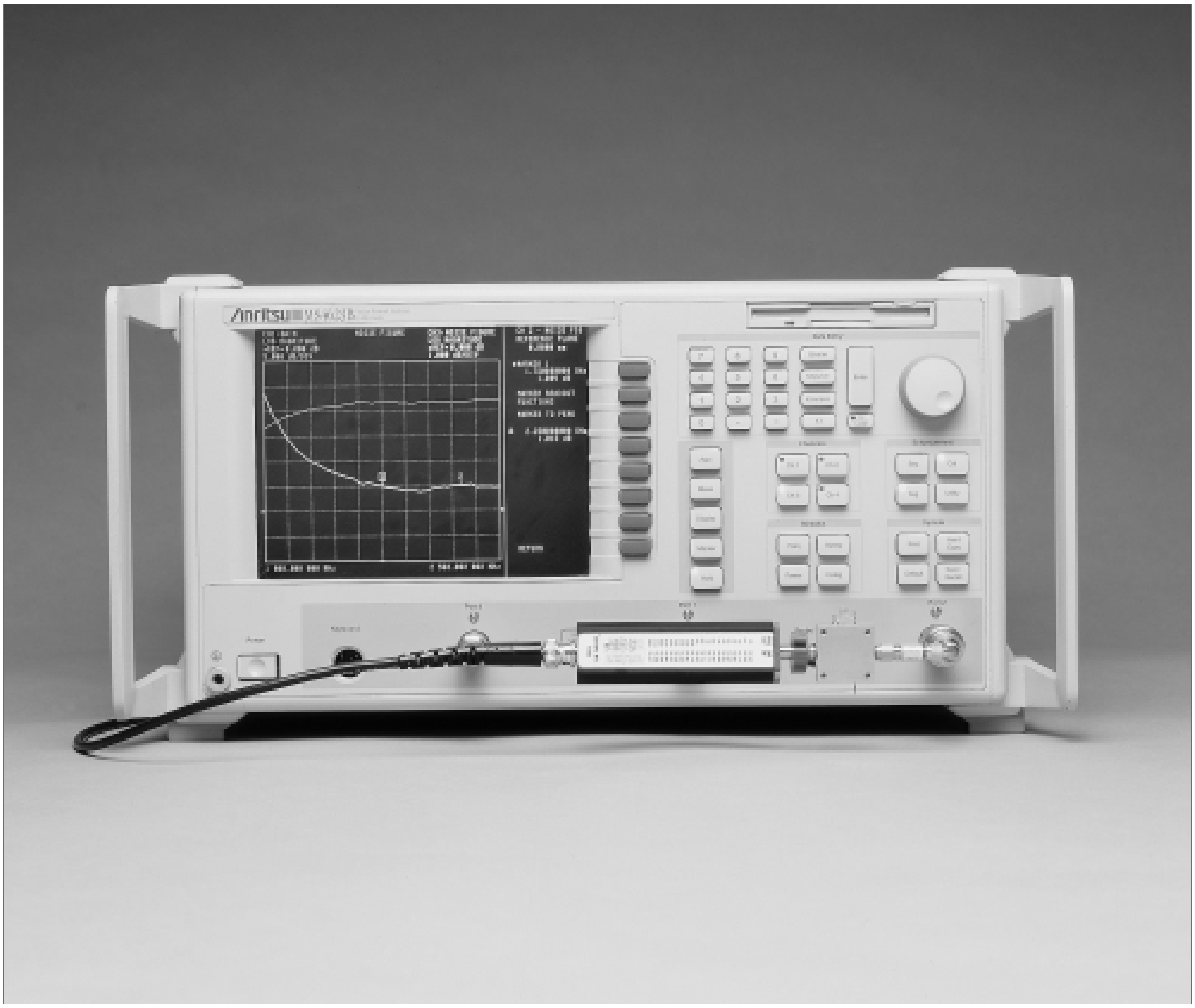
Anritsu

Noise Figure

Scorpion® Option 4

50 MHz to 3 GHz

Application Note



Vector Error-Corrected Noise Figure Measurements Using A Vector Network Measurement System

Linking the World

Introduction

The MS462xx is a powerful RF Vector Network Measurement System from Anritsu with innovative measurement capabilities. This application note addresses one of these measurement capabilities; specifically, the ability to perform vector error-corrected noise figure measurements with a single measurement system. This powerful combination of noise figure and S-parameter measurements is another demonstration of Anritsu's commitment to meet or exceed our customer's expectations for performance, reliability, delivery, and value!

The purpose of this application note is to provide enough information to perform and to understand vector error-corrected noise figure measurements using the MS462xx.

The following outline details the organization of this application note.

Noise Figure Fundamentals

The purpose of this section is to provide a concise, informative, and practical foundation for understanding, performing, and analyzing noise figure measurements. Accordingly, this section will not assume any familiarity with noise definitions or noise figure measurements. For convenience, a bibliography provides references with more thorough noise and noise figure measurement discussions.

This section precedes a discussion of the measurement advantages when using the Anritsu MS462xx RF Vector Network Measurement System for performing vector error-corrected noise figure measurements. Those familiar with noise definitions and noise figure measurements can bypass this introductory section and proceed to the next section.

The following outline briefly describes the organization of this section.

I. Noise Figure Fundamentals

A. Noise Overview
  1. Shot Noise
  2. Thermal Noise with Example Calculations

B. Signal-to-Noise Ratio Definition with Example Calculations

C. Noise Figure Definitions with Example Calculations

D. Noise Power Output Characteristics

E. Traditional Scalar Approach to Noise Figure Measurements with Example Calculations

F. Cascaded Noise Figure Definition with Example Calculations

G. Summary of Noise Figure Fundamentals

Noise Overview

Noise consists of many sources. For the purpose of noise figure measurements, shot and thermal noise are the two main components considered. Other common sources of noise are flicker noise, generation-recombination noise, partition noise and burst noise. The contribution of these other sources to noise figure is typically small, so the focus of this discussion is on shot and thermal noise.

Shot Noise Definition

Shot noise, predominately a factor in semiconductor junctions, is caused by the random, quantized nature of current flow. Current flow is not a continuous and predictable flow of electrons, but a discrete flow of electrons with random spacing. Statistical analysis of this random electron flow indicates that the current variations are essentially broadband in frequency.

Thermal Noise Definition

Thermal noise is the main component of noise and refers to the available power associated with the random thermal motion of electrons. Referring to the equation below, thermal noise is defined by kTB, where k is Boltzmann's constant (1.38 x 10^{-23} Joules/Kelvin), T is the absolute temperature (in Kelvin), and B is the bandwidth of the transmission path (in Hertz). The units of kTB are usually Joules/second which are the same as Watts.

$$P_a = kTB$$

P_a is Power available (Joules/sec or Watts)
k is Boltzmann's Constant (1.38 x 10^{-23} Joules / K)
T is absolute Temperature (Kelvin)
B is Bandwidth of transmission path (Hz)

It is important to note that kTB is the **available power**. Maximum power transfer occurs only with an optimum load (i.e., a load that does not reflect energy). This "available power" concept is important when considering noise measurements.

An explanation of kTB provides some insight. Boltzmann's constant (or k) provides the average kinetic energy per particle per degree of temperature. The absolute temperature (or T) takes into account that as temperature rises, more power is available. The bandwidth of the transmission path (or B) refers to the frequency included in the calculation. Bandwidth is more important than absolute frequency because noise is essentially broadband in frequency.

The absolute temperature of 290K (denoted by T_o) is designated by the Institute of Electrical and Electronics Engineers (IEEE) as the standard reference source temperature for noise figure. This temperature is equivalent to 16.8º C and 62.3º F and is generally used to approximate the temperature of the Earth for noise calculations. For this reason it is sometimes also referred to as the terrestrial reference temperature. The power spectral density kT for this temperature is 4.00 x 10^{-21} Watts (or –174 dBm) per 1 Hertz of bandwidth.

Some convenient conversion equations between Kelvin, Celsius, and Fahrenheit are shown below.

Conversion	Equation
Celsius to Kelvin	$T_{Kelvin} = T_{Celsius} + 273.15$
Fahrenheit to Kelvin	$T_{Kelvin} = (5/9)(T_{Fahrenheit} + 459.67)$
Fahrenheit to Celsius	$T_{Celsius} = (5/9)(T_{Fahrenheit} - 32)$

Thermal Noise Calculations

An example clarifies the application of this thermal noise equation. The amount of thermal noise contained in 100 kHz of bandwidth at 290K is calculated as shown.

$$P_a = kTB$$
$$P_a = (1.38 \times 10^{-23} \text{ Joules / K}) * (290\text{K}) * (100 \times 10^3 \text{ Hz})$$
$$P_a = 4 \times 10^{-16} \text{ Watts}$$

The more common use of thermal noise requires the conversion to dBm. To accomplish this conversion, Watts are changed to milliWatts before converting to decibels. The applicable conversion equations are shown below.

Conversion	Equation
Watts to dBm	dBm = 10 log (Watts x 1000)
dBm to Watts	Watts = $10^{(\text{dBm}/10)}$ / 1000

For the above example, the thermal power becomes:

$$P_a = 4 \times 10^{-16} \text{ Watts}$$
$$\text{dBm} = 10 \log (4 \times 10^{-16} * 1000)$$
$$P_a = -124 \text{ dBm}$$

Another convenient technique involves solving kTB for a 1 Hz bandwidth and converting to the desired bandwidth.

$$P_a = kTB$$
$$P_a = (1.38 \times 10^{-23} \text{ Joules / K}) * (290\text{K}) * (1 \text{ Hz})$$
$$P_a = 4 \times 10^{-21} \text{ Watts}$$
$$\text{dBm} = 10 \log (4 \times 10^{-21} * 1000)$$
$$P_a = -174 \text{ dBm}$$

Both of these values for thermal noise (P_a= –174 dBm and P_a= 4 x 10^{-21} Watts) indicate the amount of thermal noise in a 1 Hz bandwidth at 290K. The amount of thermal noise contained in 100 kHz of bandwidth at 290K is then calculated using a ratio of bandwidths as shown.

$$P_a = -174 \text{ dBm} + 10 \log (\text{BW} / 1 \text{ Hz})$$
$$P_a = -174 \text{ dBm} + 10 \log (100 \times 10^3 \text{ Hz} / 1 \text{ Hz})$$
$$P_a = -174 \text{ dBm} + 50 \text{ dB}$$
$$P_a = -124 \text{ dBm}$$

Both techniques produce accurate thermal noise values. It is important to note that thermal noise is essentially broadband. The absolute frequencies involved are not important; only the bandwidth of the transmission path.

Noise Summary

Noise consists of many sources. For the purpose of noise figure measurements, the two main components of noise are shot and thermal noise. Shot noise is caused by the random, quantized nature of current flow.

Thermal noise is quantified by kTB and refers to the available power associated with the random thermal motion of electrons. Both shot and thermal noise are essentially broadband in nature.

Signal-to-Noise Ratio Definition

A signal-to-noise ratio is an integral part of the noise figure definition and builds on the previous noise definitions. An understanding of a signal-to-noise ratio allows a more comprehensive understanding of the noise figure definition.

Conceptually, a signal-to-noise ratio is simple to understand. This ratio defines the difference between the magnitude of a signal and the magnitude of the surrounding noise. In practice, determining the surrounding noise requires the most calculations.

The calculations for a signal-to-noise ratio are similar to the calculations for noise. A signal-to-noise ratio also requires bandwidth and temperature because these terms define the surrounding noise.

Signal-to-Noise Ratio Calculations

An example clarifies the application of a signal-to-noise ratio. The signal-to-noise ratio of a +10 dBm signal in a 1 MHz bandwidth at 290K is calculated as shown.

First, the thermal noise equation determines the amount of noise in a 1 MHz bandwidth.

$$P_a = -174 \text{ dBm} + 10 \log (1 \times 10^6 \text{ Hz} / 1 \text{ Hz})$$
$$P_a = -174 \text{ dBm} + 60 \text{ dB}$$
$$P_a = -114 \text{ dBm}$$

Next, the signal-to-noise ratio combines the signal magnitude with the noise magnitude for the final calculation.

$$\frac{S}{N} = \frac{+10 \text{ dBm}}{-114 \text{ dBm}} = +10 \text{ dBm} - (-114 \text{ dBm}) = 124 \text{ dB}$$

Another example demonstrates the effects of temperature on thermal noise and the associated signal-to-noise ratio. The signal-to-noise ratio of a +10 dBm signal in a 1 MHz bandwidth at 350K is calculated as shown.

