in dB
bw is the noise bandwidth of the device in Hz

Alternatively the power can be measured using a power meter (with the noise source connected to DUT and in “on” state).

The total power incident to the spectrum analyzer's input mixer must be kept below -20 dBm to avoid compression effects and obtain best instrument accuracy. Since the PSA Option E444xA-1DS internal preamplifier has a nominal gain of 28 dB, the total input power to the analyzer should be below -48 to -50 dBm for best accuracy, and to account for some variation in preamplifier gain. Either attenuation or filters to reduce broadband noise should be used when high noise power is present at the device output.

Spurious signals

Spurious signals can also add to the total power incident at the system input. Any spurious signal existing within the system input frequency range, if strong enough, could potentially cause a compression error. If spurious signals are present, a filter at the device output can often be used to eliminate this source of error. The total power including any spurious signals should be kept below –20 dBm into the spectrum analyzer.

Frequency	Attenuation setting	Max input power for high accuracy	Approximate DUT characteristics
200 kHz to 3 GHz	0 dB	-50 dBm	Combined NF and Gain of DUT < 20 dB over full bandwidth
200 kHz to 3 GHz	4 dB	-46 dBm	Combined NF and Gain of DUT < 24 dB over full bandwidth
200 kHz to 3 GHz	8 dB	-42 dBm	Combined NF and Gain of DUT < 28 dB over full bandwidth
200 kHz to 3 GHz	12 dB	-38 dBm	Combined NF and Gain of DUT < 32 dB over full bandwidth
3 GHz to 26.5 GHz	0 dB	-20 dBm	Combined NF and Gain of DUT < 60 dB over full bandwidth

Table 1. Input attenuation ranges

Ambient temperature

Ambient temperature can affect noise figure measurement accuracy in two ways. Fortunately, the user of the Option E444xA-219 can readily correct for both.

One error can be caused by ambient temperature changes that occur after calibration. This causes various system parameters such as internal noise to drift from their values during calibration. To correct for changes in ambient temperature since the last calibration, first perform a basic amplitude and frequency calibration for the spectrum analyzer, then perform a noise figure calibration before measuring the device.

The other error involves the case temperature of the noise source. The "off" state noise output of the noise source is one of the parameters used to calculate the noise figure of the device under test. This "off" state noise is assumed to be that of a resistor at some known temperature. The user needs to enter this temperature into the measurement system. Error can result when the temperature entered is significantly different from the actual noise source case temperature. This is especially true when temperature testing devices. If, for example, a test is performed with the noise source in a temperature chamber at a case temperature of 100 °C and the measurement system uses an incorrect temperature of 17 °C, the resulting noise figure can be in error by as much as 1 dB.

Error from AGC in receivers

Many receivers have automatic gain control (AGC). When measuring noise figure, the noise source is switched between the high noise "on" state and the low noise "off" state. Depending on where the ACTC threshold is set, the overall gain of the receiver could change during a noise figure measurement due to these noise level changes. One must assume for the measurement that the gain of the device is constant over the course of the measurement. When this is not true, an error will be introduced. AGC generally should be disabled when measuring noise figure.

Sources of error that cannot be eliminated

Several sources of error can be reduced, but not eliminated. These non-removable factors can be divided into three groups, listed below:

Mismatch uncertainty

There are typically three types of mismatch uncertainty: mismatch between the noise source and DUT input, mismatch between the DUT output and the measurement system input, and mismatch between the noise source and the system input (during calibration).

ENR uncertainty of noise source

This is the uncertainty between the calibrated and actual (National Institute of Standards and Technology) value. This is an uncertainty only given for calibrated points; it does not take into account ENR variation with frequency between the calibrated points. However, this interpolation error is generally negligible.

Measurement system uncertainty

Uncertainty in the measuring instrumentation cannot be eliminated entirely, but the digital IF of the Agilent PSA Series dramatically reduces error sources such as log amplifier error. These errors and the resulting uncertainty are handled in the uncertainty calculators (see Chapter 5, Figure 5.1 and Figure 5.2).

