APPLICATION NOTE

NF Accuracy

Option 4x

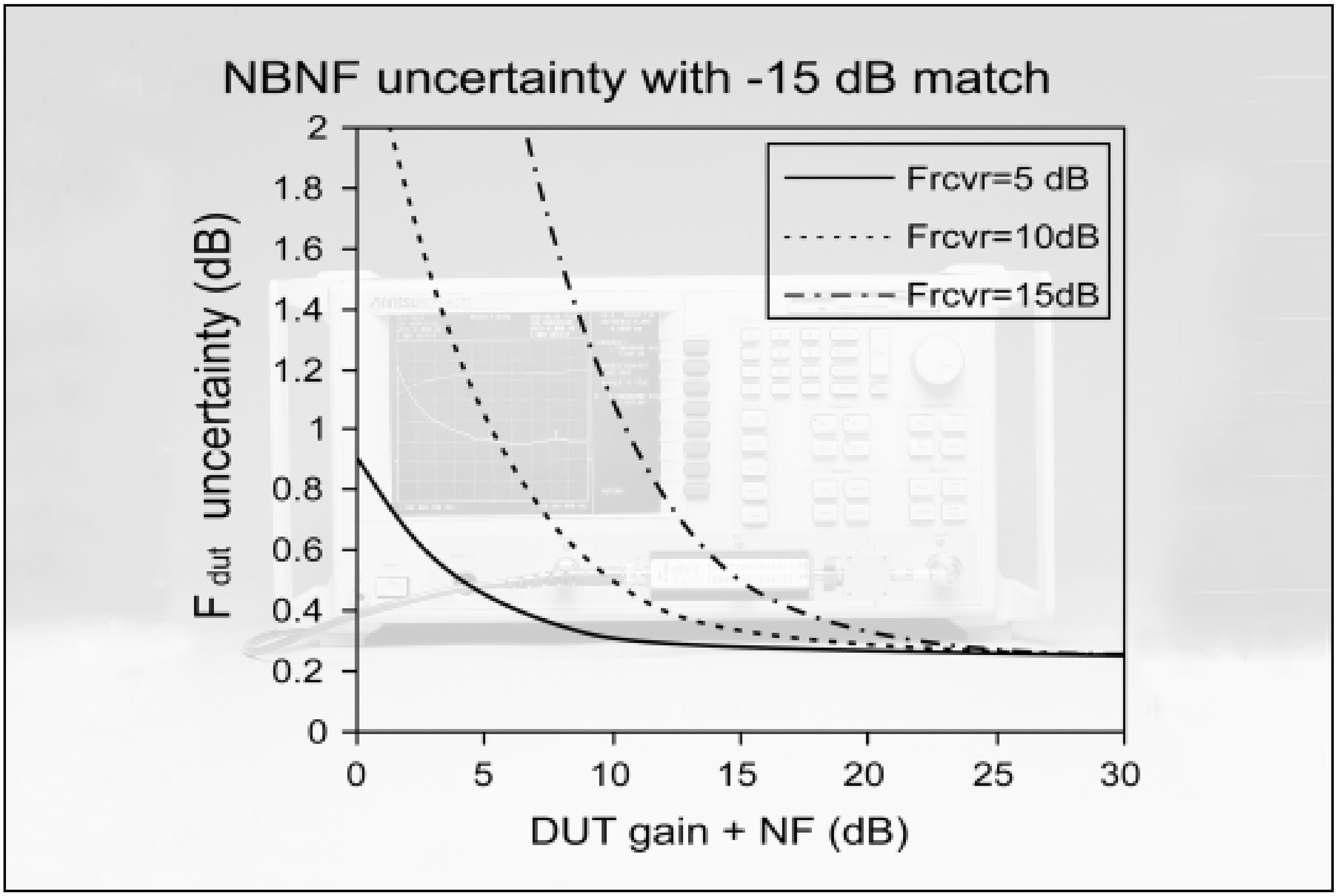
Scorpion®
50 MHz to 3 GHz or 6 GHz

Introduction

Noise Figure is a very important “money” measurement. The Anritsu MS362X Scorpion‰ Vector Network Measurement System provides SIX ways to measure Noise Figure! This is a great deal of flexibility, which one will appreciate as specific applications may benefit by the alternatives available.

Unfortunately, Noise Figure is not an exact (nth decimal place) type of measurement, it’s more like a 1.7dB (± .x dB) measurement and many who make the measurement are well aware of that fact. So, if one measures NF by the six methods offered, it’s likely that six different answers will result. There are good technical reasons for the difference.

Some noise figure meters have been used by industry for years and many regard them as standards, in terms of comparison. They have comparable uncertainties associated with any specific measurement, and some of these are well documented [5]. If you add a measurement by one of the other noise figure meters to the six above, you will have seven answers. None of these is likely to be correct, in an absolute senseæ we have no absolute NIST-traceable NF measurement standards; nonetheless, all should fall within an uncertainty window that can be analyzed. This analysis is tedious; however, it is necessary if we wish to correlate measurement results.



Scalar Noise Figure Uncertainties Related to Match and Gain

Noise Figure Uncertainty and Correlation Issues

Executive Summary

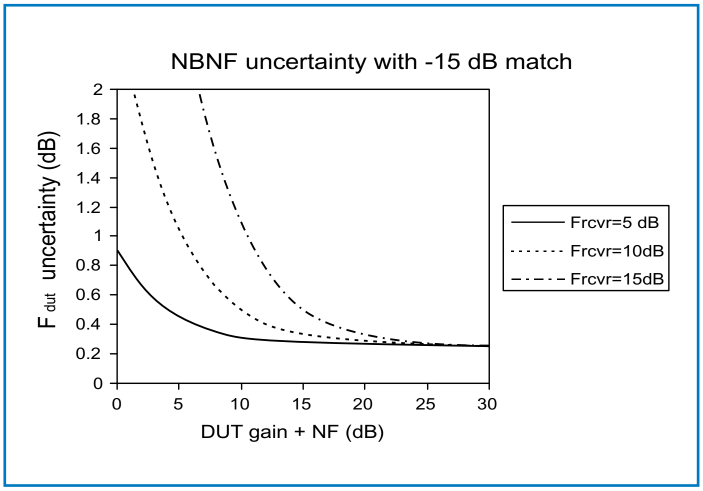
Noise figure uncertainty is determined by many factors, some of which the user must control:

- Dirty or improper connectors (particularly non-threaded connectors such as BNC)
- Strong environmental contamination signals (perhaps from nearby transmission towers or a cellular phone)
- Proper noise figure measurement technique based on DUT bandwidth and conversion behavior
- Leakage signals (particularly when measuring mixers)And others that are often beyond the user's control:
- ENR uncertainty of the noise source. A typical commercial noise source usually has at least a 0.1 dB uncertainty in its excess noise ratio. This translates directly to a noise figure uncertainty in an amplifier measurement.
- Match uncertainty. The mismatch of the DUT translates directly into uncertainty since the power coupling between the DUT and the rest of the system is in doubt. This is on the order of 0.1 dB for even relatively well-matched devices (–15 dB return loss).
- Instrumentation uncertainty. The fundamental accuracy of the instrument in measuring noise power ratios (often on the order of 0.1-0.15 dB).
- Receiver noise figure. If the DUT gain is low, the receiver noise figure is a strong contributor to uncertainty since the calculation will require the subtraction of nearly equal numbers.

This paper presents an algorithm for computing the composite measurement uncertainty under a number of different measurement conditions. The result is a family of curves describing the MS462X noise figure measurements; an example curve is below. The horizontal axis describes the DUT, the plot parameter describes the receiver noise figure and the vertical axis gives the approximate uncertainty of the measured DUT noise figure for the specified measurement approach.

