Non-Zero Noise Figure after Calibration

The increasing demand for wireless products combined with the availability of modern easy to use measurement equipment mean that Noise Figure measurements are more popular than ever. The situation is especially true in the Microwave region of the spectrum where more and more wireless standards are being developed.

Noise Figure measurements rely on a calibrated noise source as a reference. The general measurement process is shown below. In Figure 1 the noise source is connected directly to the input of the measuring instrument and a user calibration is performed. This measures and stores the instruments own Noise Figure at its various attenuator settings. These results are used to remove the effect of ‘second stage’ contribution during a corrected measurement. The measurement arrangement, with the Device Under Test (DUT) inserted between the noise source and the instrument is shown in Figure 2.

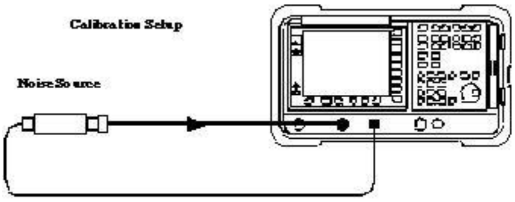


Figure 1 Calibration

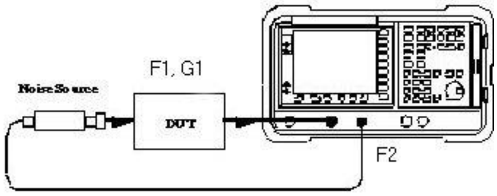


Figure 2 Measurement

Immediately after calibration the noise source is still connected directly to the instrument and the instrument automatically switches to the corrected measurement mode. In this configuration one would generally expect the instruments displayed Noise Figure and Gain to read 0dB since there is no DUT present. In practice however, the instrument may show plus or minus a few tenths of a dB Noise Figure as well as some even smaller but non-zero Gain. This is quite normal, however, some users assume that this zero-error will be added to their DUT’s Noise Figure producing an inaccurate result.

This note attempts to explain the reasons behind the zero-error and shows with examples that it does not have a compromising effect on the instrument accuracy in a measurement situation.

Theory

Figure 2 shown above along with the basic Noise Figure equation will be used as the basis of the explanation.

The general equation for the Noise Factor of two cascaded stages as defined by Friis (Proc IRE, July 1944,pp.419-422) is

$$F_{12} = F_1 + \frac{(F_2 - 1)}{G_1}$$

Where

F_{12} is the Noise Factor of the DUT and Analyzer combined
F_1 is the Noise Factor of the DUT
F_2 if the Noise Factor of the Analyzer
G_1 is the Gain of the DUT in linear form

And Noise Figure = $10LOG_{10}$(Noise Factor)

Immediately after calibration no DUT is in place so,

$F_{12}=F_2$ and $G_1=1$

Let’s assume that the Noise Figure of our Analyzer is 10dB, not for any other reason than it makes the numbers easy.

NF_2=10dB therefore F_2=10^(NF_2/10)=10

We already know that we don’t have a DUT in circuit but lets just work the Friis equation backwards to calculate F_1.

$$F_1 = F_{12} - \frac{(F_2 - 1)}{G_1} = 10 - \frac{(10-1)}{1} = 1$$

NF_1=10Log$_{10}$(1)=0dB.

No surprises here!

Now then lets see what happens when we introduce a small Gain error into G_1. Let’s say we have a 0.05dB error.