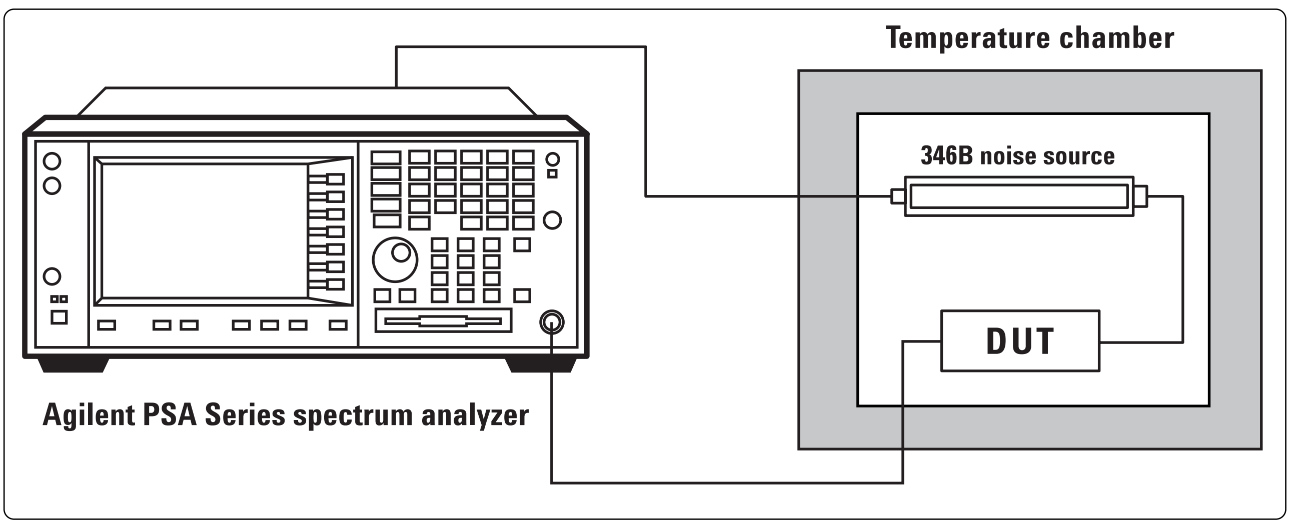


Figure 2.5. Temperature chamber with device under test and noise source inside

Chapter 3. Methods to Calculate Accuracy

Calculating noise figure accuracy is not a simple, straight-forward calculation for several reasons. First, as stated previously, many sources of error affect noise figure measurement accuracy (ENR uncertainty, instrumentation uncertainty, mismatch uncertainty, etc.). Second, the noise power measurement results are not readily available from a measurement system, so noise figure accuracy based on the power measurements cannot be calculated. Third, the results that are available, measurement system noise figure, DUT noise figure, and DUT gain, have interdependencies that must be taken into account.

This chapter discusses two methods of calculating measurement accuracy. The first method, the cascade noise figure equation method, provides an intuitive understanding of noise figure accuracy but makes simplifying assumptions that are not always valid; it will be used as an instructional tool. The second method, the statistically based measurement simulation method, provides a better representation of noise figure measurement accuracy than the cascade method. Statistically generated uncertainty curves are provided in Appendix A to help you estimate the accuracy of your measurement.

Cascade noise figure accuracy equation

A noise figure measurement system measures the combined noise figure of the DUT and the measurement system. (See Figure 3.1.)

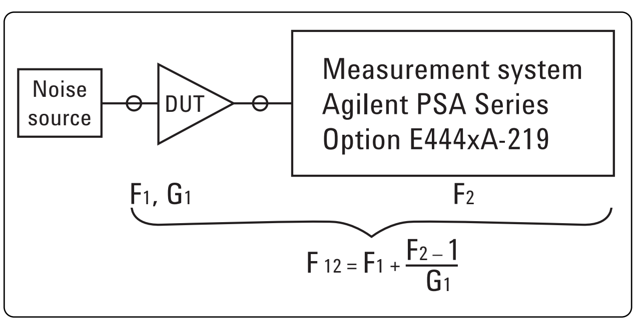


Figure 3.1. Typical noise figure measurement setup. Device and measurement system noise figures combine according to the cascade noise figure equation.

To determine the noise figure of the DUT alone, a calibrated system (such as the Agilent PSA Series Option E444xA-219) subtracts the noise contribution of the measurement system (i.e., the spectrum analyzer and system preamplifier) from the cascaded DUT/measurement system noise figure:

Equation 3.1

$F_1 = F_{12} - (F_2 - 1)/G_1$

where F_2 is the measurement system noise figure measured during calibration
F_1 is the device under test (DUT) noise figure
F_{12} is the overall noise figure measured including the DUT and measurement system noise contributions
G_1 is the device gain and is calculated by taking a noise power ratio between the measurement (F_{12}) and calibration (F_2).

(These are all linear power ratio terms (milliwatts, for example), not logarithmic terms (dBm.)

The measurement of DUT noise figure (F_1) can be thought of as a calculation based on three separate measurements – the F_{12} measurement, F_2 measurement, and G_1 measurement. (G_1 is actually not a measurement but a derivation from the F_2 and F_{12} measurements.) If one knows how F_1 varies with changes in the F_{12}, F_2, and G_1 measurements, one can calculate an overall accuracy for F_1 based on how errors in each of those measurements affect F_1.

By taking the partial derivatives of F_{12}, F2, and G_1, with respect to F_1, in Eq. 3.1, the sensitivity of F_1, relative to the three measurements can be calculated. Equation 3.2 shows this partial-derivative equation, with the measurement deviations (terms) converted to power ratios.