If this measurement mode was being used with a device with gain + NF= 20 dB and the receiver noise figure was 5 dB, the uncertainty in the DUT noise figure would be approximately ±0.27 dB. This asymptotic domain of the curves is very important since many devices have sufficient gain to meet the conditions. The asymptotic uncertainty is summarized in the table below for the various operating modes. The details of these modes are explained in the text.

When attempting to correlate measurements between



multiple instruments or between different methods, it is critical to mitigate as many of these uncertainty sources as possible. This would include using the same noise source on all tests, the same interfaces (when possible) between DUT and noise source (and DUT to receiver), the same environmental conditions (temperature, spurious signals, etc.), the same DUT power supplies, and a similar test procedure.

MODE	MATCH	External	Internal
Wideband	Perf. match	±0.17 dB	±0.18 dB
	–15 dB match	±0.27 dB	±0.34 dB
	–10 dB match	±0.41 dB	±0.53 dB
Narrowband	Perf. match	±0.15 dB	±0.17 dB
	–15 dB	±0.26 dB	±0.33 dB
	–10 dB	±0.40 dB	±0.53 dB

Overview

Noise figure uncertainty analysis is becoming increasingly important as performance demands increase in wireless, satellite and other communications systems. The noise performance of devices and subsystems has been improving and the required consistency of performance has increased as well. It is thus increasingly critical to understand the sources of uncertainty in a noise figure measurement and to mitigate them as much as possible. While this topic has been covered several times in the past, it will be revisited in this document with attention paid to some of the newer measurement options and their impact on the uncertainty picture.

Some of the discussion will relate specifically to the MS462X instruments, particularly those sections involving newer measurement options, but many of the comments apply to noise figure measurements in general. It is assumed that the reader is familiar with the basics of noise figure measurement. If not, many publications exist to help (e.g.,[1]-[3]).

Main Causes

There are many sources of uncertainty in a noise figure measurement, some of which can be more easily controlled than others.

Environmental: Radiated signals can be coupled into the network under test leading to spikes in data or overall elevated results. This is a particular problem in the active 900 and 1800 MHz communications bands.

Connectors and mechanical: Dirty connectors can lead to erroneous results as can the mechanical action of less stable connector types (e.g., BNC and other non-threaded or marginally-threaded connectors).

Gain definition: The proper gain to be used in NF analysis is available gain instead of the insertion gain measured by most NF meters [4]. This is mostly an issue for more poorly matched devices but can be important generally.

Noise source interface issues and hot/cold differentials: The ENR plane of a noise source is defined at the noise source. Hence any adapters or cables between the noise source and the DUT must be accurately accounted for. Also since the match of a noise source changes between its hot and cold state, the power coupling ratio also changes and an error can be introduced. This error can be corrected as well [4].

DSB vs. SSB issues: When the receiver and/or DUT has a double sideband nature, errors can be introduced depending on the frequency response of the DUT, the architecture of the DUT and how the device will be used.

Bandwidth issues: Aside from DSB issues, the bandwidth of the DUT must be much larger than the measurement bandwidth. Since the bandwidths are not 'brickwall', an accurate assessment of the power bandwidth is sometimes difficult to obtain but is important for any corrections.A narrowband noise figure measurement approach can help in many of these situations.

LO leakage and spurs when measuring mixers: Aside from potential DSB issues, mixer noise figure measurements are complicated by any LO imperfections. Proper filtering must be employed to prevent leakage effects and the LO must be sufficiently clean that converted spurs do not influence the measurement.

Those uncertainty causes that this document will address as part of an uncertainty model:

ENR uncertainty: The noise source calibration only has limited accuracy. In addition, the calibrations are usually at widely spaced frequency points leading to potentially serious interpolation errors (sometimes exceeding 0.15 dB).

Match: The ability to couple power in and out of the DUT is an important source of uncertainty. The coupling between stages of a DUT can also lead to measurement difficulties.

Instrumentation uncertainty: The limit on the accuracy of measuring Y factor and gain.

Receiver noise figure: Particularly important for lower gain DUTs, the receiver noise figure will be a very important limit on uncertainty because of the mathematics of the second stage noise figure correction.

Simple Analysis of Uncertainty

As a starting point to better understand noise figure measurement uncertainty, four of the more difficult to mitigate factors will be analyzed in order to calculate a composite uncertainty. These factors are ENR uncertainty, instrumentation uncertainty, match-induced uncertainty and receiver noise figure. All of these can be improved on by various techniques but are among the more difficult for a user to mitigate.

There are various techniques for analyzing the composite uncertainty. Among the more conservative approaches is that of root-sum-of-squares (RSS), a modified version of which will be employed here. In this technique, the individual component uncertainties are assumed to add on a RSS basis. Other techniques employ a Monte Carlo analysis with given confidence limits [5], which will often lead to more optimistic results (particularly at lower DUT gain levels) but may still be quite appropriate. The difference between the two approaches lies in the assumption of how likely it is for multiple parameters to experience a worst-case scenario at the same time and how independent the various terms actually are in a measurement.

ENR uncertainty as published will be used in this analysis and interpolation errors will be neglected (hence the analysis is more valid near the normal calibration points of .1,1,2,... GHz). Instrumentation uncertainty for the MS462X will be used in the analysis; values of the same order of magnitude may be expected for other instruments.

Simple Analysis of Uncertainty Continued

The contribution of match to uncertainty is quite complicated and consists of several physical models, only two of which will be dealt with in this analysis. As has been shown in the literature [6], if one ignores the interaction between the noise source and components after the first, it is possible to model the effect of multiple reflections between the noise source and DUT. In addition, since the hot and cold states of the noise source have different reflection coefficients, an additional contribution will be created. For the match contribution, a strict RSS worst-case analysis did not seem completely appropriate due to the low probability of the multiple worst-case situations arising. For this reason, a simplistic Monte Carlo analysis was performed on this contribution alone. In the analysis, the match of the noise source is used for the source match in the external measurement configurations and the MS462X port matches are used when appropriate (internal measurements). The DUT input and output match will be assumed to be equal and that single value will vary for the different curves. It is important to note that the input match is of significantly greater importance to the uncertainty than is the output match. The relative phase of the reflection coefficients are assumed to be uniformly distributed over the range of 0 to 2π. The relative phases are randomly selected over many trials (1000 in these calculations) and the Y factor error calculated. Based on multiple simulations of the match effect on Y factor, a 95% confidence limit was established to be used in the composite calculation.

The usual analysis begins with the second stage-corrected noise figure equation

$$(1)\quad F_{dut} = F_{comp} - \frac{F_{rcvr} - 1}{G}$$

Where the Fs refer to the noise figure (linear) of the DUT, the composite (DUT+receiver), and the receiver respectively. The element G refers to the DUT gain, which should be available gain but is often interpreted to be insertion gain [4],[5]. Forming the total differential from this equation, one gets

$$(2)\quad dF_{dut} = dF_{comp} - \frac{dF_{rcvr}}{G} + \frac{(F_{rcvr} - 1)dG}{G^2}$$

After some (substantial) manipulations, one can arrive at a form more suitable for uncertainty analysis

$$(3)\quad \frac{dF_{dut}}{F_{dut}} = \frac{GF_{dut} + F_{rcvr} - 1}{GF_{dut}}\frac{dF_{comp}}{F_{comp}} + \frac{F_{rcvr} - 1}{GF_{dut}}\frac{dG}{G} - \frac{F_{rcvr}}{GF_{dut}}\frac{dF_{rcvr}}{F_{rcvr}}$$

The two dF/F terms are, in themselves, composites of several other terms: Y factor instrumentation uncertainty, match-induced uncertainty and ENR uncertainty.