First convert this into linear form, so G_1=10^(0.05/10)=1.01158 and,

$$F_1 = 10 - \frac{(10-1)}{1.01158} = 10 - 8.8970 = 1.103$$

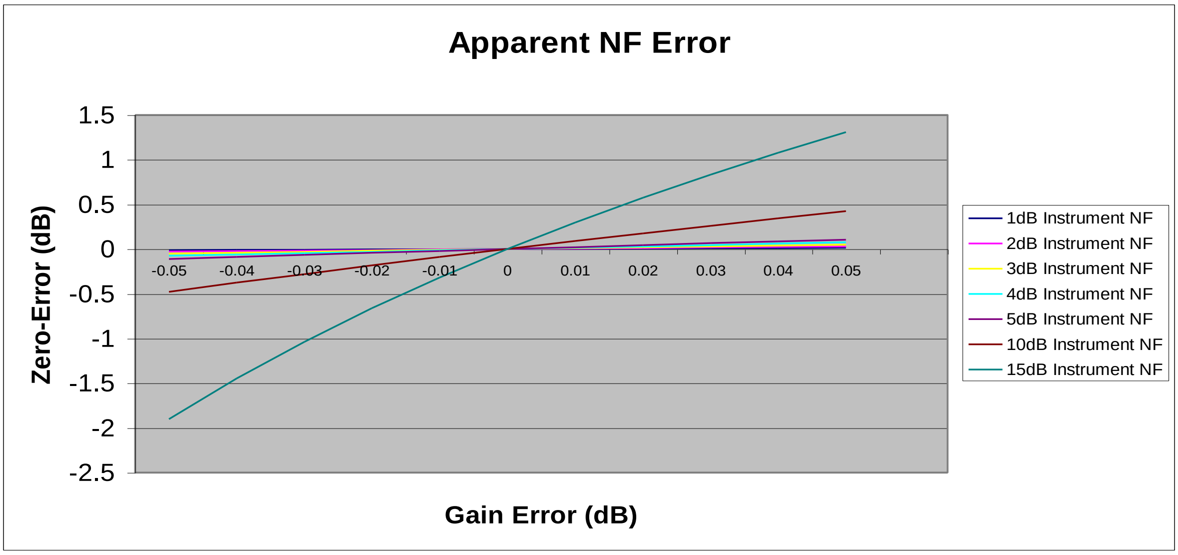
NF_1=10Log$_{10}$(1.103)=0.426dB!

This is a surprise, it seems that for a relatively minor Gain error we have a fairly significant Noise Figure error.

Lets look at the equation again.

$$F_1 = F_{12} - \frac{(F_2 - 1)}{G_1 \times GainError}$$

In our situation G_1 is 1 and so what in-fact is happening is that the Gain error is effectively multiplying the second stage noise factor F_2 to give a high apparent error (zero-error) in NF_1.
The bigger the Gain error and the higher the value of F_2, the bigger the zero-error will be. The graph below clearly shows this phenomenon.



The same phenomenon will be seen if a small error is applied to the Noise Factor. G_1 and F_1 and therefore F_{12} are entwined, any change in any one of these parameters affects the others. Our mathematical model is therefore not entirely complete. It does however show the mechanism behind the zero-error. To create an exact model would involve an analysis of the individual power levels involved in the measurement and calibration process. This would become unnecessarily complicated and distract from the exercise.
The important point is that it is small changes in power levels, Noise Factor and Gain, which effectively multiply the Noise Factor of the measuring instrument producing a zero-error.

Sources of Error

The magnitude of the power errors involved here is very small and there are many factors that can cause such errors. There are however several main candidates.

The main source of these small power errors is measurement jitter. By its very nature, noise is random and thus when measuring noise power we must allow enough measurement time to obtain a suitably accurate result. Increasing the number of averages in a Noise Figure measurement decreases the jitter.

Temperature variation is a major source of power errors. The Noise Figure and Gain of any DUT as well as any measuring instrument varies with temperature. Every effort should be made to keep the temperature of the measurement environment stable and calibration should be a regular activity.

Poor quality, dirty or inappropriate connectors, cables and adapters are a classic cause of power errors and power variation. Errors here can be quite considerable since a damaged cable for example provides an excellent means for extraneous signals entering the system. All RF connections should be inspected regularly and replaced if necessary.

Measurement Architecture

As well as the Noise Figure of the measurement equipment having an influence on the zero-error, the system architecture can also have a bearing. Figure 3 below shows the front-end architecture of a RF Noise Figure Analyzer typically extending to 3GHz.

