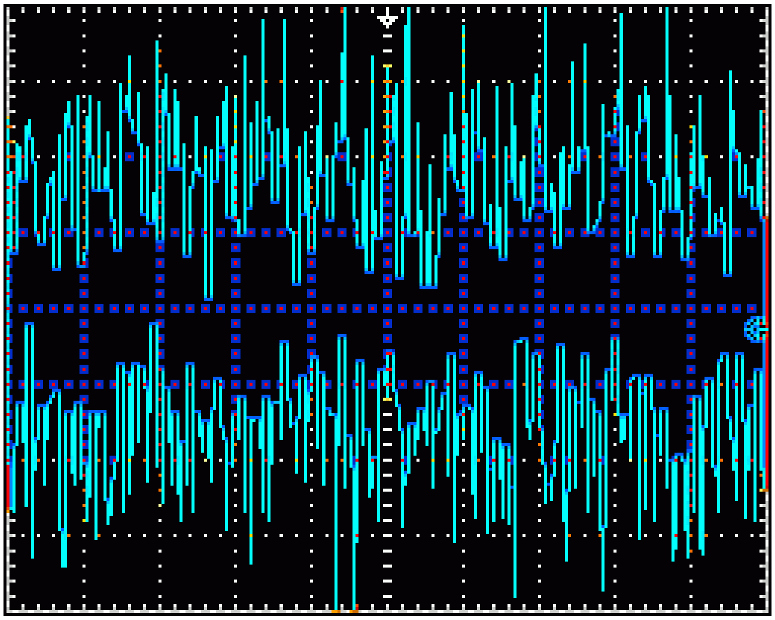
Noise Tutorial
Part VI ~ Noise Measurements with a Spectrum Analyzer



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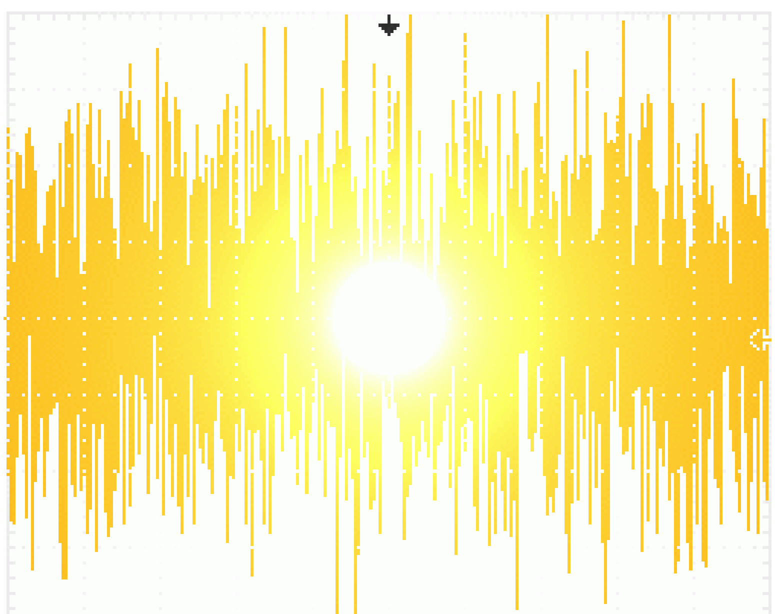

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Noise Tutorial VI ~ Noise Measurements with a Spectrum Analyzer

Abstract: With the exception of some solar radio bursts, the extraterrestrial emissions received on Earth's surface are very weak. Noise places a limit on the minimum detection capabilities of a radio telescope and may mask or corrupt these weak emissions. An understanding of noise and its measurement will help observers minimize its effects. This paper is a tutorial and includes six parts.

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6-1. Noise measurements with a spectrum analyzer

Most spectrum analyzers can be used to measure the noise factor of active devices (for example, amplifiers and mixers). Modern analyzers designed to measure digital modulation schemes associated with mobile wireless systems have provisions to measure noise and noise-like signals (figure 6-1). Spectrum analyzer accuracy may not be as good as purpose-built noise figure meters but the spectrum analyzer is more than adequate in ordinary radio work. First, we will discuss spectrum analyzer sensitivity in terms of its noise floor and then go into actual noise measurements. A low noise floor indicates good sensitivity and is necessary for measuring the noise factor of an amplifier.

Fig. 6-1 ~ Spectrum analyzers. Left: Agilient N9342C Handheld Spectrum Analyzer (HSA) weighs 3.2 kg. This high-performance instrument has many built-in features that simplify noise measurements including a power spectral density function, noise markers and a built-in low noise preamplifier. However, even with these features, additional gain from an external low noise amplifier still is needed to boost the HSA’s sensitivity for noise factor measurements of external devices. Right: Hewlett-Packard 8590A is a high-performance instrument marketed in the mid-1980s as “Portable”. It weighs 13.5 kg, and compared to the previous generation of spectrum analyzers it was very portable.