Equation 3.2

$\Delta NF_1 = [F_{12}/F_1]*\Delta NF_{12} - [F_2/(F_1G_1)]*\Delta NF_2 + [(F_2 - 1)/(F_1G_1)]*\Delta G_1$

When the magnitude of the individual uncertainties [ ] are known, the overall uncertainty, NF1 can be calculated by squaring each of the three terms, adding them, then taking the square root (i.e., root-sum-of-squares or RSS).

The cascade noise figure accuracy equation (Equation 3.2) gives a good picture of how the error-causing factors affect overall accuracy. For example, as G1 increases, two terms in the equation decrease. When the terms are then added in a root-sum-of-squares manner, overall uncertainty decreases. Equation 3.2 is not, however, recommended when calculating accuracy — it assumes that gain is a separate measurement. (Remember, G12 is only a derivation.) This assumption makes the resulting uncertainty unrealistically large

Measurement simulation method

The measurement simulation method uses a computer to simulate probable measurement conditions. It uses those conditions to simulate probable measurement results and then calculates a realistic uncertainty based on many such simulated measurements.

The simulation method assumes that each source of measurement error (instrumentation uncertainty, ENR uncertainty, etc.) is distributed in a Gaussian (bell-shaped) probability distribution. The one exception is reflection coefficient phase; this is assumed to be uniformly distributed between 0 and 2.

The standard deviations for the simulated measurement conditions are derived from instrument specifications. The instrument specifications are assumed to be based on a confidence level of three standard deviations from the mean performance.

The computer first generates a random variate corresponding to each measurement condition. It then determines the actual noise figure measurement result, based on those conditions. After many “measurements” (2,000), the computer calculates boundaries in which a certain percentage of the “measurements” lie. These boundaries define the measurement uncertainty.

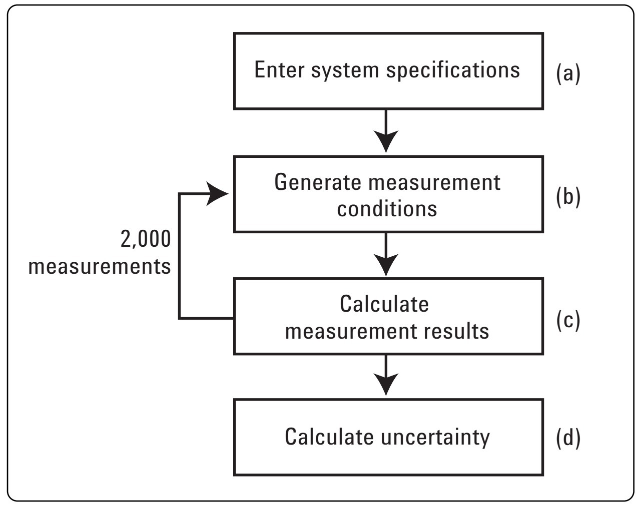


Figure 3.2. Flow graph of measurement simulation method for calculating noise figure accuracy. (a) Programmer enters measurement system specifications into the computer. (b) The computer generates typical measurement conditions based on system specifications and probability distributions. (c) Computer calculates the measurement result. After 2,000 of these measurements, (d) the computer calculates uncertainty boundaries where 95 percent of the simulated measurements fall within these boundaries.

The measurement simulation method gives a realistic representation of measurement accuracy. Like the cascade noise figure method, the measurement simulation method has some drawbacks: It can be complicated to program; computation can be time-consuming.

Chapter 4. A Practical Look at Noise Figure Accuracy

This chapter discusses several noise figure accuracy issues on a practical level. The discussions should give you a better understanding of noise figure measurement accuracy so that you will be more comfortable performing and specifying the measurement. Specifically, this chapter shows a practical way to think about noise figure accuracy and repeatability.

Each of the three non-removable error sources mentioned in Chapter 2 (mismatch, ENR, and measurement system uncertainty) affect noise figure measurement uncertainty. Their effects on measurement uncertainty depend on several system parameters: device gain, device noise figure, system noise figure, and noise source ENR.

A good way to begin to understand noise figure accuracy is to study the graphs presented here, which illustrate the effect that the system parameters have on the measurement error.

Uncertainty versus device gain

Figure 4.1 shows the effect of device gain on the noise figure error. The actual magnitude of error will depend on the system uncertainties, but there will be a trend for error to reduce with increasing device gain.

As a general rule, the higher the ratio of the noise power measured to the measurement system noise, the more accurate the measurement will be. Therefore, if a device has high gain, much amplified noise will be measured; as a result, measurement accuracy will be good.

Uncertainty versus device noise figure

Error versus the device noise figure is shown (in Figure 4.2) for two cases: high device gain and low device gain. Both curves ultimately increase for very high noise figures because the internal noise generated in the device is much larger than the ENR of the noise source. In effect, the noise source signal is masked by the device noise and becomes very small. In this case, certain system errors, particularly the log amplifier accuracy (part of the measurement system uncertainty) become significant.