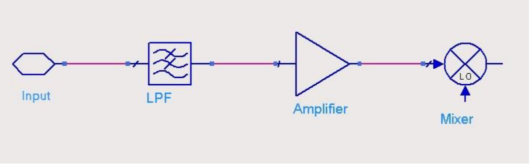


Figure 3 RF Architecture

The first mixer in this arrangement up-converts to an IF of around 4GHz. This being the case, the low pass filter on the input is all that is required to remove the image frequency from the input of the instrument. This provides a single-sideband measurement, which is the most accurate.

Microwave measurements are more of a challenge and there are generally 2 ways in which they are made. Figure 4 shows an arrangement using a RF Noise Figure Analyzer along with some external hardware to bring the frequency of interest down into an IF in the operating range of the Analyzer.

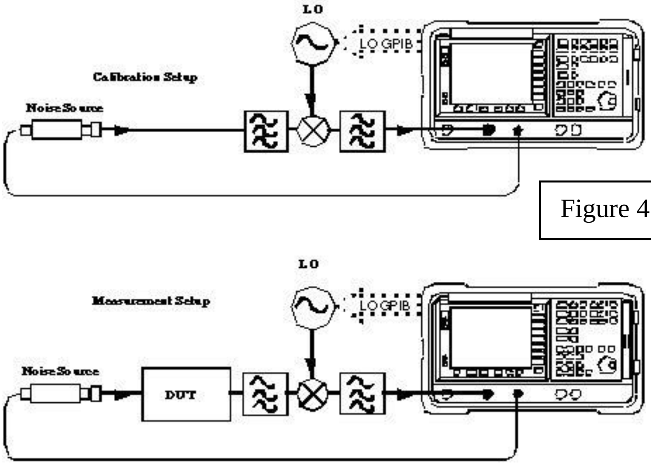


Figure 4 Microwave Measurement

Here we see a downconverter made up from an external mixer, a LO and associated filtering. The LO will typically be a high quality microwave signal generator which may or may not be controlled from the main instrument. This is a notoriously difficult set-up to develop. Care is needed to make sure that no signals of any significant level other than the one to be measured reach the Analyzer. It can be difficult to meet this criterion depending on the frequencies of interest, very specialised and expensive filters may be required to remove all the images, sidebands and particularly the LO leakage. The LO needs to have a low noise floor since along with the loss in the mixer and filters this will increase the Noise Figure of the set-up. This type of arrangement may have a limited bandwidth depending on the equipment used, this may however be quite acceptable for some measurement requirements.
Being a difficult and time-consuming arrangement to develop means that this type of set up is usually developed as part of a system. Its not generally something that would be put together in an afternoon to make a single Noise Figure measurement at 10GHz.

The alternative to this type of Microwave measurement is to use a Microwave Noise Figure Analyzer; these will typically allow measurements up to 26.5GHz. Above this, current technology does not allow any other option but the external downconverter.

Microwave Noise Figure Analyzers also cover the RF portion of the spectrum and in this region they have the same architecture as described previously. Above the 3GHz point the architecture must change. The first conversion in the RF instrument is an up conversion. Clearly this isn’t an option in the Microwave region since it would require an IF and LO of unacceptably high frequencies. In the Microwave region, the first conversion must be a down conversion. The arrangement is shown in Figure 5 below.

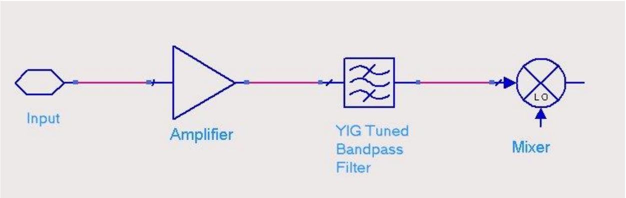


Figure 5 Microwave Architecture

Lets say that the first IF here is in the region of 300MHz. This would mean that at the input of the instrument the image frequency would only be 600MHz away from the frequency of interest and with an overall bandwidth of 26.5GHz this becomes a problem. The only way to remove the image component is to have a narrow band filter which tracks the RF frequency of interest. In Figure 5 there is a YIG (Yttrium Iron Garnet) bandpass filter preceding the mixer. YIG is a crystal that has very high Q characteristics and allows multi-octave frequency tuning when it is immersed in a variable magnetic field. This magnetic field is generally an electromagnet employing a variable current source. The variable current provides very linear tuning characteristics. These types of filter are fairly lossy and so the filter is positioned after the low noise amplifier to maintain an acceptable system Noise Figure.