The base equation for raw noise figure is the starting point for that analysis (excluding differences between cold temperature and 290K):

$$(4a)\quad F = \frac{ENR}{Y - 1}$$

so that the differential becomes:

$$(4b)\quad \frac{dF}{F} = \frac{d(ENR)}{ENR} - \frac{Y}{Y-1}\left(\frac{dI}{I} - \frac{dM}{M}\right)$$

where the bracketed term represents the combination of instrumentation and match related effects. For the purposes of computing the composite uncertainty, all terms will be added on an RSS basis. That is

$$(5)\quad \left\|\frac{dF_{dut}}{F_{dut}}\right\| = \sqrt{\left(\frac{GF_{dut} + F_{rcvr} - 1}{GF_{dut}}\right)^2\left(\frac{dF_{comp}}{F_{comp}}\right)^2 + \left(\frac{F_{rcvr} - 1}{GF_{dut}}\right)^2\left(\frac{dG}{G}\right)^2 + \left(\frac{F_{rcvr}}{GF_{dut}}\right)^2\left(\frac{dF_{rcvr}}{F_{dut}}\right)^2}$$

where

$$\left(\frac{dF}{F}\right)^2 \Rightarrow \left(\frac{d(ENR)}{ENR}\right)^2 + \left(\frac{Y}{Y-1}\frac{dI}{I}\right)^2 + \left(\frac{Y}{Y-1}\frac{dM}{M}\right)^2$$

It can be argued that this RSS quantity may overstate the uncertainty since the noise figure and gain measurements are not truly independent in most noise figure meters. Since the two calculated values (both noise figure and insertion gain derive from hot and cold noise powers as well as offsets) can respond quite differently to a pure power measurement delta, it seems appropriate to treat them as quasi-independent. In addition, the gain uncertainty is often heavily dependent on the accuracy of a step attenuator calibration, which does not affect the raw noise figure uncertainty significantly.

Before proceeding further, it is useful to examine two limiting cases. First is the case of $GF_{dut} >> F_{rcvr}$ which is met by many amplifiers. In this case, the expression simplifies dramatically

$$(6)\quad \frac{dF_{dut}}{F_{dut}} \rightarrow \frac{dF_{comp}}{F_{comp}} \qquad \text{High } GF_{dut} \text{ limit}$$

indicating that the composite measurement uncertainty is the combination of instrument Y factor uncertainty, ENR uncertainty, and match uncertainty. The effects of gain, gain uncertainty and receiver noise figure have been removed. Note that for this to hold in practice, the gain + noise figure (in dB terms) of the DUT must exceed the receiver noise figure by at least 10-20 dB. This result is extremely important in understanding the measurement of high gain devices: beyond a certain point, the receiver noise figure becomes largely irrelevant.

The other limiting case is that of a passive device where $GF_{dut}=1$ (assuming 290K cold temperature)...

$$(7)\quad \left\|\frac{dF_{dut}}{F_{dut}}\right\| \rightarrow F_{rcvr}\sqrt{\left(\frac{dF_{comp}}{F_{comp}}\right)^2 + \left(\frac{F_{rcvr} - 1}{F_{rcvr}}\right)^2\left(\frac{dG}{G}\right)^2 + \left(\frac{dF_{rcvr}}{F_{rcvr}}\right)^2}$$

which is a combination of the individual uncertainties (modified slightly) MULTIPLIED by the receiver noise figure. This is a very important concept when measuring lossy devices: any uncertainty in the base measurement will be amplified because of the nature of the correction equations. The multiplication is not pure since F_{rcvr} shows up in some denominators so there is not a dB-for-dB increase in uncertainty with F_{rcvr}.

From equation (5), it is also apparent that the overall uncertainty has a characteristic close to F_{rcvr}/GF_{dut}. One would then expect the uncertainty curves to grow in a fairly rapid fashion as GF_{dut} starts to get small relative to the receiver noise figure.

Uncertainty Curve Calculations

Before proceeding with the calculations, it is important to define some measurement modes for the MS462X:

External: When the noise source is connected directly to the DUT input. It is assumed the DUT output is connected to the receiver plane in all modes.

Internal: When a network, usually with switching, is between the noise source and the DUT. This network's S-parameters are characterized in order to calculate the effective ENR presented to the DUT [4].

Wideband (WBNF): The usual noise figure meter approach with a bandwidth of usually several MHz and a scalar power detector at the end of an analog IF. In the case of the MS462X, this mode operates with a bandwidth of about 6 MHz.

Narrowband (NBNF): A newer approach in which the receiver basically goes straight from a final down-conversion stage into an analog to digital converter (A/D). All IF processing is performed digitally. The effective bandwidth is much narrower (kHz range at worst) than in the wideband method as the names suggest.

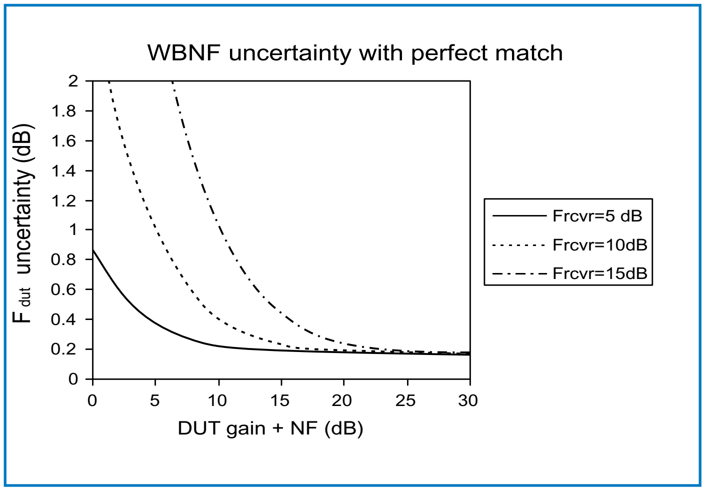
External Wideband Mode

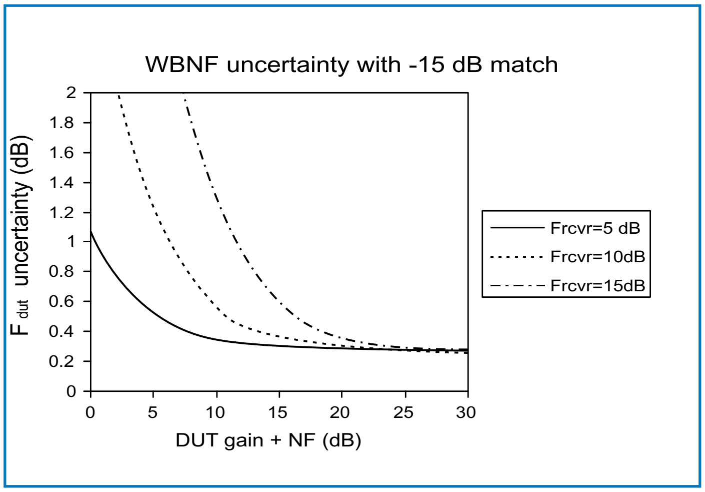
The first calculation will be for a wideband measurement mode in the MS462X, which is most analogous to conventional noise figure meters. The results for three different DUT match levels (reflection coefficients of a perfect match, –15 dB and –10 dB) are shown in Figs. 1a-1c. In all of the uncertainty curves, F_{dut} is the DUT noise figure and F_{rcvr} is the receiver noise figure. These first curves apply to the external measurement scenario where the noise source is connected directly to the DUT input. One can easily see the asymptotic behavior for large GF_{dut} that was discussed in the previous section. As also might be expected from the previous discussion, the uncertainties grow very rapidly as GF_{dut} gets small relative to F_{rcvr}.

