# Accurate Calibration of Diode Noise Sources with PNA-X Noise Receiver

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# Change Record

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# 1. Abstract

A convenient method for characterizing the noise of active devices is performing Y factor measurements using calibrated noise diodes with known ENR (Excess Noise Ratio). In the case of precision noise sources of the type used in the laboratory, the calibration of the ENR vs. frequency is usually provided by the manufacturer in the form of a table or a computer file, with data points spaced typically by 1 GHz. The recommendation of the manufacturers is to calibrate the noise sources at defined intervals of 1-2 years to maintain the initial accuracy although, in general, if the devices are not abused and the connectors are carefully handled, the ENR of the sources is quite stable. The calibration of noise sources is usually a delicate task which can be performed only by a reduced numbers of specialized calibration laboratories. This report presents the simple yet precise method used in Yebes for the in-house calibration of the ENR using the PNA-X Vector Network Analyzer with a noise figure option (opt. 029) as well as the results obtained compared with the initial manufacturer calibrations of several sources. This method has been very useful in solving inconsistencies of different calibrations, problems detected in particular frequency ranges and failures of noise sources that otherwise were very difficult to detect.

# 2. Introduction

The primary standards used for the accurate calibration of noise sources are thermal loads used in combination with precision sensitive receivers (radiometers). An example of this type of standards, which is available at Yebes, is a liquid nitrogen (LN2) load with 7 mm interface, fabricated by Maury and usable up to 18 GHz [1], [2]. However, in practice, primary standards are seldom used in the industry for the direct calibration of noise sources since they are difficult to handle and require LN2, a source of pressurized helium gas and a very stable low-noise receiver with very low input reflection. The common practice is using a “golden” noise diode as a working secondary standard to transfer the calibration of primary standards. Keysight offers the N2002A Test Set that makes easier the calibration of noise sources in the 10 MHz - 26.5 GHz frequency range using a Noise Figure Analyzer (N8975), a reference (“golden”) noise source and a Switch Driver (11713). The N2002A contains nothing but a set of isolators and switches that improve the input reflection of the receiver to reduce the mismatch error in the calibration. Using a system like that it is in principle possible to calibrate noise sources with an accuracy slightly degraded respect to that of the “golden” standard used. However, one should be very careful when using receivers like the N8975 for source calibrations purposes since, as shown in [6] they may show some artifacts in the response which are believed to be caused by hysteresis of the YIG filter used to reject undesired mixer products of the input mixer of the heterodyne receiver.

An interesting possibility that is available in Yebes laboratory is using the PNA-X with option 029 (noise figure measurement with dedicated receiver) for calibrating the ENR of a source. This possibility is not clearly documented by Keysight, and a detailed procedure is not provided, but it appears to be considered by the manufacturer. In fact, the Noise Figure Application [3] provides an ENR trace format and the Noise Figure Uncertainty Calculator [4] can extract the parameters from the PNA-X to estimate the accuracy of the ENR measurement and it can even save the ENR results in ASCII files compatible with Noise Figure Analyzers. The advantage of the calibration with the PNA-X is that it has a very good noise receiver with continuous coverage from 10 MHz to 50 GHz and without the inconvenience of the hysteresis of YIG filters. An additional benefit is the simultaneous measurement of the reflection coefficient which can be used for real time correction of noise power measurements. In the case of the PNA-X the calibration does not require the use of a “golden” reference noise source since it can also be done with some advantage with a high-accuracy accurate power meter. The next sections describe briefly some details of this method and of the setup used for the measurement presented in this report.

# 3. Equipment

- PNA-X N5247A Vector network analyzer (10 MHz-67 GHz) with option 029 (Source-Corrected Noise Figure Measurements) (Keysight).
- N4697F Flexible Cable Set, 1.85 mm (Keysight).
- 11904S Adapter Set, 2.4 mm to 2.92 mm, DC to 40 GHz (Keysight).
- N4694A Electronic Calibration Module (ECal), 10 MHz - 67 GHz, 1.85 mm (Keysight).
- N4693-6001 Electronic Calibration Module (ECal), 10 MHz - 50 GHz, 2.4 mm (Agilent) (borrowed from other setup and used only for a comparison of the results).
- N1913A EPM Series Single-Channel Power Meter (Keysight).
- 8485A Power Sensor 50 MHz – 26.5 GHz, 3.5 mm (Keysight).
- 8487A Power Sensor 50 MHz – 50 GHz, 2.4 mm (Keysight).
- Precision female-female transitions 1.85 mm and 3.5 mm for power calibration (see figure 1).
- N8975B Noise Figure Analyzer, 10 MHz to 26.5 GHz (Keysight). (used only for driving N400X smart noise sources)


**Figure 1:** Photo of the transitions used to connect the power sensor to the port 1 of the PNA-X for power calibration. Left: a short 3.5 mm female to female PN 5061-5311 used for measurements up to 26.5 GHz. Right: metrology grade 1.85 mm female to female PN 85058-60114 (included with N4694A E-cal module)