These types of filter are clearly very versatile but they are magnetic in nature and hence they have some undesirable characteristics. Magnets exhibit hysteresis, and this affects the tuning behaviour in a YTF (YIG Tuned Filter). The passband response of these types of filters is somewhat unpredictable, having several peaks that vary depending on tuning history (where the filter was last), with frequency and temperature. Tuning sensitivity is very high (perhaps 20MHz/mA) and any noise on the current source will cause jitter in the centre frequency.

What does all this mean? Well, if a YIG filter is centred on say 10GHz, and is then moved to a different frequency and back to 10GHz, it will have a slightly different response. This will generate slight power differences and for Noise Figure, it will result in a zero-error of up to a few tenths of a dB.

The zero-error can be minimised by making measurements at spot frequencies rather than use the more conventional swept measurements. This means that the filter does not move between calibration and measurement steps and will thus be more stable, this does unfortunately come with time and process implications. There is generally some form of proprietary alignment process to minimise the effects caused by YTF's, these however are not perfect.
In many cases the zero-error observed on a well designed downconverter architecture will be better than that of a wideband Microwave Noise Figure Analyzer. As we shall see however, this is of little significance.

Measuring a real DUT

Now lets look at the situation where we have a DUT of 3dB NF and 20dB Gain in the circuit.

3dB NF_1 = 10^(3/10)=F_1=1.995
20dB G_{1log} = 10^(20/10)=G_{1lin}=100

We need to work out F_{12} for this exercise.

$$F_{12} = 1.995 + \frac{(10-1)}{100} = 2.085$$

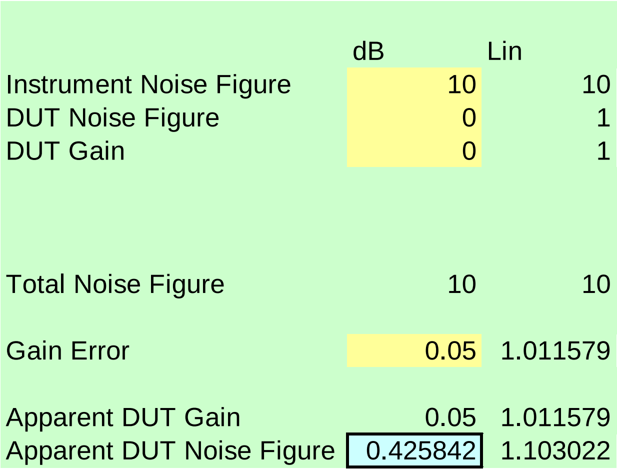
Now let's re-introduce our 0.05dB Gain error and see what effect it has on NF_1

$$F_1 = 2.085 - \frac{(10-1)}{100 \times 1.01158} = 1.996$$

NF_1=10Log_{10}(1.996)= 3.00224dB

Here we can clearly see that the small Gain error, which gave a high zero-error with no DUT in place has an almost insignificant effect.