For low noise figure low-gain devices, the error also increases because the low gain produces little noise at the device output and the measurement system noise becomes significant. For high gain devices, this is not the case, and excellent accuracy can be obtained even with very low noise figure devices.

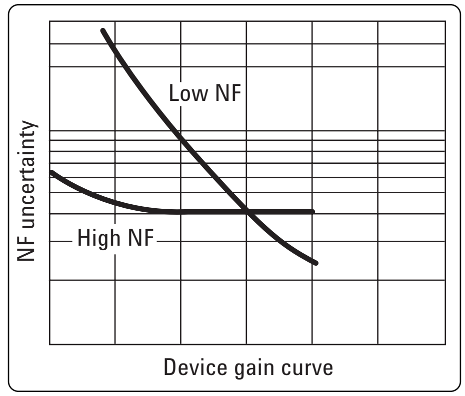


Figure 4.1 The uncertainty versus device gain curve

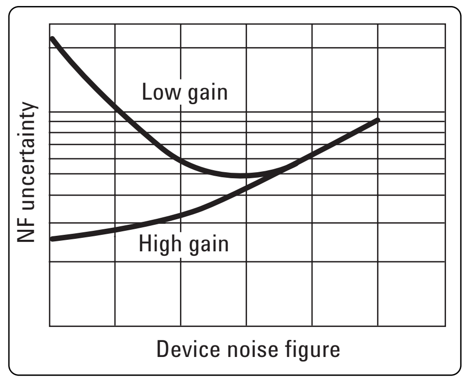


Figure 4.2. The uncertainty versus device noise figure curve

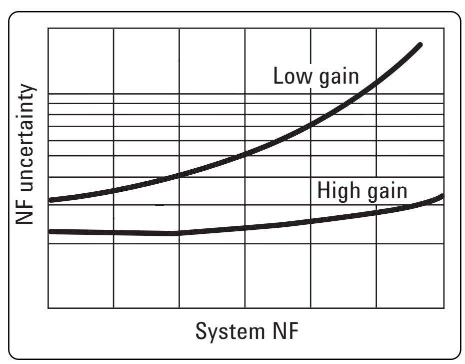


Figure 4.3. The uncertainty versus the system noise figure curve

Uncertainty versus system noise figure

The system noise figure also affects the measurement error (Figure 4.3). System noise figure is a function of the signal analyzer noise figure and the system preamplifier noise figure and gain. System noise figure can be calculated using the cascade noise figure equation (see Equation 5.2). When the system noise figure is high, more system noise is present. When the system noise figure is larger than the device output noise, measurement accuracy is degraded. The two curves show that the system noise figure is more significant for low-gain devices because low-gain devices will produce a smaller noise signal (larger system noise contribution). High-gain devices can tolerate rather high system noise figures.

The effect of measurement system uncertainty

The measurement system uncertainty of signal analyzer-based noise figure measurement systems has traditionally been significantly higher than that of dedicated noise figure meters and noise figure analyzers. The primary reason for the difference was that the precision of the analog log or linear IF detector circuits of spectrum analyzers was not as good as the IF linearity of noise figure meters/analyzers. The all-digital IF of the PSA Series has dramatically reduced or eliminated many of the errors associated with analog IF filter and detector circuits. Therefore, at frequencies to 3 GHz the instrument uncertainty of the PSA Series spectrum analyzers is comparable to that of the Agilent NFA Series dedicated noise figure analyzers.

In understanding accuracy, it is important to distinguish between instrument uncertainty and total measurement uncertainty. Some people who measure noise figure mistakenly consider the noise figure measurement system uncertainty to be the main indicator of measurement uncertainty. However, other system errors such as ENR and mismatch can dominate the measurement uncertainty calculation.

Measurement repeatability due to jitter

Though it is possible, with sufficient averaging time, to have negligible measurement repeatability error due to jitter, it is often important to minimize the measurement time required to achieve a specified degree of repeatability. The trade-offs between repeatability and measurement time are especially important when using narrow measurement bandwidths, since it takes much longer to accumulate a given number of independent measurement samples for averaging.

Noise can be thought of as a series of random events, electrical impulses in this case. The goal of any noise figure measurement system is to find the mean noise level at the output of the device when the noise source is off, as well as when it is on. These levels can be used, with the appropriate corrections, to calculate the actual noise figure of the device. In principle, the time required to find the true mean noise levels would be infinite. In practice, averaging is performed over some finite time period. The difference between the measured average and the true mean will fluctuate from measurement to measurement and give rise to a repeatability error.