In order to generate these curves, equation 5 is used with the following parameters:

- ENR uncertainty of 0.09 dB per manufacturers' specifications
- Noise figure instrumentation uncertainty of 0.15 dB
- Gain instrumentation uncertainty of 0.2 dB
- Receiver noise figure uncertainty of 0.2 dB (includes instrumentation plus match effects)
- Match effects based on system matches and a Monte Carlo analysis resulting in contributions of 0, 0.21 dB, and 0.36 dB for perfect DUT match, –15 dB match, and –10 dB match respectively.

All terms are combined on a linear basis before being expressed in dB terms for the figures. A relatively high ENR





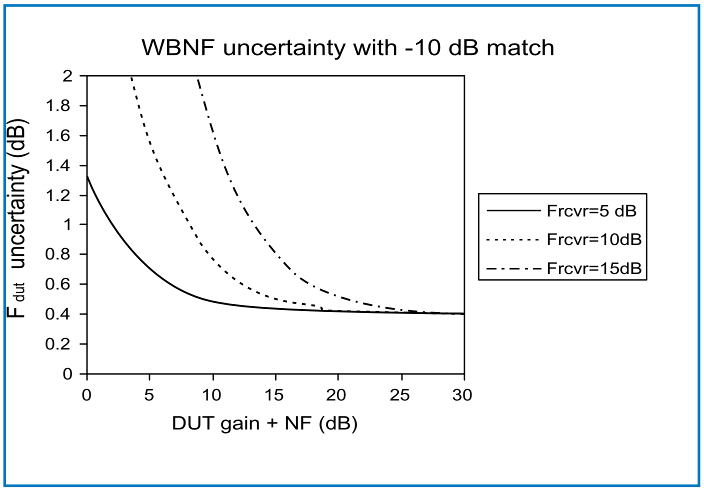


Figure 1a-1c. Calculated uncertainties for external wideband noise figure for three different DUT matches: perfect, –15 dB, and –10 dB.

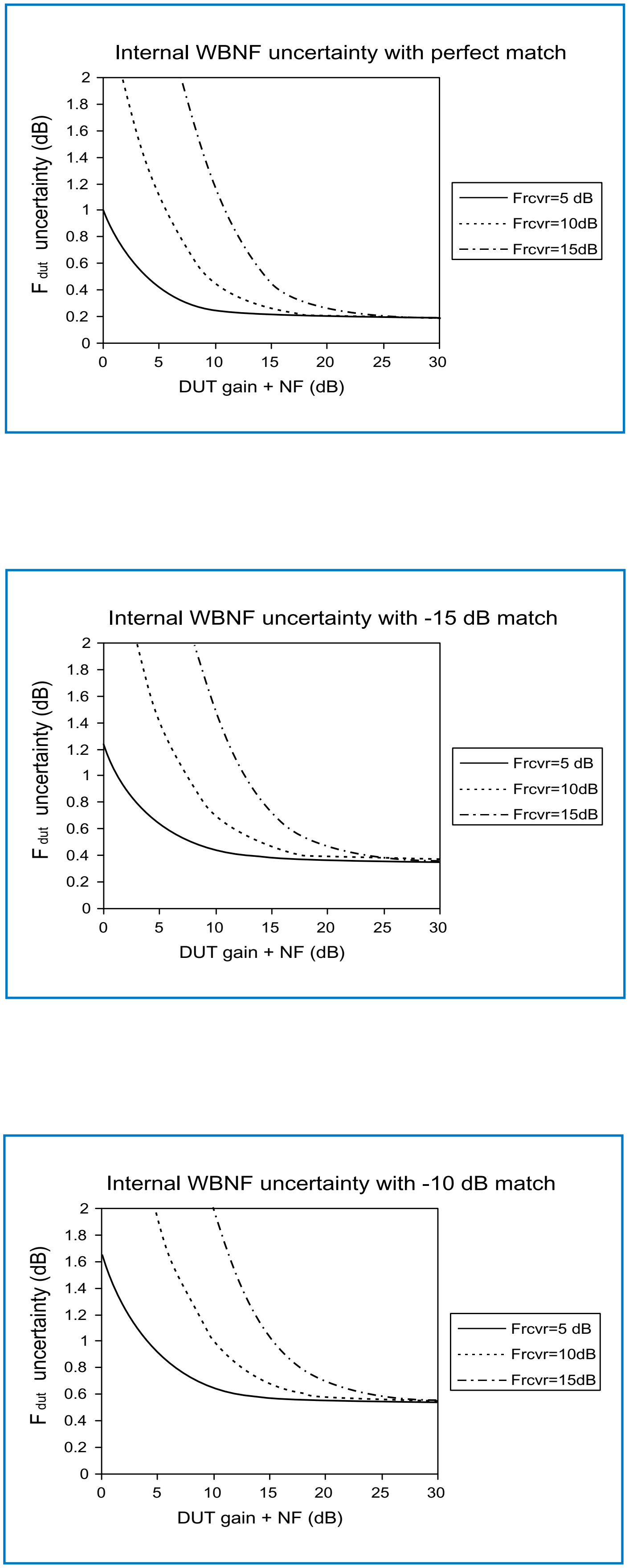


Figure 2a-2c. Calculated uncertainties for internal wideband noise figure measurements for three different DUT matches: perfect, –15 dB, and –10 dB. The uncertainties are somewhat elevated over those in the external measurement due to some added uncertainty in computing the effective ENR and a slightly different port match.

Internal Wideband Mode

The next series of calculations are for the wide internal mode where the noise source is routed to the DUT through a switching network. The purpose of the setup is to enable multiple measurements with a single connection. The S-parameters of the network are characterized so that the network's effect on ENR can be removed. There is some uncertainty associated with that S-parameter characterization and the match facing the DUT is somewhat degraded from that of the noise source itself. These curves are shown in Figs. 2a-2c. The differences between the Fig.1 and Fig.2 curves are not enormous; the difference in the asymptote is a few hundredths of a dB to about 0.1 dB (due largely to the compounding match effects at port 1).

To calculate these curves, a similar procedure was used as for Figure 1. The ENR uncertainty increases to 0.11 dB to include the effect of uncertainty in the S-parameters of the internal routing network (which leads to an uncertainty in effective ENR). The match uncertainties increase to 0.3 dB and 0.51 dB, for –15 dB and –10 dB DUT matches respectively, since the port match is worse than the raw noise source match. Again combinations are done on a linear basis.

External and Internal Narrowband Mode

An entirely different measurement mode available on the MS462X is narrowband. The usual approach of filter-amplify-scalar detect is replaced with a downconversion to a lower IF, some amplification and then direct sampling by an analog-to-digital converter. The fundamental noise figure of that process is rather high but is mitigated by the front-end gain of the overall noise figure receiver. To obtain useful information, enough samples must be taken so that offsets and leakage signal can be mathematically removed. Different IFs are used and much of the processing chain is different hence one must be quite careful in comparing measurements.