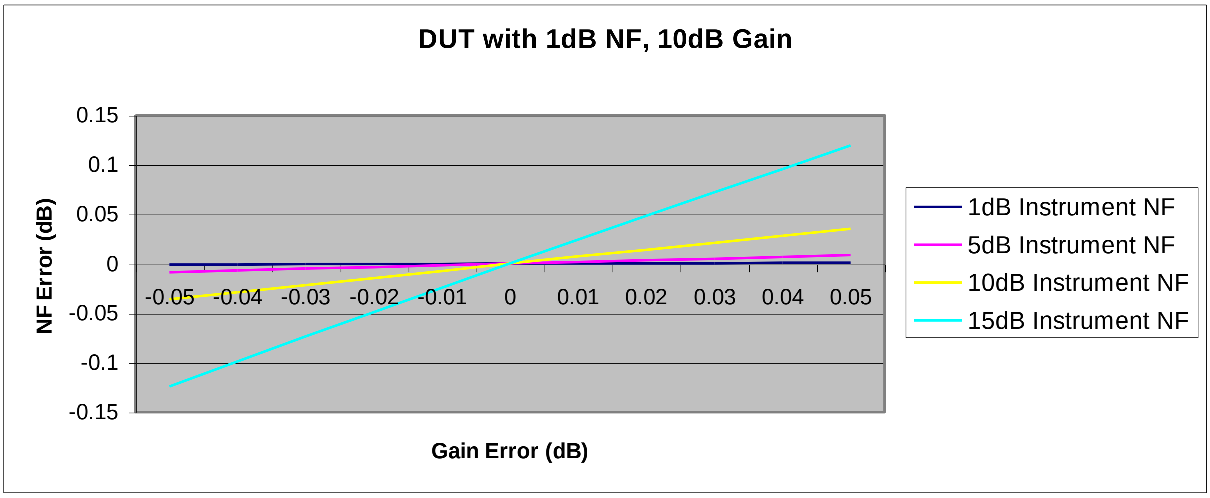
The spreadsheet calculator below can be used to experiment with different situations, the items in yellow are the user variables. Double click on the spreadsheet to activate it.

