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# Make Accurate Sub-1 dB Noise Figure Measurements Part 2: The Measurements

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**In addition to the actual test sequence, stable low noise figure measurements require careful attention to the equipment selection, laboratory setup, environmental conditions and calibration procedures**

The first part of this article (*High Frequency Electronics,* January 2010 [6]) presented the fundamental concepts of noise figure and its measurement. Part 2 concludes this noise measurement tutorial with a discussion of the instrumentation and methodology of noise measurement used at the author's company.

## Measurement and Practical Considerations

*Equipment Selection*

Only two pieces of equipment are needed to perform noise measurements with the Y-Factor method: a noise receiver and a noise source. Probably the lowest cost option is to use a spectrum analyzer with a noise figure personality and an internal preamplifier. The preamplifier option is critical to perform low noise measurements as the noise figure of spectrum analyzers is typically high. The use of a preamplifier brings the instrument's noise figure down to a usable range. If an external preamplifier is used, it must be placed between the output of the DUT and the instrument and must be included in the calibration loop.

*Importance of Noise Source Selection*

Noise sources are described by their frequency range and their ENR range. The frequency range is typically very wide and one simply needs to make sure the test frequencies are within the specified range. ENR range has mainly two types: high and low. A low ENR noise source—approximately 6 dB ENR—is preferred for low noise figure measurements. Table 1 (on the next page) lists some noise sources available from Agilent Technologies and their key parameters.

The impedance of a noise source varies between the ON and OFF states which may be the source of measurement errors for devices that are highly sensitive to input match. A low ENR source can be thought of as a high ENR source with a 10 dB attenuator at its output and is therefore less susceptible to mismatch. Another advantage of the low ENR source is the noise power difference between the ON and OFF states. For high gain devices a 10 dB increase in noise power may drive the instrument out of its linear range and thus require added attenuation at the output of the DUT. Nonetheless, DUTs which have gain over 40 dB may require output attenuation even with a low ENR noise source. If attenuation is required at the output of the DUT, it is a good practice to avoid calibrating with the attenuator in the calibration loop but account for it in post-processing to insure enough noise power reaches the instrument during calibration Use of a low ENR noise source should only be avoided when measuring devices with very high noise figure. In such cases, the noise contribution from the DUT may be so high that it overwhelms the change in noise power emanating from the noise source between the ON and OFF states making it very difficult to detect the difference accurately. One should also remember the ENR table of a noise sources is only valid at a $T_0$.

Agilent Technologies offers a unique family of "smart" noise sources (SNS) which includes a built in thermocouple in the noise

| Noise Source | ENR (dB) | VSWR (Max.) | Uncertainty (dB) | DUT NF Range (dB) |
|---|---|---|---|---|
| N4000A | 4.6-6.5 | 1.04 | 0.15 | < 16 |
| N4001A | 14-16 | 1.13 | 0.13 | > 16 |
| N4002A | 12-17 | 1.22 | 0.13 | > 16 |

**Table 1 · SNS noise source parameters from Agilent Technologies.**

source itself which facilitates continuous measurement of the noise source's physical temperature. This option makes measurements more repeatable over time in avoiding repetitive inputs from the user and compensates for slight temperature changes due to ambient conditions or heat transmission through the setup (i.e., over temperature measurements).

*What To Do If Only a High ENR Source is Available*

As was explained above, one problem with high ENR noise sources in measuring low noise devices that are sensitive to input match is the change of impedance of the source between the ON and OFF states. There are two simple setup changes that can improve impedance mismatch and the quality of the measurement: an isolator or an attenuator.

An isolator is a two-port device that allows energy to propagate in one direction with low loss, but strongly attenuates energy that would propagate in the reverse direction. Isolators are often used to protect sensitive devices from reflected signals, which are directed to a resistive load within the isolator. The insertion loss of an isolator is typically small but will decrease on a dB-for-dB basis the equivalent ENR of the noise source. It therefore still presents a higher risk of driving the instrument out of its linear range when measuring high gain (>30 dB) devices. The isolator's insertion loss can be accounted for in post processing the data in which case calibration should be performed without the isolator in the system. It is also possible to correct the ENR table and calibrate with the isolator in place. Isolators are typically very selective devices that make measurements over a broader range of frequencies very time consuming.