In all narrowband measurements, a standard IF path is used and the test channel vector signal (b_2) is measured. The real and imaginary parts are processed separately which is the key to this measurement. A given measurement on the test channel will be composed of a noise term ($\Delta C + j\Delta D$) and a leakage term ($A + jB$) where the leakage term may be non-negligible. Both terms are complex.

$$(8) \quad b_2 = (A + jB) + (\Delta C + j\Delta D)$$

Consider the following quantity

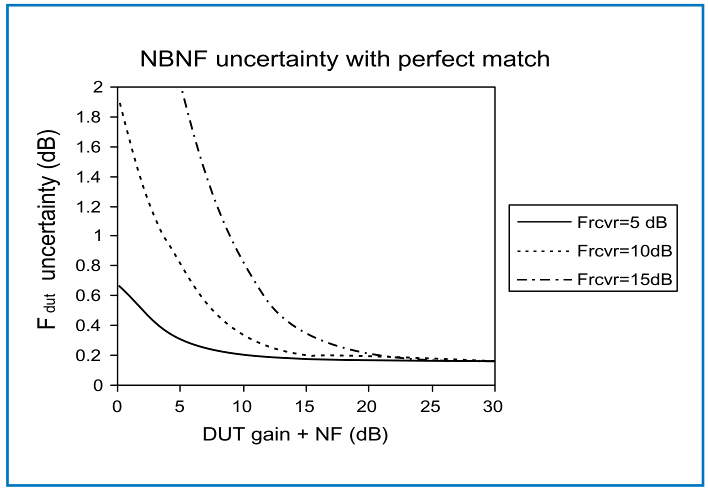
$$(9) \quad \langle |b_2|^2 \rangle - \left(\langle \mathrm{Re}\{b_2\} \rangle\right)^2 - \left(\langle \mathrm{Im}\{b_2\} \rangle\right)^2 = \langle (A+\Delta C)^2 + (B+\Delta D)^2 \rangle$$
$$- \langle A + \Delta C \rangle^2 - \langle B + \Delta D \rangle^2 = \langle 2A\Delta C + 2B\Delta D + (\Delta C)^2 + (\Delta D)^2 \rangle$$

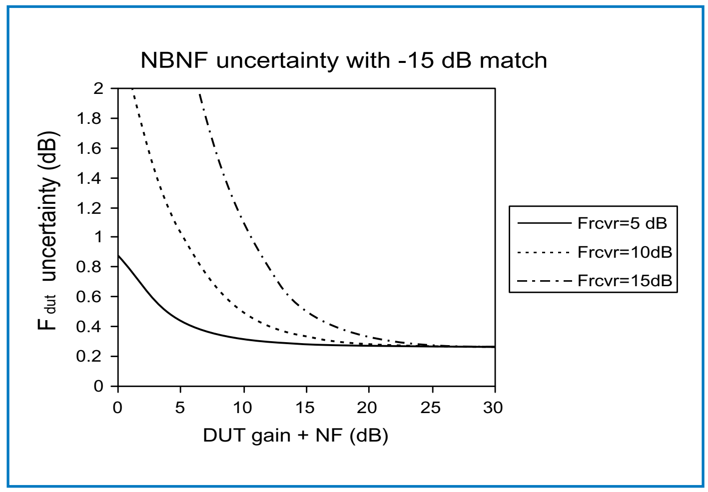
Where the <> denotes an ensemble average. Over a sufficiently large number of measurements the first two terms in the final expression average converge to 0 (the noise is assumed to be zero mean, if not the mean is incorporated in the leakage term). Thus the calculation produces the desired result of the mean squared noise voltage (proportional to it at least) which will be proportional to noise power. Thus the noise power can be extracted by averaging a sufficiently large number of $|b_2|^2$ samples and subtracting off the average real and imaginary components (averages squared separately). The number of samples required for this statement to be statistically valid can be quite large hence the measurement may be somewhat slower than the conventional wideband approach. The benefit comes in the situation, discussed in the first section, where the DUT bandwidth is on the order of or smaller than the measurement bandwidth. For many noise figure meters and the MS462X in wideband mode, this occurs for DUT bandwidths less than about 10 MHz (ignoring DSB issues). For such DUTs, bandwidth correction terms may be required which can introduce large uncertainties if not performed carefully. In the limit of very narrowband DUTs (less than a few hundred kHz), the corrections are of very dubious utility and the measurement must usually be abandoned using these tools. A practical example of this scenario is an assembly consisting of an amplifier and a crystal filter. Such DUTs can be successfully measured with the narrowband algorithm just described.

Because the need for calibrated gain ranging is eliminated, the gain uncertainty relative to a wideband measurement is reduced. Since the receiver noise figure is a bit higher, however, this other uncertainty component can increase somewhat. The resulting curves for narrowband measurements, external and internal, are shown in Figs. 3a-3c and 4a-4c. The differences between these curves and the corresponding wideband curves are not large (again a few hundredths of a dB in the asymptote). Normally one may be operating at a slightly higher receiver noise figure so there will be a disadvantageous shift with respect to the plotting parameter.

The calculations are done in a similar manner to that discussed for figures 1 and 2. The match and ENR components for external narrowband are the same as for external wideband since the observable receiver has not changed. The instrumentation uncertainties decrease to 0.13 dB and 0.12 dB for noise figure and gain respectively. The drop in gain uncertainty is somewhat substantial since errors in attenuator calibration are no longer an issue. Similarly the receiver noise figure uncertainty drops to about 0.14 dB.

For internal narrowband, the match and ENR components are the same as for internal wideband. The instrumentation uncertainties do not change from external narrowband but the receiver noise figure uncertainty increases to about 0.2 dB due to match effects.





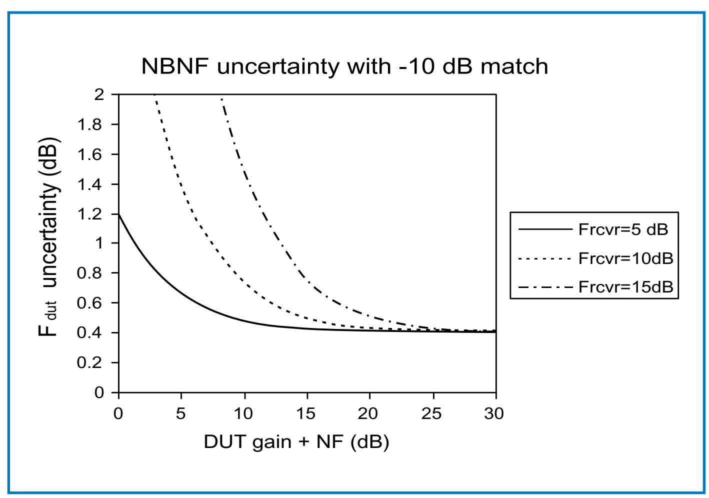
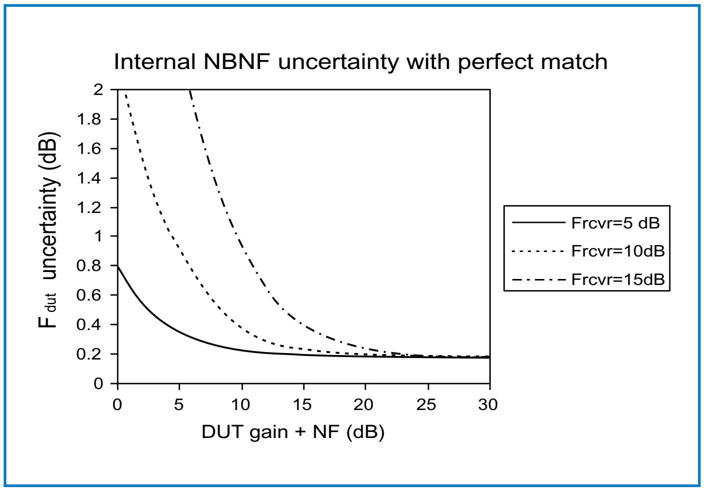
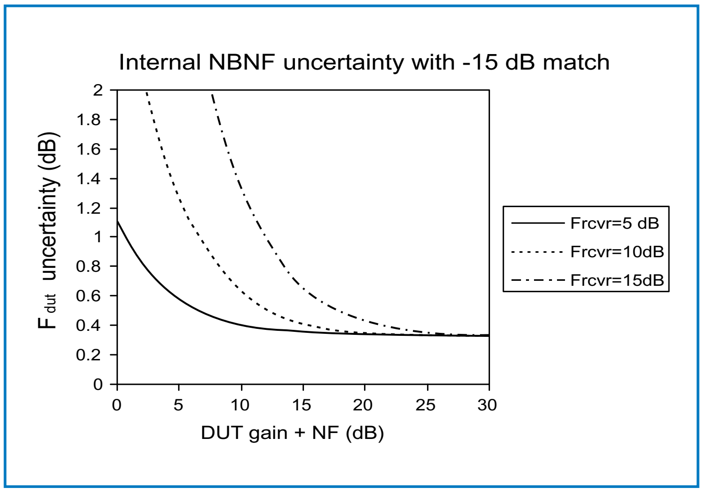


Figure 3a-3c. Calculated uncertainties for the external narrowband noise figure measurement for three different DUT matches. The curves are slightly better than the corresponding wideband curves but assume heavier averaging and generally a higher F_{rcvr} value will apply.