Spectrum analyzer specifications include a parameter called *displayed average noise level* (DANL), which is the amplitude of the analyzer’s noise floor over a given frequency range with the input terminated in 50 ohms and the internal attenuator set to 0 dB. DANL values are normalized to a bandwidth of 1 Hz, so it is necessary to compensate for the resolution bandwidth (RBW) setting of the analyzer. The change in displayed noise level $\Delta Noise$ is related to the ratio of the old and new RBW by

$$\Delta Noise = 10\log\left(\frac{RBW_{New}}{RBW_{Old}}\right)\text{dB} \qquad (6\text{-}1)$$

where RBW_{New} and RBW_{Old} are in the same frequency units, usually Hz. When RBW_{Old} is 1 Hz, equation (6-1) can be reduced to a bandwidth factor (BF)

$$BF = -10\log\left(RBW\right)\text{dB} \qquad (6\text{-}2)$$

For example, if a noise measurement is made in dBm at a resolution bandwidth of 10 kHz, the displayed noise power would need to be lowered by 40 dB [$BF = -10\log(RBW) = -10\log(10^4) = -40$ dB] for the equivalent noise in a bandwidth of 1 Hz.

DANL measurements often are at the narrowest RBW setting, but analyzer datasheets usually specify the DANL measurement conditions. The easiest way to measure a spectrum analyzer's noise floor is to place a noise marker at the desired frequency. Modern analyzers internally compensate and display the noise marker value in dBm/Hz for any RBW setting and also take into account the difference in RBW filter bandwidth compared to an ideal noise filter.

A noise marker uses an rms (root mean square) detector with averaging performed on a logarithmic scale, called log power averaging. The log power averaging lowers the displayed noise by 2.51 dB (if root-mean-square, rms, averaging is used, the 2.51 dB factor is not used the calculation). Some analyzers automatically select the right settings for a noise marker. However, depending on the measurement, it may be necessary to manually set some parameters. For example, the input attenuator in most spectrum analyzers has to be manually set to 0 dB when making DANL measurements. Trace averaging also needs to be set and for noise measurements usually is at least 40 to 50 sweeps. Trace averaging is used to reduce jitter in the displayed marker value. The sweep times in older (analog) spectrum analyzers are much longer than modern analyzers so noise measurements with trace averaging require patience.

For an input noise temperature T_0, the DANL in terms of spectrum analyzer noise factor NF_{SA} is given by

DANL dBm/Hz = –174 dBm/Hz + NF_{SA} – 2.51 dB (6-3)

If we are interested in measuring the spectrum analyzer noise factor, solve for NF_{SA}, or

NF_{SA} = DANL dBm/Hz +174 dBm/Hz + 2.51 dB (6-4)

As an example, we will measure the noise factor of two spectrum analyzers, an older (1986) model and a much newer (2013) HSA. The newer model is equipped with an internal preamplifier that significantly lowers the analyzer noise factor, so comparative measurements will be made with the preamplifier on and off.

Example 6-1 ~ HP8590A spectrum analyzer: The setup is simple (figure 6-2). The spectrum analyzer display shows the noise produced by the 50 ohm input termination at T_0 combined with the noise produced by the spectrum analyzer itself (figure 6-3).

Fig. 6-2 ~ Hewlett-Packard 8590A spectrum analyzer terminated in 50 ohms (just right of center) to measure the spectrum analyzer's noise floor and noise factor.