Another method is to use an attenuator on the output of the noise source. The attenuator will improve return loss at the noise source by twice its insertion loss (in terms of dB), by attenuating a big portion of the reflected power before it reaches the noise source. As with the isolator, the equivalent ENR of the noise source will be reduced dB-for-dB by the insertion loss of the attenuator. Accounting for the attenuator is done the same way as for an isolator although a post processing correction is typically preferred. The advantage of an attenuator over an isolator is the attenuator's broader frequency range.

Any correction error in adjusting the ENR table or compensating for input loss will also contribute dB-for-dB to the measurement error. One should also remember the physical temperature of the isolator or attenuator will also play a role in the correction and should be accounted for. Therefore, the use of a low ENR source is still the recommended option as it is precisely characterized and calibrated.

*Measurement of a Mismatched DUT*

The use of an isolator or an attenuator can also be useful for a mismatched DUT since a scalar noise measurement system cannot account for vectorial reflections. Vectorial reflections typically result in a “wavy” noise figure response over frequency as the noise power emanating from the noise source combines vectorially with the reflected power from the DUT. In this case it may help to correct for the mismatch loss of the DUT as a portion of the noise power is actually being reflected into a load or an attenuator, therefore lowering the apparent noise figure of the DUT. If a low ENR source is used, the isolator approach is preferred to avoid lowering the ENR too much.

*Choosing the Measurement Bandwidth and Averaging*

Most instruments use a resolution bandwidth of about 4 MHz for measuring noise figure which is a good compromise for most applications. Increasing the bandwidth yields more noise power increasing the likelihood to drive the instrument beyond its linear range. It also reduces the resolution over frequency as the total noise power is averaged through the whole bandwidth. Reducing the bandwidth too much may drive the instrument closer to its noise floor resulting in increased jitter or false measurements. For most devices, the measurement bandwidth may remain the instrument's default value.

A problematic situation may be encountered with highly selective devices where the bandwidth of the DUT is smaller than the resolution bandwidth of the instrument. Typically, RF amplifiers alone have a bandwidth much bigger than the default bandwidth of instruments, but this may not be the case if the amplifier is cascaded with a very selective filter. In this case a portion of the noise power is being attenuated and is therefore not available at the output of the device. Thus, if the resolution bandwidth of the instrument is not set properly, the instrument may integrate the noise power over a bandwidth larger than the bandwidth of the DUT, resulting in an erroneously lower noise figure measurement. When measuring highly selective devices, one should always set the resolution bandwidth of the instrument so that it is reasonably smaller than the bandwidth of the DUT but sufficiently wide to allow enough noise power to reach the instrument.

Low noise figure measurements are jittery by nature and often require the use of time averaging to make a good reading. Also, the signal is averaged over the resolution bandwidth. Therefore, reducing the resolution bandwidth will also increase the jitter of the measurement which can be compensated by increasing the number of samples to calculate the average by a 1:1 factor. For example, reducing the resolution bandwidth by a factor of 10 while increasing the average setting by a factor of 10 will result in the same amount of jitter.

*Non-linearity, Interference, and Instability*

The noise source selection section already mentioned driving the instrument out of its linear range, which should be avoided at all times during noise measurements. The same rule applies to the any element present during the measurement. It is therefore important to avoid overdriving a DUT too close to saturation or to include in the setup devices that may clip, compress or adjust gain automatically. Both the DUT and the measurement system gain must be as constant as possible when the noise source switches between the ON and OFF states.

Interference is a very common problem for noise figure measurements. Low noise amplifiers (LNAs) are designed so that a very weak signal can be detected and amplified, which makes LNAs extremely susceptible to interference. For example, an LNA designed for the GSM cellular telephone band may easily pick up a signal emanating from a nearby base station or cell phone handset. With the breadth of portable devices available today, interferers are literally everywhere. Interference in a noise figure measurement typically appears as spikes or dips in the noise figure response. If the interference is narrow and localized, it is sometimes possible to discard some of the collected data or to avoid making measurement at certain frequencies.

In other situations like the one just described, proper shielding of the DUT and measurement system may be the only viable solution. For that reason, noise figure measurements are often performed within a specially built and qualified screened room. A screened room consists of a metal shielded room devoid of any unnecessary interferers such as computers, LAN computer networks, cell phones, etc., and where AC lines entering the room are electrically filtered to isolate it as much as possible from the outside environment. Some frequency bands may also be prone to wideband noise which elevates the noise floor in the form of a plateau. The wideband nature of this interference makes it very difficult to detect and in most situations can only be removed by making measurements in a screened room or a shielded box.