First, the thermal noise equation determines the amount of noise in a 1 MHz bandwidth.

$$P_a = kTB$$
$$P_a = (1.38 \times 10^{-23} \text{ Joules / K}) * (350\text{K}) * (1 \times 10^6 \text{ Hz})$$
$$P_a = 4.83 \times 10^{-15} \text{ Watts}$$
$$\text{dBm} = 10 \log (4.83 \times 10^{-15} * 1000)$$
$$P_a = -113.2 \text{ dBm}$$

Next, the signal-to-noise ratio combines the signal magnitude with the noise magnitude for the final calculation.

$$\frac{S}{N} = \frac{+10 \text{ dBm}}{-113.2 \text{ dBm}} = +10 \text{ dBm} - (-113.2 \text{ dBm}) = 123.2 \text{ dB}$$

Indeed, the signal-to-noise ratio is simple to calculate after completion of the noise calculation. This example also demonstrates that the noise portion of this ratio requires bandwidth and temperature.

Noise Figure Definition

The previous noise and signal-to-noise ratio definitions allow a more comprehensive understanding of the noise figure definition. The noise figure definition provides the foundation for performing noise figure measurements.

Noise figure describes the decrease (or degradation) in signal-to-noise ratio. Noise figure in dB is a logarithmic ratio of the input signal-to-noise ratio (in power) to the output signal-to-noise ratio (in power). This noise figure definition in terms of power is shown below.

$$F\ (dB) = 10 \cdot \log \left[\frac{\left(\frac{S_i}{N_i}\right)}{\left(\frac{S_o}{N_o}\right)} \right]$$

S_i is the input signal power (Watts)

N_i is the input noise power (Watts)

S_o is the output signal power (Watts)

N_o is the output noise power (Watts)

Similarly, noise figure is also the difference between the input signal-to-noise ratio (in decibels) and the output signal-to-noise ratio (in decibels). This more convenient definition in terms of decibels is shown below.

$$F\ (dB) = \left(\frac{S_i}{N_i}\right)_{dB} - \left(\frac{S_o}{N_o}\right)_{dB}$$

S_i is the input signal power (dBm)

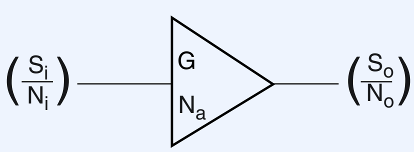
N_i is the input noise power (dBm)

S_o is the output signal power (dBm)

N_o is the output noise power (dBm)

The following example clarifies the use of these noise figure definitions. Consider the output signal-to-noise ratio for an amplifier.

AMPLIFIER GAIN = G
AMPLIFIER NOISE = N_a



$$\left(\frac{S_o}{N_o}\right) = \left(\frac{GS_i}{GN_i + N_a}\right)$$

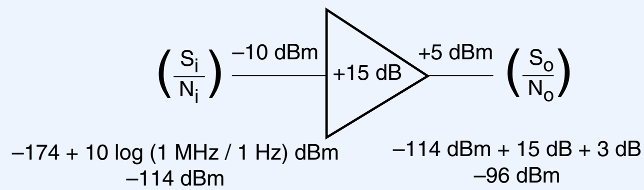
Clearly, the input signal power, S_i, and the input noise power, N_i, increase by a factor of G when passing through an amplifier. Less clear is that the shot and thermal noise generated within the amplifier, N_a, adds to the output noise power, N_o. In this case, N_o is the combination of GN_i and N_a. Indeed, the resulting output signal-to-noise ratio degrades from the input signal-to-noise ratio by the addition of this inherent amplifier noise power, N_a.

It is important to eliminate common misconceptions regarding noise figure; therefore, it is helpful to explain what noise figure does not characterize. First, noise figure applies only to two-port measurements; not one-port devices, terminations, oscillators, or modulation. Noise figure is independent of gain since gain applies to both signal and noise in the signal-to-noise ratios of the definition. Similarly, noise figure is independent of input signal level because of the typical linear region of operation.

Noise Figure Calculations

Some examples clarify the application of these noise figure definitions. Consider an amplifier at 290K under the following conditions.

Amplifier Gain = 15 dB
Amplifier Noise Figure = 3 dB
Input Signal Power = –10 dBm
Transmission Bandwidth = 1 MHz



The following table verifies the noise figure of 3 dB by applying both noise figure definitions to this amplifier under the given conditions. The values in Watts have been converted from the corresponding values in dBm.

Terms	Noise Figure Calculations in Power (dBm)	Noise Figure Calculations in Power (Watts)
	$F\ (dB) = \left(\frac{S_i}{N_i}\right)_{dB} - \left(\frac{S_o}{N_o}\right)_{dB}$	$F\ (dB) = 10 \cdot \log \left[\frac{\left(\frac{S_i}{N_i}\right)}{\left(\frac{S_o}{N_o}\right)} \right]$
Si	–10 dBm	1×10^{-4} Watts
Ni	–114 dBm	4×10^{-15} Watts
S_o	+5 dBm	3.16×10^{-3} Watts
N_o	–96 dBm	2.51×10^{-13} Watts
S_i / N_i	–10 dBm – (–114 dBm) 104 dB	$1 \times 10^{-4} / 4 \times 10^{-15}$ 2.50×10^{10}
S_o / N_o	+5 dBm – (–96 dBm) 101 dB	$3.16 \times 10^{-3} / 2.51 \times 10^{-13}$ 1.26×10^{10}
Noise Figure	104 dB – 101 dB 3 dB	$10 \log (2.5 \times 10^{10} / 1.26 \times 10^{10})$ 3 dB

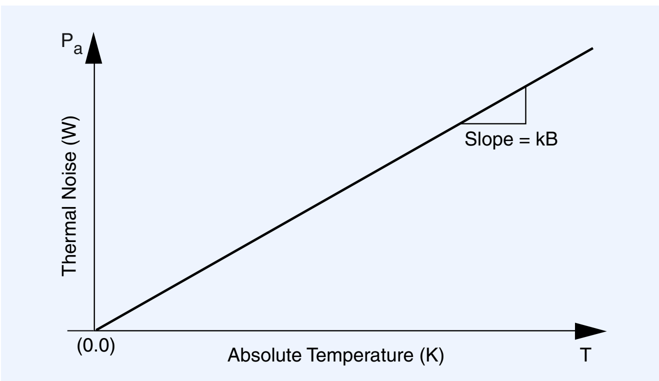
Indeed, these calculations indicate that the noise figure is 3 dB regardless of the implemented definition; however, the noise figure calculations in dBm appear easier to perform.

Noise Power Output Characteristics Overview

These definitions so far do not conveniently support accurate noise figure measurements. Part of the difficulty lies in the ability to accurately measure noise, or very small signal levels. An alternative technique that overcomes this difficulty requires an understanding of noise power output characteristics. With this understanding, noise figure measurements become accurate, convenient, and straightforward.

Linear Properties of Noise

The strategy of noise figure measurements is to exploit the linear properties of noise. Consider thermal noise for a constant bandwidth. With a constant bandwidth, thermal noise (P_a=kTB) has linear characteristics. The following graph shows thermal noise versus absolute temperature for a constant bandwidth.



In this graph, the Y-axis indicates noise power and the X-axis indicates the absolute temperature. It is significant to note that the slope of this output is kB and that an absolute temperature of 0K produces thermal noise of zero Watts. This zero crossing also describes a Y-axis intercept. Incorporating this slope and this Y-axis intercept into the equation for a line yields the following equation for thermal noise.

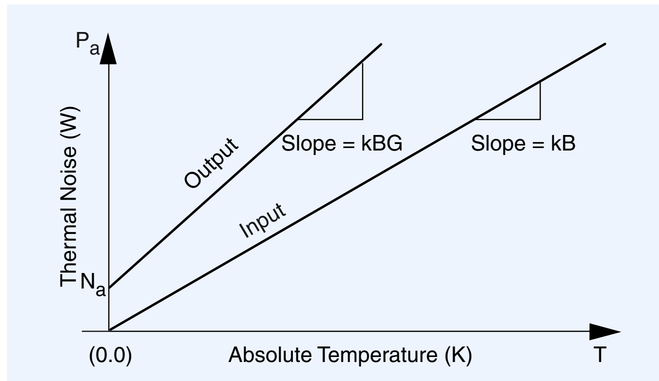
$$y = mx + b$$
(m is slope and b is Y-axis intercept)

$$P_a(T) = kB(T) + 0$$
$$\text{or } P_a(T) = kB(T)$$

For a constant value of bandwidth, this equation yields thermal noise for any absolute temperature. Clearly, this equation is an alternative form of the previous equation for thermal noise. It is important to note that this noise versus absolute temperature representation completely describes thermal noise characteristics. More importantly, this representation implies that any two points on this line completely describe the thermal noise characteristics.

Output Characteristics

Remember that a signal-to-noise ratio is an integral part of the noise figure definition. Now consider a signal-to-noise ratio when the signal portion is set to zero while carefully maintaining impedance such that there are no reflections. Using this signal-to-noise ratio as an input to an amplifier with gain, G, produces some interesting noise power output characteristics. Clearly, this input is essentially limited to the thermal noise; subsequently, the output is also limited to the product of thermal noise and amplifier gain. The following graph shows noise power output characteristics overlaying the previous thermal noise versus absolute temperature graph.



The noise power output characteristics are the product of the amplifier gain and kTB, or kTBG. The slope of this noise power output is kBG; furthermore, the noise power output for absolute temperature of zero is the added noise power, N_a, generated within the amplifier. This observation leads to a straightforward technique for measuring the added noise power generated within the amplifier.

It is important to note that this straight-line characteristic is a complete description of noise performance. In practice, it is not practical to sweep absolute temperature, but it is more common to find two points on the straight-line characteristic. These two points define a line. The slope and Y-axis intercept of this line provide the gain and noise figure, respectively.

Traditional Scalar Approach to Noise Figure Measurements

The culmination of these definitions is a traditional scalar noise figure measurement. In the traditional scalar noise figure measurement, a noise source, often consisting of an avalanche diode with matching hardware, provides two input noise source temperatures. The noise outputs from these two input noise source temperatures provide the required two points that will completely characterize the noise performance.

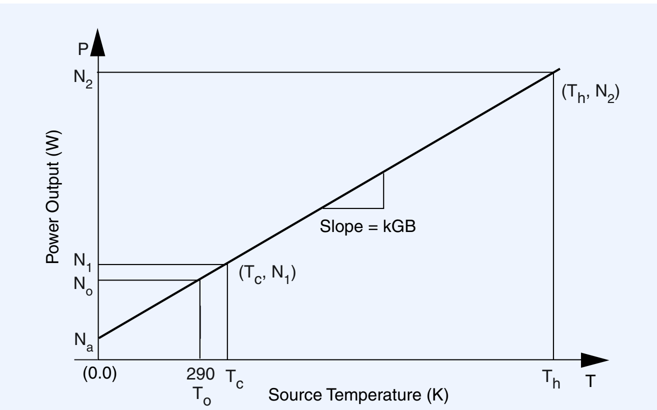
Within the noise source, the application and removal of bias causes the transition between these two noise source temperatures. With bias, the first noise temperature (T_h where h represents hot) is large, but calibrated (NIST traceable). Without bias, the second noise temperature (T_c where c represents cold) is small.

The manufacturers of noise sources specify the Excess Noise Ratio (ENR) instead of T_h.

The following equations indicate the relationships between ENR and T_h.

Conversion	Equation
T_h to ENR	$ENR = 10 \log (T_h - T_o)/T_o$
ENR to T_h	$T_h = T_o\ 10^{(ENR/10)} + T_o$

The following graph shows the details of the traditional scalar noise figure measurement in terms of the familiar noise power output versus absolute temperature format.



The terms T_{on} and T_{off} are sometimes substituted for T_h and T_c. The noise power associated with T_h is labeled N_2 and the noise power associated with T_c is labeled N_1. The ratio of N_2/N_1 is the Y-Factor. Using ordinary algebra, these two points determine the noise power ratio and the noise figure for the measurement.