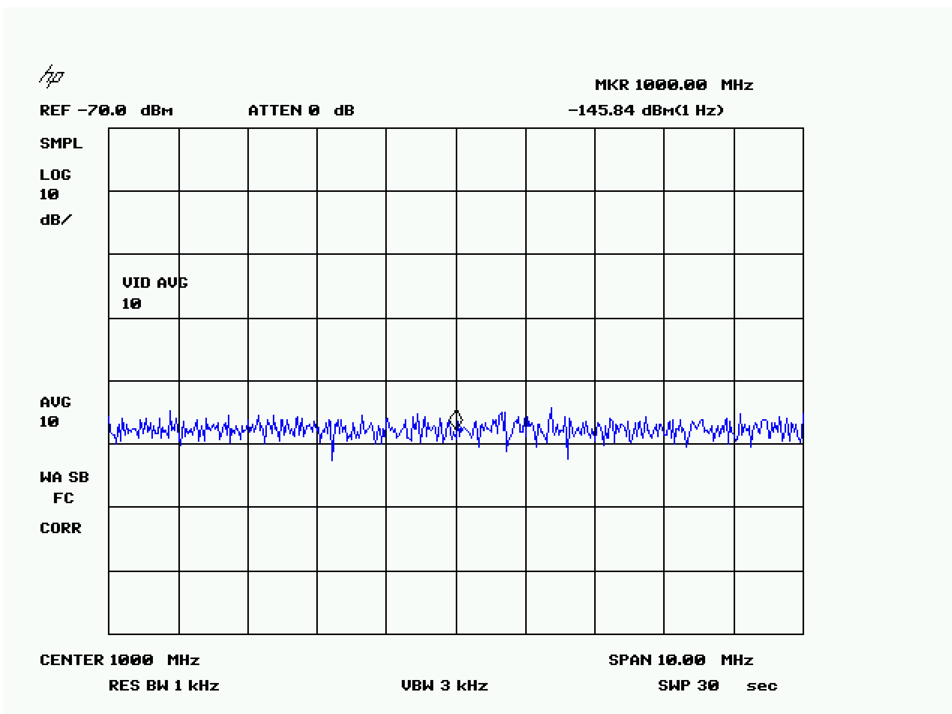

Fig. 6-3 ~ Spectrum analyzer display over a 10 MHz frequency band centered on 1 GHz. The reference level is set to –70 dBm with a noise marker set to the center frequency (diamond shape partially hidden by the noise spectra at center). The noise trace can be seen at a level of approximately -118 dBm with the 1 kHz resolution bandwidth setting. The noise marker value seen on the upper-right indicates the DANL of –145.84 dBm/Hz at 1 GHz. The vertical scale is 10 dB/division.

The noise factor of this spectrum analyzer at 1 GHz is

NF_{SA} = –145.84 dBm/Hz +174 dBm/Hz + 2.51 dB = –145.84 dBm/Hz + 174 dBm/Hz + 2.51 dB = 30.7 dB (linear ratio 1166.8)

The noise marker in this example indicates the noise power density and it was only necessary to compensate for log power averaging by adding 2.51 dB to the difference between the measured level and the theoretical noise floor of −174 dBm/Hz. An alternate calculation provides comparable results (figure 6-4). First, the measured noise level in dBm is adjusted for the resolution bandwidth (RBW), in this case 1 kHz, by lowering the measured level by $10\log(RBW)$ dB. Next, it is necessary to compensate for the RBW filter's noise bandwidth. The amount of compensation depends on the type of filter in the spectrum analyzer and for the 8590A and similar HP analog spectrum analyzers is 0.52 dB [Agilent 1303, HP 8590A].

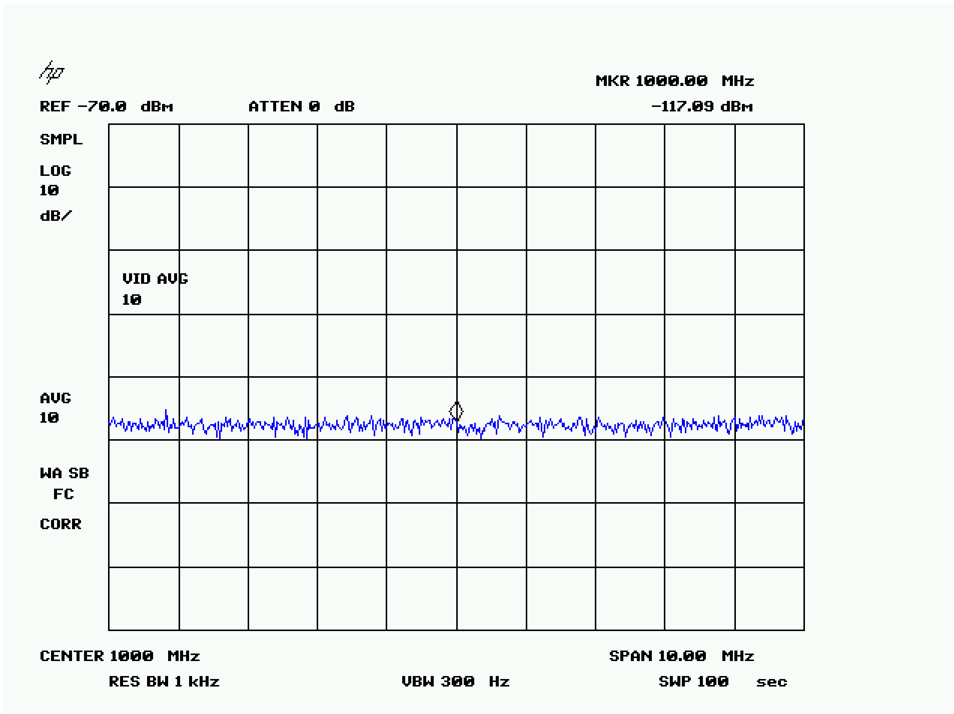

Fig. 6-4 ~ Spectrum analyzer is setup the same as the previous example but in this case a normal marker is used. The marker value seen on the upper-right indicates –117.09 dBm at 1 GHz.