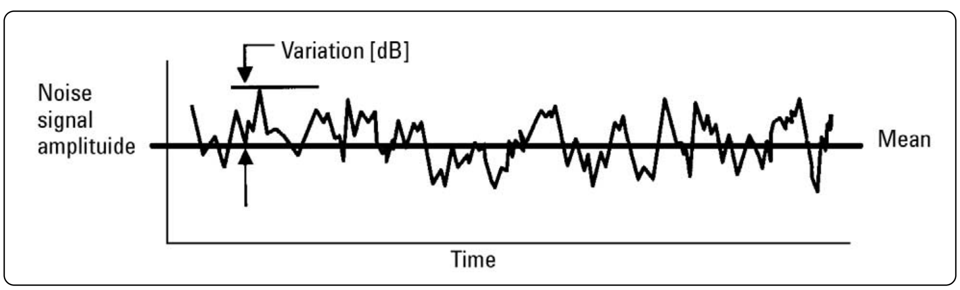


Figure 4.4. Noise jitter

The expected variation (three standard deviations) in the measurement of a noise level on a signal analyzer in log mode can be approximated by Equation 4.1:

Equation 4.1

$$\text{variation [dB]} \approx 10*\log_{10}(1 + 3/\sqrt{(bw*t)}),\ (t>>1/bw)$$

where bw is the predetection system bandwidth in Hz (i.e. IF noise bandwidth)
t is the effective post-detection averaging time of the noise signal in seconds.

$$t \approx \frac{1}{3 * \text{Video BW [Hz]}} \quad \text{for video BW [Hz]} \geq \frac{128}{\text{Sweeptime [s]}}$$

$$t \approx \frac{\text{Sweeptime [s]}}{400} \quad \text{for video BW [Hz]} < \frac{128}{\text{Sweeptime [s]}}$$

For small variations, the deviation is proportional to $1/\sqrt{(t)}$ so that longer averaging times will produce better averages. Because the average includes more events, it is closer to the true mean. The variation is also proportional to $1/\sqrt{(bw)}$. Larger measurement bandwidths will produce a better average because there are more noise events per unit of time in a large bandwidth; therefore, more events are included in the average.

Precisely determining the uncertainty effect of noise jitter when measuring device noise figure can be a tedious calculation if done by hand. A noise figure measurement involves the measurement of four levels over the desired frequency range: noise source on and off during calibration and noise source on and off during measurement. These levels are functions of the device noise figure and gain, system noise figure, and ENR. Figure 4.5 shows the general effect of jitter on measurement uncertainty.

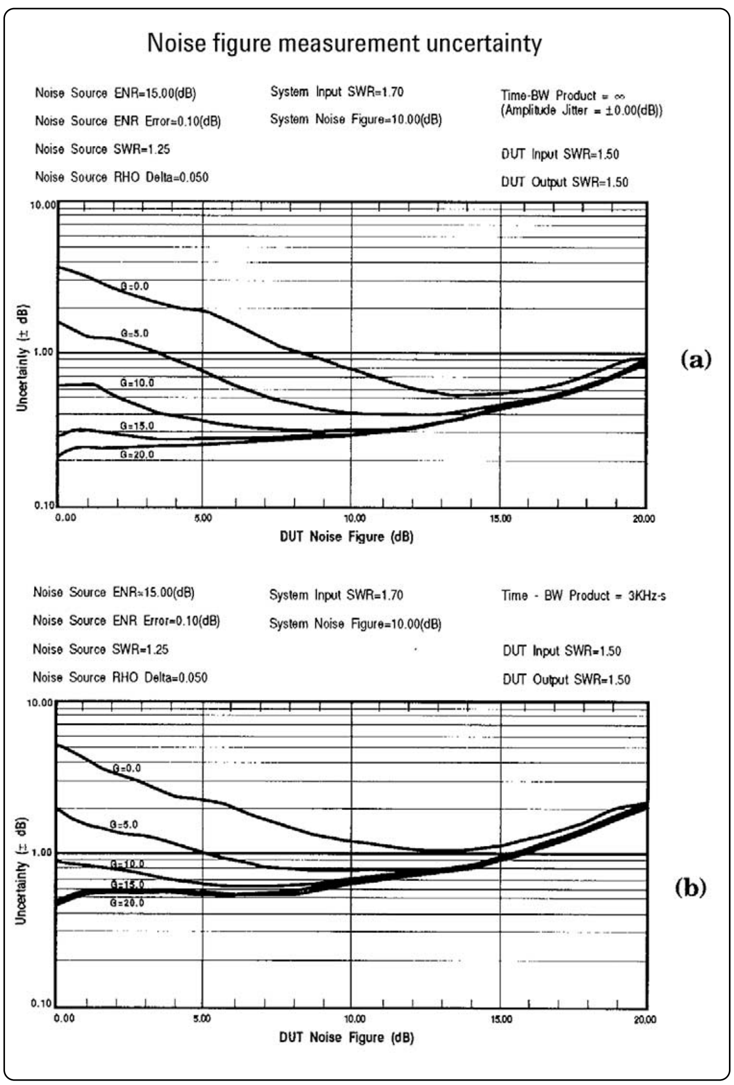


Figure 4.5. Effect of jitter on measurement error, (a) without jitter and (b) with jitter.