First, the following Y-Factor equation represents the noise power ratio for the measurement.

$$Y = (N_2 / N_1)$$

Next, the following equation (presented without derivation) represents the noise figure from the measurement.

$$F = \frac{\left(\frac{T_h}{T_o} - 1\right) - Y\left(\frac{T_c}{T_o} - 1\right)}{Y - 1}$$

For $T_c = T_o$, this equation simplifies to the following equation.

$$F\ (dB) = ENR\ (dB) - 10 \log (Y - 1)$$

Clearly, these equations allow the calculation of Y-Factor and noise figure from the two input noise source temperatures. With this technique, noise figure measurements become convenient, straight-forward, and efficient.

Traditional Scalar Noise Figure Calculations

An example clarifies the application of the traditional scalar noise figure measurement. Find the noise power ratio and the noise figure for the following traditional scalar noise figure measurement. The measurement is on a device at a temperature of 290K (T_c = 290K). The measurement uses a 15 dB ENR (T_h = 9461K) noise source.

Term	Measured Noise Power
N_2	8.51×10^{-15} Watt
N_1	4.14×10^{-16} Watt

The following table shows the results of the noise power measurement.

First, the following calculations using the Y-Factor equation determine the noise power ratio from the measurement.

$$F = \frac{\left(\frac{T_h}{T_o} - 1\right) - Y\left(\frac{T_c}{T_o} - 1\right)}{Y - 1}$$

$$F = \frac{(31.62) - 20.56\ (0)}{20.56 - 1}$$

$$F = 1.62$$

$$F = 10 \log (1.62) = 2.1\ dB$$

$$Y = (N_2 / N_1)$$

$$Y = 8.51 \times 10^{-15} / 4.14 \times 10^{-16}$$

$$Y = 20.56$$

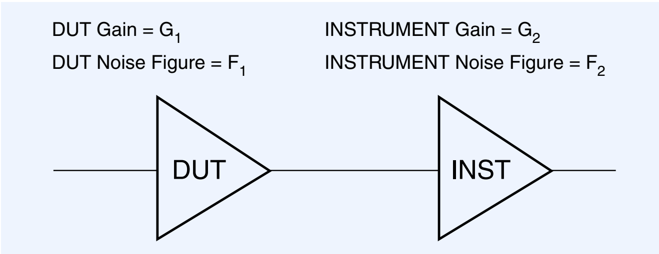
Next, the following calculations using the noise figure equation determine the noise figure for the measurement.

These calculations demonstrate that these equations allow the calculation of noise power ratio and noise figure from the two input noise source temperatures. Indeed, this technique supports convenient, straight-forward, and efficient noise figure measurements.

Cascaded Noise Figure Definition

A noise figure measurement is the combination of the Device Under Test (DUT) noise figure and the measurement instrument noise figure. The term second-stage contribution describes the noise contributed by the measurement instrument. A cascaded noise figure equation allows removal of this second-stage contribution from the overall noise figure measurement such that only the DUT noise figure remains.

The following diagram shows a cascaded network of a DUT and an instrument for analysis.



The DUT has available gain of G_1 and noise figure of F_1. Similarly, the instrument has gain of G_2 and noise figure of F_2, typically acquired during calibration. The following equation yields the overall noise figure (F) for this cascaded network.

$$F = F_1 + \{(F_2 - 1) / G_1\}$$

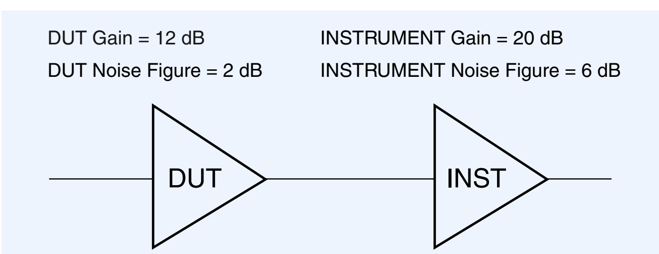
Solving this equation for F_1 allows the instrument to calculate the DUT noise figure from the overall cascaded noise figure measurement. The following equation shows the results after solving for F_1.

$$F_1 = F - \{(F_2 - 1) / G_1\}$$

Note that this equation indicates that the second-stage contribution becomes more significant as the DUT available gain decreases. This concept is important when considering noise figure measurement uncertainties.

Cascaded Noise Figure Calculations

An example illustrates the application of this cascaded noise figure equation. Consider the following situation.



The cascaded noise figure equation is in linear terms; therefore, convert the noise figure and gain from the logarithmic to the linear form. Perform all the calculations in linear terms and convert to logarithmic for the final results. The following conversion equations indicate the relationship between the logarithmic and linear terms.

Conversion	Equation
dB to Linear	Linear = $10^{(dB/10)}$
Linear to dB	dB = 10 log (Linear)

The following table shows the converted values for subsequent calculations.

Parameter	Logarithmic Value	Linear Value
DUT Gain	12 dB	15.85
DUT Noise Figure	2 dB	1.58
Instrument Gain	20 dB	100
Instrument Noise Figure	6 dB	3.98

The following calculations show the overall noise figure for this cascaded network.

$$F = F_1 + \{(F_2 - 1) / G_1\}$$
$$F = 1.58 + \{(3.98 - 1) / 15.85\}$$
$$F = 1.58 + 0.19$$
$$F = 1.77$$
$$F = 10 \log (1.77) = 2.48 \text{ dB}$$

This noise figure of 2.48 dB represents the overall noise figure as seen by the measurement instrument. The following calculations show how the measurement instrument determines the noise figure of the DUT for this overall noise figure of 2.48 dB (or 1.77).

$$F_1 = F - \{(F_2 - 1) / G_1\}$$
$$F_1 = 1.77 - \{(3.98 - 1) / 15.85\}$$
$$F_1 = 1.77 - 0.19$$
$$F_1 = 1.58$$
$$F_1 = 10 \log (1.58) = 2.0 \text{ dB}$$

These equations allow removal of the contributed noise from the measurement instrument. In this example, the second-stage contribution is only 0.48 dB. The following calculations show the noise figure of the cascaded network when the DUT Gain (G_1) equals 6 dB (or 3.98) instead of 12 dB.

$$F = F1 + \{(F2 - 1) / G1\}$$
$$F = 1.58 + \{(3.98 - 1) / 3.98\}$$
$$F = 1.58 + 0.75$$
$$F = 2.33$$
$$F = 10 \log (2.33) = 3.67 \text{ dB}$$

This second example shows that as the DUT Gain (G_1) decreases, the second-stage contribution becomes more significant. In this example, the second-stage contribution increased from 0.48 dB to 1.67 dB as the DUT Gain (G_1) decreased from 12 dB to 6 dB. This increase in second-stage contribution is important when considering noise figure measurement uncertainty.

Summary of Noise Figure Fundamentals

This concludes the introductory discussion regarding the fundamentals of noise figure measurements. This discussion began by defining noise and progressed towards the techniques for measuring noise figure. This discussion included definitions of noise, signal-to-noise ratio, noise figure, and noise power output characteristics. The application of these definitions led to the traditional scalar noise figure measurement. Finally, the cascaded noise figure equations allowed the removal of noise contributed from the measuring instrument.

The following are the major concepts presented in this discussion:

- Available thermal noise power is given by kTB and is useful for noise figure calculations.
- Noise figure describes the decrease (or degradation) in signal-to-noise ratio.
- Noise figure measurements are more practical using noise power output characteristics than signal-to-noise ratios.
- Noise power output characteristics use the linear properties of noise.
- The slope with respect to temperature of the noise power output is kBG and the Y-axis intercept is the noise power added by the DUT.
- An avalanche diode noise source provides two input noise source temperatures for a noise figure measurement.
- Ordinary algebra allows calculation of noise figure and noise power ratio from these two input noise source temperatures. The Y-Factor represents the noise power ratio (hot/cold).
- A noise figure measurement is the combination of the DUT noise figure and the measurement instrument noise figure. A cascaded noise figure equation allows removal of this second-stage noise contribution from the measurement instrument.

With this understanding of noise figure measurement fundamentals, this discussion now continues with the measurement advantages when using Anritsu's MS462xx for performing vector error-corrected noise figure measurements.

Advantages of the MS462xx Noise Figure Measurement Approach:

Improved receiver technology has played a major role in this era of improved wireless communications. Pagers, cell phones, television digital satellite systems (DSS), global positioning satellite (GPS) products, and space exploration are modern communication applications with improved receiver technology. This era of improved communications is also generating requirements for more accurate noise figure measurement.

Modern communication applications are possible (and popular) today because modern receiving systems can process weaker signals. Noise figure is the most important parameter that quantifies an application's ability to process weak signals. Accordingly, more accurate noise figure measurements will support the development of improved communication applications.

To support requirements for more accurate noise figure measurements, Anritsu is introducing a new Vector Network Measurement System. The MS462xx is a new RF Vector Measurement System that offers an option for vector error-corrected noise figure measurement from 50 MHz to 3 GHz. Compared to the traditional scalar approach, the noise figure measurement in combination with the S-parameter characterization allows more accurate noise figure measurements.

The purpose of this section is to understand the advantages of using the MS462xx for performing vector error-corrected noise figure measurements. This section of the discussion assumes familiarity with noise figure measurements.

The following outline briefly describes the organization of this section.

II. Advantages of the MS462xx Noise Figure Measurement Approach

A Similarities Between Traditional Scalar and Vector Error-Corrected Approaches

1. Noise Figure Definition
2. Measurement Employing the Y-Factor Method
3. Removal of Instrument Receiver Noise Figure

B. Differences In Terms of Measurement Uncertainties

1. Receiver Architecture with Comparison
2. Insertion Gain Versus Available Gain

C. Accounting for Cables, Test Fixtures and Other Networks

1. Losses Before the DUT
2. Losses After the DUT

D. Summary of Measurement Advantages

Noise Figure Fundamentals: What's in Common

It is essential to understand noise figure and the traditional scalar approach in order to appreciate the accuracy improvement of the vector error-corrected approach. Appropriately, the fundamentals begin with the similarities between the scalar and vector approach.

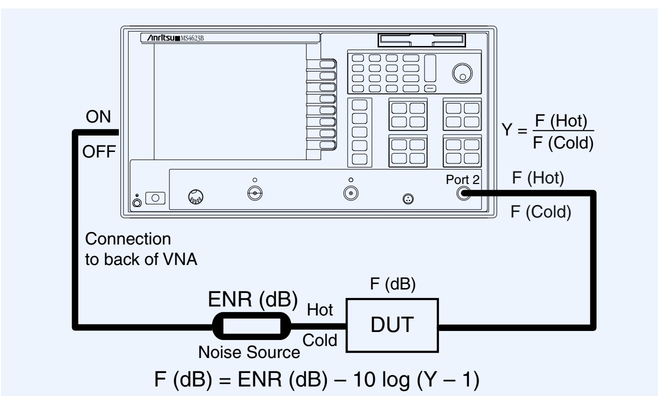
The most important parameter that quantifies a device's ability to process weak signals is noise figure. The following equation is the noise figure equation.

$$F\ (dB) = 10 \cdot \log\left[\frac{\left(\frac{S_i}{N_i}\right)}{\left(\frac{S_o}{N_o}\right)}\right]$$

Noise figure, typically expressed in dB, is the log ratio of the input signal-to-noise ratio to the output signal-to-noise ratio.

This definition quantifies the amount of thermal and shot noise generated within a device. More noise generated within a device causes more degradation in the output signal-to-noise ratio. This degradation causes a higher noise figure.

The following diagram presents the scalar noise figure measurement configuration using the MS462xx. In this configuration, the noise source location is external.

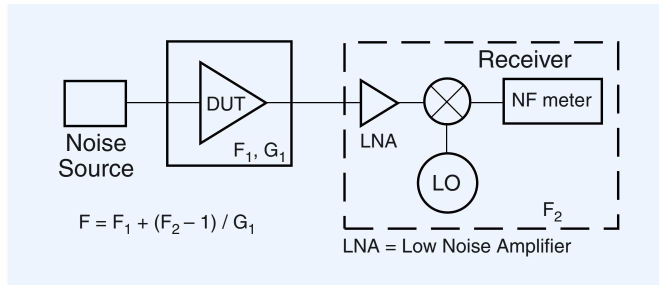


Noise figure measurements employ the Y-Factor method for measuring noise figure. This method uses a calibrated (NIST traceable) broadband noise source to apply two different noise signals to the Device Under Test (DUT). Within the noise source, the application and removal of bias to an avalanche diode causes the transition between these two noise signals. With bias, the first noise signal (hot) is large, but calibrated. Without bias, the second noise signal (cold) is small. Note that there could be impedance changes (caused by changing diode impedance with bias) between these hot and cold states. The ratio of measured power in these two cases (hot/cold) leads to the Y-Factor.