The noise factor for this measurement is

$$NF_{SA} = -117.09 \text{ dBm } -10\log\left(10^3\right) \text{dB} + 0.52 \text{ dB} + 174 \text{ dBm/Hz} + 2.51 \text{ dB} = 29.94 \text{ dB}$$

which is within 0.8 dB of the previous measurement. This difference can be the result of many small factors and not necessarily the different marker type.

<u>Example 6-2 ~ N9342C spectrum analyzer (preamplifier off and on)</u>: The same physical setup is used in this example (spectrum analyzer input terminated with 50 ohms). The internal preamplifier is set to off, the trace captured, preamplifier set to on and the trace captured again (figure 6-5). With the internal preamplifier off, the noise factor will be that of the spectrum analyzer alone, and with the preamplifier on, the noise factor will be a composite value that includes the spectrum analyzer and its internal preamplifier.

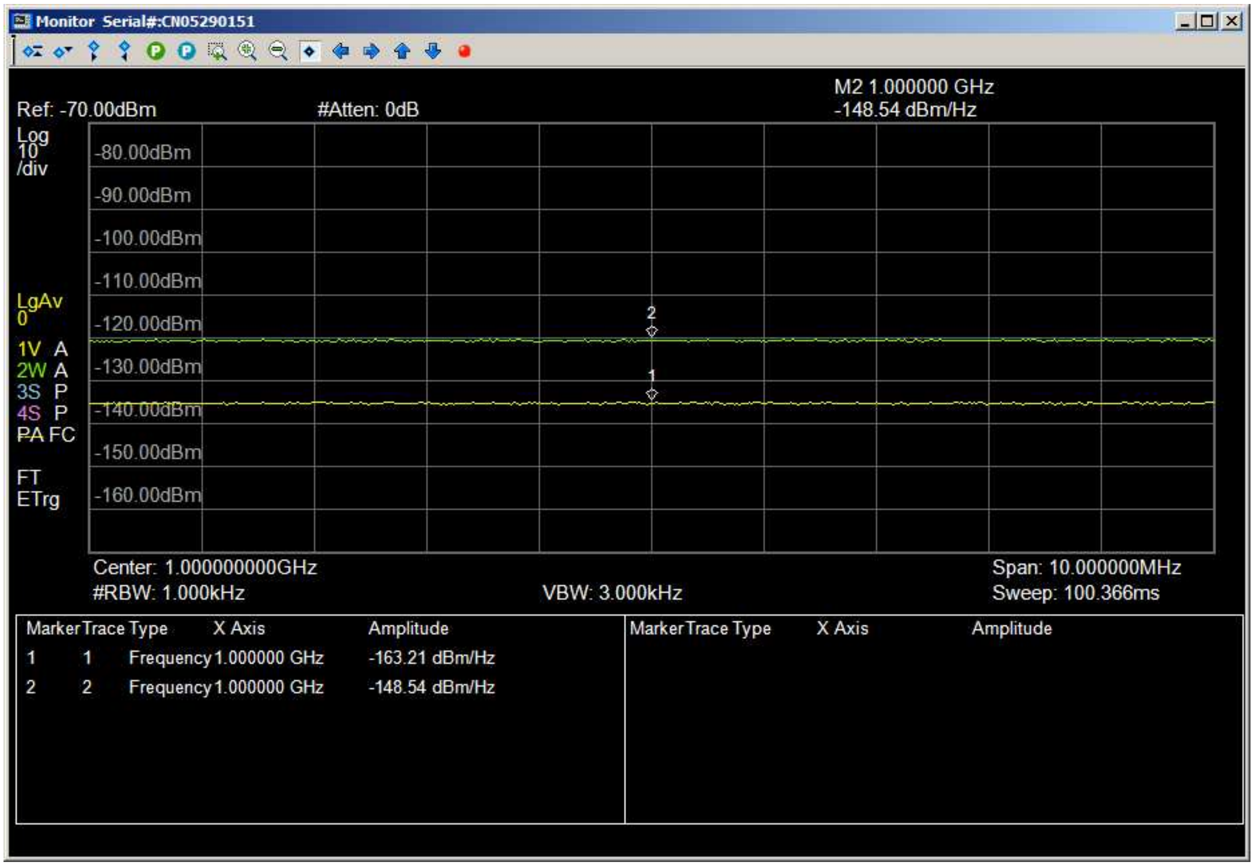

Fig. 6-5 ~ The spectrum analyzer display has been setup to show the traces in the upper part of the window and marker table below. The green (upper) trace with marker 2 shows the spectrum analyzer noise with the preamplifier turned off. The yellow trace with marker 1 shows the noise with the preamplifier turned on.

