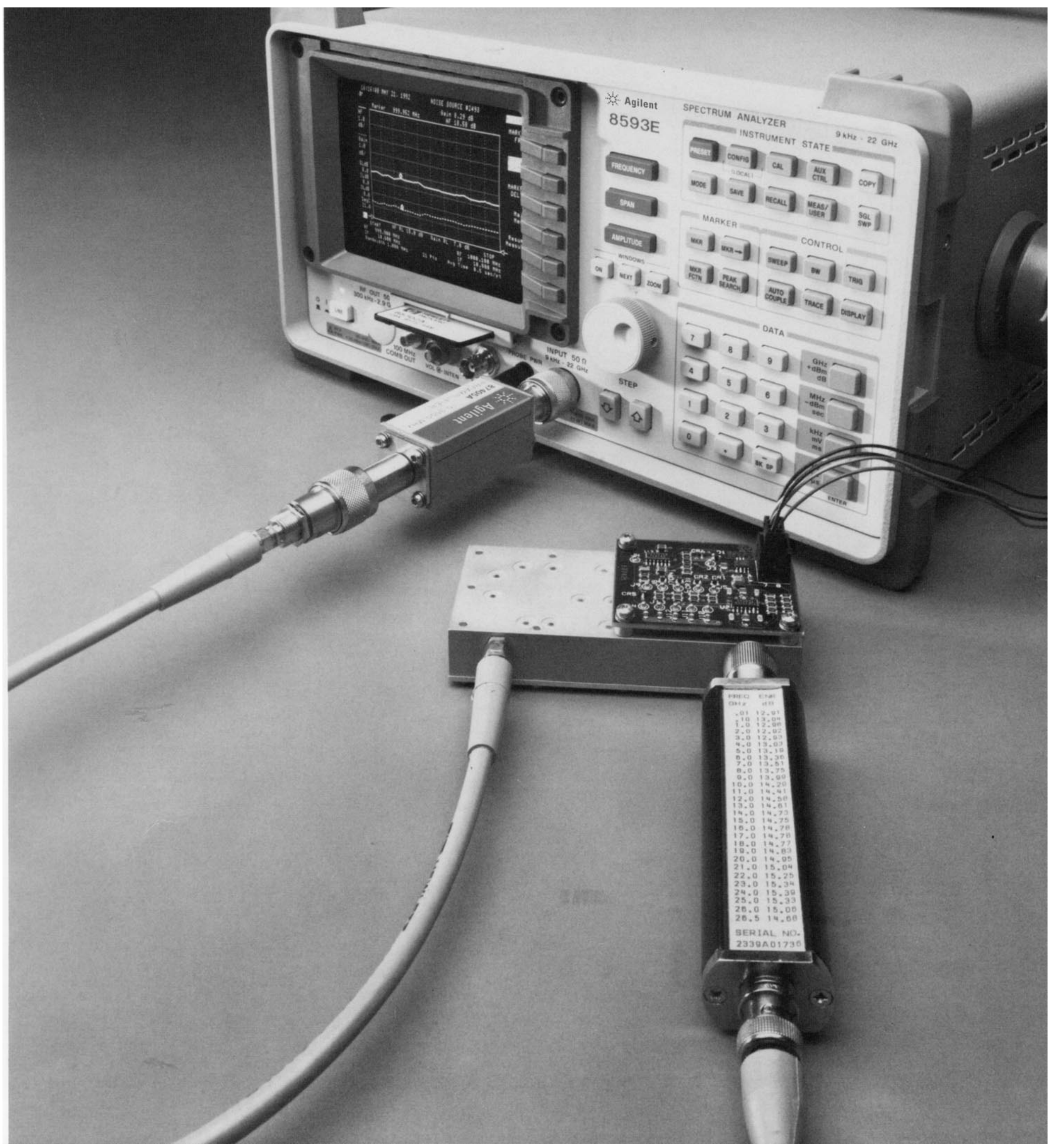
Agilent PN 85719A-1

Maximizing Accuracy in Noise Figure Measurements

Product Note



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Chapter 1. Introduction

Spectrum analyzer based noise figure measurements

Anyone involved in RF and microwave communications is likely to 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 meter. 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. In field service testing, users can perform noise figure measurements using a portable, multipurpose spectrum analyzer. 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 Agilent Technologies 85719A noise figure measurement personality is an optimized system that uses the 8590 E-series spectrum analyzers and minimizes system errors. The system provides a user interface similar to that of a noise figure meter. Features such as variable measurement bandwidths and loss corrections allow the flexibility to configure the measurement, while the built-in repeatability error calculator allows measurement time repeatability trade-offs to be readily made.

Although accurate noise figure measurements are very important, measurement accuracy is seldom calculated. Many factors affect a noise figure measurement, so calculating its accuracy is often complicated and time consuming.

What reading this note will do for you

This note is designed to demonstrate the following:

1. Many factors can affect the accuracy of noise figure measurements (Chapter 2).

2. You can estimate measurement accuracy using statistically generated curves (Chapter 3 and Appendix A).

3. Although it appears complicated, noise figure accuracy can be understood in a practical sense (Chapter 4).

4. Noise figure measurement accuracy can be optimized by following a few simple rules (Chapter 5).

5. Accuracy issues relating to "special" measurements (microwave, low frequency, and 75 ohm) are included in Appendices 2, 3, and 4.

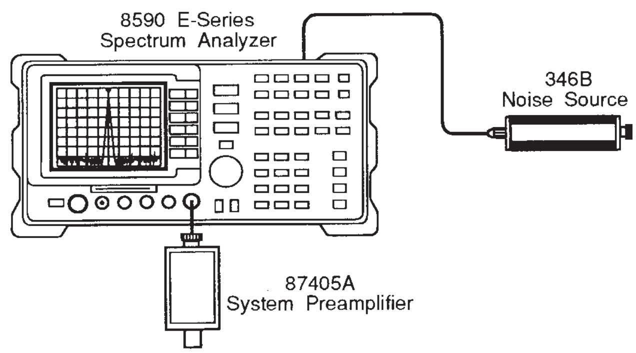


Figure 1.1. The 85719A noise figure measurement personality operates in the noise figure measurement system shown. The 8590 E-series spectrum analyzer is used as the measurement receiver. The system preamplifier reduces the system noise figure to improve accuracy and allow faster measurement.

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 85719A, many of these errors are eliminated. Some sources of error, however, can only be 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 for Service Note 346B-4 *"Agilent 346B Noise Source RF Connector Care"* (lit. no. 00346-90023).

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, 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 85719A 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.)

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 the 85719A 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.

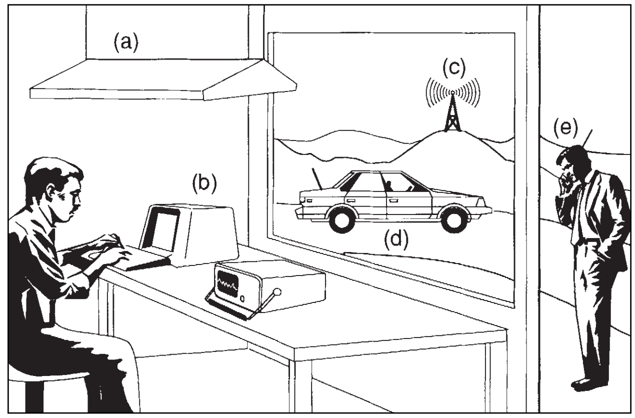


Figure 2.1. Signals can get coupled into a noise figure measurement from many different sources (a) fluorescent lights (b) computer and other instruments (c) local tv/radio stations (d) mobile radio (e) portable two-way radio or phone.