Chapter 5. Tips on Optimizing Accuracy

Knowing a systematic way to improve measurement accuracy is just as important as knowing how to improve the sources of error. The following discussion presents a logical process for improving measurement accuracy:

1. Eliminate all removable errors
2. "Increase" device gain
3. Reduce system noise figure, if needed
4. Reduce individual uncertainties

1. Eliminate all removable errors

Removable errors and how to eliminate them are discussed in Chapter 2.

2. "Increase" device gain

Device noise figure and gain usually cannot be changed to obtain a more accurate measurement. However, the device can sometimes be "chosen" for the best possible measurement accuracy. In a receiver front end, the down converting mixer is followed by an IF amplifier. Typically, the combination mixer/IF amplifier noise figure is the important noise figure specification of the receiver. Because of the added IF amplifier gain, a better measurement uncertainty results if the mixer/IF amplifier combination is measured, rather than the mixer alone.

As a general rule, for a more accurate measurement, "choose" the device under test for as much gain as possible (but avoid compression effects as discussed in Chapter 2).

3. Reduce system noise figure, if needed

When measuring devices that have both low gain and low noise figure, reducing the system noise figure may improve accuracy. Here is a useful "rule of thumb" in determining whether the system noise figure is low enough:

Equation 5.1

$$NF_{system}[dBm] < NF_{dut} + GAIN_{dut} - 5$$

where NF_{dut} is the device noise figure in dB
$GAIN_{dut}$ is the device gain in dB
NF_{system} is the system noise figure in dB

To determine the system noise figure that will result from a given combination of spectrum analyzer noise figure, preamplifier gain, and preamplifier noise figure, use the cascade noise figure equation as follows:

Equation 5.2

$$F_{system} = F_{preamp} + (F_{analyzer} - 1)/G_{preamp}$$

where F_{preamp} is the preamplifiers noise figure
G_{preamp} is the preamplifiers gain
F_{preamp} is the spectrum analyzer noise figure
$F_{analyzer}$ is the resulting system noise figure

(All terms in this equation are linear power ratios, not logarithmic.)

If needed, the spectrum analyzer noise figure can be found by running a noise figure calibration without the preamplifier (the preamplifier should be switched off.) Alternatively, the spectrum analyzer noise figure can be derived from the displayed average noise level using the approximate formula:

Equation 5.3

$$NF_{analyzer}\,[dB] = DANL - 10*\log10(RBW) + 174 + 2$$

where DANL is the displayed average noise floor of the spectrum analyzer referenced to a given resolution bandwidth
RBW is the reference bandwidth of DANL in Hz
$NF_{analyzer}$ is the approximate noise figure of the spectrum analyzer in dB.

For example, the analyzer noise figure for the PSA Series, models E4440A, E4443A, E4445A, can be 22 dB maximum from 1.2 to 2.5 GHz maximum, as derived from the specifications, but is typically lower.

The PSA Series internal preamplifier Option E444xA-1DS is suitable for noise figure measurements to 3 GHz. With this preamplifier in place, the analyzer noise figure for the PSA Series models and frequencies as described above can be 8 dB maximum, but it typically lower.

While lower system noise figures can result if a higher-gain preamplifier is used, a reduced dynamic range would result because measurements will be made closer to compression limits. As described in Chapter 2, the total power incident at the spectrum analyzer input must be limited to avoid increased uncertainty due to compression effects. For this reason, system noise figure should be reduced only when needed, and one should avoid using preamplifiers with excessive gain.

4. Reduce individual uncertainties

Once removable errors have been eliminated and the system noise figure is sufficiently low, measurement accuracy can be improved further only by reducing the individual uncertainties.

Reduce mismatch (add an isolator to the measurement system input)

An isolator at the measurement system input can reduce mismatch and, in turn, measurement uncertainty.

Because the measurement system will calibrate out the loss present at the system input, the isolator loss should not be entered as a loss compensation.

Pads (attenuators) also reduce mismatch. Pads, however, have high noise figures. The accuracy improvement gained in improved mismatch is often lost in degrading the system noise figure. An isolator provides a match as good or better than a pad with lower noise contribution.

An isolator between the noise source and the device input is not suggested. With a quality noise source such as the 346B, the minor reduction in mismatch rarely helps to reduce measurement uncertainty and often introduces other problems such as out-of-band resonances and reflections from lower-quality connectors.

Reduce ENR uncertainty (have the noise source calibrated as accurately and as often as possible)

The commercially available 346 noise source is two or three calibration generations removed (depending on frequency) from the National Institute of Standards and Technology. Each level of calibration adds a small amount of uncertainty.