The analyzer noise factor with preamplifier turned off is

NF_{SA} = –148.54 dBm/Hz + 174 dBm/Hz + 2.51 dB = 28.0 dB (linear ratio 626.6)

With the preamplifier turned on, the composite noise factor is

$NF_{Composite}$ = –163.21 dBm/Hz + 174 dBm/Hz + 2.51 dB = 13.3 dB (linear ratio 21.38)

These calculations show the internal preamplifier significantly reduces the noise floor and, consequently, the noise factor. The preamplifier in the N9342C has 25 dB gain (linear ratio of 316.23), providing considerable amplification without adding a lot of noise to the analyzer.

The noise factor of the preamplifier, by itself, can be determined from the equations for cascaded amplifiers given in Part III. Solving for the noise factor of the first amplifier in the cascade (in this case, the internal preamplifier) where $NF_{Cascade} = NF_{Sys}$, $NF_2 = NF_{SA}$, $NF_1 = NF_{Preamp}$, and $G_1 = G_{Preamp}$, gives

$$NF_{Preamp} = NF_{Sys} - \frac{(NF_{SA} - 1)}{G_{Preamp}} = 21.38 - \frac{(626.61 - 1)}{316.23} = 19.40 \rightarrow 12.9 \text{ dB}$$

In the above measurements, the analyzer's internal attenuator was set to zero. This was necessary to increase the sensitivity. An analyzer is designed for unity gain so that it correctly displays the input signal levels. Adding attenuation or gain changes the transfer function from the input to the display. If the input attenuator is set to anything but zero, the analyzer must increase its internal gain (usually in its intermediate frequency, IF, stages) to maintain a correctly displayed level. However, this raises the noise floor an equivalent amount. The concept is similar for the internal preamplifier except that the spectrum analyzer reduces its internal gain, thus lowering the noise floor. The noise floor is

$$NoiseFloor_{dBm} = DANL_{dBm} + L_{A,dB} - G_{\mathrm{Preamp},dB} \text{ dB} \qquad (6\text{-}5)$$

where

$L_{A,dB}$ Attenuator setting in dB

$G_{Preamp,dB}$ Preamplifier gain in dB

It was previously shown that the hot power of a 5 dB ENR noise source is approximately –168 dBm/Hz. The DANL of the N9342C spectrum analyzer with the preamplifier turned on and attenuator set to zero is about –163 dBm/Hz. This is 5 dB above the noise source hot power, and there is little chance the noise source output will be visible on the display. Setting the analyzer attenuator to 10 dB attenuation, increases the difference to 15 dB. It should be noted that an attenuator is necessary to prevent overloading the spectrum analyzer mixer, but it usually can be set to zero for very low power measurements.

The above discussion indicates that measuring the noise factor of external devices is slightly more involved than measuring the spectrum analyzer itself. Even with the internal preamplifier, most spectrum analyzers by themselves do not have enough sensitivity to measure the noise factor of external devices. It is necessary to use a good-quality low noise amplifier for additional gain between the device being measured and the spectrum analyzer (figure 6-6).

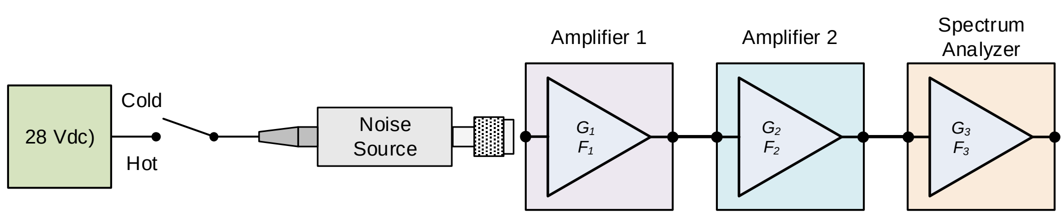

Fig. 6-6 ~ Two amplifiers are connected between the noise source and the spectrum analyzer. Amplifier 1 is the amplifier being measured and Amplifier 2 is used to provide additional gain. For best results, all interconnections should be of the best quality and lowest loss possible.

