Non-Zero Noise Figure After Calibration

Application Note 1484

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. This 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 in the figures 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 instrument's own noise figure at its various attenuator settings. These results are used to remove the effect of "second-stage" noise 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.

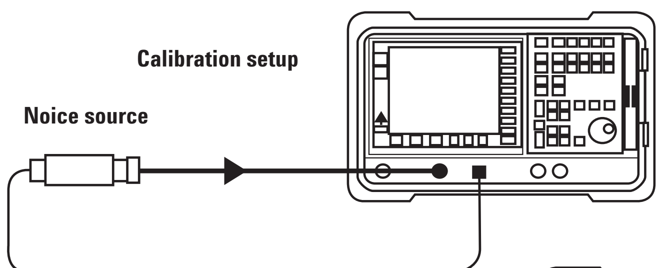

Figure 1. Calibration

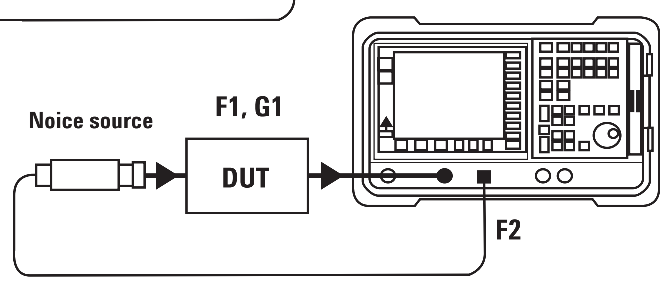

Figure 2. Measurement

Immediately after calibration, the noise source is still connected directly to the instrument, which automatically switches to the corrected measurement mode. In this configuration the instrument would be expected to display a noise figure and gain of 0 dB, because there is no DUT present. In practice however, the instrument may show a noise figure of plus or minus a few tenths of a dB as well as an even lower level of gain, but not zero. While this is quite normal, some users assume that this zero-error will be added to their DUT's noise figure, producing an inaccurate result.

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

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Theory

Figure 2 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 (Proceedings of the IRE, July 1944, pp.419-422) as:

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

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

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

The noise figure of the analyzer will be assumed to be 10 dB in this discussion to make explanation simpler. In this case

$$NF_2 = 10 \text{ dB so } F_2 = 10\text{^}(NF_2/10) = 10$$

Although there is no DUT in the circuit, the Friis equation can be worked backward to calculate F_1

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

$$NF_1 = 10Log_{10}(1) = 0 \text{ dB}$$

However, when a small gain error of 0.05 dB is introduced into G_1 an interesting result occurs. First this is converted into linear form, so G_1 = 10^(0.05/10) = 1.01158 and

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

$NF_1 = 10Log_{10}(1.103) = 0.426$ dB

It seems that for a relatively minor gain error a fairly significant noise figure error has been produced.

Looking at the equation again

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

In this situation G_1 is 1, so the gain error is multiplying the second-stage noise factor F_2 to give a high apparent error (zero-error) in NF1. The bigger the gain error and the higher the value of F2, the bigger the zero-error will be. Figure 3 clearly shows this phenomenon.