# 4. Calibration

The PNA-X with option 029 is used in the Measurement Class marked as “Noise Figure Cold Source” for all the measurements. As said before, instead of using a “golden” noise source standard as a reference, the choice was made to calibrate the system with reference to an accurate power sensor of the thermocouple type. This is based on the fundamental equivalence between noise temperature and power expressed by the following equation [7]:

$$P = k \cdot T \cdot B \cdot G_{max}$$

were P is the emerging noise power (watts), T is the effective noise temperature (Kelvin), k the Boltzmann’s Constant (1.38 x $10^{-23}$ joules/Kelvin) and B the noise bandwidth (Hz) which can be calculated as:

$$B = \int_0^{\infty} \frac{G(f)}{G_{max}} df$$

Were G is the frequency dependant gain of the system. The ENR is defined after the effective noise temperature of a source as:

$$ENR_{dB} = 10 \log \frac{T_H - T_C}{T_0}$$

Were $T_H$, $T_C$ are the effective noise temperatures of the source in the hot (on) and cold (off) states and $T_0$ is the reference temperature of 290 K.

According to this, we can avoid using a noise standard if our system has an accurate absolute power calibration and the noise bandwidth B is well determined. This can be easily performed in the PNA-X and it is included in the automatic calibration procedure for noise measurement. The first step is the calibration of the power output at port 1 of the VNA and the determination of the equivalent noise bandwidth of the system at each frequency with a thru connection and a numerical integration. After that, complete calibration for S parameters is performed and the noise receiver is calibrated. Unfortunately more detailed information on exactly how this calibration is performed is not available from Keysight.

The thermocouple power sensors of the type used in our calibration basically measure the heat dissipated is a matched termination. The calibration factors provided by the manufacturer account for the frequency dependant microwave loss of the transmission line between the input connector and the sensing element. Due to this, the calibration curves show a quite predictable shape. Figure 2 present a graph of the calibration factor and the reflection coefficient of the two sensors used. In general the calibration of power sensors is more accurate than that of the noise sources for the same frequency range, the curves are smoother and the reflection coefficient lower.

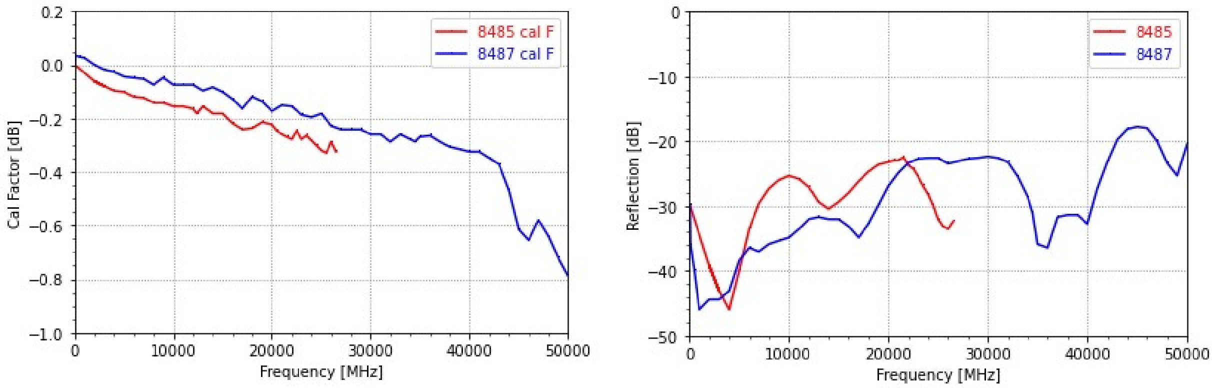



**Figure 2:** Calibration factor and reflection coefficient of the two thermocouple power sensors used for the calibration of the PNA-X for ENR measurements.

One of the weak points of the method used is that the E-cal module used and the cables and connectors are either 1.85 mm or 2.92 mm (using adapters and a custom calibration of the E-cal module). However, in most cases, the noise sources measured and the power sensors used are either 2.4 mm (to 50 GHz) or 3.5 mm (to 18 and 26.5 GHz). These connectors are compatible but not totally equivalent, and the discontinuity in the interface appears to have a measurable effect in the reflection coefficient of the sources but not much in the ENR.

# 5. Hints for the measurements

- The equipment should be warmed up for several hours before calibration and measurement.
- The ambient temperature of the environment should be kept very stable and preferably at a temperature close to 23ºC.
- The calibration and the measurement should be done one just after the other. A measurement of two or three noise sources in a row with the same calibration is admissible if done fast, carefully and efficiently. The calibration quality can be degraded quickly by the drift of the equipment.
- Have all the equipment ready (transitions, sources, cables…) before starting, and do not take breaks during all the process.
- Other important source of error is the change in cable loss and phase by movement. Try to minimize cable movement between calibration and measurement.
- The +28 V supply from the PNA-X to the noise source is always on by default and its control is not easily accessible from the instrument panel. Keep the source disconnected until the measurement to avoid excessive heating. Use the BNC connector to switch it on and off.
- Use a frequency list with the frequencies strictly needed for the calibration (0.1, 1, 2, 3… GHz). This will speed up testing and minimize drift errors. Take into account than the minimum calibrated frequency of the power sensors is 50 MHz (not 10 MHz).
- Set the noise bandwidth to 4 MHz and the S-parameter bandwidth to 100 Hz.
- Use 200 averages for the noise measurement (typically).
- Set the measurement mode (in calibration) to “Scalar Noise Figure”. This avoids the measurement presenting different input impedances to a 2-port DUT which it is not useful for a measurement of a 1-port (noise source). The calibration of the receiver with different impedances to extract its noise parameters is still performed,