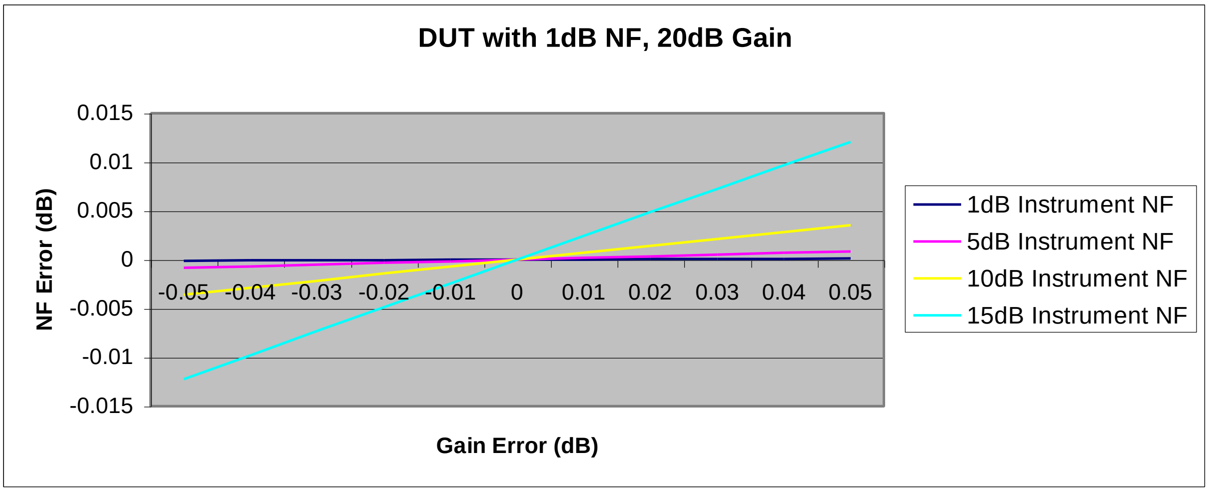


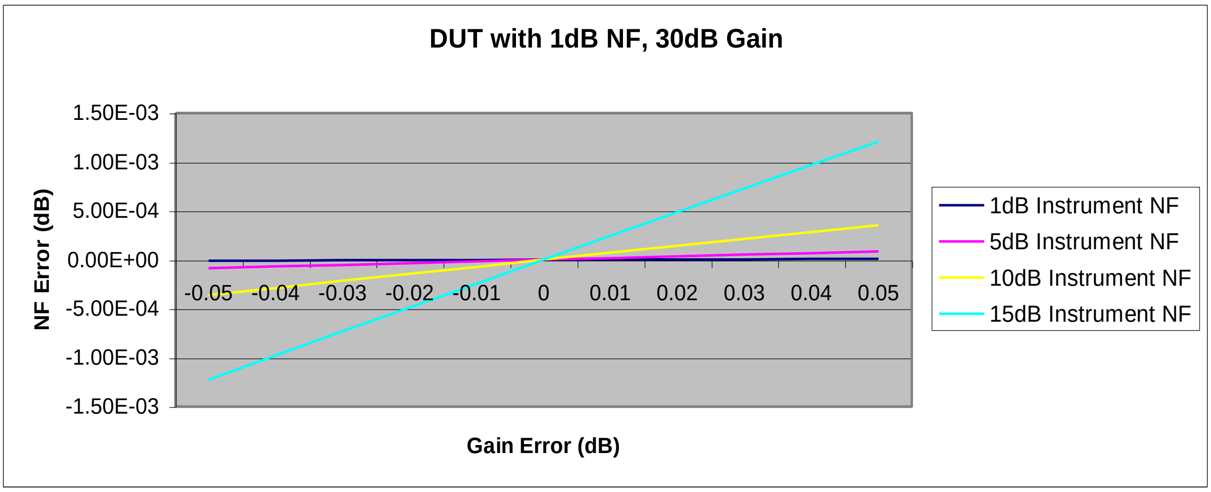
	dB	Lin
Instrument Noise Figure	10	10
DUT Noise Figure	0	1
DUT Gain	0	1
Total Noise Figure	10	10
Gain Error	0.05	1.011579
Apparent DUT Gain	0.05	1.011579
Apparent DUT Noise Figure	0.425842	1.103022

Examples

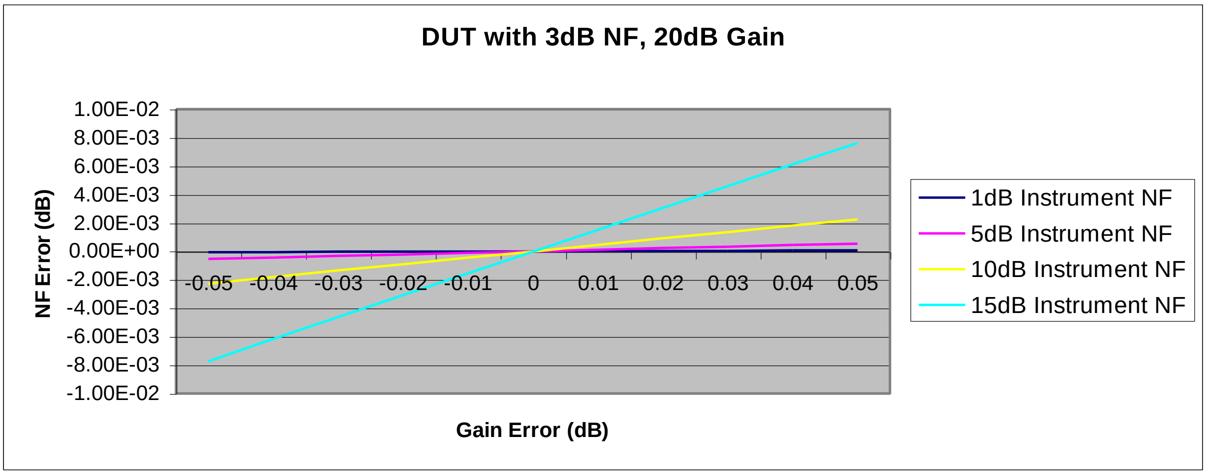
Presented here, are some examples of different DUT's and the effect that a small Gain error has on the measured Noise Figure.