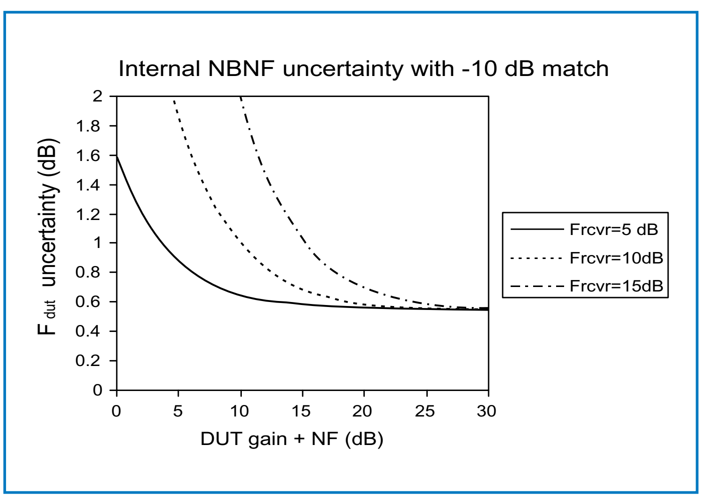


Figure 4a-4c. Calculated uncertainties for internal narrowband measurements for three different DUT matches.

Comparison Conclusions

The curves presented thus far do not show great, qualitative differences. This is due to several reasons

- The uncertainties due to the noise source itself and due to match are somewhat independent of method or configuration and can be quite significant, particularly in the asymptote.
- The base instrumentation uncertainties of narrowband and wideband measurements are quite similar (more of a difference in gain uncertainty)
- As they are presented, the curves mask the difference in receiver noise figure between wideband and narrowband (assuming an external preamplifier is not employed). A higher parametric curve must normally be employed for narrowband measurements.

Aside from the method-dependent issues, one can make several general comments:.

- Higher DUT gain always helps (up until one overloads the noise receiver, most of an issue when ENR+DUT gain exceeds 35-40 dB).
- Lower receiver noise figure helps if DUT gain is not large. The use of an extra preamp before the receiver can lower the effective receiver noise figure and improve the measurement (although stability of this preamplifier can be an issue).
- DUT match can be quite important. The use of isolators can sometimes help. The input match is more important that the output match in determining uncertainty (even more so for devices with gain).
- Fundamental ENR uncertainty is not negligible. A noise source cal with a high level of traceability can help as can having a calibration performed at additional frequency points.
- The uncertainties do not scale with DUT noise figure beyond a certain point. All other things being equal, one may have a 0.25 dB noise figure uncertainty on both a DUT with 2 dB NF and one with 0.8 dB NF. The expectation may be that the uncertainty would drop but this is generally not true.

Correlation Issues

It is often asked how one can correlate measurements between different modes (such as the four discussed above) or between different instruments. The limit on this correlation is generally established by the uncertainties discussed in the previous sections but common factors can be removed to lower the relative measurement uncertainty. Clearly, it is critical to remove as many variables as possible. Among the easiest steps to take:

- Use the same noise source
- Use the same connectors and adapters on all measurements
- Use the same reference planes, when possible, for calibrations
- Use the same power supplies for active DUTs
- Use the same DUT temperature (most of an issue with poorly heatsunk amplifiers)
- Use the same test environment to hopefully get similar environmental contamination effects.

Even with a high level of care, there are extraneous issues that complicate the analysis such as a difference in how two systems respond to a spurious signal. Assuming that most of the above factors can be mitigated and that a DUT used for comparison between methods and/or instruments falls into the asymptotic regime of $GF_{dut} >> F_{rcvr}$, then the relevant uncertainty is

$$\frac{dF_{dut}}{F_{dut}} \rightarrow \sqrt{\left(\frac{dI}{I}\right)^2 + \left(\frac{dM}{M}\right)^2} \qquad (10)$$

which is just a combination of match-induced uncertainties and instrumentation uncertainties. For a given method or instrument, the above quantity establishes the error bars that should be put on the data FOR THE PURPOSE OF COMPARING TO ANOTHER INSTRUMENT OR METHOD. If the method is external for the comparison, and the noise source is always connected to the DUT in the same manner, the input portion of dM/M is mitigated and if the DUT is well matched to begin with, this M term may become quite small.

As an example, suppose one wanted to correlate a wideband internal measurement to a wideband external measurement. The same amplifier will be used with the same bias supply and the same noise source will be used in both measurement types. The amplifier was measured in both modes with an approximately constant case temperature; this is less of an issue in this case since this amplifier is not dissipating a large amount of power and it is reasonably well heat-sunk.

Because of the use of internal and external modes, it is not possible to use exactly the same connectors or noise reference plane but the receive-side reference planes were kept the same.

This particular amplifier has a match of about –17 dB over the frequency range of 1600-2000 MHz that is under analysis, hence one would use the curves for –15 dB match to take into account any additional adapter effects. The DUT noise figure is about 3.7 dB and its gain is about 14.5 dB for a DUT gain + NF of about 18 dB. Since the receiver noise figure in this case is about 5 dB, the uncertainty function is in the asymptote. The one element of the model that has been completely mitigated by this experimental setup is the noise source uncertainty. The match effect has been partially mitigated since the same output network is used. Since the same receiver path is being used, one might suspect that the instrumentation uncertainty would be completely mitigated. Since the absolute power levels are different (due to the reduced effective ENR in the internal case), a different section of the receiver dynamic range will be used. Hence, some instrumentation uncertainty does remain. After correcting the model (i.e., removing noise source uncertainty, reducing the match effect terms, ...) for these changes, the relative uncertainties are approximately 0.15 and 0.18 dB. The measured data is shown in Fig. 5 for this comparison measurement.

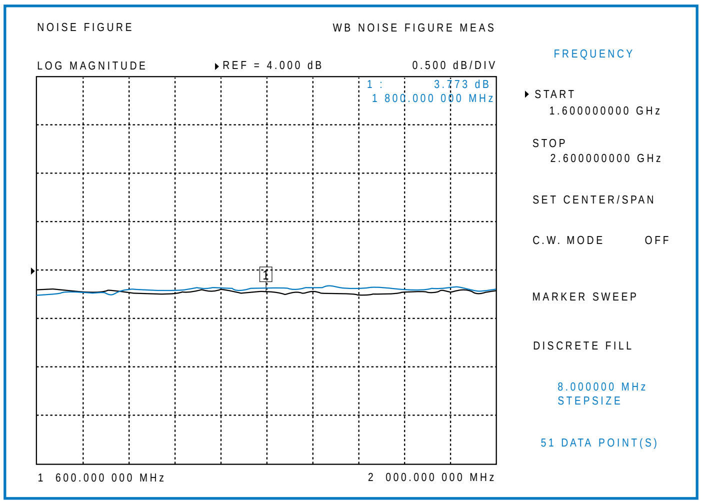


Figure 5. A comparison between internal and external wideband measurements of the same amplifier is shown here. The experiment described in the text details some of the appropriate steps to take in a comparison measurement.

