

A New Noise Parameter Measurement Method Results in More than 100x Speed Improvement and Enhanced Measurement Accuracy

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Abstract — A new method for noise parameter measurements is introduced, with better than 100x speed improvement over traditional methods. The setup is simple and easy to configure, and the entire calibration and measurement process is very fast, making dense frequency spacing practical. The new method produces smoother data with lower scatter, and the dense frequency spacing eliminates shifts due to aliasing and makes it easier to identify the scatter and outliers.

Index Terms — microwave measurements, noise figure, noise parameters, low noise amplifiers

Introduction

Noise occurs naturally in any active device or circuit, and limits the minimum levels of useful signals. With a cell phone, for example, it can interfere with a weak signal, and interrupt a call. Therefore, it is important to design circuits to minimize the effects of noise. To do this, the noise must be quantified and measured.

The most common measure of added circuit noise is a figure-of-merit called noise figure, which quantifies the signal-to-noise degradation caused by an amplifier. While noise figure is most commonly measured in a 50-ohm environment, a device's noise figure varies with the source impedance presented to the device. This variation can be expressed in terms of noise parameters, which are essential to know when designing low-noise amplifiers using highly mismatched devices.

Noise parameters may be in different forms, including various versions of the noise correlation matrix, but all forms consist of four scalar numbers, and have the same underlying device information (similar to s-parameters versus y-parameters). A common form of the noise parameters is shown in equation 1. This is shown graphically in figure 1.

$$F = F_{min} + 4rn \frac{|\Gamma_s - \Gamma_{opt}|^2}{|1 + \Gamma_{opt}|^2 (1 - |\Gamma_s|^2)} \quad \text{Equation 1}$$

Where

- F_{min} = minimum noise figure (linear)
- Γ_{opt} = optimum source gamma (to produce F_{min})
- rn = equivalent noise resistance
- F = noise figure (linear)
- Γ_s = source gamma

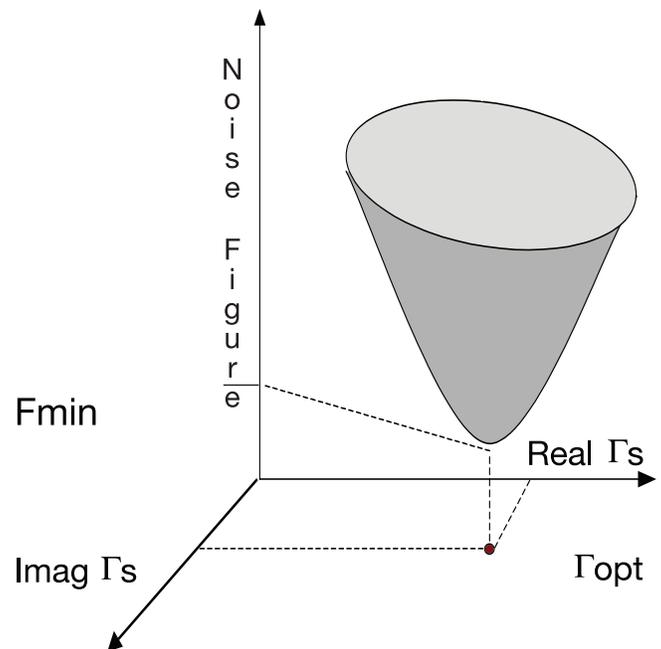


Figure 1. 3D representation of noise figure vs. source impedance.

The basic approach to noise parameter measurements is to measure the noise figure at multiple source impedance values. For each measurement, Γ_s and F are plugged into equation 1, resulting in simultaneous equations that can then be solved for the noise parameters. Four measurements give four simultaneous equations, which should be sufficient in theory to solve for the four noise parameters. However, noise measurements are sensitive to small errors, so in practice it is common to measure the noise at more than four values of source impedance, and then use a least-mean-squares algorithm to reduce the overdetermined data[1][2].