If the spectrum analyzer has a low noise preamplifier, a total of about 40 to 50 dB external gain is needed, including the amplifier being measured. Even more gain may be necessary if the analyzer does not have an internal low noise preamplifier. It should be remembered that measurements close to the analyzer's noise floor are problematic because P_{Hot} and P_{Cold} measurements are nearly the same, resulting in trying to calculate the logarithm of a number close to zero. It should be noted that external amplifiers introduce problems of their own and can increase measurement uncertainty.

Examples follow that use the Y-Factor method to measure the noise factor of two amplifiers at 1 GHz, a Mini-Circuits ZKL-2 and a Chinese amplifier marketed as a low noise amplifier and designated here as CxLNA. Attempts to measure the noise factor of one of these devices without the gain of the other failed, that is, measurement of either amplifier is not possible without the additional gain provided by the other. The ZKL-2 has a nominal gain of 30 dB and 3.45 dB noise factor and the CxLNA has a nominal gain of 17 dB and 1 dB noise factor.

<u>Example 6-3 ~ CxLNA as Amplifier 1 and ZKL-2 as Amplifier 2</u>. The noise source ENR_{dB} = 5.32 dB at 1 GHz (RFD2305). The spectrum analyzer's internal preamplifier is turned on to increase the analyzer's sensitivity. However, to maintain proper internal levels the analyzer's internal attenuator is set to auto. The Y-factor method is used in which a noise measurement is made with the noise source off (P_{Cold}) and another measurement with the noise source on (P_{Hot}). The measured noise factor is a composite value that includes the spectrum analyzer, its internal preamplifier and the two external amplifiers (figure 6-7).

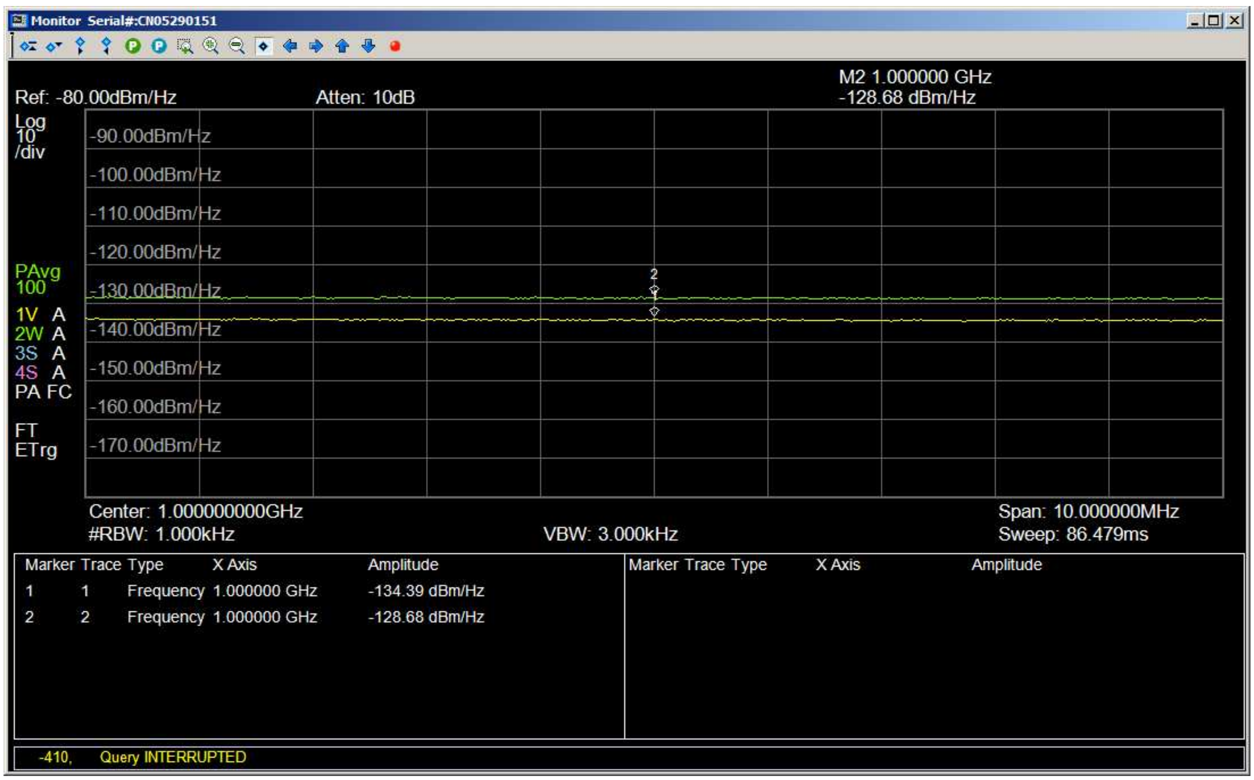

Fig. 6-7 ~ Spectrum analyzer with traces and marker table for CxLNA as Amplifier 1 and ZKL-2 as Amplifier 2. For these measurements the analyzer was placed in the power spectral density measurement mode, which sets up the proper detector and averaging protocols. The yellow (lower) trace with marker 1 shows the noise level with the noise source off (cold). The green trace with marker 2 shows the noise with the noise source on (hot). The attenuator was set to Auto resulting in 10 dB of attenuation (setting shown just above the grid to the left of center).