- For the power calibration of port 1, set the desired accuracy to 0.001 dB and the power level to 0 dBm (if maximum frequency is 26.5 GHz) or -4 dBm (if maximum frequency is 50 GHz).
- Do not forget to select the adequate calibration table for the power sensor used.
- For the power calibration, it is necessary to use a female-female adapter. The loss of this adapter is calibrated in the process, but it is convenient to use a high quality low loss part.
- Take a single sweep and read the measured data when the instrument is in hold mode.
- Save the ENR file data using the software of [3] (minimize the NA window and run the software directly in windows).
- If the reflection coefficient in "on" and "off" states is needed, take the data from an S-parameters window and save the results.
- The utility [3] saves the reflection coefficient in the ENR file. However, it does it only in the "on" state. Besides, the phase data saved is incorrect.
- Calibrations of sources with low ENR values (ENR<5 dB) are affected by higher measurement errors due to the noise floor of the PNA-X receiver. In the case of noise sources of high ENR used with an additional attenuator it is better to calibrate independently the noise source ENR and the loss of the attenuator to obtain better accuracy.

# 6. Measurements

Figure 3 shows an example of the calibration of a 50 GHz coaxial noise source compared with the original data from the manufacturer. The estimated errors are presented by the corresponding light color fringes. From the comparison is clear that the values agree quite well in general, although there are some discrepancies beyond the estimated measurement error in the 41-44 GHz region. However, although this argument may not appear to be too scientific, the smoothness of the curve obtained with the PNA-X is clearly superior, and the discrepancy mentioned before is located in a region of the original calibration curve where there is an anomalous sharp peak which does not appear to be real. The smoothness and cleanliness of the PNA-X curve is a good sign of the efficiency of the algorithm used by the PNA-X to deal with the effect of the reflections in the system.

Appendix I presents the results of the calibration of all the coaxial noise sources available in the Yebes laboratory.

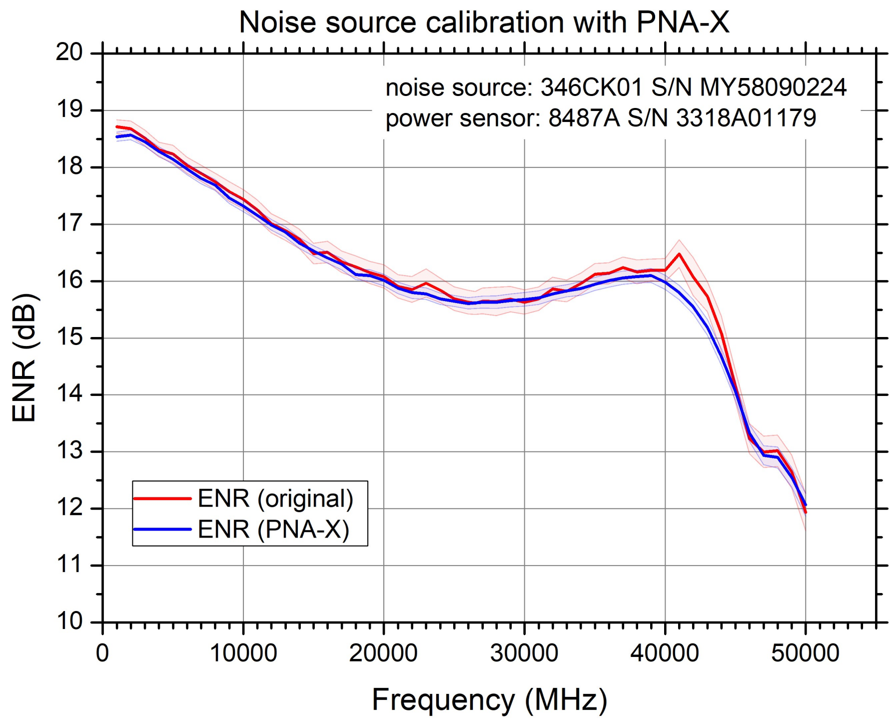



**Figure 3:** Comparison of the ENR measurement obtained with the PNA-X and the original data provided by the manufacturer.

# 7. References

[1] Pastori, W. E., "Applications of the Maury Noise Calibration Systems," Application Note 5C-028, Maury Microwave Corporation, April 2020.

[2] Noise Calibration Systems and Accessories Data Sheet 4N-062, March 2018.