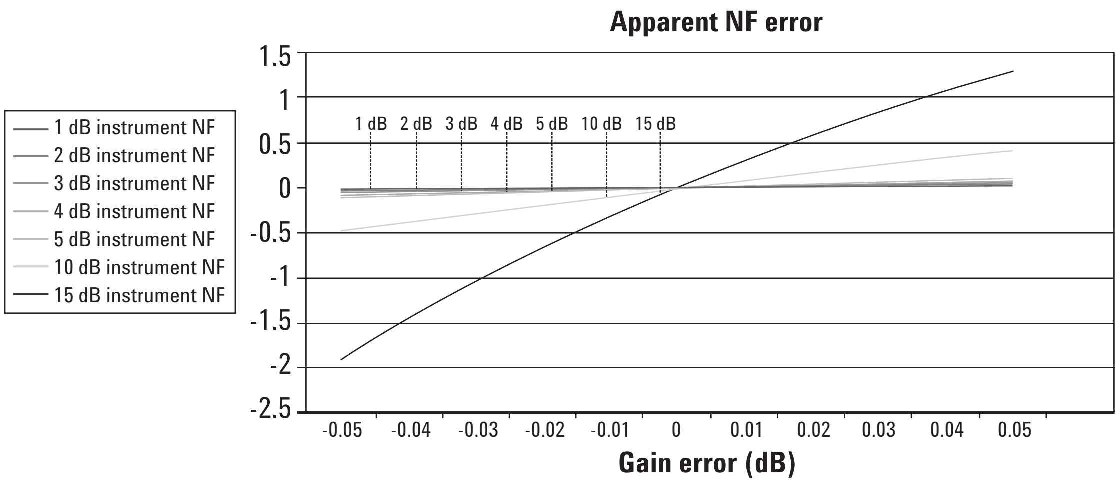

Figure 3. Apparent noise figure error

The same phenomenon will be seen if a small error is applied to the noise factor. G_1, F_1, (and therefore F_{12}) are entwined, so any change in any one of these parameters affects the others. The mathematical model is therefore not entirely complete, but does 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.

The important point is that small changes in power levels, noise factor and gain, effectively multiply the noise factor of the measuring instrument, producing a zero-error.

Sources of error

The magnitude of the power errors involved is very small and many factors can cause them. However, there are several main candidates, of which measurement jitter is the most likely. Noise is by nature random, so when measuring noise power enough measurement time must be allowed to obtain a suitably accurate result. Increasing the number of averages in a noise figure measurement decreases the jitter.

Temperature variation is also 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 primary cause of power errors and power variation. Errors caused by these sources can be quite large since a damaged cable (for example) provides an excellent way for extraneous signals to enter the system. All RF connections should be inspected regularly and replaced if necessary.

Measurement architecture

The system architecture as well as the noise figure of the measurement equipment has an influence on the zero-error. Figure 4 shows the front-end architecture of a RF noise figure analyzer that has coverage to 3 GHz.

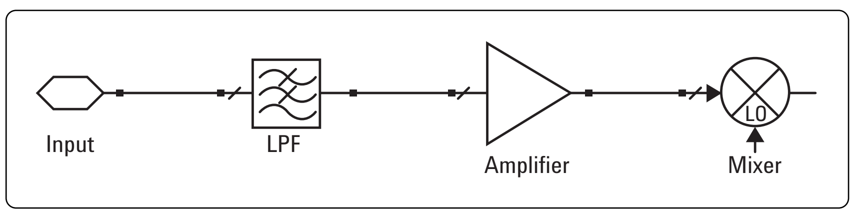

Figure 4. RF architecture

The first mixer in this arrangement upconverts to an IF around 4 GHz, so only a low-pass filter on the input 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 two ways to make them. Figure 5 shows an arrangement using an RF noise figure analyzer along with some external hardware to bring the frequency of interest down to an IF in the operating range of the analyzer.