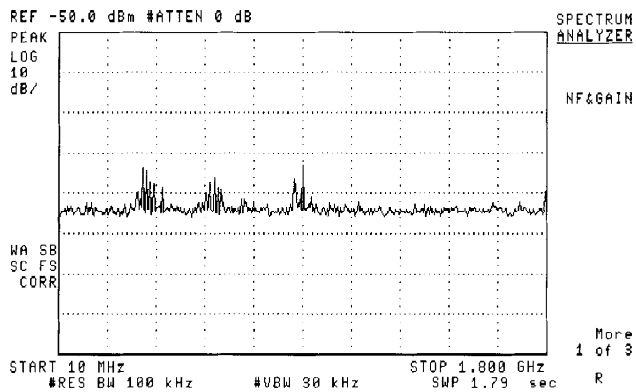


Figure 2.2. Stray signals can be seen directly using the 85719A in spectrum analyzer mode.

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 85719A.

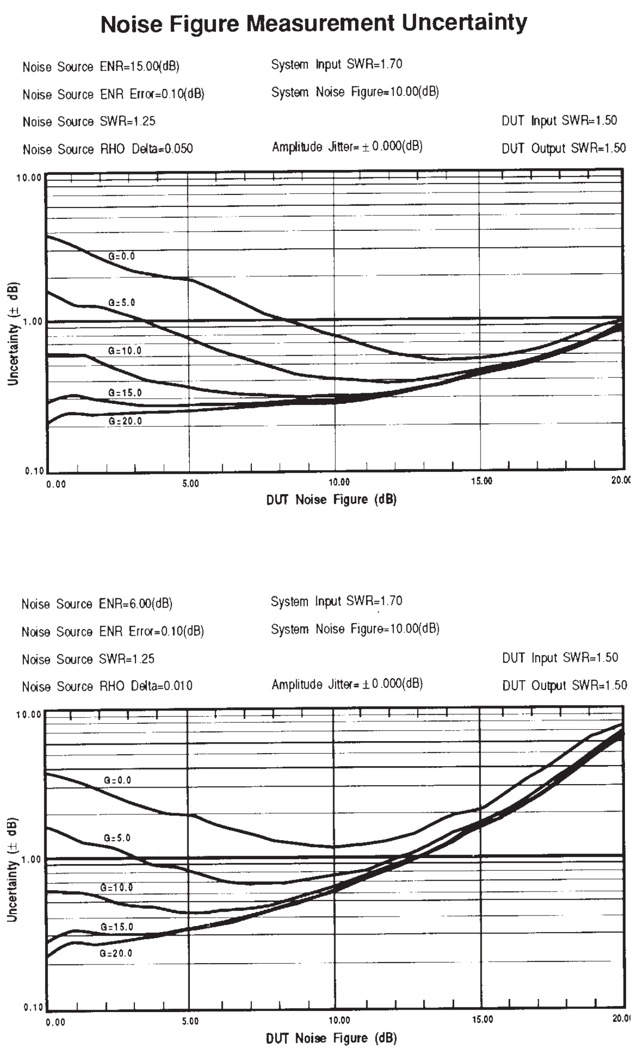


Figure 2.3. The effect of the noise source ENR on noise figure measurement uncertainty

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.

Jitter

All noise measurements exhibit some degree of instability, 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 large averaging time. 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. The 85719A has a repeatability calculator mode which provides a simple way to determine the repeatability due to jitter for a specific measurement. The repeatability 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. Many noise figure meters 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 prevent introducing error.

The 85719A 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. (Recalibration will be needed when changing 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. (See repeatability in Chapters 4 and 5.)

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 lower 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 is low by approximately 3 dB. If the device response of the two sidebands is not equal, it 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, 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.

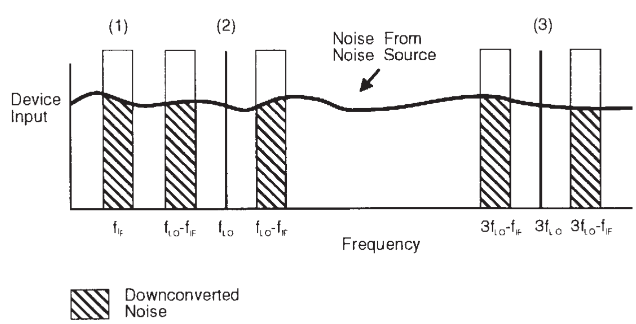


Figure 2.4. Possible noise conversion mechanisms with mixers and converters. (1) IF feedthrough response, (2) double sideband response, (3) harmonic response

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. 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.

The Agilent 5719A makes this level setting automatically, based on the system preamplifier gain that has been entered. When the 87405A system preamplifier is used, its minimum gain specification, 22 dB, should be entered. When other preamplifiers are used, the minimum gain over the frequency range of interest should be used.

The maximum noise signal that must be handled in the system is a function of the device gain when the device noise figure is less than the ENR (NF <15 dB). With very high noise figure devices (NF >15 dB) the maximum signal will be a function of the gain plus the noise figure of the device to be tested. The 85719A can accommodate gain to about 40 dB for NF <15 dB with good results by automatically inserting internal attenuation in the system. For high noise figure devices (NF >15 dB), device gain plus noise figure should be kept below 55 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:

Eq. 2.1

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

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 needs to be kept below approximately –18 dB in over the 0 to 3 GHz range. When the 87405A system preamplifier is used, because it has a maximum gain specification of 27 dB, total power at its input should be kept below –45 dBm for best accuracy. Either output attenuation at the device 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 –18 dBm into the spectrum analyzer (45 dBm into the 87405A preamplifier).

Ambient temperature
Ambient temperature can affect noise figure measurement accuracy in two ways. Fortunately, the user of the 85719A 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 log-amplifier curve and 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.

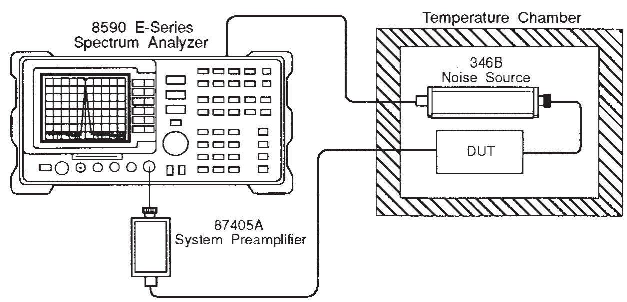


Figure 2.5. Temperature chamber with device under test and noise source inside

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 errors are listed below.

These non-removable factors can be divided into three groups:

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

Noise figure instrumentation uncertainty with spectrum analyzer-based systems such as the Agilent 85719A typically includes error from the log amplifier. The error is given as a specification for the 85719A.

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.)