Instability of both the DUT and setup may also be a problem. An oscillation is interference in the system and may affect the measurement at multiple frequencies. Semiconductors always have some level of non-linearity and can mix an oscillation signal in various combinations. An oscillating device may also deviate from its bias conditions affecting its input and output impedances as well as its noise parameters.

### *Example:* Noise Figure Measurement over Temperature with Loss Correction

This section is a step-by-step example detailing how the correction is applied in a more complex setup, the instruments and settings used, and other practical observations.

*Skyworks equipment selection and typical settings*

Skyworks operates multiple noise figure measurement stands using equipment from various vendors. One stand is used as a true noise figure measurement reference for all others and is located in a certified screened room. The room is also equipped with heating/cooling equipment for noise measurements over temperature and is used for true characterization of devices. Other stands are used for tuning purposes. The list below describes the equipment and settings used in the screen room.

As was already mentioned, an SNS noise source allows reading the temperature of the noise source automatically. We have observed the temperature reading is actually 6 ºC above the actual ambient temperature probably

| Manufacturer | Instrument | Type | Option | Settings |
|---|---|---|---|---|
| Agilent Technologies | MXA<br>N9020 | Spectrum Analyzer | Preamplifier<br>NF personality | Preamp = ON<br>RBW = 4 MHz<br>T_COLD = SNS<br>ATT = 0 dB<br>Settling time = 80 ms<br>Avg time/pt = 80 ms<br>Averaging = 10 |
| Agilent Technologies | N4000A | Smart Noise Source:<br>Low ENR | None | None |

**Table 2 · Instrumentation used and typical settings for sub-1 dB noise figure measurements.**

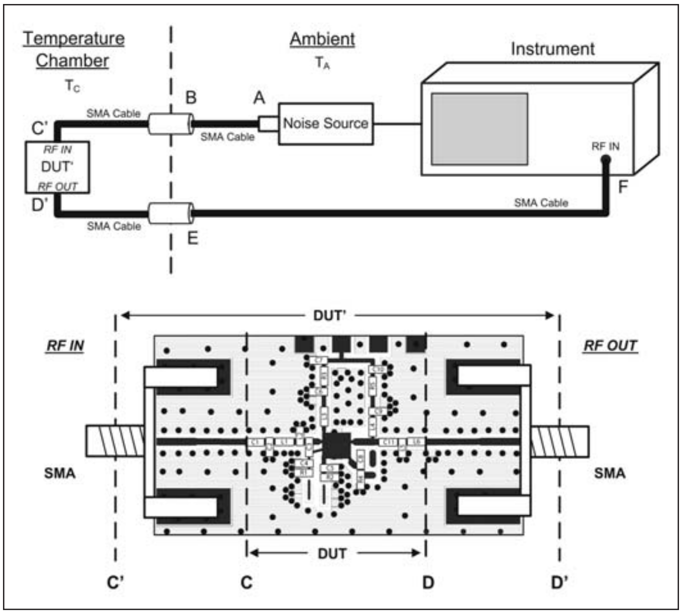


**Figure 8 · Typical measurement setup for noise figure measurement over temperature.**

| Frequency (GHz) | $S_{11}$ (dB) | $S_{22}$ (dB) | $S_{21}$ (dB) |
|---|---|---|---|
| 2 | –20 | –20 | 24 |

**Table 3 · *S*-parameters of DUT' (DUT plus lines and connectors), between nodes C' and D'.**

because of internal heating and sensing of the noise source. We also observed the same temperature offset applied on a number of 346A noise sources (non-SNS) yield the same noise figure measurement result. This may have to be taken into account if an SNS noise source is not available.

Noise figure measurements over temperature complicate the setup by adding extra cables and connectors, the effects of which must be removed from the measurement either by calibration or post processing. It is best to keep cables short at least on the input side of the DUT which in turn may cause the noise source to change its internal temperature. As noise sources are typically specified to be operated over a limited temperature range, some cable length may be required to provide thermal insulation. It is always a good practice to make a reference room temperature measurement first while having only the DUT between the source and the instrument. In more complex and lossy setups, it is not uncommon to have small errors in the loss compensation preventing an exact reading of noise figure for sub-1 dB devices. In those situations, the reference can be used to correct or at least scale the measurement results. Figure 8 illustrates Skyworks' typical setup for noise measurements over temperature where letters refer to connection nodes.