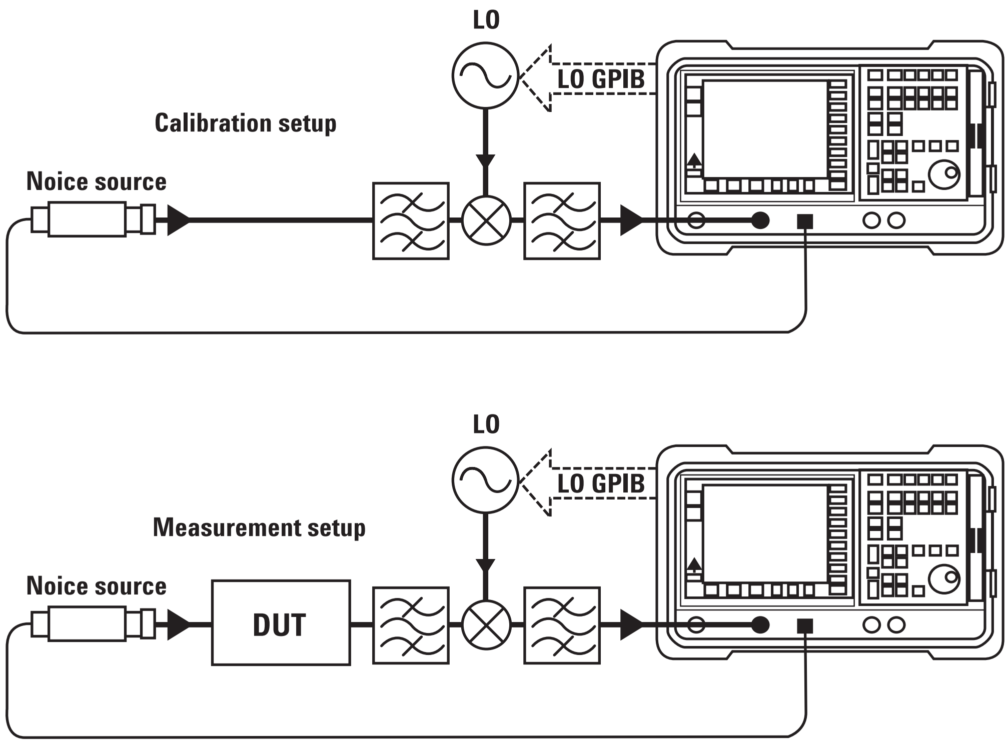

Figure 5. Microwave measurement

The downconverter is comprised of an external mixer, 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 must be taken to make sure no signals of any significant level reach the analyzer other than the one to be measured. It can be difficult to meet this criterion depending on the frequencies of interest, and very specialized, expensive filters may be required to remove all the images, sidebands and particularly the LO leakage. The LO must have a low noise floor because 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, and may be acceptable for some measurement requirements. The difficulty of this set-up relegates its use primarily in systems, and not as a test set-up put together in a single afternoon in order to make a single noise figure measurement.

The alternative to this type of microwave measurement configuration is a microwave noise figure analyzer that typically allows measurements up to 26.5 GHz. Above this, current technology does not allow any other option but an external downconverter. Microwave noise figure analyzers also cover the RF portion of the spectrum, and have the same architecture as their RF counterparts. Above 3 GHz the architecture must change. The first conversion in the RF instrument is an upconversion. Clearly this option is not possible in the microwave region because it would require an IF and LO of unacceptably high frequencies. In the microwave region, the first conversion must be a downconversion. The arrangement is shown in Figure 6 below.

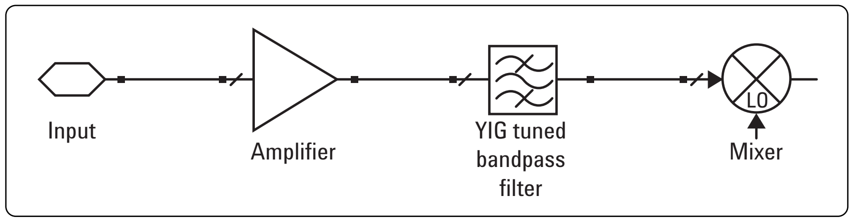

Figure 6. Microwave architecture

If the first IF is around 300 MHz the image frequency at the input of the instrument would only be 600 MHz away from the frequency of interest. With an overall bandwidth of 26.5 GHz this becomes a problem. The only way to remove the image component is to have a narrowband filter that tracks the RF frequency of interest. In Figure 6 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. This type of filter is fairly lossy so it is positioned after the low-noise amplifier to maintain an acceptable system noise figure.

YIG-tuned filters are very versatile but because they are magnetic in nature they have some undesirable characteristics. Magnets exhibit hysteresis, and this affects tuning behaviour. The passband response is somewhat unpredictable, with several peaks that vary depending on tuning history (the frequency to which the filter was last tuned), with frequency and temperature. Tuning sensitivity is very high (perhaps 20 MHz/mA) and any noise from the current source will cause jitter in the center frequency.

All this means that if a YIG-tuned filter is centered on 10 GHz, and is tuned to a different frequency and back to 10 GHz, it will have a slightly different response. This will generate slight power differences, and for noise figure will result in a zero-error of up to a few tenths of a dB.