[3] Keysight Technologies, High-Accuracy Noise Figure Measurements Using the PNA-X Series Network Analyzer, Application Note AN1408-20, 2014.

[3] PNA-X Noise Figure Uncertainty Calculator, version A.02.01.25, 2018-02-14.

[4] Noise Source Calibration: Using the Agilent N8975A Noise Figure Analyzer and the N2002A Noise Source Test Set, Keysight product note, literature number 5988-7229EN, 2007.

[5] N2002A Noise Source Test Set, Keysight product overview, literature number 5988-7228EN, 2007

[6] J. D. Gallego, R. Amils, C. Diez González, I. López, I. Malo, "Using Keysight PNA-X and NFA Noise Receivers for Noise Temperature Measurements with Cryogenic Variable Temperature Loads", CDT Technical Report 2019-17. https://icts-yebes.oan.es/reports/doc/IT-CDT-2017-17.pdf

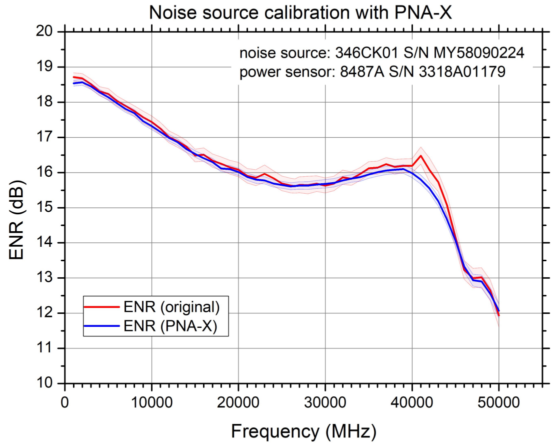
[7] Fundamentals of RF and Microwave Noise Figure Measurements, Agilent Application Note 57-1, literature number 5952-8255E, 2006.

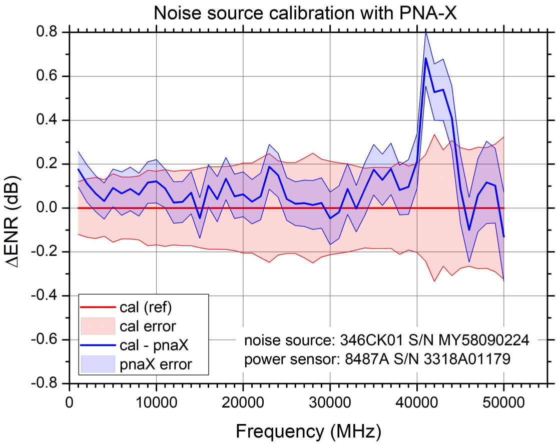
# 8. Appendix I: Measurements

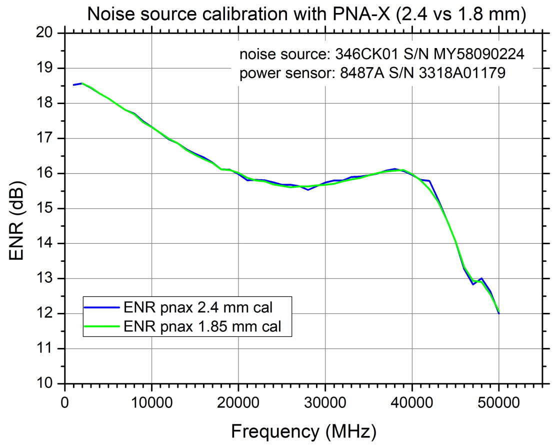
## 346 K01 Noise Sources

20/10/2020 BW= 4 MHz, AVG=200, 1.85 or 2.4 mm cal, Power Meter cal, 50 MHz-50 GHz