A better approach than the noise figure equation is to use the noise power equation[3], as shown in equation 2. With this, a noise power measurement with a cold noise source is separate from a measurement with a hot noise source. This allows the reflection coefficient difference between the noise source states to be taken into account rigorously. It also allows any combination of hot and cold measurements, including the “cold only” measurements. Therefore, this method is normally used in practice.

$$P = kB\{[t_{ns}+t_0(F_1-1)]G_{a1}+t_0(F_2-1)\}G_{r2} \quad \text{Equation 2}$$

Where

- P = the total measured noise power
- k = Boltzmann's constant
- B = the system bandwidth
- t_0 = 290 kelvins
- t_{ns} = temperature of the noise source in kelvins
- F_1 = the DUT noise figure (function of source impedance)
- F_2 = the receiver noise figure (function of the DUT output impedance)
- G_{a1} = the DUT available gain (function of the source impedance)
- G_{r2} = the receiver transducer gain (function of DUT output impedance)

Traditional Noise Parameter Measurements

A traditional noise parameter measurement setup is shown in figure 2. It includes a vector network analyzer (VNA) and a separate noise figure analyzer. For s-parameter measurements, the tuner is set to 50 ohms, and the two RF switches connect the device under test (DUT) to the VNA. For noise measurements, the switches connect the noise source to the DUT input and the noise receiver to the DUT output. An optional load tuner (not shown) is sometimes used when the DUT is highly reflective, to reduce sensitivity to error.

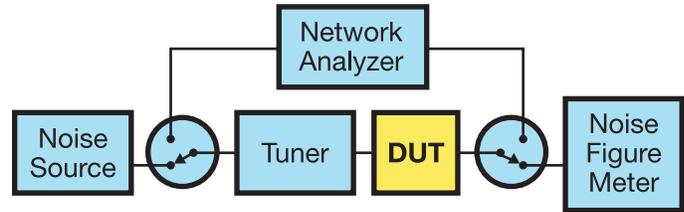


Figure 2. A traditional noise parameter measurement setup.

The tuner is pre-characterized at every frequency independently. This means that there is a unique set of tuner positions for each frequency, ensuring a good spread of source impedance points at every frequency. The tuner can be characterized separately, or as part of an in-situ system calibration. The advantage of doing it separately is that the same tuner file can be used for a long time, and then a hybrid in-situ calibration can quickly get the remaining s-parameter blocks.

The in-situ system calibration normally uses two VNA calibrations: a 2-port calibration at the DUT reference planes, and a 1-port s22 calibration at the noise source reference plane. By subtracting error terms, the 2-port s-parameters from the noise source to the DUT can then be determined. If the optional load tuner is used, then a 1-port s11 calibration at the noise receiver reference plane is also used to determine the 2-port s-parameters from the DUT to the noise receiver.

A hybrid in-situ calibration uses tuner data that is already characterized. The same VNA calibrations are still used to determine the 2-port s-parameters from the noise source to the DUT plane, which are then de-embedded to remove the tuner s-parameters. The result will be s-parameter blocks that include everything except the tuner.

After the system calibration, the traditional noise receiver calibration and DUT noise parameter measurement are both done one frequency at a time[3][4]. This is because the noise parameter extraction involves complex math that is sensitive to small errors, and the pattern of source impedance points is important to get well-conditioned data[2]. Measuring one frequency at a time solves this by allowing the impedance pattern to be selected in an optimal manner for each frequency.

One problem with this method is that the measurement time is very long, due to the large number of tuner positions that must be set and the high number of associated noise measurements. With s-parameters, it is common to



sweep 400 or more points to see details of the amplifier's performance. But measuring noise parameters with that many frequencies can take days, so it is impractical in most cases. If it is done, temperature drift can cause significant errors if the laboratory is not carefully temperature controlled. This is exacerbated by the many lengths of cables required to connect all of the instruments and switches in figure 2.

Since the noise parameter measurements tend to take a long time with the traditional approach, it is typical to only measure a sparse set of frequencies. But this makes the scatter, outliers, and cyclical-frequency errors difficult to interpret. A cyclical error is common with imperfect VNA calibrations, where system errors add at some frequencies and cancel at others. With a small number of frequencies, aliasing can shift the data set up or down if the measurements fall on high points or low points caused by cyclical errors. Smoothing techniques are often employed to make the data look better, but will not correct for shifted data.

The New Noise Parameter Measurement Method

A new noise parameter measurement method (patent pending) has been developed that typically speeds up the calibration and measurement time by over two orders of magnitude. This makes it practical to sweep a much larger frequency set.

The new method has two key features that contribute to the breakthrough speed improvement: 1) The tuner is characterized with one set of states (physical tuner positions) that are selected to give a reasonable impedance spread over the frequency band of interest; and 2) the noise power measurement is swept over the frequency range at each state, so that the tuner only moves to each position once. This takes advantage of the fast sweep capability of modern instruments, as well as saving time by minimizing tuner movement.