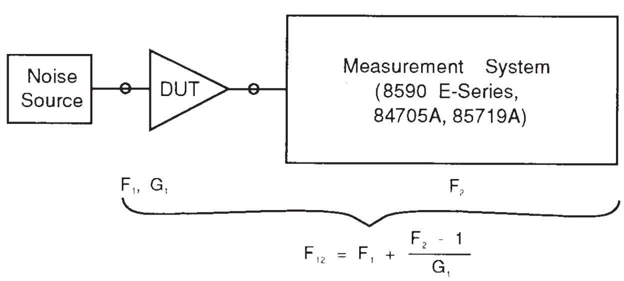


Figure 3.1. Typical noise figure measurement setup. Device and measurement system noise figures combine according to the cascade noise figure equation.

To determine the noise figure of the DUT alone, a calibrated system (such as the Agilent 85719A) subtracts the noise contribution of the measurement system (i.e., the spectrum analyzer and system preamplifier) from the cascaded DUT/measurement system noise figure:

Eq. 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, not logarithmic terms.)

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}, F_2, 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. Eq. 3.2 shows this partial-derivative equation, with the measurement deviations (terms) converted to power ratios.

Eq. 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, NF_1 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 (Eq. 3.2) gives a good picture of how the error-causing factors affect overall accuracy. For example, as G_1 increases, two terms in the equation decrease. When the terms are then added in a root-sum-of-squares manner, overall uncertainty decreases. Eq. 3.2 is not, however, recommended when calculating accuracy—it assumes that gain is a separate measurement. (Remember, G_{12} 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.

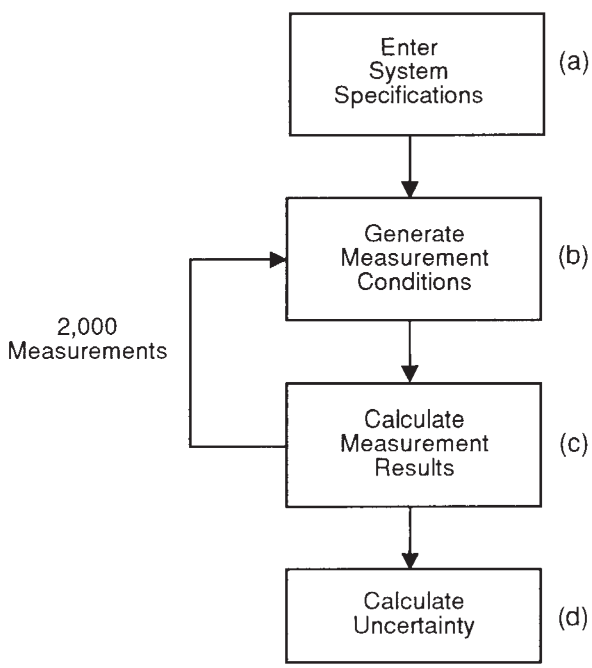


Figure 3.2. Flow graph of measurement simulation method for calculating noise figure accuracy. (a) Programmer enters measurement system specifications into the computer. (b) The computer generates typical measurement conditions based on system specifications and probability distributions. (c) Computer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

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. (95% boundaries were used for the curves in Appendix A.) These boundaries define the measurement uncertainty.

Appendix A shows uncertainty curves generated with the measurement simulation method. If your measurement conditions are close to those of the curves, these curves should be used to calculate your measurement uncertainty.

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. The curves in Appendix A, however, should be sufficient to show you the accuracy of many of your measurements.

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.

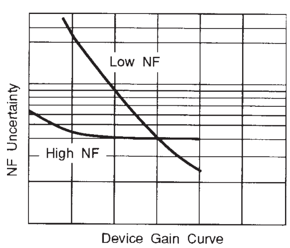


Figure 4.1 The uncertainty versus device gain curve

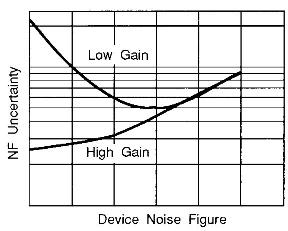


Figure 4.2. The uncertainty versus device noise figure curve

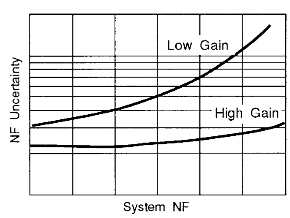


Figure 4.3. The uncertainty versus the system noise figure curve

Uncertainty versus 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.

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 Eq. 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 is often higher than that of noise figure meters. The primary reason for this is the precision of the log or linear IF circuits of a spectrum analyzer is generally not as good as the IF linearity of good noise figure meters. The Agilent 85719A system has several advantages over other signal analyzer-based systems. First, certain internal corrections for errors associated with noise type signals are removed by the 85719A personality. Second, temperature-induced log amplifier errors are removed with the self-calibration feature provided on the Agilent 8590 E-series spectrum analyzers.

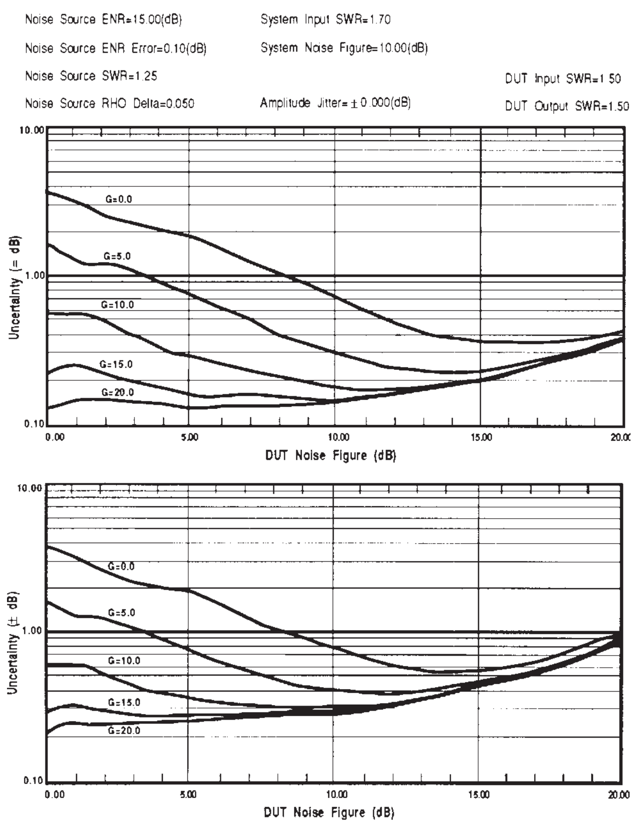


Figure 4.4. Comparison of effect of normal and zero instrumentation uncertainty on the total NF measurement uncertainty. (a) Zero instrumentation uncertainty (b) with instrument uncertainty.

Many people who measure noise figure mistakenly consider the noise figure measurement system uncertainty as the main indicator of measurement accuracy. However, the other two system errors ENR and mismatch, can dominate. Figure 4.4 shows the difference between 0 dB measurement system uncertainty (a perfect spectrum analyzer) and the actual uncertainty of the 85719A (specified to be 0.5 dB maximum for NF<15 dB), with a typical case of ENR and mismatch uncertainty.

Measurement repeatability due to jitter

While with sufficient averaging time, it is possible to have negligible measurement repeatability due to jitter, it is often important to minimize measurement time. The trade-offs between repeatability and measurement time are especially important when using narrow measurement bandwidths. The built-in repeatability calculator of the 85719A simplifies these tradeoffs and is discussed in Chapter 5. However, a practical description is presented here as an aid to better understanding.