The simplified noise figure equation in terms of the Y-Factor (assuming $T_c = T_o$) is shown below.

$$F\ (dB) = ENR\ (dB) - 10 \log (Y - 1)$$

Frequency translation within the measurement instrument allows noise figure measurements at reasonable IF frequencies. There may be multiple frequency translations in some instruments. In this situation, the overall noise figure is the cascade of both the DUT noise figure and the instrument receiver noise figure. The following diagram shows how the cascaded noise figure equation allows removal of the instrument receiver noise figure from the overall noise figure measurement. Note that F_2 is acquired during calibration.



Solving this equation for F_1 allows the instrument to calculate the DUT noise figure from the overall cascaded noise figure measurement. The following equation shows the results after solving for F_1.

$$F_1 = F - \{(F_2 - 1) / G_1\}$$

Note that this equation indicates that the second-stage contribution becomes more significant as the DUT gain decreases.

Indeed, the foundation of both scalar and vector approaches is similar. Both approaches use the noise figure definition, the Y-Factor method for measurement, and the cascaded noise figure equation to remove the measurement receiver noise figure effect. A comparison of these approaches beyond this foundation continues with a discussion of the uncertainties that affect measurement accuracy.

Uncertainties Overview

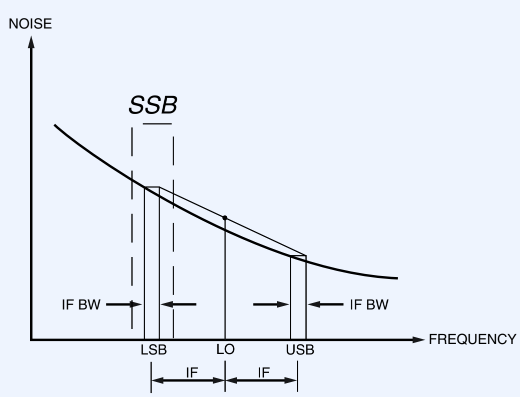
When measuring small noise figure values, measurement uncertainties become more significant regardless of the measurement approach. A discussion of factors that contribute to measurement uncertainty emphasizes the differences between the scalar and vector approaches. Many sources can contribute to measurement uncertainty considering each one of these sources during measurements can result in more accurate measurements.

Uncertainties: Good Measurement Practice

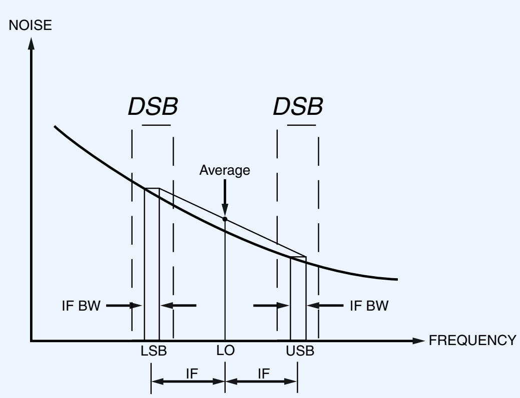
Good measurement practice is the foundation of all accurate noise figure measurements. Be aware of interference and avoid measurements in occupied RF or IF frequencies of the test environment. Minimize interference by using shielded cables, threaded connectors, enclosures, and shielded rooms for the DUT. Cables and connectors should be clean and of high quality. Avoid any DUT discontinuities and spurious responses. These simple steps can eliminate significant uncertainties.

Uncertainties: Receiver Architecture

The receiver architecture includes the frequency translations that allow measurements at reasonable IF frequencies within the measurement instrument. The receiver architecture is either a single or a double sideband architecture. A description of these receiver architectures is appropriate before discussing their contribution to measurement uncertainty. The following diagrams show the included frequencies for both receiver architectures.



Spectrum of SSB Noise Measurement



Spectrum of DSB Noise Measurement

In the traditional scalar approach, a single sideband (SSB) receiver architecture performs the frequency translation. By definition, **either** the upper (USB) **or** lower (LSB) sideband is translated to an intermediate frequency (IF). Under certain circumstances, the SSB receiver architecture can be less susceptible to abrupt DUT noise figure variations versus frequency (i.e., band limited devices).

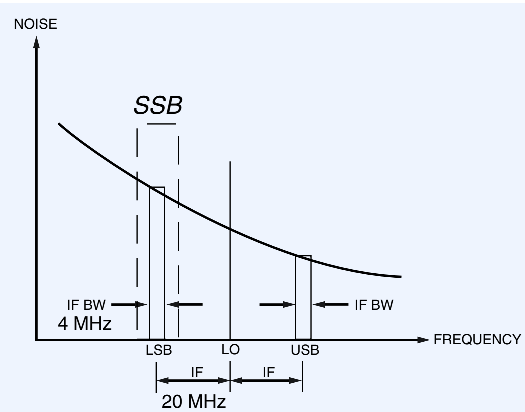
In the vector approach, a double sideband (DSB) receiver architecture performs the frequency translation. By definition, **both** the upper (USB) **and** lower (LSB) sidebands are translated to an IF. An average of both the upper and lower sidebands represents the measurement. A significant advantage of this DSB receiver architecture is that one receiver can perform both a noise figure measurement and an S-parameter characterization. The combination of these two measurements is an accurate vector error-corrected noise figure measurement.

Uncertainties related to receiver architecture are an issue for measurements where noise figure varies substantially versus frequency. Band limited devices exhibit this type of noise figure performance. A DSB receiver architecture can be more susceptible to DUT noise figure variations than an SSB receiver architecture; however, a narrowband (as opposed to a wideband) DSB receiver architecture can accurately measure this kind of DUT performance.

Uncertainties: Receiver Architecture Comparison

The best way to evaluate these receiver architectures is to understand noise figure variation and the effect on uncertainty. Clearly, significant uncertainty is introduced when there is a noise figure variation in the frequency range of the measurement. An example of this type of variation is exhibited in band limited devices. Obviously, more noise figure variation can be accommodated by limiting the amount of frequency included in the measurement. This observation implies that less measurement frequency range allows more noise figure variation. Considering the frequency range included in the measurement will be the basis for evaluating the two receiver architectures.

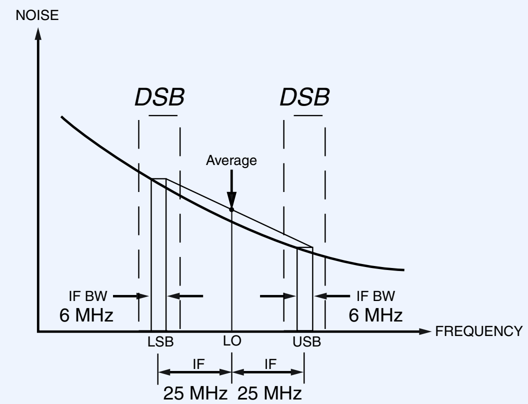
The following diagram shows the included frequencies for the traditional scalar SSB noise measurement architecture.



Traditional Scalar SSB Noise Measurement

In the traditional scalar receiver architecture, the IF is 20 MHz and the bandwidth is 4 MHz. The frequency measurement range is 4 MHz with this SSB receiver architecture. Note that this traditional scalar approach contains more uncertainty as the bandwidth of the DUT decreases from 4 MHz. This frequency range represents the standard for comparison with the following wideband and narrowband DSB receiver architectures.

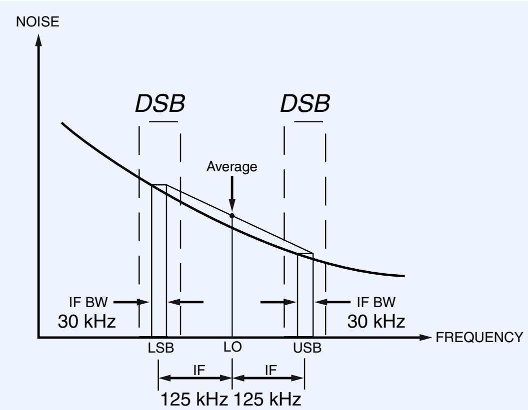
Next, the following diagram shows the included frequencies for the wideband DSB noise measurement architecture.



Wideband DSB Noise Measurement

In the wideband DSB receiver architecture, the IF is 25 MHz and the bandwidth is 6 MHz. The frequency measurement range is comprised of 12 MHz of frequency separated by 44 MHz, or 56 MHz (12 + 44 MHz). As expected, this architecture can be more susceptible to DUT noise figure variations than the SSB architecture, which only used 4 MHz. This comparison indicates more measurement uncertainty can be associated with the wideband DSB receiver architecture than the SSB receiver architecture.

Finally, the following diagram shows the included frequencies for the narrowband DSB noise measurement architecture.



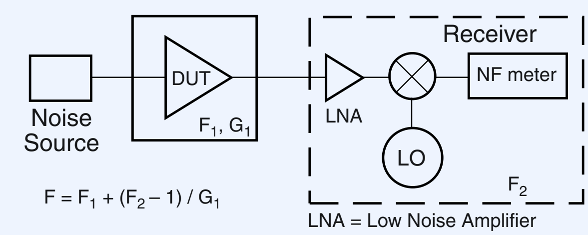
Narrowband DSB Noise Measurement

In the narrowband DSB receiver architecture, the IF is 125 kHz and the bandwidth is less than 30 kHz. Similarly, the frequency measurement range is comprised of 60 kHz of frequency separated by 220 kHz, or 280 kHz (60 + 220 kHz). This narrowband DSB architecture can be less susceptible to DUT noise figure variations than both the SSB and wideband DSB architectures. In addition, this narrowband DSB approach allows more accurate measurement of band limited devices than the traditional scalar approach (particularly as the DUT bandwidth decreases from 4 MHz). This comparison clearly shows that the least measurement uncertainty can be associated with the narrowband DSB receiver architecture.

Using the DSB receiver architecture of the Vector Network Measurement System allows more accurate vector error-corrected noise figure measurements. In addition, the narrow-band DSB receiver architecture can be less susceptible to noise figure variations than the traditional scalar approach.

Uncertainties: Insertion versus Available Gain

The noise figure calculation is a function of the Y-Factor, the receiver noise figure, and the **available** gain. The uncertainty associated with removal of the receiver (or second-stage) noise figure depends on whether insertion or available gain is included in these calculations. For this reason, a more detailed description of insertion and available gain provides a better understanding of their effect on measurement uncertainty. The following diagram shows the cascaded noise figure network consisting of the DUT and the measurement instrument.



Second-stage uncertainty occurs because the receiver following the DUT has a noise figure. The evaluation of this second-stage effect is not straight-forward. The cascaded noise figure equation for correction is $F_1 = F_{meas} - [(F_2 - 1) / G_1]$, where G_1 is the available gain of the DUT. The scalar approach substitutes insertion gain for available gain in this equation; whereas, the vector approach calculates available gain directly from the S-parameter characterization. **By definition, the available gain provides the more correct measurement!**

Insertion gain measurements are based on the existing matches in the test setup. The first measurement takes place with the noise source connected to the receiver. The second measurement takes place with the DUT connected between the Noise Source and the receiver. By definition, the ratio between these two measurements (second/first) is insertion gain. Note that the power measurement is always made at the input of the receiver; therefore, accommodations for mis-matches are not possible. Indeed, mismatches can contribute significant uncertainty for the scalar approach.

Available gain is the ratio of power available from the DUT to power available from the source. Note that S-parameter characterization provides the DUT input and output reflection characterization for these measurements. Accordingly, available gain is more accurate because it takes into account the effect of mismatches during measurements.

Available gain calculations can minimize the uncertainties of mismatches and second-stage removal calculations by including S-parameter characterization during the measurement. Specifically, available gain addresses mismatches during measurements which allows more accurate removal of the second-stage noise figure and results in a more accurate vector error-corrected measurement.

Uncertainties: Instrument Related

The Excess Noise Ratio (ENR) uncertainty, instrumentation uncertainty, and instrument noise figure contribute to overall uncertainty in the noise figure measurement. Explanation of these uncertainties is straightforward and applicable for both approaches.