Noise source ENR uncertainty can be improved by eliminating one or more calibration generations. The Standards Lab offers noise source recalibration services, typically eliminating one calibration generation. (Contact your nearest Agilent service center for more details.)

The National Institute of Standards and Technology also has noise calibration services. For more details, contact the NIST directly.

Using the internal and Web-based uncertainty calculators

Improving system performance in applications such as mobile and satellite communications and radar often requires improving the noise figure performance of subsystems and components. Making reliable measurements of devices with very low noise figure requires a good understanding of measurement accuracy or uncertainty.

To estimate total measurement uncertainty it is necessary to understand how a number of factors affect the measurement. As described in Chapters 2 and 4, measurement system uncertainty is only one of these factors, and is often not the dominant one in determining overall accuracy. Other factors associated with the device under test must also be considered to accurately model total measurement uncertainty.

Option E444xA-219 for the PSA Series includes an internal uncertainty calculator, as shown in Figure 5.1. This internal calculator includes default values for the relevant PSA specifications. It also includes values for the specifications of the appropriate Agilent 346A/B/C noise sources. The user need only enter measurement specific parameters such as the input and output match of the DUT, along with the gain/noise figure of the DUT from the measurement display.

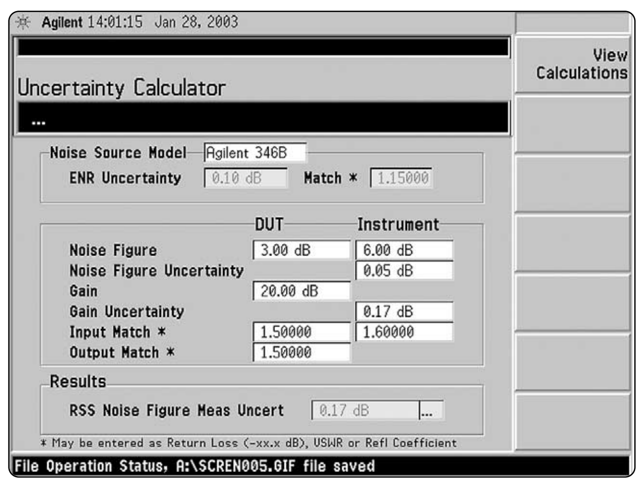


Figure 5.1. Internal measurement uncertainty calculator for the PSA Series Option E444xA-219

Agilent also provides a Web-based uncertainty calculator. This calculator can be used to calculate the uncertainty of two-port devices like amplifiers or of frequency converting devices like mixers or receivers. The calculator includes a sweep function that allows a number of the input parameters to sweep between two different values. In this way the variation in uncertainty due to changes in the selected parameter can be seen.

For more information or to use the Web-based uncertainty calculator, point your Web browser to **www.agilent.com** and search under "noise figure uncertainty calculator."

Summary

This product note includes the information needed to optimize your noise figure measurements.

It has demonstrated several important considerations for noise figure measurements:

- Many factors can affect the accurate measurement of noise figure (Chapter 2).
- Measurement accuracy can be estimated using statistically generated curves (Chapter 3).
- Although it appears complicated, noise figure can be understood in a practical sense (Chapter 4).
- Tips on optimizing measurement accuracy (Chapter 5).

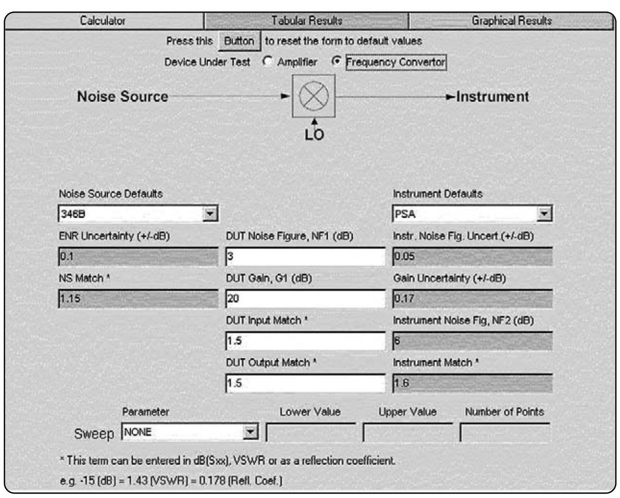


Figure 5.2. Agilent Web-based uncertainty calculator display

Appendix A. Low Frequency Measurements

Low frequency measurements (below 10 MHz are possible with the PSA Series and Option E444xA-219). The built-in preamplifier (Option E444xA-1DS) covers the analyzer's entire frequency range to 3 GHz, eliminating the need for a separate preamplifier for low frequency measurements. It is necessary to use a noise source or noise generator, which covers the frequency range of interest.

A major factor in measuring low-frequency noise figure is the presence of the 0 Hz LO feedthrough response of the spectrum analyzer. A sufficiently narrow measurement bandwidth must be used to reject this signal at the lowest measurement frequency. In general, this means that the measurement bandwidth must be less than 1/30 of the lowest measurement frequency.