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.

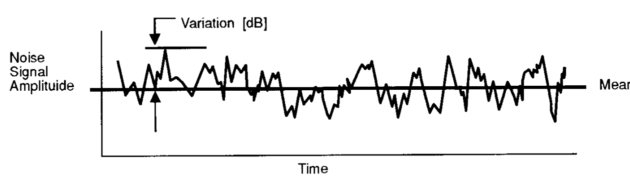


Figure 4.5. Noise jitter

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

Eq. 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.

Finding the actual effect of noise jitter when measuring device noise figure is a tedious calculation by hand. A noise figure measurement involves the measurement of four levels: 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 4.6 shows the general effect of jitter.

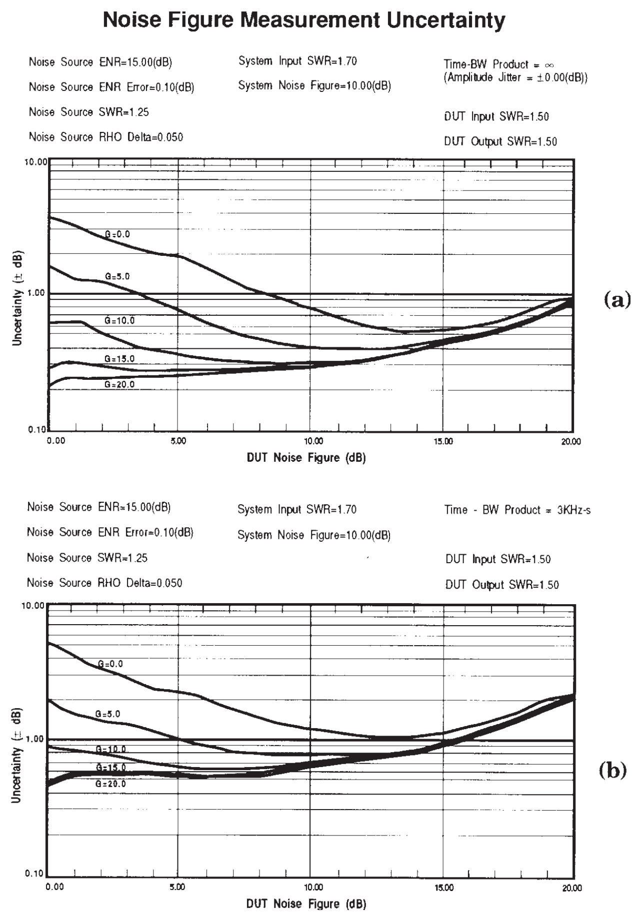


Figure 4.6. Effect of jitter on measurement error, (a) without jitter and (b) with jitter.

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:

Eq. 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:

Eq. 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 a system preamplifier (0 dB preamp gain must be entered). Alternatively, the spectrum analyzer noise figure can be derived from the displayed average noise level:

Eq. 5.3

$$NF_{analyzer}[dBm] = DANL - 10*\log_{10}(RBW) + 174 + 2$$

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 the 8591E, the analyzer noise figure can be 33 dB maximum as derived from the specifications, but is usually much less.

The Agilent 87405A system preamplifier suggested for use with the 85719A system is a good general-purpose amplifier for measurements to 2.9 GHz. When using the 87405A system amplifier, the system noise figure is specified to be 12 dB maximum and will usually be much less. The system noise figure is displayed on the spectrum analyzer during calibration. While lower system noise figures would result if a higher-gain preamplifier is used, a reduced dynamic range would result because measurements will be made closer to compression limits. The total power incident at the spectrum analyzer input must be kept below approximately –18 dBm. (See Chapter 2 for more on compression effects.) For this reason, the system noise figure should be reduced only when it is clearly needed, and to 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. (See sample curves in Appendix A.)

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 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 repeatability calculator

The repeatability calculator feature of the Agilent 85719A provides an easy way of making measurement time/repeatability trade-offs. Entering the expected device noise figure and gain, the system noise figure (which can be determined by performing a calibration), and the noise source ENR is all that is required. The time-bandwidth product (in kHz) corresponding to the measurement bandwidth and the averaging time (per point) can be adjusted to obtain an acceptable measurement repeatability. The actual measurement time per point will be about 1 s greater than the averaging time due to the downloadable program execution time and the internal routines of the spectrum analyzer. For this reason, there is little speed benefit in using averaging times less than about 0.5 s because the total measurement time will be dominated by the other factors.

As mentioned in Chapter 4, an inverse square root proportionality exists for time and bandwidth. For example, if the repeatability error must be reduced by one-half, the time-bandwidth product will need to be increased by a factor of four.

A tip to remember when measuring devices with both low gain and noise figure: The system noise figure and ENR will have a large effect on the repeatability.

If any loss corrections have been entered, the repeatability calculator will automatically include their effect. System input loss (loss is present both during measurement and calibration) should not be treated as a loss correction since its effect is included during calibration. However this system input loss increases the system noise figure and should be included when entering the system noise figure.

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).

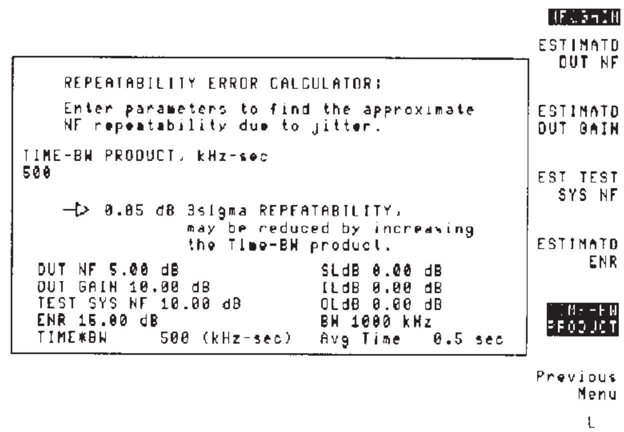


Figure 5.1. Calculator screen

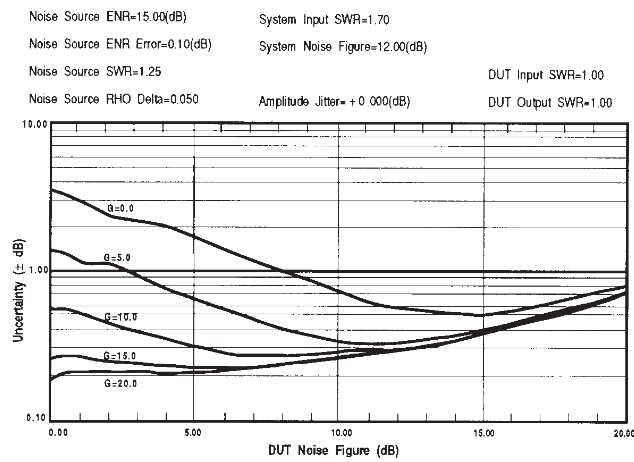
Appendix A. Noise figure measurement uncertainty curves

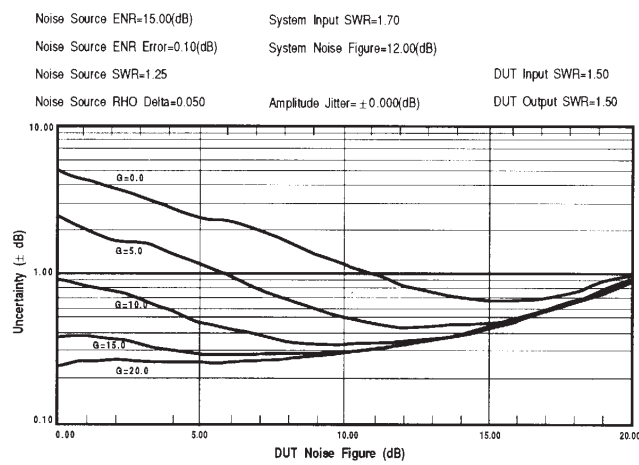
The following are uncertainty-versus-device noise figure graphs. For each measurement condition, several gain curves are shown. The uncertainty for device gains in excess of 20 dB will be very close to the curve given for 20 dB gain.