Clearly, the ENR accuracy of the noise source contributes heavily to the accuracy of the noise figure measurement. Calibration of the noise source with devices from NIST provides the greatest accuracy. Maintain ENR accuracy by ensuring calibration of the noise source at regular intervals. Both scalar and vector approaches are susceptible to this uncertainty.

In application, the ENR values provided by the manufacturer assume perfect matches; consequently, any mismatches introduce significant ENR accuracy uncertainties. The error-corrected approach adjusts the ENR values to reflect the matching characteristics of the measurement including impedance changes between the “on” and “off” states of the noise source. In addition, the error-corrected approach supports ENR extension compensation for routing the noise through the Vector Network Measurement System to the test port. The traditional approach does not address these sources of uncertainty.

Instrumentation uncertainty affects the repeatability of measurements. Typically, higher performance receivers contribute less uncertainty. Know the instrument specifications and their contribution to this uncertainty.

One very important specification is the noise figure of the instrument. The higher the noise figure of the instrument, the more uncertainty associated with the second-stage removal calculations. The second-stage uncertainty becomes more significant as the DUT available gain decreases. In this case, the receiver noise figure is a more significant portion of the measurement and, consequently, more difficult to remove. Again, the error-corrected approach can help minimize this uncertainty.

Noise Figure Measurements:
Correcting for Cables, Test Fixtures, and Other Networks

The ideal noise figure measurement is usually pictured as having the DUT placed directly between a noise source and the noise receiver. Reality intrudes in the need for cables, adapters, test fixtures and other networks that must be connected between the fundamental components. The increasing requirement for integrated measurement systems to speed test time further complicates the picture. The switching and related hardware required for the additional measurements represent a network whose effects must be taken into account in the noise figure measurement. The corrections apply in both narrowband and wideband measurement modes and may apply in scalar as well as vector-corrected operation.

Networks Before the DUT

When making noise figure measurements, one normally relies on the calibrated ENR values provided for the noise source by the manufacturer or by some calibration agency. While the accuracy of these values may or may not be an issue, the measured noise figure (raw and, for devices with high gain, corrected) is directly proportional to the effective ENR under certain assumptions. The moment anything is connected between the noise source and the measurement plane, the ENR values are no longer valid. This network may be an adapter, a cable set, a test fixture, or almost anything else. If the match of the network is good and the loss is very low (<0.1 dB), the effect may not be noticeable. If the network has different characteristics or high accuracy is required, the network effects must be corrected.

There are two ways, within the MS462X instrument, to accomplish this correction:

- Extension files
- Loss Before DUT

Internal Extension File

This is a file type generated at the factory to describe the network between the rear panel noise port and port 1 on the front panel. This path is used for INTERNAL noise measurements when the user desires multiple measurements with one connection. The user may generate a new internal extension file if required but this is normally not advised. The S-parameters of the path are measured and stored in an S2P format (real-imaginary data form) with a file name extension .EXT. An additional pair of columns is added on the end of the S2P file to describe the noise source match. For more details on the exact file format, see the MS462X Operation Manual.

The important points of this file type are:

- It is invoked only when the internal noise mode is active
- It must be invoked for both calibration and measurement (forced to by the system)
- It is usually only used to describe an internal path but that can be changed if the circumstances warrant (e.g., a network is attached to port 1 semi-permanently)
- Accuracy of the measured S-parameters is important, a careful calibration and measurement is advised.

External Extension File

This is a user file type of the S2P format (magnitude-angle form which the system uses for an S2P save) with a file name extension .NFX. The file is used to describe a user network between port 1 and the DUT/receiver (internal mode) or between the noise source and the DUT/receiver (external mode). Usually the frequency range of this file should match or exceed the measurement frequency range but the system can accommodate other ranges (as long as they are not disjoint). Extrapolation and interpolation will be employed to compute values as necessary.

For both types of extension files, the available gain of the network is computed in order to adjust the ENR of the noise source. Be aware that if the loss of the network is high relative to the ENR, measurement uncertainty can radically increase. If the external extension file is applied and the system is in internal mode, the two files (internal and external extension) will be concatenated before being applied to the ENR table.

Normally the external extension file must be used during both calibration and measurement (and it must be the same extension) since the system would have difficulty computing DUT gain if the network were to be changed. If the gain is of little interest and it is sufficiently high that it does not affect the noise figure calculation, this proviso can be taken more lightly (the algorithm will still correctly do its job of correcting the effective ENRs). If a change is necessary and the gain is important (e.g., the need for an RF filter for a mixer measurement), then use loss-before-DUT described below.

The important points of this file type are:

- It is invoked when the External Extension mode is turned on.
- It can be applied in either external or internal mode. In the case of internal, the internal and external extension files will be properly concatenated.
- The file should be invoked for both calibration and measurement (the network must, of course, be present during both calibration and measurement).
- Accuracy of the measured S-parameters is important, a careful calibration and measurement is advised.

Loss Before DUT

This function can be used for a user network between the noise source and the DUT that is well-matched and has a loss that is flat with frequency (cables and adapters may fall into this category if the frequency range is not too large). In this case, the user enters a numerical value describing the network loss in dB, which should be entered prior to calibration and used throughout the measurement (assuming the network is present during calibration). If the DUT has significant gain (so that receiver noise figure is less relevant), it is less important that the correction be applied during the calibration.

Some important notes:

- It is invoked whenever a non-zero value is entered
- If the network is in place for both calibration and measurement, the value should be in place for both steps. If different networks are in place during cal and measurement, enter the appropriate values during those steps (the system will remember what value was entered during the calibration).
- If in internal mode, this correction will be applied in addition to the internal extension file

Networks After the DUT: Loss After DUT

The networks after the DUT must also be corrected for but they usually have less impact if the DUT has gain. This is easy to understand based on the second stage noise figure correction equation (see basic application note). Aside from test fixtures, cables, etc., one may often have a pad on the DUT output in order to avoid overload conditions. If the loss is present during calibration, it need not be corrected for in this case (it will be ignored if a value is entered) since it will be incorporated into the receiver noise figure.

This correction, operationally similar to the ‘loss before DUT’, is applicable to both external and internal modes and will only be applied if a calibration is active. The latter is a requirement since the DUT gain must be known for the correction to be applied.

Summary of Measurement Advantages

This discussion has described the similarities and differences between scalar and vector noise figure measurements. The emphasis has been on making more accurate noise figure measurements using the vector error-corrected approach. Refer to the table below for the similarities and differences between these two approaches.

Similarities and Differences Between the Scalar and Vector Approach

Factors or Uncertainty	Scalar Approach	Vector Approach
Good Measurement Practice	Yes	Yes
Noise Figure Measurement Using Y-Factor Method	Yes	Yes
Receiver Architecture	Single Sideband (SSB)	Double Sideband (DSB)
Noise Figure Calculation Using Available Gain	No	Yes
IF Bandwidth	IF = 20 MHz Bandwidth = 4 MHz	Wideband: IF = 25 MHz Bandwidth = 6 MHz Narrowband: IF = 125 kHz Bandwidth < 30 kHz
Measure DUT << 4 MHz	No	Yes
Noise Figure	4-7 dB	Wideband: 3-7 dB Narrowband: 5-10 dB
Instrumentation Uncertainty	Comparable	Comparable
ENR Uncertainty	Yes	Yes
"On" and "Off" Noise Source Correction	None	Corrected

- More accurate measurements require the consideration of these uncertainties.
- The foundation of all accurate measurements is good measurement practice.
- Understand the differences in receiver architectures and apply the correct architecture to suit the DUT.
- Most importantly, remember that vector error-corrected measurements calculate available gain, which accounts for mismatches during measurements.
- In addition, the vector approach offers enhanced ENR accuracy by compensating for mismatches during measurements.
- Finally, be aware of how the instrument specifications contribute to the accuracy of the measurement.

In summary, the MS462xx supports the vector approach for noise figure measurements. The vector error-corrected approach is more accurate because it can minimize uncertainties more than the traditional scalar approach. Indeed, the MS462xx is a powerful system for accurate noise figure measurements.

Noise Figure Measurements Using the MS462xx

The purpose of this section is to provide a procedure for performing a noise figure measurement using the MS462xx. This procedure requires a basic understanding of the preceding discussions. This section also briefly explains menu nomenclatures and calibration considerations. Upon completion of the section, noise figure measurements will be straightforward and intuitive to perform using the MS462xx.

The following outline briefly describes the organization of this section.

III. Noise Figure Measurements Using the MS462xx

A. Software Organization
   1. Noise Figure Application

B. Hardware Organization
   1. Noise Source Location

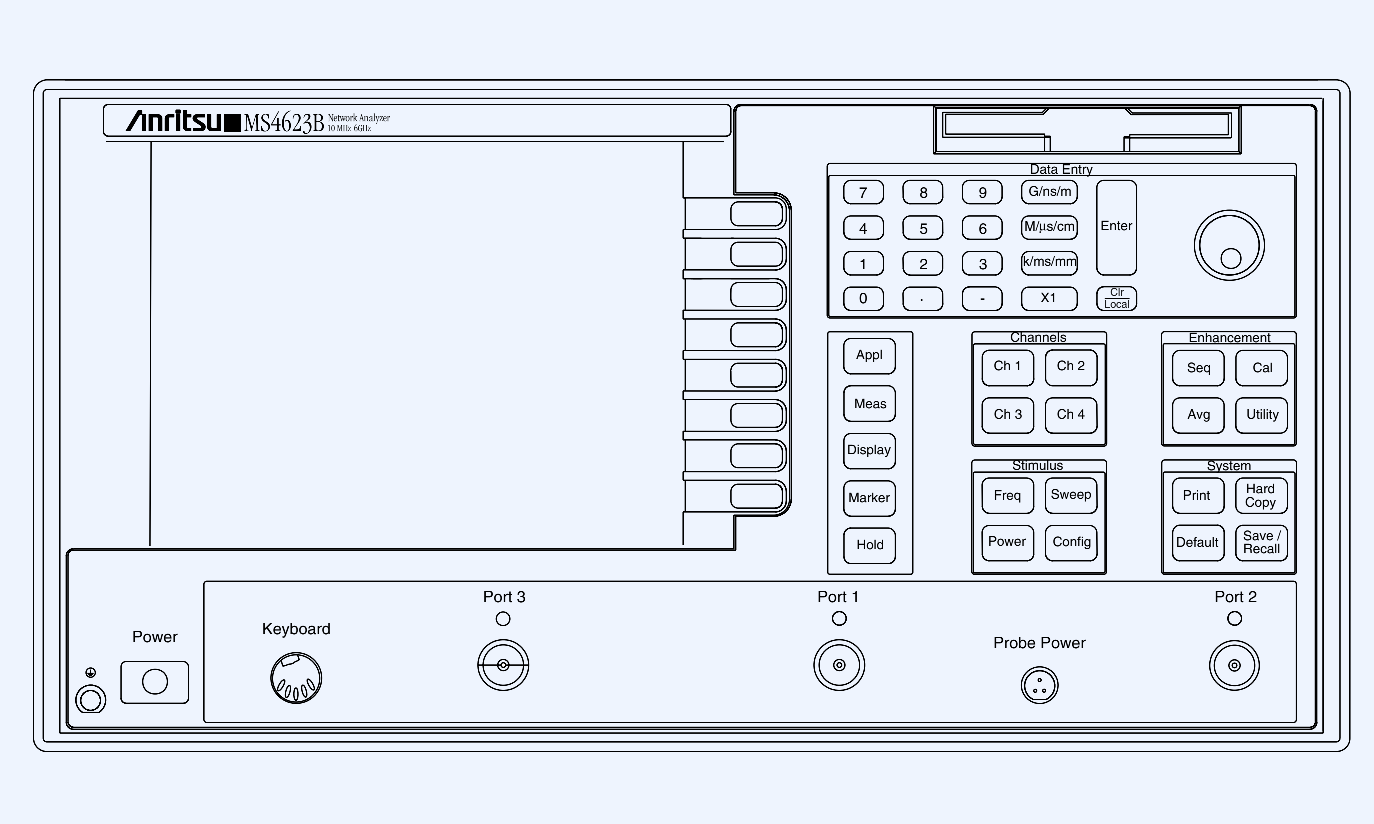
C. Noise Figure Measurement Procedure
   1. Noise Figure Setup
   2. Noise Figure Calibration
   3. Noise Figure Measurement

D. Typical Noise Figure Data for an Amplifier

E. Recommended Evaluation Approach

F. Summary of Noise Figure Measurements

G. Bibliography

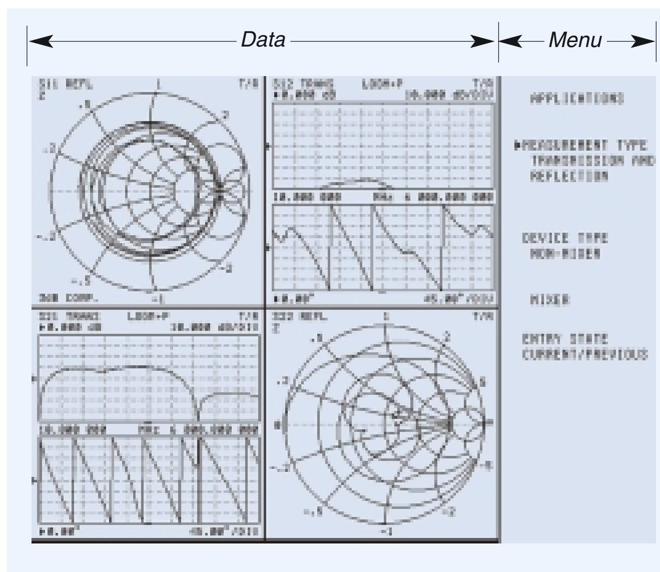


Software Organization

The MS462xx organizes measurement capabilities into applications accessible from an applications key (Appl) on the front panel. The MS462xx front panel view is provided below for reference. Note that the Appl key is directly below the zero key of the number pad.