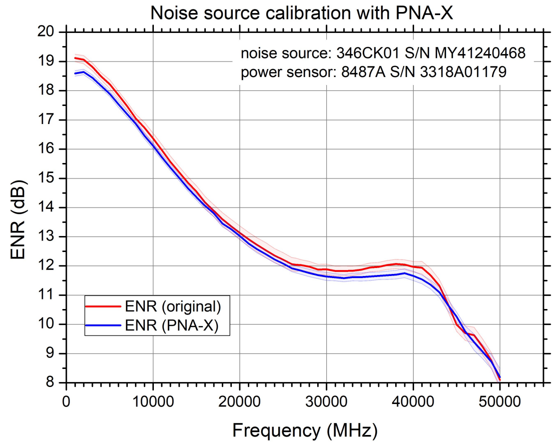
**New source (for Keysigh 8975B)**

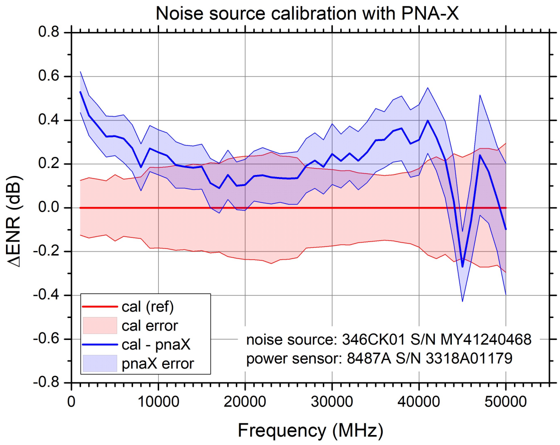


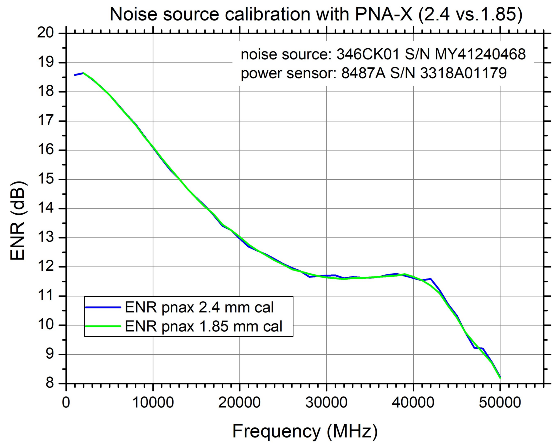



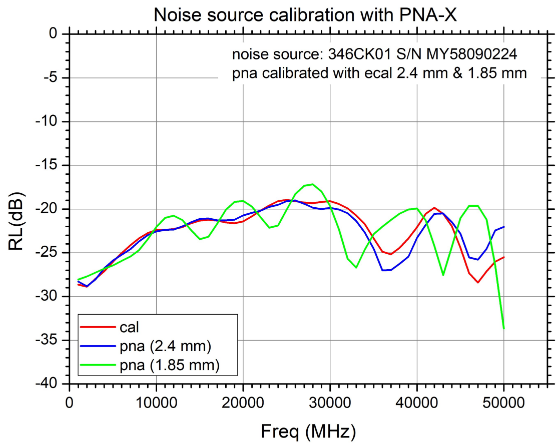

**Source SYS 1020-1 (for Agilent 8970B)**



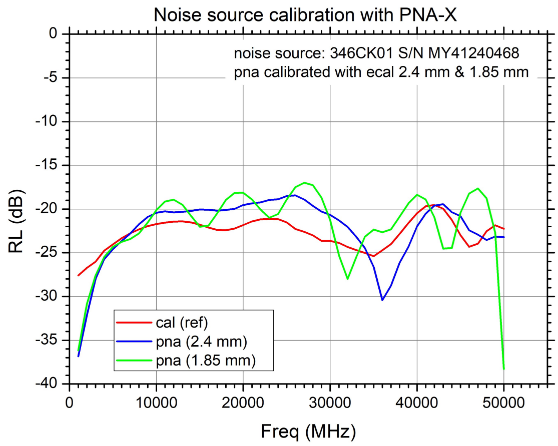



**New source (for Keysigh 8975B)**




**Source SYS 1020-1 (for Agilent 8970B)**



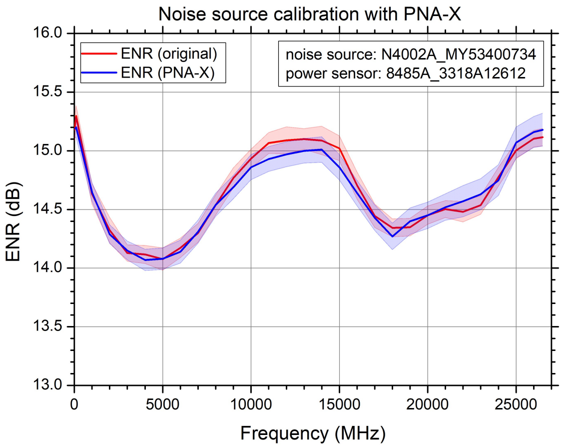

## Notes on 346K01 Noise Sources

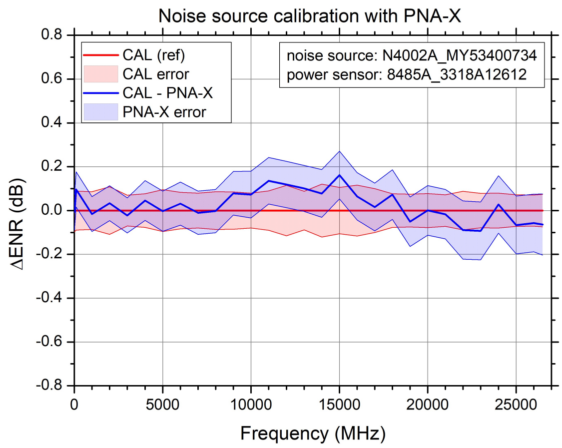
- PNA-X, cables and calibration module have 1.85 mm connectors while the noise sources, attenuator and power sensor have 2.4 mm. The interface between 2.4 mm and 1.85 mm should have a discontinuity effect which manifests in differences in the reflection coefficient measured.
- The errors in the ENR measurements were determined using Agilent software (Agilent Noise Figure Uncertainty Calculator ver. A.02.01.25).
- The values of the reflection coefficient are shown for the noise sources ON.
- If the PNA-X is calibrated with a 2.4 mm ecal module (but keeping the 1.85 mm cables) the measured reflection is closer to the values in the original calibration table, however the ENR measured shows some additional small ripples. The best quality of the ENR seems to be obtained with the calibration with the 1.85 mm ecal module.