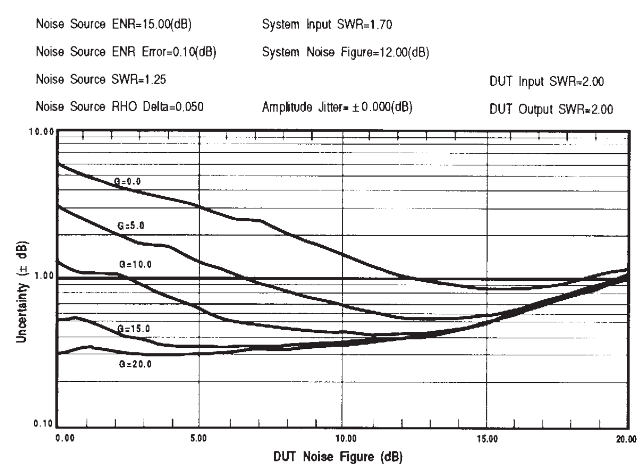
The graphs show the resulting uncertainty for various cases of device input and output mismatch and are presented for system noise figures of 12, 6, and 3 dB. For the case of 3:1 device output SWR, an additional graph is given to show the effect of using an isolator at the measurement system input.

All curves assume that the Agilent 85719A personality is used with an Agilent 8590 E-series spectrum analyzer. The measurement system uncertainty is included with a statistical confidence level of 3 standard deviations above the mean performance. (This corresponds with the 85719A specification of 0.5 dB max. for NF<15 dB.)

System NF: 12 dB

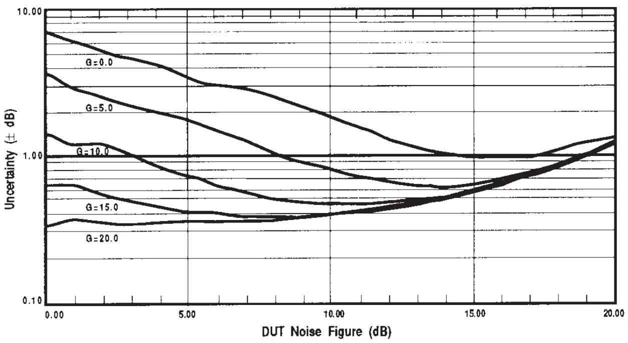






System NF: 12 dB

Noise Source ENR=15.00(dB) System Input SWR=1.70
Noise Source ENR Error=0.10(dB) System Noise Figure=12.00(dB)
Noise Source SWR=1.25 DUT Input SWR=2.50
Noise Source RHO Delta=0.050 Amplitude Jitter=±0.000(dB) DUT Output SWR=2.50



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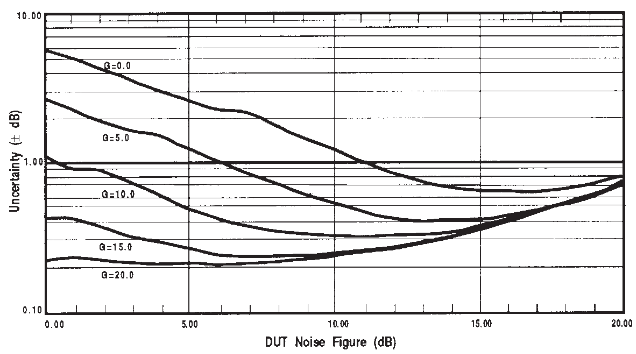
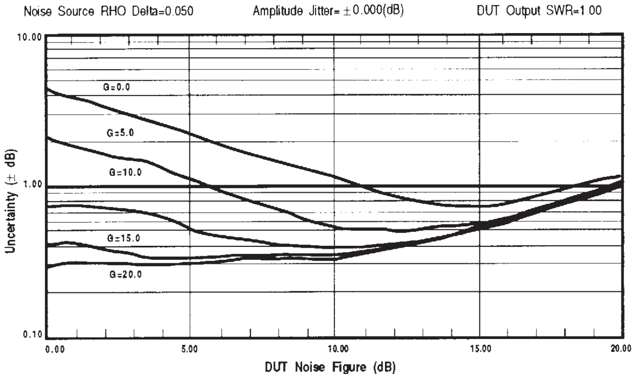
Noise Source ENR Error=0.10(dB) System Noise Figure=12.00(dB)
Noise Source SWR=1.25 DUT Input SWR=1.00
Noise Source RHO Delta=0.050 Amplitude Jitter=±0.000(dB) DUT Output SWR=2.00



Noise Source ENR=15.00(dB) System Input SWR=1.70
Noise Source ENR Error=0.10(dB) System Noise Figure=12.00(dB)
Noise Source SWR=1.25 DUT Input SWR=2.00
Noise Source RHO Delta=0.050 Amplitude Jitter=±0.000(dB) DUT Output SWR=1.00



System NF: 12 dB

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Noise Source ENR Error=0.10(dB) System Noise Figure=12.00(dB)
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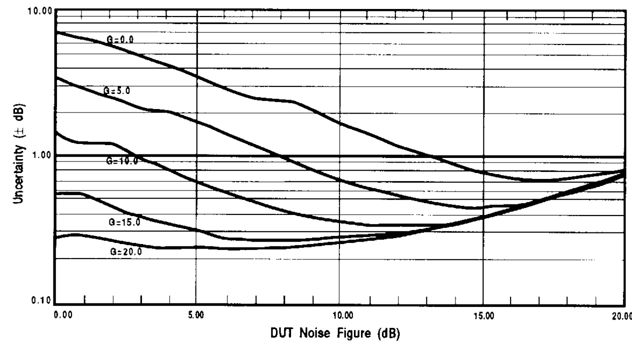
Noise Source RHO Delta=0.050 Amplitude Jitter=±0.000(dB) DUT Output SWR=3.00



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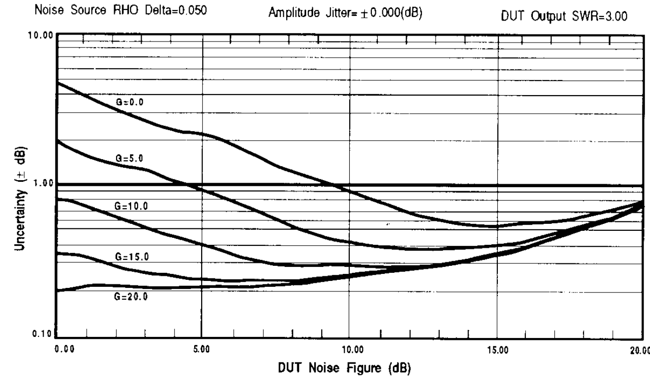