The peak difference between the results is about 0.06 dB, which is well within the spread predicted from the uncertainties. Even if one removed the match effect entirely (leaving in instrumentation uncertainty), the uncertainty would still be on the order of 0.12 - 0.14 dB allowing a spread of 0.24 - 0.28 dB. Assuming the above plot is indicative of performance on multiple instruments, then one can then conclude that the methods tend to correlate at least in this small part of the global parameter space defining possible DUT behavior.

As a second example, consider a comparison of wideband external and narrowband external measurements with an MS462X. The candidate amplifier has about 15 dB of gain, about a 1 dB noise figure, and input and output matches of –15 dB and –30 dB respectively. The same noise source will be used (in external mode) as will the same receiver connection hence the match component of uncertainty is effectively mitigated.

Correlation Issues Continued

Again since the same noise source is used, ENR uncertainty is not particularly relevant. The full instrumentation uncertainty is important, however, since these two measurements use completely different IF chains. The gain is sufficiently high and the receiver noise figure low enough that one can assume asymptotic behavior. In this case the uncertainties are approximately 0.15 and 0.12 dB respectively for wideband and narrowband. These numbers are arrived at removing the ENR and match uncertainties from the calculations. The data for the measurement is shown in Fig. 6.

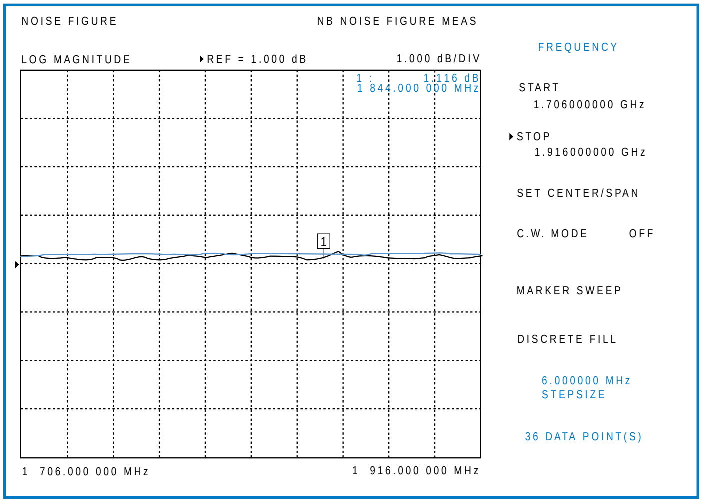


Figure 6. Wideband and narrowband noise figure measurements of the same amplifier.

The maximum difference between the traces is approximately 0.1 dB which is well within the 0.27 dB allowed spread from the uncertainty calculations. Since similar performance has been observed in many instruments, one can probably conclude that these measurements tend to correlate within the section of parameter space covered by this DUT.

Vector Uncertainties

An alternative internal measurement mode, termed vector corrected noise figure, can work to mitigate some of the uncertainties associated with match and gain. As addressed elsewhere, this measurement combines vector S-parameter measurements of the DUT and of the instrument ports together with noise figure measurements to produce a more correct result. The DUT's available gain is calculated from the S-parameters which (a) is the correct gain to use as opposed to the insertion gain used in most noise figure meters [5], and (b) tends to have lower uncertainties than do gains extracted from noise data. Also since the reflection coefficients of the noise source are measured directly (in both hot and cold states), a portion of the uncertainty induced by match effects can also be removed. The improved gain uncertainty will primarily affect the uncertainty curves away from the asymptote while the improved match uncertainty will globally improve the uncertainty curves.

Vector Corrected Uncertainty Curves

One of the more important but lesser-known noise figure measurement modes is vector corrected. This mode combines S-parameter measurements with noise figure measurements (on a sweep-by-sweep basis) to help resolve a few common measurement issues [1]:

- Use available gain instead of insertion gain. Since the S-parameters are measured on every sweep, the available gain can be calculated directly which is impossible with ordinary noise figure meters or with a spectrum analyzer approach. The difference between the two gains is most significant in the case of poor DUT match (i.e., worse than about 10-12 dB return loss) which describes many amplifiers commercially in use. The measurement impact will not be severe if the gain is high but can be noticeable even for 15 dB gain devices. Aside from the benefit in measuring the correct gain, the uncertainties associated with the S-parameter gain measurement tend to be much lower than for the insertion gain derived from noise data (as is done in conventional noise figure meters). More details on the effect of this change can be found in [2].

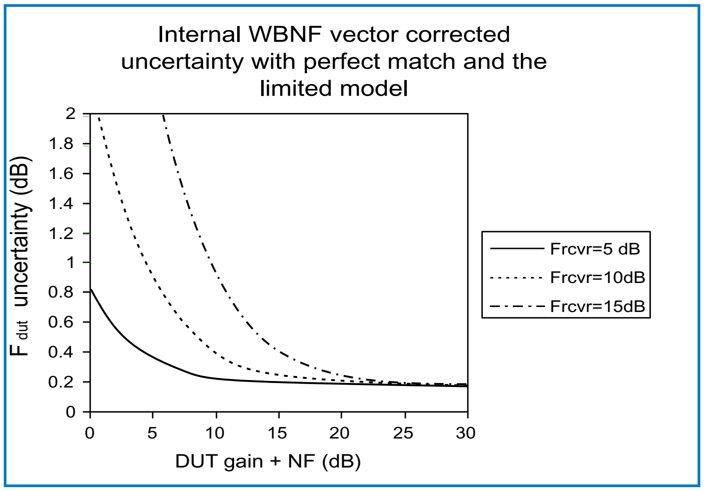
- Take into account the hot/cold differential in noise source match. Since S-parameters are being acquired during calibration, the noise source hot/cold differential can be acquired as well and used to correct Y factors. With modern noise sources, this correction is usually small but can be quite relevant for measurements of DUTs with poor match and/or very low noise figure. More details on this correction can also be found in [2].

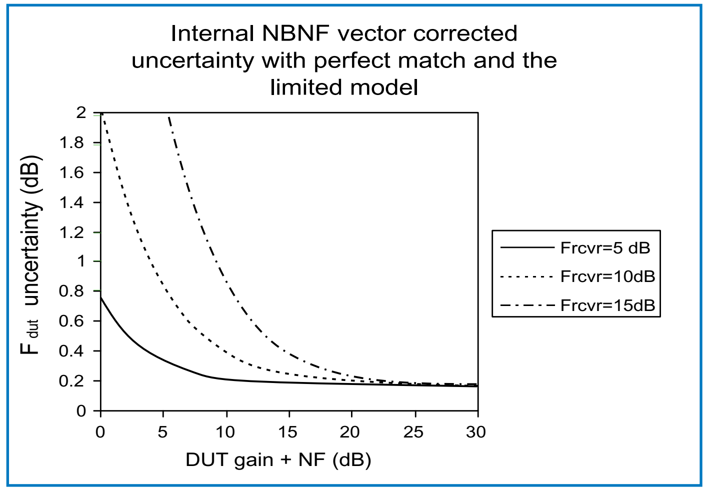
While these issues can be quite important in many measurements, their effects do not always fold into the simple uncertainty analysis [1] in a straightforward way. The gain uncertainty is decreased by use of the vector correction so the portions of curves related to lower DUT gain + NF values will improve but the asymptotic uncertainty (high DUT gain + NF) will not change appreciably. The inclusion of the correction for noise source match differential will improve the match terms subject to the uncertainties involved in measuring the relevant reflection coefficient phases. As a result, the match uncertainties, which affect all portions of the uncertainty curves, improve but do not vanish.