The following data are from the marker table:

$P_{Cold,dB}$ = –134.39 dBm/Hz

$P_{Hot,dB}$ = –128.68 dBm/Hz

and $Y_{dB} = P_{Hot,dB} - P_{Cold,dB}$ = –128.68 dBm/Hz – (–134.39 dBm/Hz) = 5.71 dB

From Eq. (4-9)

$$NF_{Composite,dB} = ENR_{dB} - 10 \cdot \log\left(10^{\frac{Y_{dB}}{10}} - 1\right) = 5.32 - 10 \cdot \log\left(10^{\frac{5.71}{10}} - 1\right) = 0.97 \text{ dB (1.25 linear ratio)}$$

The composite noise factor includes the combined effects of the spectrum analyzer and the two external amplifiers. To find the noise factor of Amplifier 1 alone it is necessary to use the calculations for cascaded amplifiers as before. In this case we assume Amplifier 2 noise factor is 3.45 dB (2.213 linear ratio). It is necessary to know the gain of the Amplifier 1. A measurement using the spectrum analyzer's tracking generator gives 17.17 dB (52.12 linear ratio) at 1 GHz. Therefore,

$$NF_{Amplifier1} = NF_{Composite} - \frac{(NF_{Amplifier2} - 1)}{G_{Amplifier1}} = 1.25 - \frac{(2.213 - 1)}{52.12} = 1.23 \rightarrow 0.89 \text{ dB}$$

The contribution of the spectrum analyzer is ignored in the calculation. Examination of the composite noise factor for a cascade of three devices shows that the noise factor of the third device (in this case the spectrum analyzer) is reduced by the factor $1/G_1G_2$, where G_1 and G_2 are the power gains of the two external amplifiers. For this example the reduction factor is about 1/60500, which reduces the spectrum analyzer's contribution to a negligible value.

Example 6-4 ~ ZKL-2 as Amplifier 1 and CxLNA as Amplifier 2. As before, noise measurement is made with the noise source off and another with the noise source on (figure 6-8).