System NF: 6 dB

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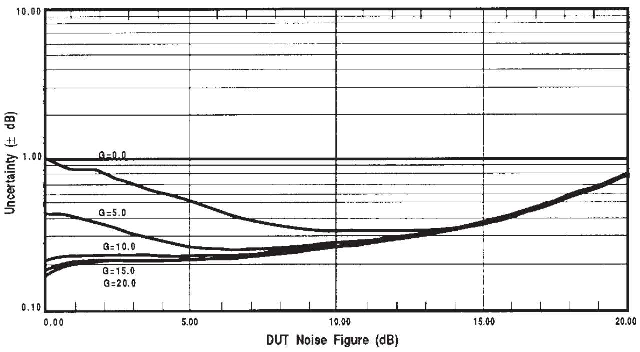

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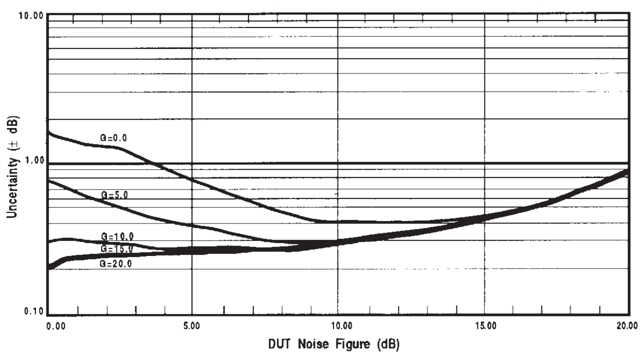

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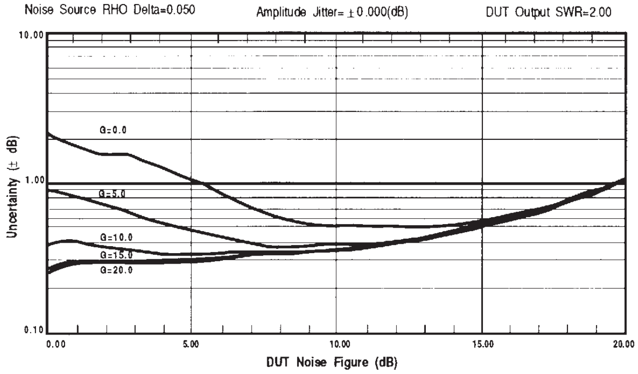

System NF: 6 dB

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Noise Source ENR Error=0.10(dB) System Noise Figure=6.00(dB)
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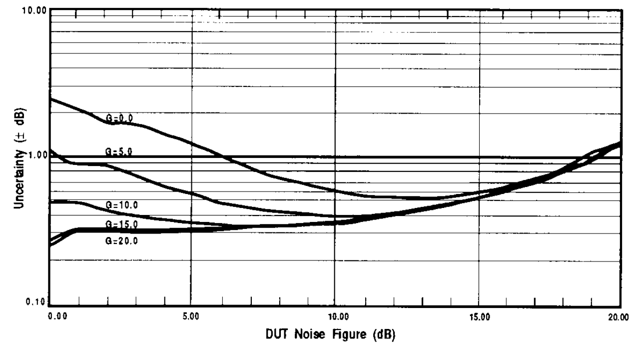
Noise Source RHO Delta=0.050 Amplitude Jitter= ±0.000(dB) DUT Output SWR=2.50



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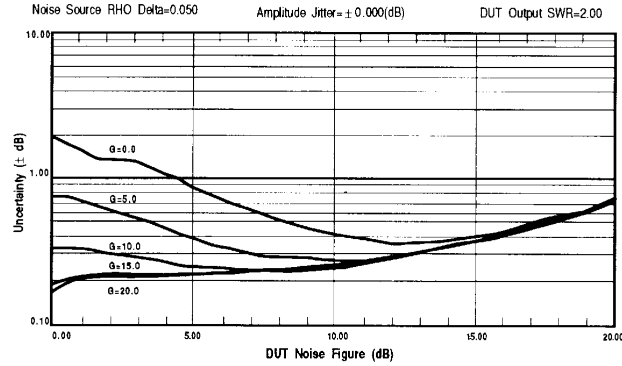

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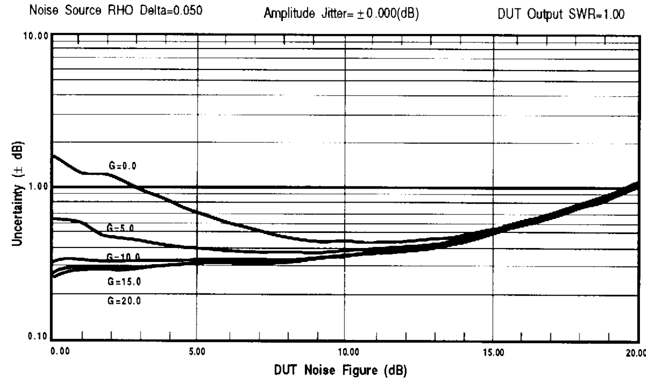

System NF: 6 dB

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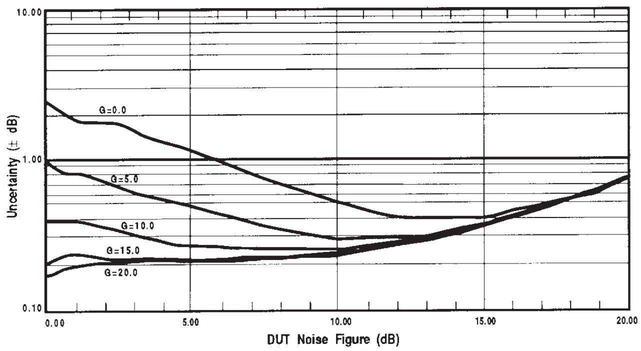

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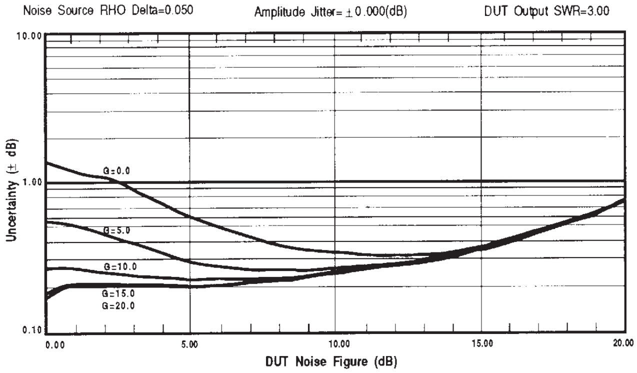
Noise Source RHO Delta=0.050 Amplitude Jitter= ±0.000(dB) DUT Output SWR=3.00