Since one set of tuner states is used across the entire frequency band, the impedance pattern may not be as ideal as that used with the traditional method. However, one can compensate for this by using more impedance states, and the resulting measurement quality and repeatability indicates well-conditioned data.

The new method is implemented using a new VNA that includes a built-in noise receiver, simplifying the

measurement block diagram as shown in figure 3. This arrangement reduces the number of cables and connections, helping to stabilize the setup. Because of the fast measurement time and simpler setup, temperature drift is no longer a significant factor in system errors. A photo of the new setup is shown in figure 4.

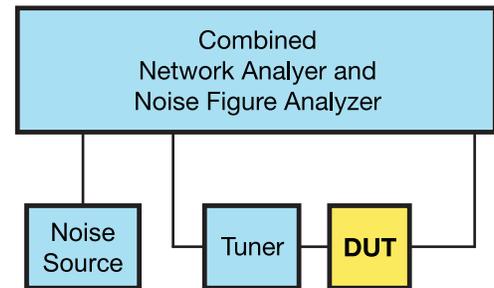


Figure 3. Noise parameter setup used with new measurement method.



Figure 4. Photo of the new setup with the coaxial DUT.

The new method may be done in multiple frequency bands if the tuner uses different mismatch probes for different frequency ranges. Two frequency bands were used to produce the data shown here, as the tuner was a Maury model MT982EU30, with a low frequency probe covering 0.8 to 2.8 GHz, and a high frequency probe covering 2.8 to 8.0 GHz. The VNA with a noise receiver was an Agilent N5242A PNA-X network analyzer. The measurement was done with Maury noise parameter software running in the PNA-X itself. Alternatively, it could have been run on a Windows-based PC.

The tuner-state selection for a mechanical tuner should use carriage positions that are non-uniformly spaced. Otherwise, the impedance points might overlay or alias at



some frequencies and produce poorly conditioned data. An example of this problem is shown in figure 5. Figure 6 shows a typical impedance pattern used with the new

method at the low, middle and high end of the band for tuner states chosen with logarithmic spacing along the line.

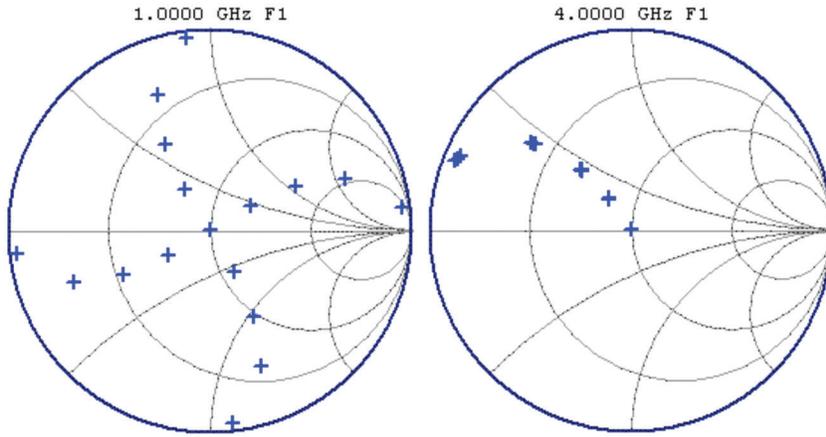


Figure 5. Example of uniform spacing of tuner states, with aliased results shown at 4 GHz.

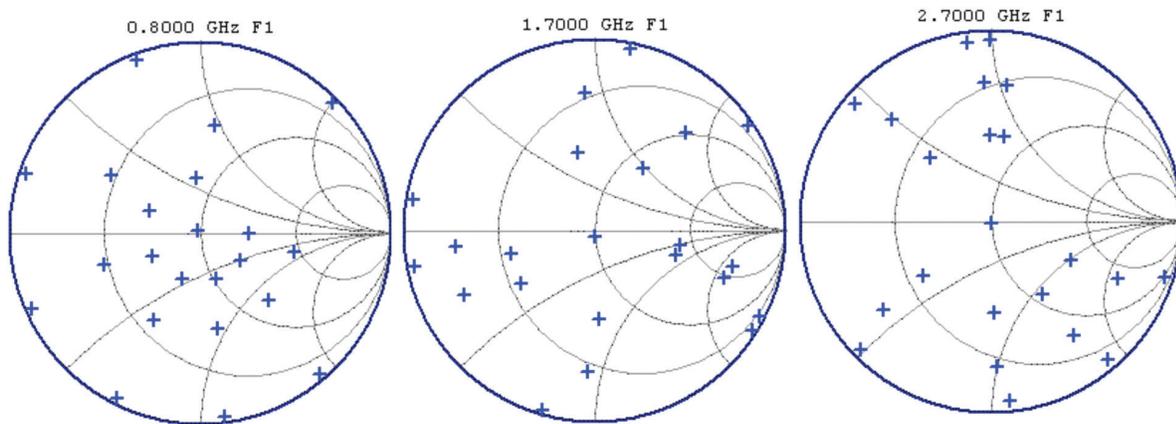


Figure 6. Example of tuner states of new method.