This organization allows straightforward and intuitive measurement operation not only for noise figure but for gain compression, time domain, harmonic, intermodulation distortion, and other future measurements. This organization also allows a convenient approach for switching between measurement configurations.

The following graphic is a typical display following the selection of the Appl key.



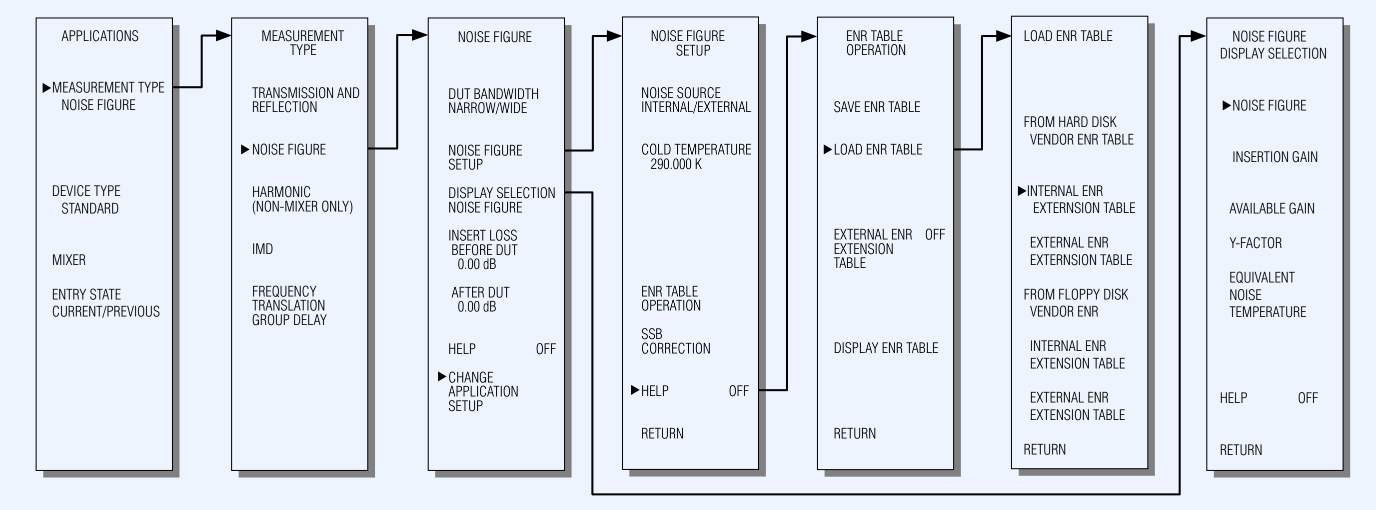
Notice that the display is partitioned into the data and the menu display areas separated by a vertical line. The menu display area provides the selection mechanism for the MS462xx and will be the focus of this section.

Noise Figure Application

Selection of the applications key (Appl) is the first step in the procedure for performing a noise figure measurement. Selection of the Appl key provides the following Noise Figure Application Menu Structure.

Selection of E.N.R. TABLE OPERATION from the NOISE FIGURE SETUP menu displays the E.N.R. TABLE OPERATION menu.

Note that each menu has a title corresponding to the functions available in the menu.



Noise Figure Setup Menu Structure

This menu tree allows configuration of the noise figure measurement. A thorough understanding of this menu structure is required for the rest of this discussion; therefore, a brief explanation is appropriate.

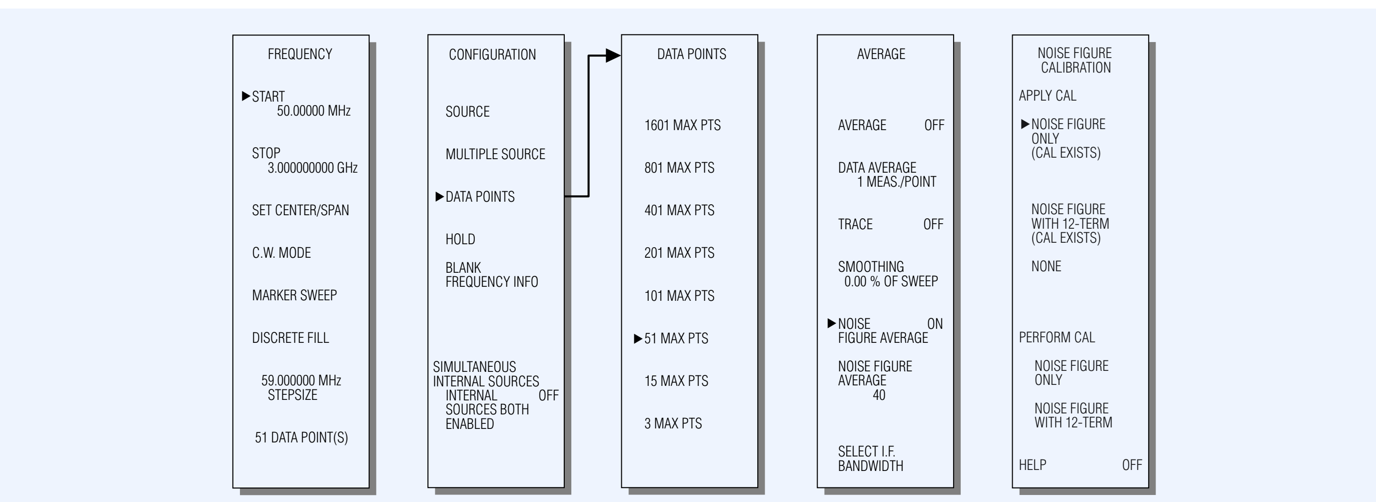
The first menu on the left is displayed following the selection of the Appl key. The second menu is displayed following the selection of MEASUREMENT TYPE. Similarly, the third menu is displayed following the selection of NOISE FIGURE. At this point, the MS462xx is configured for a noise figure measurement.

From the NOISE FIGURE application, selection of NOISE FIGURE SETUP displays the NOISE FIGURE SETUP menu. Similarly, selection of DISPLAY SELECTION brings up the DISPLAY SELECTION menu.

The Calibration Menu Structure, at the bottom of this page, is also referenced during this discussion.

It is important to note that the calibration menus are not sequential in their implementation. This means that frequency, data points, and averaging are accessible in any sequence as long as all these settings are in place before calibration. In addition, the Frequency, Configuration, Average, and Noise Figure Calibration menus are all accessible as front panel key selections. Specifically, the Frequency and Configuration keys are in the Stimulus area of the front panel and the Average and Noise Figure Calibration keys are in the Enhancement area of the front panel.

The Noise Figure Setup Menu structure and the Noise Figure Calibration Menu structure provide the primary interface for configuring the noise figure measurement.



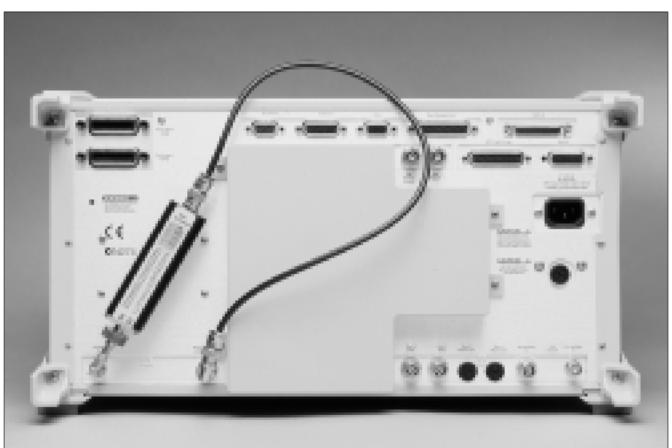
Noise Figure Calibration Menu Structure

Hardware Organization

The noise figure measurement application requires the location of the noise source to correctly configure the instrument for measurement. The two choices are external or internal. The following photos show the noise source location for both configurations.

Noise Source Location = External

Noise Source Location = Internal



Noise Source Location = Internal

Noise Figure Setup

Reference the Setup Menu Structure for the following noise figure setup discussion.

The MS462xx is configured for a noise figure measurement when NOISE FIGURE is selected as the Measurement Type. Next, the setup procedure further configures the system for the noise figure measurement by specifying the DUT Bandwidth, the Noise Source Location, and the loading of the appropriate ENR Files. The remaining setup parameters allow Cold Temperature, Bandwidth Correction, and SSB Correction selection.

The following table provides further explanation for these setup parameters.

Setup Parameter	Explanation
DUT Bandwidth	Wide indicates that the DUT noise figure performance is relatively broadband (BW ≥ 6 MHz). Wide also provides the fastest measurement. Narrow allows measurements for band limited DUTs (BW < 6 MHz).
Noise Source	Internal indicates that the Noise Source is connected to the rear panel. External indicates that the Noise Source is not connected to the rear panel. Note that External Error-Corrected measurements are not possible.
ENR Table Operation	This controls the loading of the ENR values.
— Load Vendor ENR Table	This refers to the ENR values for the noise source. The table on the noise source(s) is stored in a tab-delimited ASCII format for retrieval.
— Load ENR Extension Table	This refers to the S-Parameter characterization file between the rear panel noise source connection and the Test Port 1 connection to the DUT. This file contains up to 101 points and combines S2P data with the noise source reflection coefficient data.
Cold Temperature	This represents the noise source temperature for the measurement.
Wideband BW Corr Freq	For DUT Bandwidth = Wide, this allows bandwidth correction when Narrowband is not desired. This frequency should correspond to the “brickwall” bandwidth of the DUT.
Wideband BW Corr Mode	For DUT Bandwidth = Wide, this allows enabling and disabling of the BW Correction.
SSB Correction	This allows compensation for a DUT (usually a mixer) with single sideband (SSB) behavior.
Loss Before DUT	Numerical value describing the network loss in dB before the DUT
Loss After DUT	Numerical value describing the network loss in dB after the DUT
ENR .EXT Files	S2P file from factory describing the network between rear panel to Port 1. Used in internal noise measurements.
ENR .NFX Files	S2P file that is user defined describing user network between Port 1 and the DUT/Receiver for both internal and external noise measurements modes.
External Extension Table	Select ON when using External Extension Table and a Network during both calibration and measurement.

Noise Figure Calibration

Refer to the Calibration Menu Structure for the following noise figure calibration discussion.

The calibration procedure combines the previous noise figure setup with the system settings for Frequency, Data Points, and Noise Figure Averaging for a noise figure calibration. This calibration can include 12-term correction when using the Internal selection for Noise Source.

The following table provides further explanation for these calibration parameters.