System NF: 3 dB

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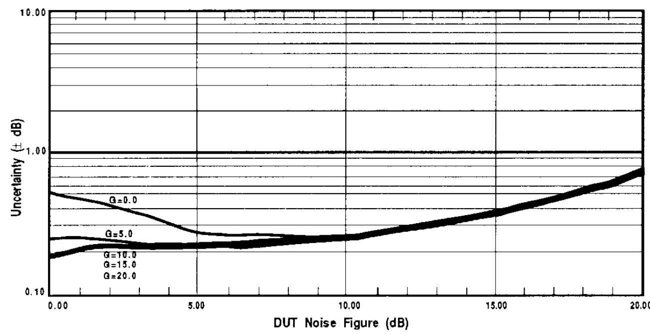

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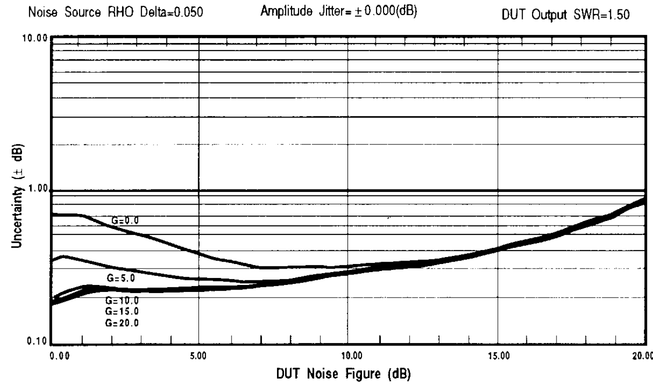

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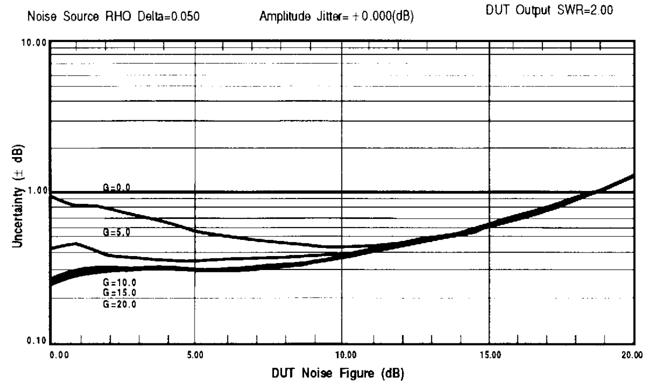

System NF: 3 dB

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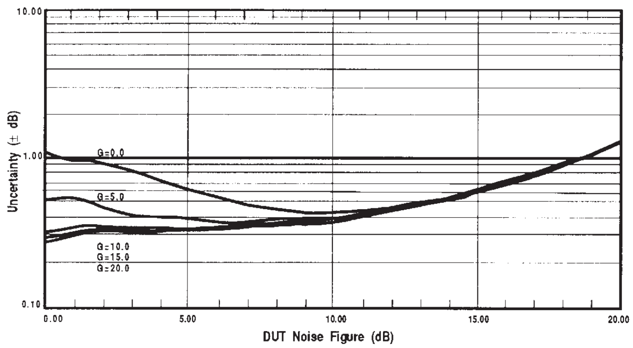

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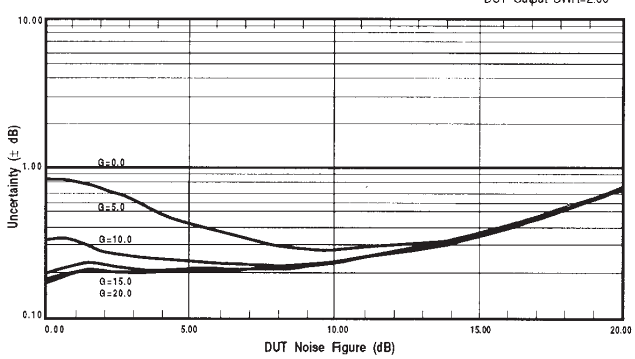

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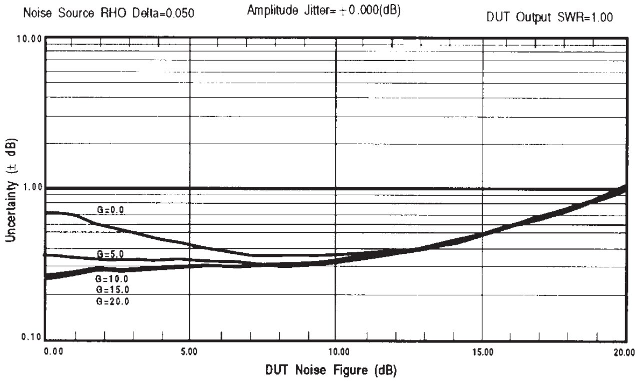

System NF: 3 dB

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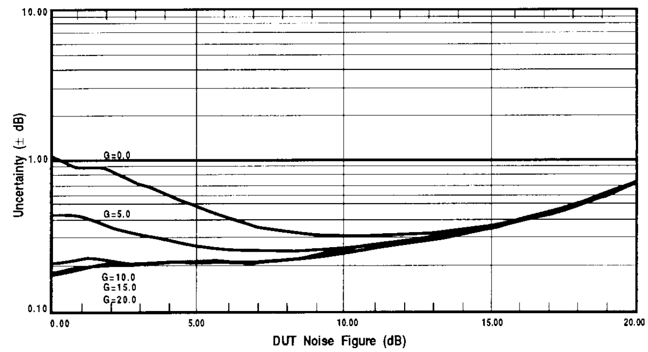

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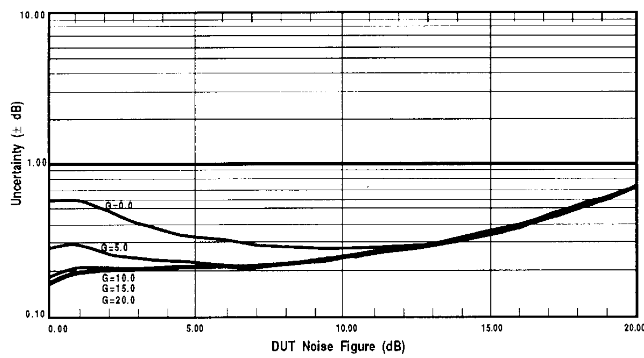


Appendix B. Microwave noise figure measurement

Microwave measurements can be divided into two basic categories, each with several subcategories:

1. Measurement of non-frequency-converting microwave devices such as amplifiers

    a. Direct noise figure measurement

    b. Measurement at a lower frequency range using a converter with a fixed LO frequency

    c. Measurement at a fixed lower frequency using a converter with a programmable LO frequency.

2. Measurement of microwave converters or mixers

    a. Lower IF frequency, noise figure measured directly

    b. Microwave IF frequency, noise figure measured directly

    c. Microwave IF frequency, measured at a lower frequency range by using a second converter with a fixed LO frequency

    d. Microwave IF frequency, measured at a fixed lower frequency by using a converter with a programmable LO frequency

Each of these measurement configurations have different requirements regarding the measurement system. Each specific configuration is described as follows:

Frequency non-converter

If the measurement frequency falls within the 10 MHz to 2.9 GHz frequency range of the Agilent 87405A system preamplifier, the noise figure can be measured directly. (When an 8591E spectrum analyzer is used, 1.8 GHz is the maximum frequency.)