Comparison of the Two Methods

To compare the new method with the traditional method, a microwave FET was measured with both methods from 0.8 to 8 GHz, with a step frequency of 0.1 GHz, resulting in 73 test frequencies. Note that this is a much larger number of frequencies than is typically used with the traditional method. The FET was permanently mounted in a 3.5mm fixture with built-in bias tees to make a stable comparison, and the measurement reference planes were at the coaxial connectors. The fixture is shown in the setup of the new method in figure 4.

Figure 7 shows the measured data from the traditional method with 73 frequencies, and figure 7a shows a subset of the same data with only 15 frequencies which is more typical of that method. Figure 8 on page 6 shows the measured data from the new method with 73 frequencies. No smoothing is applied in any case. A time comparison is shown on page 6 in table 1.

Figure 7a (15 points taken from the data in figure 7), clearly shows that the Fmin readings appear to be shifted,

and the data appears smooth, but in reference to figure 7, we can see that it is just an alias of the true measured response. Figure 8 on page 6 shows the same DUT as figure 7, but the improved method reduces errors, and we can see that the data of the new method is truly smoother.

The data shows the major advantages of the new method: 1) the total measurement time is over two orders of magnitude faster for the examples described here; and 2) the data is much smoother and has lower scatter. The larger scatter in the Fmin data shown using the traditional method is often not observed by RF designers, since many fewer frequency points are typically measured. The smaller number of frequency points may produce data that appears smooth, but the data will vary around the true value shown by the new high-frequency-density method, as shown by Figure 7a. This also means that smoothing techniques may produce offsets with the small number of points but become more meaningful with a larger number of points.

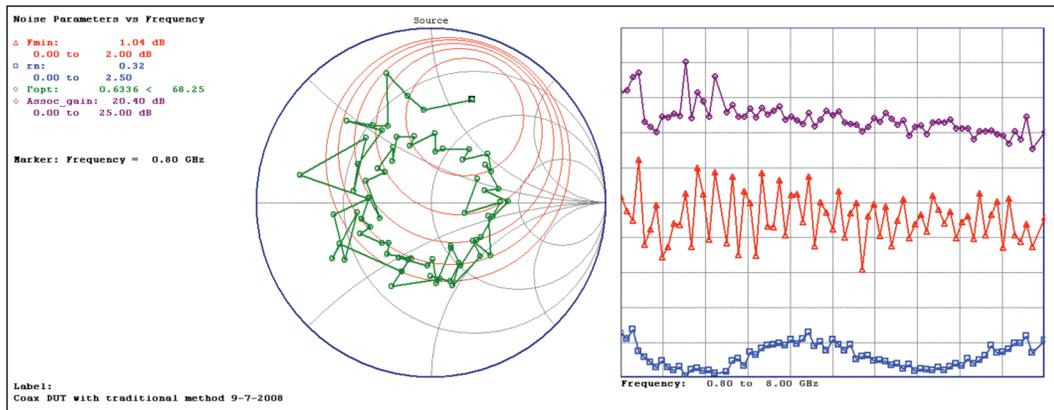


Figure 7. Measured noise parameter data with 73 frequencies using the traditional method showing Fmin (red), rn (blue), and Associated Gain (purple)