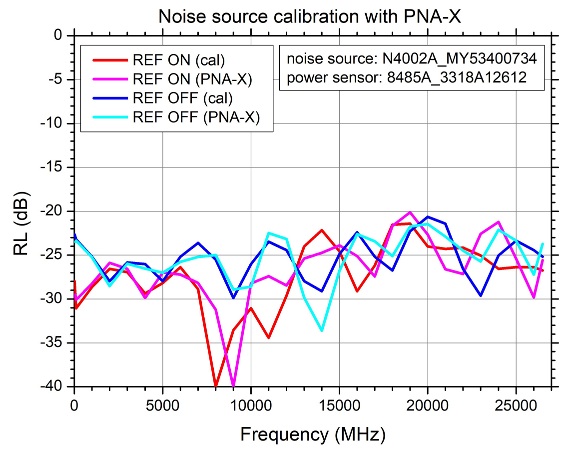
# N4002 Noise Sources

29/10/2020 BW= 4 MHz, AVG=200, 2.92 mm cal, Power Meter cal, 50 MHz-26.5 GHz

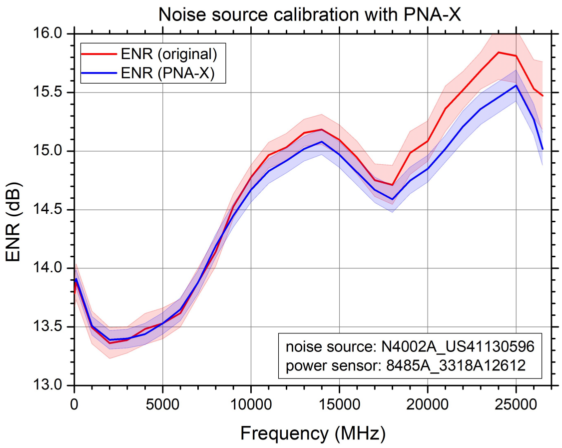
**New source (for Keysigh 8975B)**

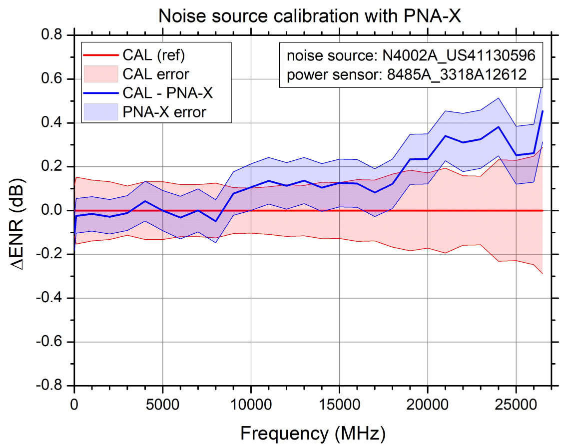


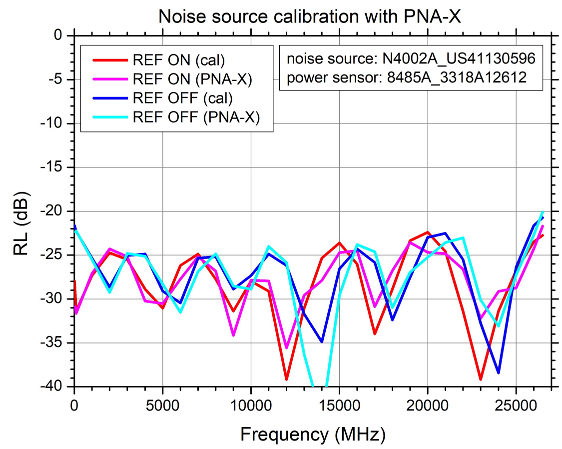




**Source SYS 1020-3 (for Agilent 8975A)**



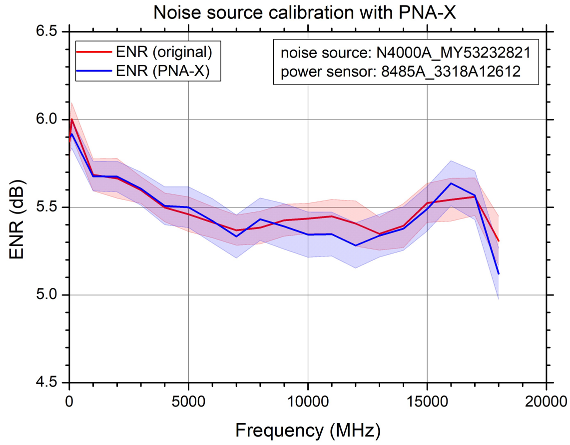