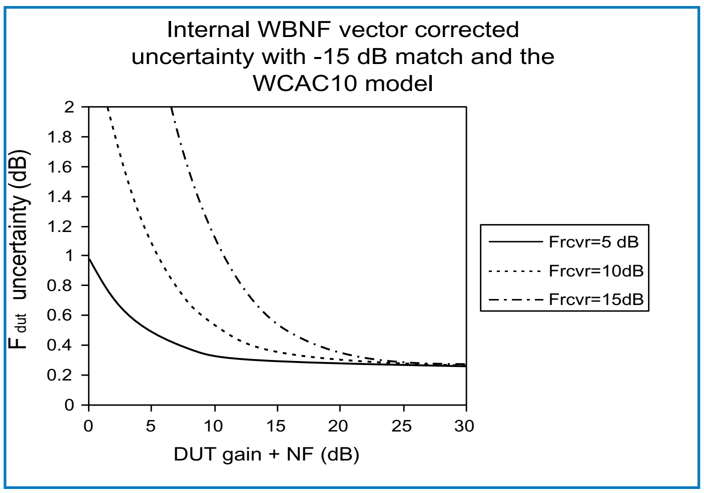
An analysis similar to that performed for the scalar measurements was initiated for the vector corrected case. The effect of the gain definition does not appear (since the Ga-Gi difference is not included in the simple analysis) but the improved uncertainty in gain does (on the order of 0.05 dB per the S-parameter uncertainty curves vs. up to 0.2 dB for the scalar methods). The match uncertainty is computed using residual uncertainties from the reflection coefficients and a variant on the simplified Monte Carlo technique discussed previously [1].

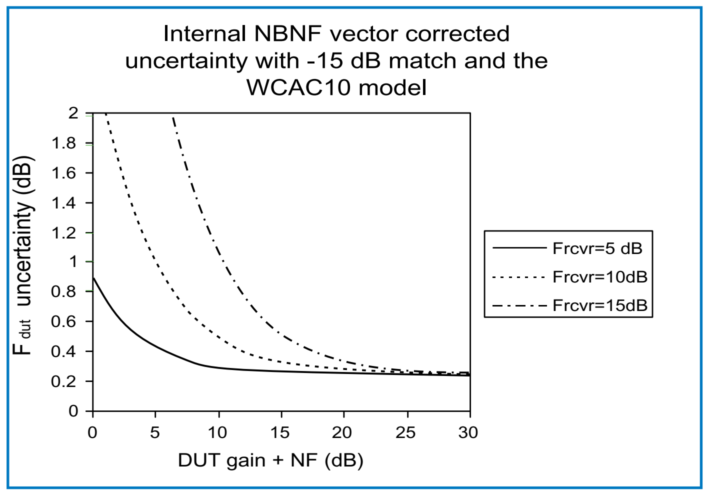
Many choices are available in how to model the residual phase uncertainty effects since the sensitivity to these uncertainties is a function of the absolute cold and hot reflection coefficients. The Monte Carlo engine was expanded to fully cover these domains and the worst case angle combination (WCAC) was selected. An additional variable describes the residual uncertainties in the phase angles, the WCAC10 model adopts a very conservative stance of three times the specified angular uncertainty to take into account adapter changes, dynamic reflection issues, and drift between calibration and measurement.

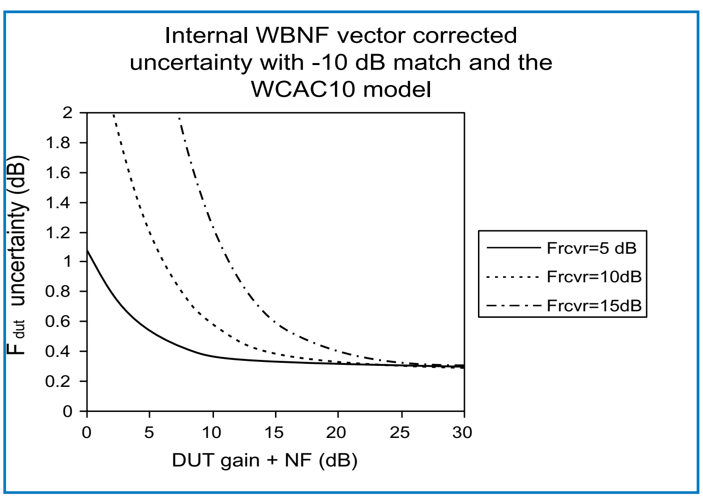
The reflection magnitude uncertainty was assumed to range from 0.3 dB at a –10 dB match to 0.5 dB at a -15 dB match as is consistent with the usual VNA uncertainty analysis. The residual match uncertainties then become approximately .18 dB for a DUT with –15 dB match and .23 dB for a DUT with –10 dB match. The uncertainties on the receiver noise figure improve slightly to .22 dB and .18 dB for wideband and narrowband respectively due to match knowledge. As with the scalar computations, jitter is not included in the model.











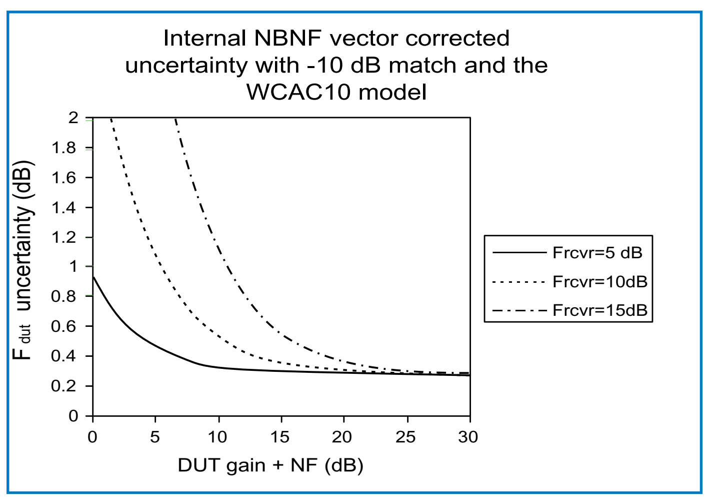


Figure 7a-7c. Calculated uncertainties for internal narrowband vector measurements for three different DUT matches.

Figure 6a-6c. Calculated uncertainties for internal wideband vector measurements for three different DUT matches.

Enough information is now available to regenerate the uncertainty curves for both wideband and narrowband vector modes using a perfectly matched DUT, one with –15 dB match, and one with –10 dB match. All curves are for the internal mode since this is normally how one would collect the S-parameter data simultaneously with the noise data.

Observations

The most dramatic difference between these curves and the scalar curves occurs for poorly matched DUTs as one might expect. The match uncertainty is dramatically lower which shifts the entire uncertainty curve lower. Within a given DUT match, the largest difference between scalar and vector curves will be for DUTs with lower gain + NF values since the gain uncertainty decrease has more effect in this regime.

As a brief summary of the impact, a chart showing the asymptotic uncertainties is below.

MODE	Perfect Match	–15 dB Match	–10 dB Match
WB scalar ext	±0.17 dB	±0.27 dB	±0.41 dB
WB scalar int	±0.18 dB	±0.34 dB	±0.53 dB
WB vector int	±0.18 dB	±0.25 dB	±0.29 dB
NB scalar ext	±0.15 dB	±0.26 dB	±0.40 dB
NB scalar int	±0.17 dB	±0.33 dB	±0.53 dB
NB vector int	±0.17 dB	±0.24 dB	±0.28 dB

Conclusions

This document has reviewed some of the main causes of noise figure uncertainty and some suggestions on how to mitigate their effects. A simple model to compute overall measurement uncertainty was presented along with results for four different measurement modes that may be found in modern equipment. Since many factors were not included in the model and some method-independent factors are significant, the uncertainty curves for the different modes do not differ radically. When one is interested in relative uncertainty analysis as opposed to absolute uncertainty analysis, as when comparing methods or instruments for example, several steps may be taken to ease the comparison.

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