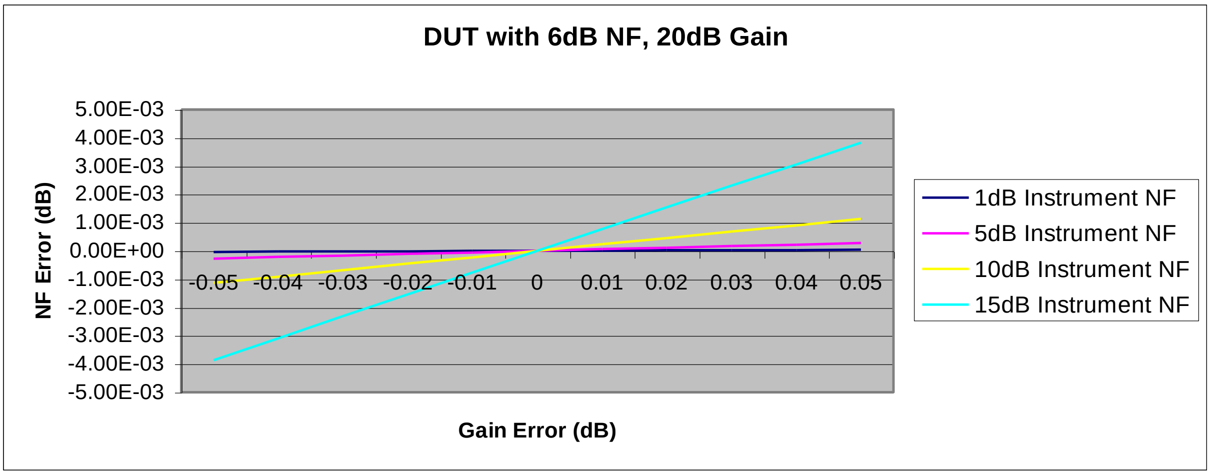






In the three graphs above we can see that for every 10dB increase in Gain there is a corresponding 10dB reduction in the Noise Figure Error.





These two graphs show that the error also decreases as the Noise Figure of the DUT increases.

These points can be summarised as a reduction in second stage contribution, the ratio F_{12}/F_1. F_{12} being a function of the instruments Noise Figure and the DUT's Gain and Noise Figure. The closer the ratio F_{12}/F_1 gets to 1 the better the result will be.

From this data a rule-of-thumb may be constructed such that the contribution from the zero-error is reduced by the DUT's (Gain+Noise Figure)dB

In some instances users may not be measuring a DUT which has any Gain, a mixer for example. In such situations the zero-error is actually a real error. A typical mixer may have a noise figure of 8dB or more so an error of a few tenths of a dB may not be important. The zero-error can however be reduced as mentioned previously by using spot measurements, stable temperature environments etc. In this situation however by far the best way to reduce the zero-error is to precede the measurement instrument with a low noise amplifier such that the ratio F_{12}/F_1 tends towards 1. The gain of such an amplifier should however be minimised in order that the instruments dynamic range is not compromised.

Zero-error is only one of many factors that contribute to the bigger picture of measurement uncertainty which has been covered in detail elsewhere. Zero-error is one of the minor players in this bigger picture with for example the noise source accuracy being a more prominent player with accuracy specifications in the region of 0.1dB. Unlike the zero-error this type of error is not reduced by the DUT's Gain or Noise Figure. A Noise Figure Measurement Uncertainty calculator can be found on Agilent's Web pages.

Conclusions

This note has shown the mechanism behind non-zero Noise Figure after calibration and has discussed the main components that contribute to the zero-error. Examples have demonstrated that the zero-error does not compromise the measurement accuracy when a test device is in place.

The differences in architecture between a RF instrument and the Microwave portion of a Microwave instrument have been discussed and the influence the YIG tuned filter has on the zero-error has been highlighted. Some direction has been given to aid the reduction of the zero-error in the few application's where it may be useful to do so.

The zero-error has been discussed as a small player in the bigger picture of measurement uncertainty.