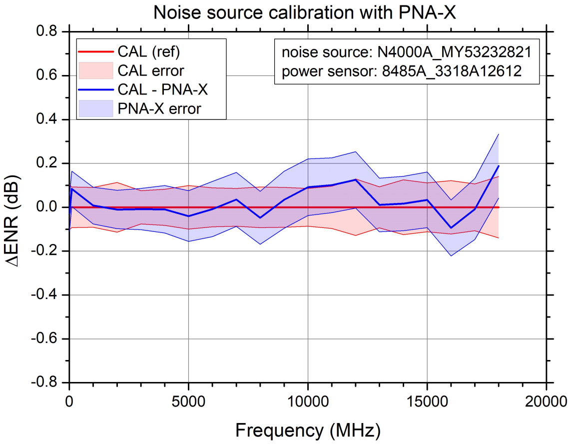



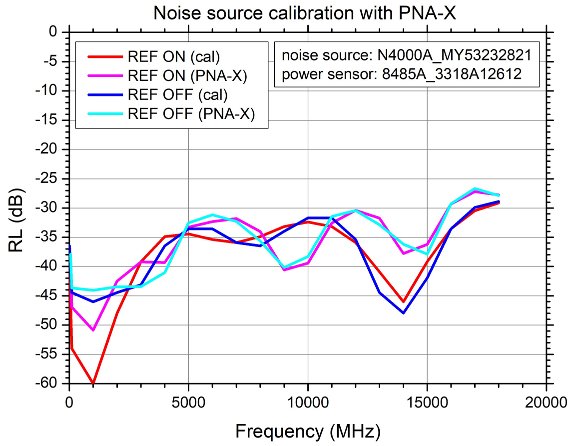
## N4000 Noise Sources

29/10/2020 BW= 4 MHz, AVG=200, 2.92 mm cal, Power Meter cal, 50 MHz-26.5 GHz

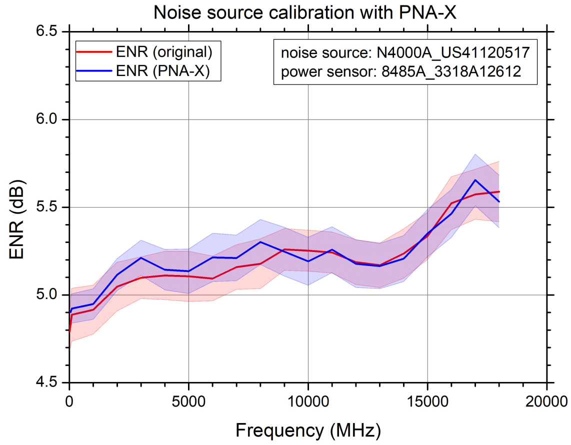
**New source (for Keysigh 8975B)**

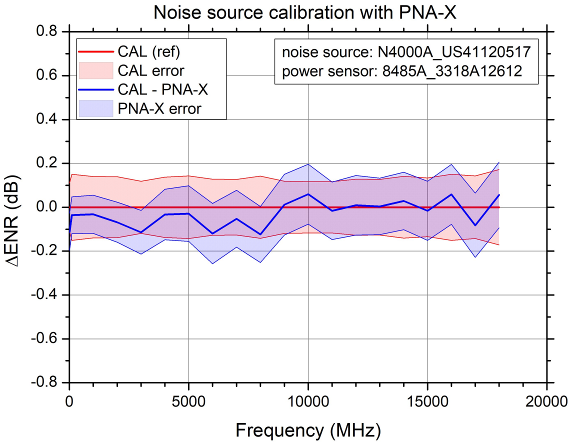


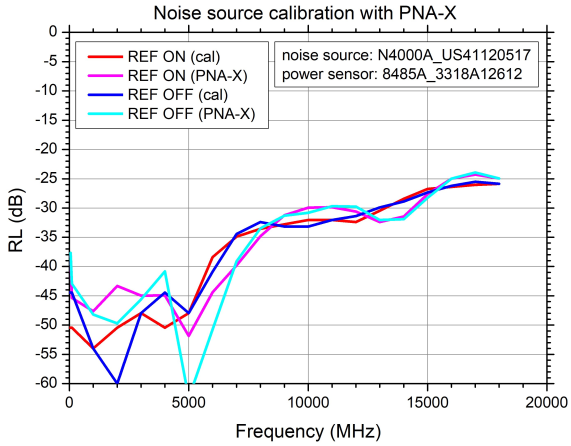




**Source SYS 1020-3 (for Agilent 8975A)**



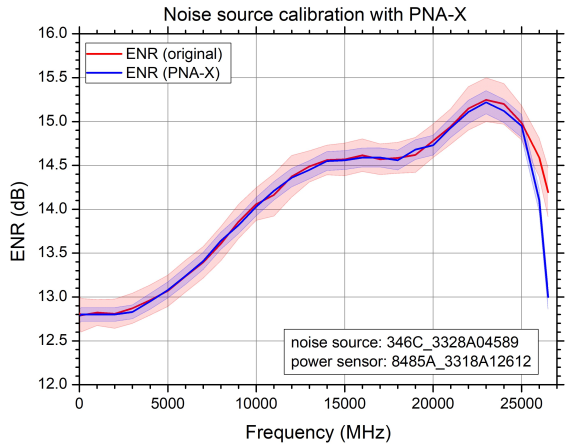