The measurement architecture of the PSA Series offers a number of benefits for these measurements. The all-digital IF provides resolution bandwidth filters which are narrow, stable, accurate, and which have excellent shape factor. For low frequency measurements, spectrum analyzer LO phase noise may have the effect of increasing the apparent noise figure of the analyzer. The very low phase noise of the LO in the PSA Series eliminates this problem in most measurements, making the PSA Series an excellent solution for low frequency noise figure measurements.

Appendix B. 75 Ω Measurements

75 Ω measurements can be accommodated with the PSA Option E444xA-219 measurement personality by using auxiliary 75 to 50 Ω transformers or minimum loss pads. The loss of the transformers or pads is then entered as a loss correction to the measurement. There are three ways of correcting for this loss, each with advantages and disadvantages.

Setup (a) is the simplest approach. The mismatch presented by 75 Ω at the 50 Ω system preamplifier input is 1.5 SWR. In many cases, particularly when testing devices with large gain, the resulting measurement error is acceptable.

Setup (b) presents 75 Ω to both device ports. The two losses are entered as corrections. Accurate numbers should be entered for these corrections, as any error associated with them will contribute to the overall measurement error. This setup is suggested for most measurements.

Setup (c) presents 75 Ω to both ports of the device and requires only that the source pad be entered as a correction. (The system input pad gets included in the calibration automatically.) A disadvantage exists, however. Loss for both pads is present during calibration and reduces the calibration signal level. For this reason, the measurement repeatability due to jitter will be higher than in setup (b). This effect is most significant when measuring low gain devices.

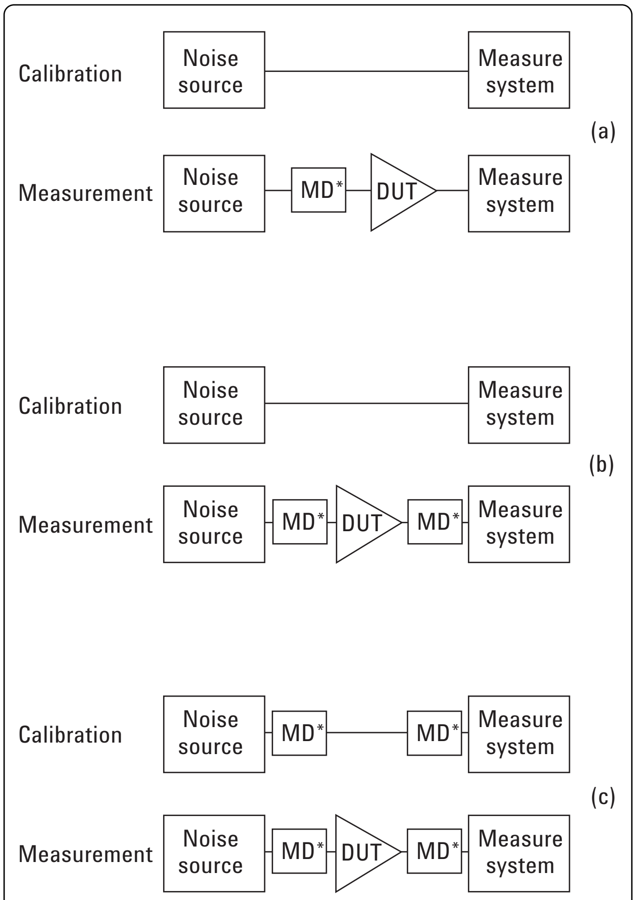
For any of the above configurations, a minimum loss pad rather than a transformer is recommended at the device input or noise source. Minimum loss pads are generally more precise devices, and they introduce less mismatch error than transformers. They also have a well defined loss (usually about 5.7 dB). The device output or system input generally can use either a transformer or minimum loss pad, as uncertainty at this point has somewhat less effect on the measurement error.

Measurement options

(a) Use minimum loss pad at device input. Use no output pad or transformer and accept the output mismatch. Enter pad loss as input loss correction. Calibrate 50 Ω system without pad.

(b) Use minimum loss pad affixed to the device input. Use minimum loss pad or transformer affixed to the device output. Enter corresponding input and output loss as corrections. Calibrate 50 Ω system without pads or transformers.

(c) Use minimum loss pad affixed to the noise source. Use minimum loss pad or transformer affixed to the system preamplifier input. Enter source loss correction for the source pad only. Calibrate 75 Ω system including transformer/pad(s).



MD = Matching device
*Minimum loss pad or matching transformer

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Application Note 57-3 10 Hints for Making Successful Noise Figure Measurements
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Application Note 1354 Practical Noise-Figure Measurement and Analysis for Low-Noise Amplifier Designs
literature number 5980-1916E

PSA Series Product Note Amplitude Accuracy
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