The zero-error can be minimized by making measurements at spot frequencies rather than by making more conventional swept measurements. In this way, the filter does not move between calibration and measurement steps and will be more stable. Unfortunately, this has time and process implications. There is generally some form of proprietary alignment process to minimize the effects caused by filter but they are not perfect.

In many cases the zero-error observed of a well-designed downconverter architecture will be better than that of a wideband microwave noise figure analyzer. However, this is of little significance.

Measuring a real DUT

This discussion will add a DUT with a 3 dB noise figure and 20 dB of gain in the circuit.

3 dB NF_1 = 10^(3/10) = F_1 = 1.995

20 dB G_{1log} = 10^(20/10) = G_{1lin} = 100

F_{12} must be solved for this exercise.

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

Reintroducing the 0.05 dB gain error will show what effect it has on NF_1

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

$$NF_1 = 10Log_{10}(1.996) = 3.00224 \text{ dB}$$

The small gain error that gave a high zero-error with no DUT in place now has an almost insignificant effect. A spreadsheet can be construed to experiment with different values in the above equation. The following examples were generated using this method.

	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	$\boxed{0.425842}$	1.103022

Figure 7. Example of a spreadsheet calculator

Examples

The examples of different DUTs in figures 8, 9, and 10 show the effect that a small gain error has on the measured noise figure. For every 10-dB increase in gain there is a corresponding 10-dB reduction in noise figure error.