Calibration Parameter	Explanation
Frequency	Specify the Frequency range for the noise figure measurement. The Start and Stop Frequencies correspond to the frequencies of the lower (LSB) sidebands.Typically, a range slightly larger than the passband is chosen. Alternately, the range of the 12-term calibration is chosen.
Data Points	Specify the Number of Points for the noise figure measurement. The noise figure measurement requires more time for more data points.
Noise Figure Average ON/OFF	This allows enabling and disabling of the Noise Figure Averaging function.
Noise Figure Average	This indicates the quantity of measurements to include in the average function. The default value is 40 and this averaging is adequate for both Wideband and Narrowband Measurements.

The noise figure calibration requires a decision whether to include the 12-term calibration. When including the 12-term calibration, the noise figure calibration defaults to the exact system settings as the 12-term calibration. The relevant system settings include Start Frequency, Stop Frequency, and Data Points. For this reason, these system settings are important to consider before the noise figure measurement.

An example clarifies this concern. Consider an amplifier with a 3 dB noise figure between 800 and 900 MHz. The relevant system settings for a typical S-parameter calibration are 201 Data Points between 750 and 950 MHz. These same system settings for noise figure would lead to a noise figure measurement that typically only requires 15 Data Points. Considering the noise figure system settings before selecting the S-parameter system settings will help optimize both measurements for speed.

A noise figure calibration is straightforward with or without the 12-term calibration. The noise figure calibration only requires one through connection between the noise source and the MS462xx receiver. The S-parameter of this through connection are simultaneously measured when Noise Figure with 12-term is selected.

Noise Figure Measurement

Refer to the Setup Menu Structure for the following noise figure measurement discussion.

The noise figure measurement follows the calibration process. Choosing between the Display Selections allows convenient viewing of the noise figure measurement results. The Display Selections are accessible from the Noise Figure Application and include Noise Figure, Insertion Gain, Available Gain, Y-Factor, and Equivalent Noise Temperature.

The following table provides further explanation of these Display Selections.

Display Selection	Explanation
Noise Figure	With 12-term calibration applied, this represents vector error-corrected noise figure; otherwise, this represents scalar noise figure.
Insertion Gain	Available with or without 12-term correction, this represents the gain measurement making no corrections for matching characteristics.
Available Gain	Only available with 12-term correction, this represents the gain as determined by the S-parameter measurements.
Y-Factor	The DUT output measurement ratio between the hot and cold states of the noise source.
Equivalent Noise Temperature	The temperature of a resistor whose noise power is equal to the input-referred noise-added power of the DUT.

An example clarifies the use of these Display Selections. Consider a scalar noise figure measurement output which consists of both insertion gain and noise figure. The following table outlines a procedure to configure the Vector Network Measurement System for the appropriate output.

Step	Description	Path (Referenced to Front Panel)
1	Select Channel 1 as the Active Channel	Press Ch 1 on the Front Panel
2	Change Graph Type to Log Magnitude	Display/Graph Type/ Log Magnitude
3	Change Display Selection to Noise Figure	Appl/Display Selection/ Noise Figure
4	Adjust the Scale	Display/Scale/Resolution
5	Select Channel 3 as the Active Channel	Press Ch 3 on the Front Panel
6	Change Graph type to Log Magnitude	Display/Graph Type/ Log Magnitude
7	Change Display Selection to Insertion Gain	Appl/Display Selection/ Insertion Gain
8	Adjust the Scale	Display/Scale/Resolution
9	Change Display Mode to Overlay Dual Channels 1 & 3	Display/Display Mode/ Overlay Dual Channels 1 & 3

A similar procedure allows comparison between insertion gain and available gain. Simply replace the noise figure display above (Step 3) with available gain (and make sure the calibration includes the 12-term correction). Another interesting output is the use of Trace Memory (Display/Trace Memory) on a Single Channel (Display/Display Mode/Single Channel) to make comparisons between vector error-corrected and scalar noise figure measurements. Clearly, this flexible output capability allows some creativity in displaying the measurement results.

Typical Noise Figure Data for an Amplifier

The previous sections provide the foundation for performing a noise figure measurement using the MS462xx. The following data demonstrates the application of this noise figure measurement for a typical amplifier. The emphasis is on application rather than the measurement setup, calibration, and display details. In this way, the flexibility of this noise figure measurement capability is clearly demonstrated.

The typical data includes S-parameter and noise figure measurement data. The S-parameter data consists of input and output matching characteristics (S_{11} & S_{22}), isolation (S_{12}), and gain (S_{21}). This data is displayed in four-channel log magnitude format. The noise figure data consists of traditional scalar and vector error-corrected noise figure measurements using overlay dual channels.

The amplifier has the following typical specifications.

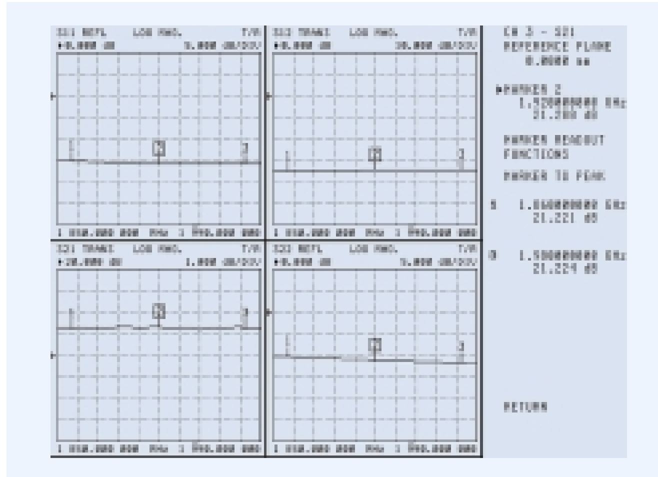
Parameter	Specification
Frequency Range	1850 to 1990 MHz
Gain	21 dB
Noise Figure	1.0 dB
1 dB Power Output Compression	+12 dBm

The MS462xx is configured with the following relevant settings for these measurements.

System Parameter	Setting
Frequency	1850 to 1990 MHz
Source 1 Power	-15 dBm
Data Points	51 Points
I.F. Bandwidth	1 kHz
Averaging	25
DUT Bandwidth	Wide
Noise Source (15 dB ENR)	Internal
NF Averaging	40

S-Parameter Measurements

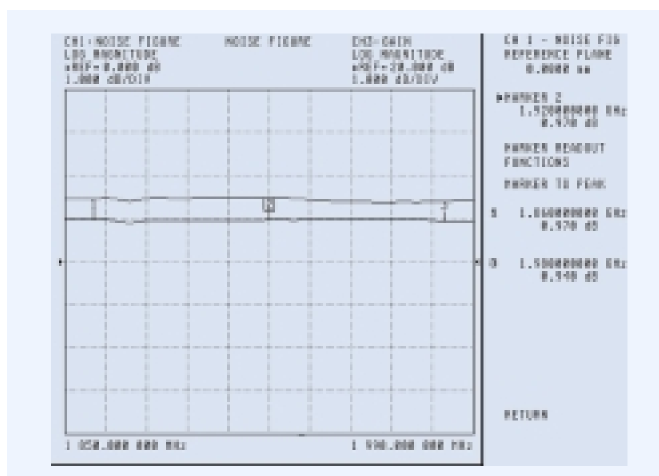
The following data shows the S-parameter measurements of the amplifier using the previous relevant system settings.



Note that the input matching is greater than 15 dB and the output matching is greater than 10 dB. The scalar and vector error-corrected noise figure measurements should produce similar results based on this matching performance.

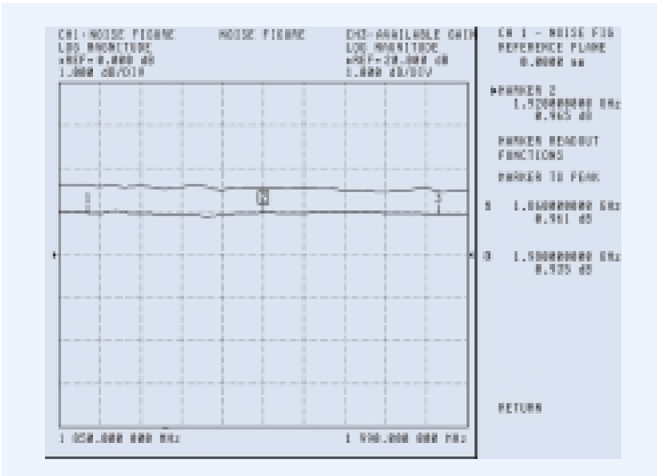
Scalar Noise Figure Measurement

The following data shows the scalar noise figure measurement of the amplifier using the previous relevant system settings. In this case, the noise figure calibration is performed **without** the 12-term correction. Note that the top trace is Gain (Insertion Gain).



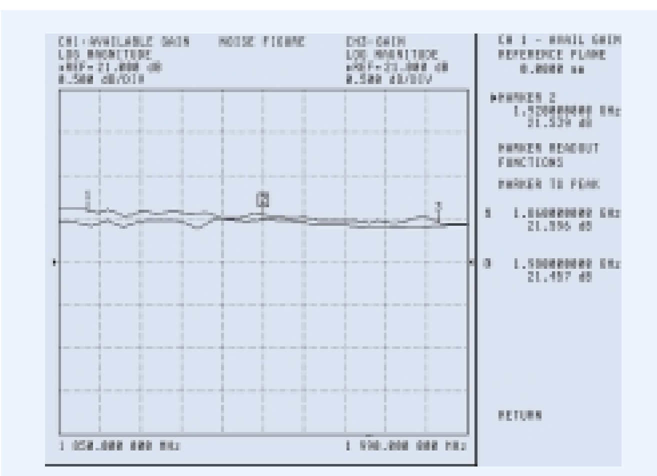
Vector Error-Corrected Noise Figure Measurement

The following data shows the vector error-corrected noise figure measurement of the amplifier using the previous relevant system settings. In this case, the noise figure calibration is performed **with** the 12-term correction. Note that the top trace is Available Gain.



Comparison of Available Gain to Insertion Gain

The following data shows the Available Gain versus Insertion Gain measurement of the amplifier using the previous relevant system settings. In this case, the noise figure calibration is performed **with** the 12-term correction, but only applied during the Available Gain measurement. Note that the markers are on the Available Gain trace.



Summary of Typical Data

The following table summarizes the results of the previous data.

Parameter	Scalar	Vector Error-Corrected	S_{21}
Gain	Mkr 1: 21.455 dB Mkr 2: 21.474 dB Mkr 3: 21.395 dB	Mkr 1: 21.596 dB Mkr 2: 21.539 dB Mkr 3: 21.457 dB	Mkr 1: 21.221 dB Mkr 2: 21.288 dB Mkr 3: 21.224 dB
Noise Figure	Mkr 1: 0.970 dB Mkr 2: 0.970 dB Mkr 3: 0.940 dB	Mkr 1: 0.961 dB Mkr 2: 0.965 dB Mkr 3: 0.935 dB	N/A

The previous prediction (based on the S-parameter data) that both approaches should produce similar results is clearly indicated by this data. Indeed, both the scalar and vector error-corrected measurements provided similar results.

Note that the Vector Error-Corrected and S_{21} values for gain are similar but, the interpretation of these values requires an understanding of the calculations. The differences are related to the way these parameters are measured. Remember that the Vector Error-Corrected measurement uses **available** gain. For this reason, the available gain calculations are based on conjugate matches to the amplifier; whereas, the S_{21} gain assumes 50 ohm matches. Only as the conjugate matches approach 50 ohms does the available gain approach the S_{21} gain.

This data represents typical amplifier measurements using the foundation provided in the previous sections. This data also demonstrates the flexible noise figure measurement capability of the MS462xx.

Recommended Evaluation Approach

Develop confidence and familiarity with the noise figure measurement capability of the MS462xx by performing the following five measurements.

1. Perform a 12-term (using 51 points) calibration and measurement of the DUT. Note both input and output return loss performance. Expect differences between vector error-corrected and scalar noise figure measurements for return loss performance of less than 10 dB.
2. Perform an External noise figure measurement (NOISE SOURCE = EXTERNAL) for comparison with traditional scalar measurement. Be sure to use DUT BANDWIDTH = Wide.
3. Next, perform an Internal noise figure measurement (NOISE SOURCE = INTERNAL) **without** 12-term correction for comparison with the previous measurement.
4. Finally, perform an Internal noise figure measurement (NOISE SOURCE = INTERNAL) **with** 12-term correction for the vector error-corrected noise figure measurement.
5. Additionally, compare noise figure measurements using DUT Bandwidth = Narrow versus DUT Bandwidth = Wide.