When the frequency is above 2.9 GHz but within the frequency range of the spectrum analyzer (for example the Agilent 8593E covers up to 22 or 26.5 GHz), then direct measurements can be made as above. However, the user must supply a system preamplifier that covers the measurement frequency, and the specifications of the 85719A do not necessarily apply. An additional error from YIG filter tuning drift can be present, especially for low system gains. Also, the spectrum analyzer noise figure is higher at higher frequencies, so more system preamplifier gain will be needed. (See information regarding system noise figure in Chapter 5.) The dynamic range can be less because measurements may be closer to the compression limit. (Compression error is discussed in Chapter 2.) In the case of microwave measurements (above 2.9 GHz), the noise bandwidth used in Eq. 2.1 should be the YIG filter bandwidth (about 90 MHz maximum), and the system amplifier must be kept below its compression limit.

To avoid some of these problems, a system mixer or converter can be added to the measurement system to convert to a lower frequency that is within the RF range of the spectrum analyzer (2.9 GHz: 8593E, 8594E, 8595E, or 8596E; 1.8 GHz: 8591E). When the system frequency converter has a fixed LO frequency, the measurement can be performed using the 85719A. Two methods can be used to include the gain and noise figure effects of the converter:

- Calibrating the system with the converter in the signal path.
- Calibrating the system with the 87405A preamplifier and including the converter as part of the DUT but correcting for its effect with an output loss correction. The device then can be measured as a frequency converter.

The first method has potential accuracy advantages over the second method. However, the 85719A does not provide for using the proper ENR frequency in the data table, and system specifications may not apply. Unwanted responses from converters should be avoided. (See frequency converter errors in Chapter 2.)

The second method is supported with the 85719A system, but some errors may be introduced. The noise figure contribution of the converter is not accurately represented as a loss. The error from this effect can be minimized by ensuring that the converter noise figure is much lower than the device gain.

All converter measurements, require you to beware of unwanted responses. (See frequency converter errors in Chapter 2.)

A different approach uses a system converter or mixer with a programmable frequency LO. The LO frequency is stepped to make a frequency-swept microwave measurement with the measurement receiver kept at a fixed lower frequency. This method is popular with the Agilent 8970 noise figure meter, which has the capability of controlling a GPIB controlled LO source. Although a GPIB controller and special software can be used to make this type of measurement with the 85719A personality, it is not a directly supported capability.

Microwave converters
If the IF output frequency falls within the 10 MHz and 2.9 GHz frequency range of the 87405A system preamplifier, the device noise figure can be measured directly by specifying that the device is a frequency converter and entering the frequencies. (When an 8591E spectrum analyzer is used, 1.8 GHz is the maximum IF frequency.)

All that is required to make this type of measurement is a noise source covering both the IF and microwave input frequencies. (In the case of millimeter wave converters, two noise sources can be used—one for the IF frequency, used during calibration, and another millimeter wave noise source used for the measurement. There is a trick: a hybrid ENR data table must be created that has both the IF noise source data at IF frequencies and the millimeter wave data at millimeter wave frequencies.)

When measuring frequency converters, your attention is required for unwanted responses. Frequency converter errors can be reviewed in Chapter 2.

When the IF frequency is above 2.9 GHz but within the frequency range of the spectrum analyzer (for example the 8593E covers to 22 or 26.5 GHz), then direct measurements can be made as above. However, the user must supply a system preamplifier that covers the IF frequency, and the specifications of the 85719A may not apply. Additional errors may be present as described for direct microwave measurement of non-converters.

Alternatively, a system frequency converter with a fixed frequency LO can be used to convert the IF frequency to a frequency within the RF frequency range of the spectrum analyzer in much the same way as with non-converters. The DUT is then treated as a double conversion device, and the proper frequencies are entered into the 85719A. The second converter is treated as a loss. For good accuracy, the second converter noise figure should be much less than the gain of the converter to be tested and may require an additional amplifier between converters.

Using a second converter with a programmable LO is not directly supported with the 85719A.

Appendix C. Low frequency measurements

Low frequency measurements (below 10 MHz) are possible with the 85719A measurement personality providing that a low frequency system preamplifier (such as the Agilent 8447) and a low frequency calibrated noise source are used. However, specifications of the 85719A system may not apply.

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. This means that, in general, the measurement bandwidth must be 1/30th of the lowest measurement frequency or less. This places the lower frequency limit of measurements at about 100 kHz (3 kHz bandwidth).

The phase noise associated with the LO may have the effect of increasing the effective spectrum analyzer noise figure. In some cases, additional system preamplifier gain may be needed to reduce the system noise figure.

If the above conditions are satisfied, good measurement accuracy should result.

Appendix D. 75 Ω measurements

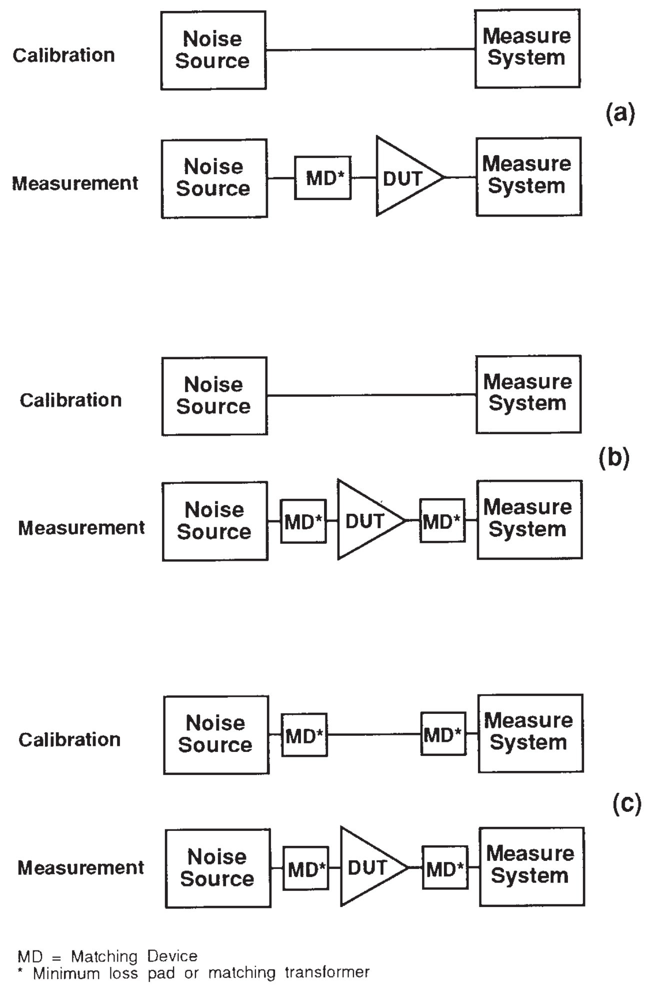
75 ohm measurements can be accommodated with the 85719A measurement personality by using auxiliary 75 to 50 ohm transformers or minimum loss pads. The loss of the transformers or pads is then entered as a loss correction to the measurement. There are three ways of correcting for this loss, each with advantages and disadvantages.

The setup of figure (a) is the simplest approach. The mismatch presented by 75 ohms at the 50 ohm system preamplifier input is 1.5 SWR. In many cases, particularly when testing devices with lots of gain, the resulting measurement error is acceptable.

Setup (b) presents 75 ohms 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 ohms 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. Chapter 5 explains how to use the repeatability calculator.

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.



(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 ohm 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 ohm 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 ohm system including transformer/pad(s).

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