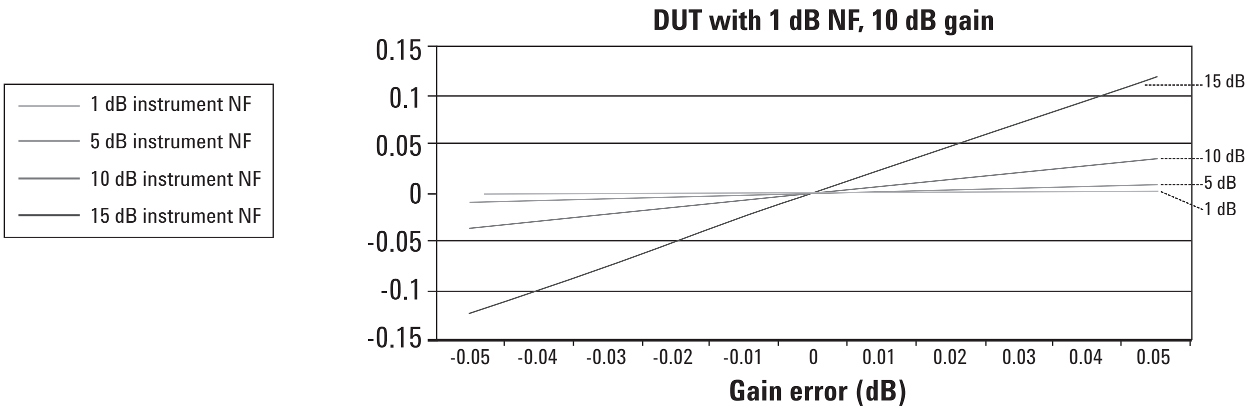

Figure. 8

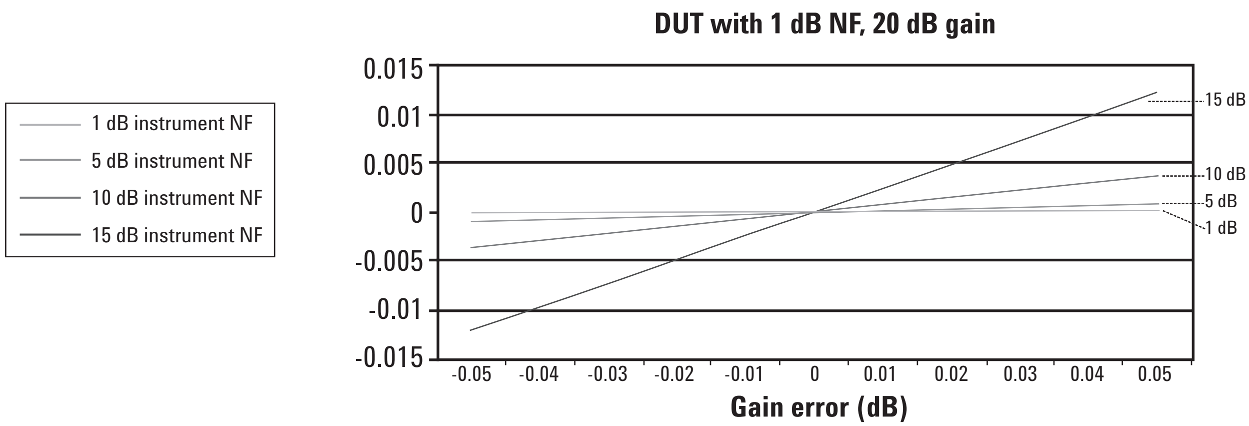

Figure. 9

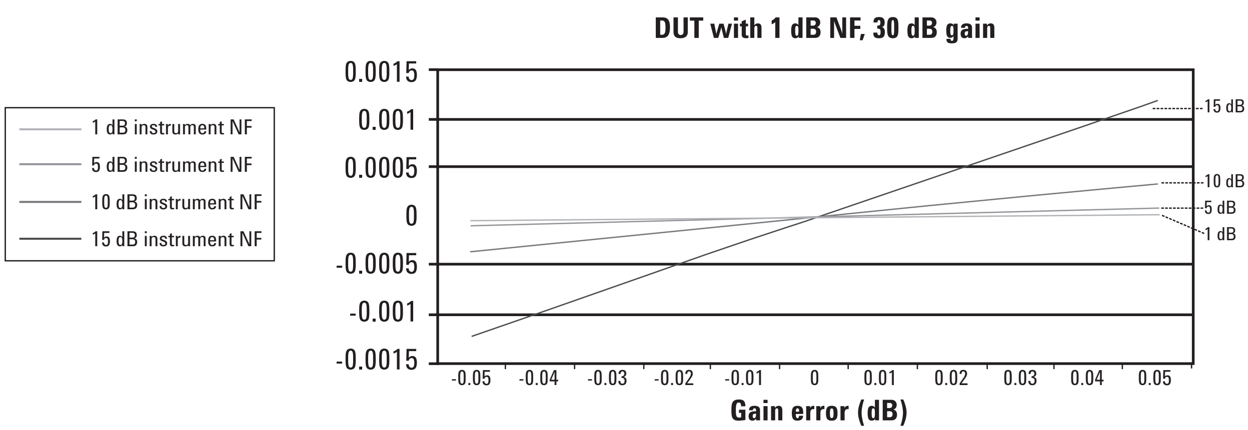

Figure. 10

Figures 11 and 12 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 instrument's 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 dictating that the contribution from the zero-error is reduced by the DUT's (gain + noise figure) dB.