*Step 1: Obtain a true reference noise figure measurement of the DUT*

As described by Figure 8, the DUT is enclosed between two SMA connectors, between the nodes C and D. With the help of a "thru" board equivalent to twice the length of C'-C, the input loss was determined to be 0.1 dB at 2 GHz using a vector network analyzer (VNA). Since the output section of the board is identical to the input, the loss D-D' is also 0.1 dB. Table 3 list the *S*-parameters of DUT", between the nodes C' and D'.

The noise instrument is calibrated by connecting the noise source directly to the instrument at node F. A reference room temperature noise measurement is then performed while having the noise source connected directly to node C' and the instrument to node D' without using any other connectors. The ambient temperature is also found to be $T_A$ = 297 K.

The actual noise figure of the DUT is the noise figure of DUT' corrected for its input and output loss. Table 3 data shows DUT' is very well matched so there is no need to account for mismatch loss. As the gain is 24 dB and given the information in Figure 6, the output loss due to the D'-D section of the board can also be neglected. Therefore the only loss for which correction is necessary is the input loss. Using Eq. 15 and knowing the ambient temperature, the noise figure of the DUT, $NF_{DUT}$ is calculated as shown in Table 4.

*Step 2: Characterization and validation of the setup*

In order to correct the final measurement, the insertion loss of every section of the setup needs to be determined and split based on their location and physical temperature during the measurement. Table 4 lists the measured insertion loss of all sections and their physical tem-

| | | | Correction for loss sections | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Description | Uncorrected NF | E-F | | | D-E | | | B-C | | | A-B | | |
| | | (dB) | Loss (dB) | Temp. (ºC) | Corrected NF (dB) | Loss (dB) | Temp. (ºC) | Corrected NF (dB) | Loss (dB) | Temp. (ºC) | Corrected NF (dB) | Loss (dB) | Temp. (ºC) | Corrected NF (dB) |
| Step 1 | Reference | 0.75 | 0.00 | 24 | N/A | 0.10 | 24 | N/A | 0.10 | 24 | 0.65 | 0.00 | 24 | 0.65 |
| Step 2 | Validation | 0.99 | 0.59 | 24 | N/A | 0.21 | 24 | N/A | 0.21 | 24 | 0.78 | 0.14 | 24 | 0.64 |
| Step 3 | Measurement | 1.39 | 0.59 | 24 | N/A | 0.21 | 85 | N/A | 0.21 | 85 | 1.14 | 0.14 | 24 | 1.00 |

**Table 4 · Measured setup insertion losses and computed noise figure corrections.**

perature. Similarly to step 1, the output section D-D' is neglected as well as section D'-F since its loss is only 0.7 dB.

Performing the noise figure measurement between nodes A-F while setting the temperature chamber to the ambient temperature recorded earlier and correcting for all losses should give the same value as in Step 1. If the difference is greater than 0.05 dB the system losses probably need to be looked at again. Table 4 shows Step 1 and Step 2 correlate very well.

*Step 3: Measurements over temperature*

Now that the setup is validated, the actual noise figure measurement can begin. In this example the temperature in the chamber is raised to 85 ºC and the results are shown in Table 4.

## Conclusion

The proper techniques or methods to ensure the best possible accuracy for sub-1 dB noise figure measurement have been described. For best accuracy in sub-1 dB noise figure measurements, the following recommendations should be applied:

- Use a low ENR noise source—preferably SNS.
- Add the preamplifier option if the instrument is a spectrum analyzer.
- Ensure proper calibration techniques.
- Never include elements located before the DUT in the calibration loop.
- Connect the noise source as close as possible to the DUT.
- Remove any unnecessary connector or adaptors from the setup.
- Ensure accurate temperature inputs (noise source and losses).
- Use a screened room if available.
- Take into account losses, especially before the DUT.
- Ensure there is no oscillation, and gain of the measurement is constant.
- Ensure the instrument and DUT are driven in their linear range.

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## Author Information

Eric Marsan received his M.Sc degree in Microwave Engineering from Ecole Polytechnique, University of Montreal, Canada in 2003. He then contributed to a number of R&D partnerships including work on RF properties of materials, the development of early commercial radio prototypes and characterization services up to 100 GHz. Eric joined Skyworks Solutions in 2006 as a design engineer and has since worked on the development of various low noise and high linearity amplifier products on GaAs destined for the commercial market. He can be reached at: sales@skyworksinc.com.