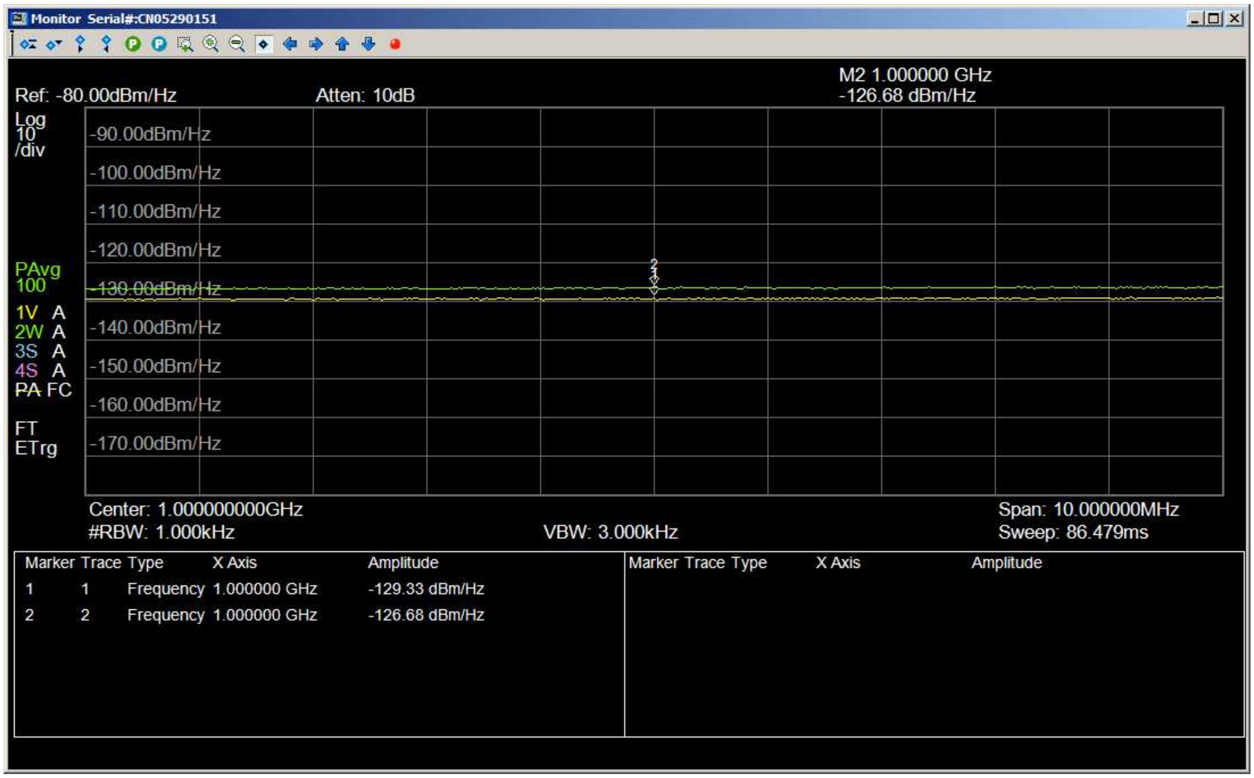

Fig. 6-8 ~ Spectrum analyzer traces and marker table with the ZKL-2 as Amplifier 1 and CxLNA as Amplifier 2. The yellow (lower) trace with marker 1 shows the noise level with the noise source off (cold). The green trace with marker 2 shows the noise with the noise source on (hot). The attenuator was automatically set to 10 dB.

The following data are from the marker table:

$P_{Cold,dB}$ = –131.85 dBm/Hz

$P_{Hot,dB}$ = –128.05 dBm/Hz

and $Y_{dB} = P_{Hot,dB} - P_{Cold,dB}$ = –128.05 dBm/Hz – (–131.85 dBm/Hz) = 3.80 dB

From Eq. (4-9)

$$NF_{Composite,dB} = ENR_{dB} - 10\cdot\log\left(10^{\frac{Y_{dB}}{10}} - 1\right) = 5.32 - 10\cdot\log\left(10^{\frac{3.80}{10}} - 1\right) = 3.92\text{ dB (2.467 linear ratio)}$$

The noise factor of Amplifier 1 (ZKL-2) alone is determined as previously described. Amplifier 2 (CxLNA) noise factor was measured as 0.89 dB (1.23 linear ratio). The measured gain of Amplifier 1 at 1 GHz is 30.66 dB (1164.13 linear ratio). Therefore,

$$NF_{Amplifier1} = NF_{Composite} - \frac{(NF_{Amplifier2} - 1)}{G_{Amplifier1}} = 2.47 - \frac{(1.23-1)}{1164.13} = 2.47 \rightarrow 3.92\text{ dB}$$

The noise factor of the ZKL-2 is found to be the same as the composite noise factor because its high gain (30+ dB) reduces the noise contributions of any down-stream devices. These calculations depend on the noise factor of Amplifier 2 (CxLNA). However, this noise factor is based on the noise factor of Amplifier 1, which was obtained as a typical value from its datasheet. It is seen that the measured noise factor of Amplifier 1 (3.92 dB) is about 0.5 dB higher than the assumed value, potentially leading to an error in the calculation. However, in this case, the high gain of Amplifier 1 reduces the error to a negligible value. There are other potential sources of error in noise factor calculations and measurement; for example, see [Agilent 1484].

For comparison with the above spectrum analyzer measurements, the noise factors of the two amplifiers were separately measured with an HP 8970B noise figure meter and HP 346A noise source (table 6-1).

Table 6-1 ~ Comparison of noise factor measurements of CxLNA and ZKL-2 amplifiers with HP 8970B noise figure meter and N9342C spectrum analyzer

Amplifier	**Gain (dB)**	**Noise factor (dB)**
Measured with 8970B noise figure meter		
CxLNA	17.10	0.85
ZKL-2	30.84	3.64
Measured with N9342C spectrum analyzer		
CxLNA	17.17	0.89
ZKL-2	30.66	3.92

6-2. References

[Agilent 1303] Spectrum and Signal Analyzer Measurements and Noise, Application Note 1303, Document No. 5966-4008E, Agilent Technologies, 2012

[Agilent 1484] Non-Zero Noise Figure after Calibration, Application Note 1484, Document No. 5989-0270EN, Agilent Technologies, Inc., 2004

[HP 8590A] HP 8590A Portable RF Spectrum Analyzer Installation Manual, Manual P/N 08590-90003, Hewlett-Packard Corp., Jan 1987

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Document information

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