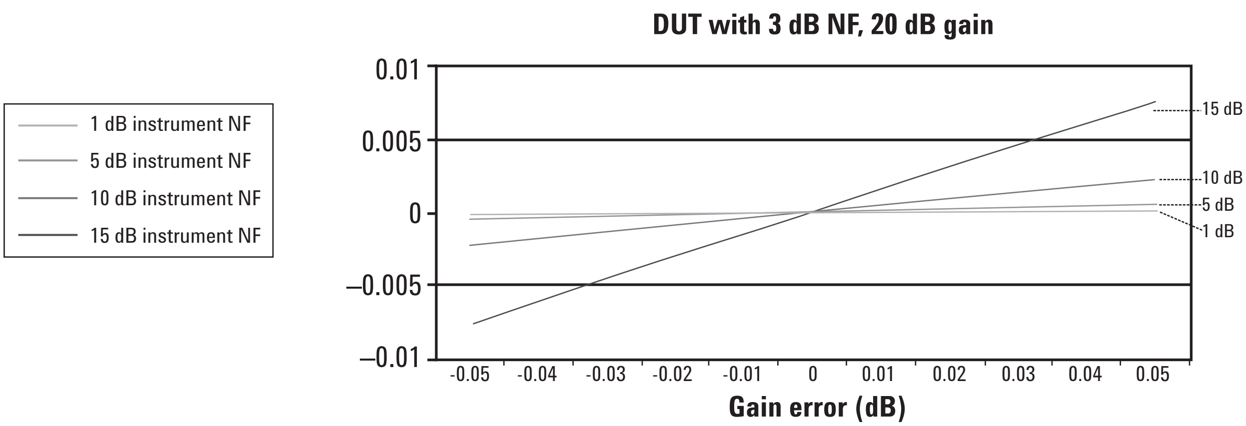

Figure. 11

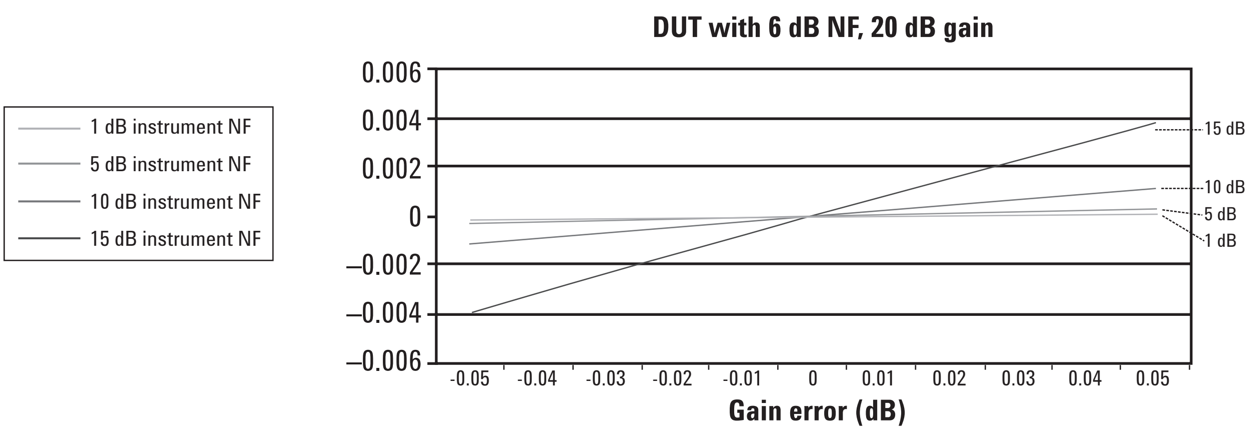

Figure. 12

In some instances, such as a mixer application, users may not be measuring a DUT that has any gain. In these cases the zero-error is actually a real error. A typical mixer may have a noise figure of 8 dB or more so an error of a few tenths of a dB may not be important. Using spot measurements, and stable temperature environments can reduce the zero-error. By far the best way to reduce the zero-error is to precede the measurement instrument with a low-noise amplifier so that the ratio F_{12}/F_1 tends toward 1. The gain of the amplifier should be minimized to ensure that the instrument's dynamic range is not compromised.

Zero-error is only one of many factors that contribute to total measurement uncertainty that has been covered in detail elsewhere. Zero-error is one of the minor considerations, and noise source accuracy is more prominent with accuracy specifications of about 0.1 dB. Unlike 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 at **www.agilent.com/find/nfu.**

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 applications where it may be useful to do so.

Related Literature

Fundamentals of RF and Microwave Noise Figure Measurements
application note 57-1, Publication number 5952-8255E

Noise Figure Measurement Accuracy – The Y-Factor Method
application note 57-2, Publication number 5952-3706

10 Hints for Making Successful Noise Figure Measurements
application note 57-3, Publication number 59890-02-88E

Web Sites

Noise figure analysis web site: **www.agilent.com/find/nf**

Calculate the Uncertainty of NF Measurements: **www.agilent.com/find/nfu**

Noise figure analyzers web site: **www.agilent.con/find/nfa**

Noise figure for spectrum analyzers:
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