Summary of Noise Figure Measurements

This section provided a procedure for performing a noise figure measurement using the MS462xx. The following summarizes the information presented in this section:

- An understanding of the software and hardware organization provides the foundation for performing noise figure measurements using the MS462xx. Presentation of the menu structures and the block diagrams ensures proper measurement setup.
- The front panel application key (Appl) allows convenient selection and initialization of measurement applications available with the MS462xx. This discussion addresses the noise figure application, but other applications include gain compression, time domain, harmonic, intermodulation distortion, and other future measurements.
- The setup for a noise figure measurement requires specifying the DUT Bandwidth, the Noise Source Location, and loading of the appropriate ENR Files. Other setup parameters include Cold Temperature, Bandwidth Correction, SSB Correction, Loss Before DUT and Loss After DUT.
- The calibration for a noise figure measurement requires system settings for Frequency, Data Points, and Noise Figure Averaging.
- The noise figure calibration can include a 12-term calibration; however, the noise figure system settings will conform to the 12-term calibration system settings.
- In the Noise Figure Application, Display Selections allows convenient viewing of the noise figure measurement results. These selections include Noise Figure, Insertion Gain, Available Gain, Y-Factor, and Equivalent Noise Temperature.
- Utilizing the two-channel overlay display capability of the MS462xx, the Vector Network Measurement System can simultaneously display gain and noise figure. In addition, the instrument can display any combination of Display Selections in a similar manner.
- Some typical noise figure measurement data for an amplifier is also included as reference.
- A recommended evaluation approach allows quick familiarization with the flexible organization of the noise figure application.

The MS462xx supports the vector error-corrected approach to noise figure measurements. The seamless integration of this noise figure application into the MS462xx user interface allows intuitive and straightforward noise figure measurements. This powerful combination of noise figure and S-parameter measurements demonstrates Anritsu's commitment to providing innovative measurement solutions.

The bibliography provides references with more thorough noise and noise figure measurement discussions.

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Friis, H.T. "Noise Figures of Radio Receivers," Proceedings of the IRE, Vol. 32, July 1944, pp. 419-422.

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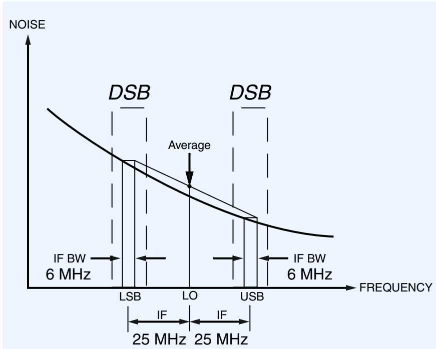
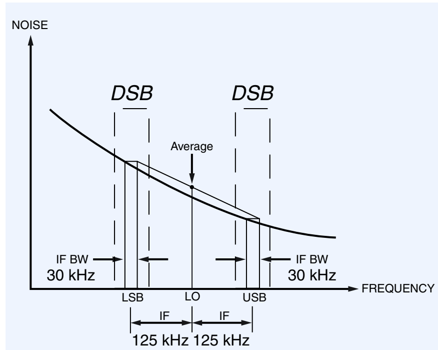
Miller, C.K.S., Daywitt, W.C., and Arthur, M.G. "Noise Standards, Measurements, and Receiver Noise Definitions," Proceedings of the IEEE, Vol. 55, No. 6, June 1967, pp 865-877.

Motchenbacher, C.D. and Connelly, J.A. "Low Noise Electronic System Design," Wiley, New York, 1993.

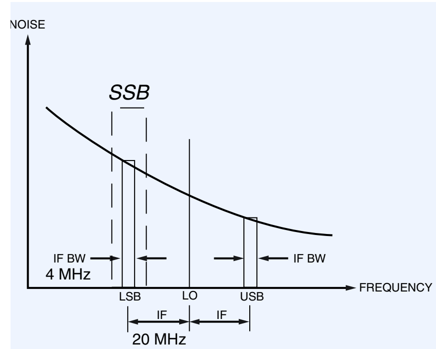
Noise Figure Quick Reference Guide



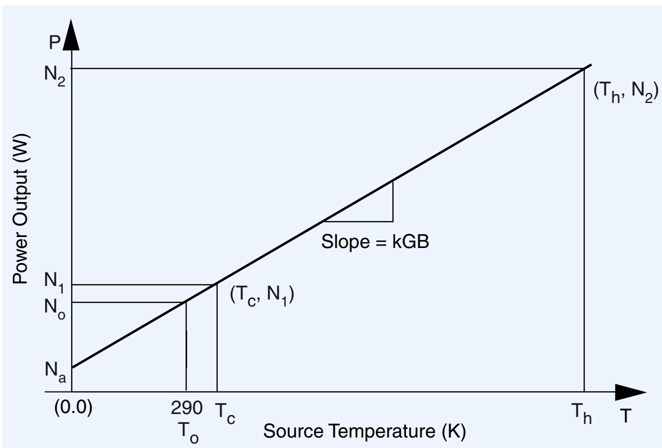
Wideband DSB Noise Measurement



Narrowband DSB Noise Measurement



Traditional Scalar SSB Noise Measurement



$$F\ (dB) = 10 \cdot \log \left[\frac{\left(\frac{S_i}{N_i}\right)}{\left(\frac{S_o}{N_o}\right)} \right]$$

S_i is the input signal power (Watts)

N_i is the input noise power (Watts)

S_o is the output signal power (Watts)

N_o is the output noise power (Watts)

$$Y = (N_2 / N_1) \qquad F = \frac{\left(\frac{T_h}{T_o} - 1\right) - Y\left(\frac{T_c}{T_o} - 1\right)}{Y - 1}$$

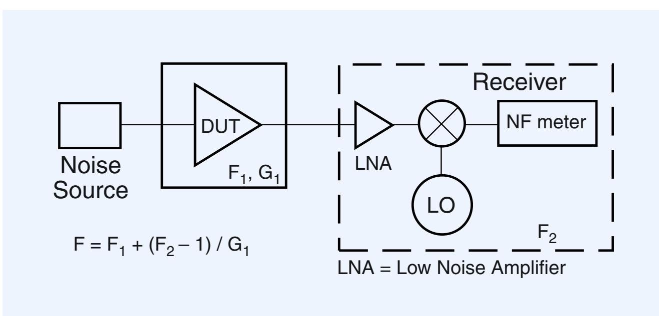
$$F\ (dB) = \left(\frac{S_i}{N_i}\right)_{dB} - \left(\frac{S_o}{N_o}\right)_{dB}$$

S_i is the input signal power (dBm)

N_i is the input noise power (dBm)

S_o is the output signal power (dBm)

N_o is the output noise power (dBm)



Conversion	Equation
Celsius to Kelvin	$T_{Kelvin} = T_{Celsius} + 273.15$
Fahrenheit to Kelvin	$T_{Kelvin} = (5/9)\ (T_{Fahrenheit} + 459.67)$
Fahrenheit to Celsius	$T_{Celsius} = (5/9)\ (T_{Fahrenheit} - 32)$
Watts to dBm	dBm = 10 log (Watts x 1000)
dBm to Watts	$Watts = 10^{(dBm/10)}/1000$
T_h to ENR	$ENR = 10 \log (T_h - T_o) / T_o$
ENR to T_h	$T_h = T_o\ 10^{(ENR/10)} + T_o$
dB to Linear	$Linear = 10^{(dB/10)}$
Linear to dB	dB = 10 log (Linear)

$P_a = kTB$

P_a is Power available (Joules/sec or Watts)

k is Boltzmann's Constant (1.38 x 10^{-23} Joules/K)

T is absolute Temperature (Kelvin)

B is Bandwidth of transmission path (Hz)

$P_a = -174$ dBm for B = 1 Hz

$P_a = -174$ dBm + 10 log (BW/1 Hz)

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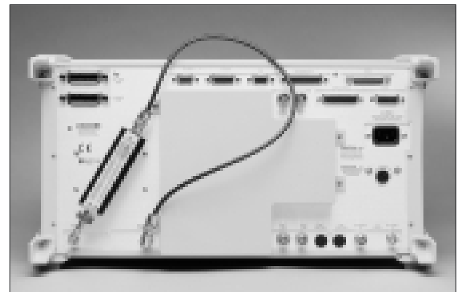
Noise Figure Quick Reference Guide

Noise Source Location = External

Noise Source Location = Internal



Noise Source Location = Internal

Noise Figure Measurement Algorithm

I. Setup

Algorithm Action	Path
A. Initiate Noise Figure Application	Appl/Measurement Type/Noise Figure
B. Configure Noise Figure Measurement	
1. DUT Bandwidth Narrow Wide	Appl/
2. Noise Source Location Internal External	Appl/Noise Figure Setup/
3. Load ENR Values Vendor ENR Table ENR Extension Table	Appl/Noise Figure Setup/Load E.N.R. File/

Setup Parameter	Explanation
DUT Bandwidth	Wide indicates that the DUT noise figure performance is relatively broadband (BW ≥ 6 MHz). Wide also provides the fastest measurement. Narrow allows measurements for band limited DUTs (BW < 6 MHz).
Noise Source	Internal indicates that the Noise Source is connected to the rear panel. External indicates that the Noise Source is not connected to the rear panel. Note that External Error-Corrected measurements are not possible.
Load E.N.R. File	This controls the loading of the ENR values.
— Load Vendor ENR Table	This refers to the ENR values for the noise source. The table on the noise source(s) is stored in a tab-defined ASCII format for retrieval.
— Load ENR Extension Table	This refers to the S-Parameter characterization file between the rear panel noise source connection and the Test Port 1 connection to the DUT. This file contains up to 101 points and combines S2P data with the noise source reflection coefficient data.
Cold Temperature	This represents the noise source temperature for the measurement.
Wideband BW Corr Freq	For DUT Bandwidth = Wide, this allows bandwidth correction when Narrowband is not desired. This frequency should correspond to the "brickwall" bandwidth of the DUT.
Wideband BW Corr Mode	For DUT Bandwidth = Wide, this allows enabling and disabling of the BW Correction.
SSB Correction	This allows compensation for a DUT (usually a mixer) with single sideband (SSB) behavior.
Loss Before DUT	Numerical value describing the network loss in dB before the DUT.
Loss After DUT	Numerical value describing the network loss in dB after the DUT.
ENR .EXT Files	S2P file from factory describing the network between rear panel to Port 1. Used in internal noise measurements.
ENR .NFX Files	S2P file that is user defined describing user network between Port 1 and the DUT/Receiver for both internal and external noise measurements modes.

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II. Calibration

Algorithm Action	Path
A. Specify…	
1. Frequency Start Frequency Stop Frequency	Freq/
2. Data Points	Config/
3. Noise Figure Average	Avg/
B. Perform Calibration	Cal/
1. Noise Figure Only	
2. Noise Figure With 12-Term	

Calibration Parameter	Explanation
Frequency	Specify the Frequency range for the noise figure measurement. The Start and Stop Frequencies correspond to the frequencies of the lower (LSB) sidebands.Typically, a range slightly larger than the passband is chosen. Alternately, the range of the 12-term calibration is chosen.
Data Points	Specify the Number of Points for the noise figure measurement. The noise figure measurement requires more time for more data points.
Noise Figure Average ON/OFF	This allows enabling and disabling of the Noise Figure Averaging function.
Noise Figure Average	This indicates the quantity of measurements to include in the average function. The default value is 40 and this averaging is adequate for both Wideband and Narrowband Measurements.

III. Measurement

Algorithm Action	Path
A. Select Display Selection	Appl/Display Selection/
1. Noise Figure	
2. Insertion Gain	
3. Available Gain	
4. Y-Factor	
5. Equivalent Noise Temperature	

Display Selection	Explanation
Noise Figure	With 12-term calibration applied, this represents vector error-corrected noise figure; otherwise, this represents scalar noise figure.
Insertion Gain	Available with or without 12-term correction, this represents the gain measurement making no corrections for matching characteristics.
Available Gain	Only available with 12-term correction, this represents the gain as determined by the S-parameter measurements.
Y-Factor	The DUT output measurement ratio between the hot and cold states of the noise source.
Equivalent Noise Temperature	The temperature of a resistor whose noise power is equal to the input-referred noise-added power of the DUT.

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