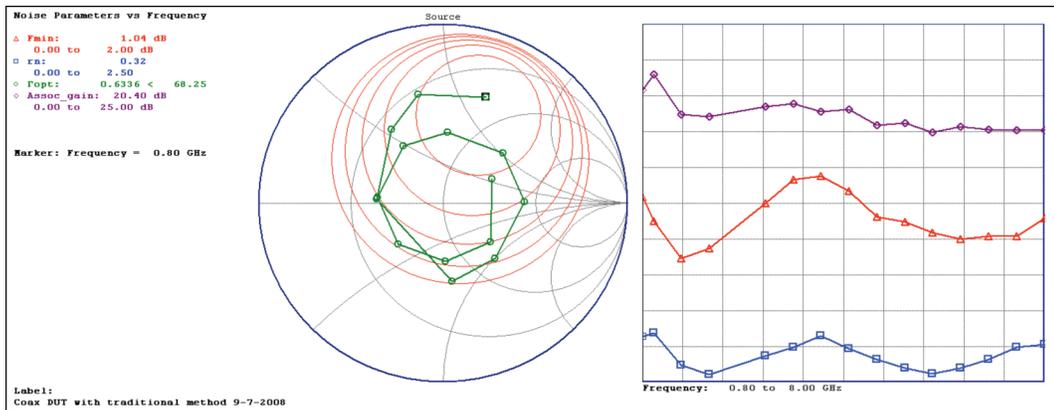


Figure 7a. 15-frequency subset of the measured noise parameter data using the traditional method showing Fmin (red), rn (blue), and Associated Gain (purple).

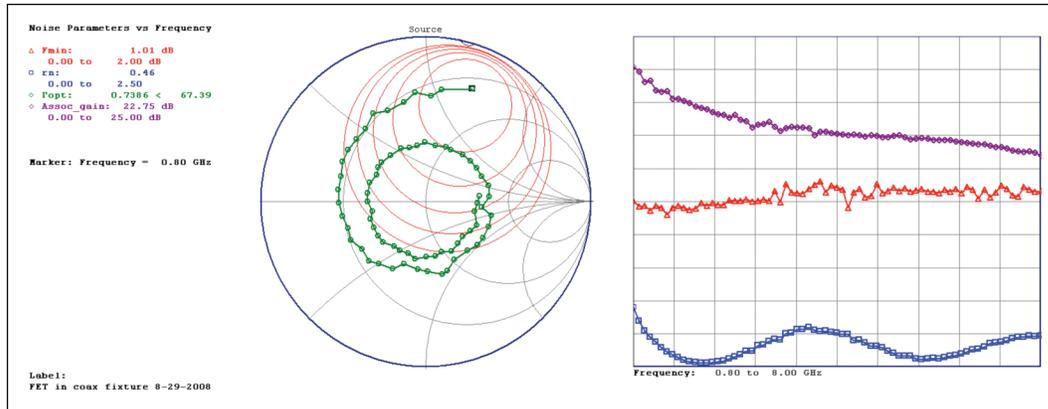


Figure 8. Measured noise parameter data using the new method, no smoothing applied, showing Fmin (red), rn (blue), and Associated Gain (purple).

	Traditional method measurement time, 73 frequencies	New method measurement time, 73 frequencies	Traditional method measurement time, 401 frequencies *	New method measurement time, 401 frequencies
System Cal	25 hrs, 29 min	1 min, 56 seconds	139 hrs, 59 min	3 min, 12 seconds
Noise Receiver Cal	2 hrs, 24 min	2 min, 56 seconds	13 hrs, 13 min	10 min, 44 seconds
DUT Measurement	2 hrs, 22 min	3 min, 15 seconds	13 hrs, 2 min	10 min, 54 seconds
Total Time excluding connections	30 hrs, 15 min	8 min, 7 seconds	166 hrs, 14 min	24 min, 50 seconds
Time Ratio		224X		400X

* Estimated, based on time to measure per frequency

Table 1. Measurement time comparison of the new method vs. the traditional method.

The speed of the new method also improves the typical calibration methodology. Because of the time required, the hybrid in-situ calibration is often used with the traditional method, because then the same tuner file can be used over and over, saving time. However, that introduces an additional VNA calibration and a number of extra connections, which increases the overall error level. With the new method, there is no need to compromise – a full in-situ calibration including the tuner characterization can be done every time to minimize the errors.

Finally, using one instrument with the VNA and noise receiver functions combined simplifies the setup and eliminates many cables, adapters, and connections that must be held stable. This provides much better system integrity and stability, which also contributes to significantly better and more consistent data. It also requires less operator skill to get good data.



Conclusions

The new noise parameter measurement method provides two orders of magnitude speed improvement. It also produces data that is smoother and has less scatter than the traditional method. The fast measurement speed eliminates temperature drift, and using a VNA with an internal noise receiver simplifies the setup and makes it much more stable and consistent.

The much higher speed makes it practical to always do a full in-situ calibration to minimize errors, and to measure more frequencies to get a better view of scatter and cyclical errors, and to be able to use smoothing with more confidence. The higher frequency density also enhances accuracy by reducing shifts due to aliasing.

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