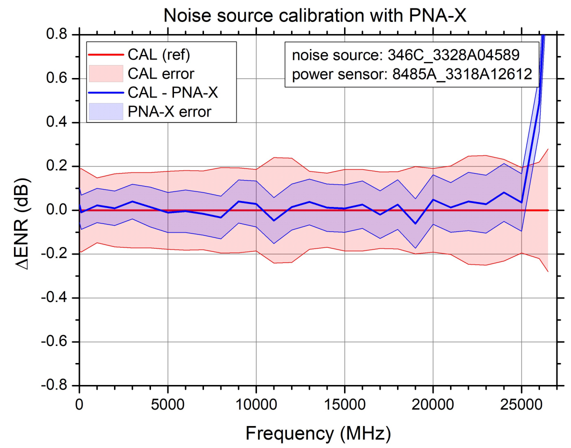



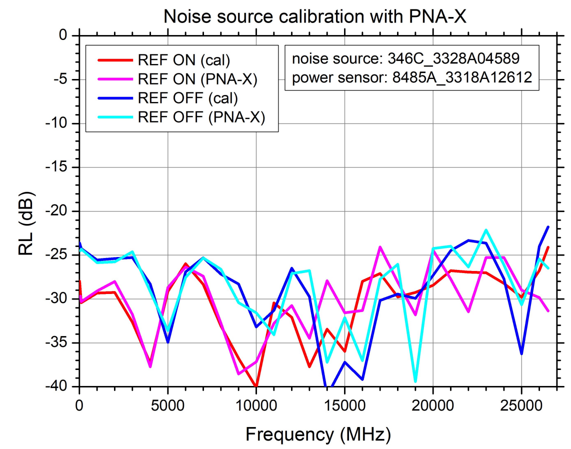
# 346C Noise Sources

02/11/2020 BW= 4 MHz, AVG=200, 2.92 mm cal, Power Meter cal, 50 MHz-26.5 GHz

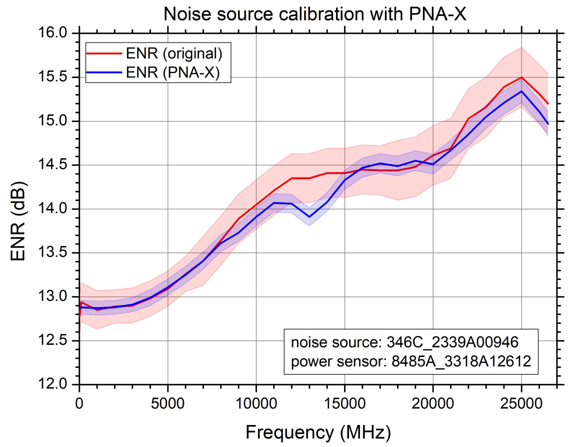
**Source SYS 1020-1 (for HP 8970B)**

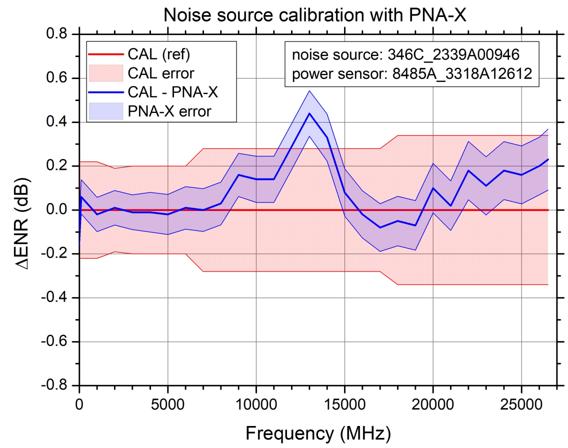


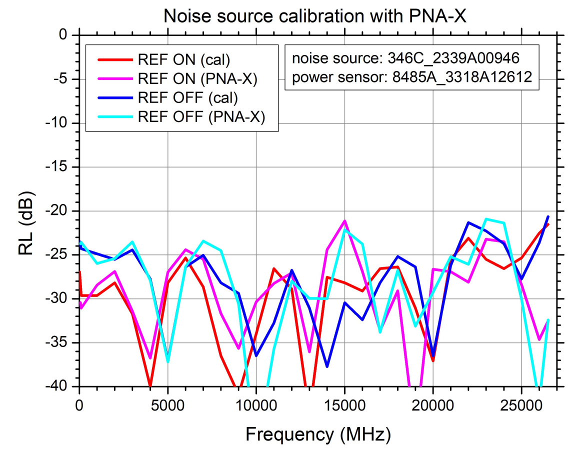




**Source SYS 350 (for HP 8970B)**



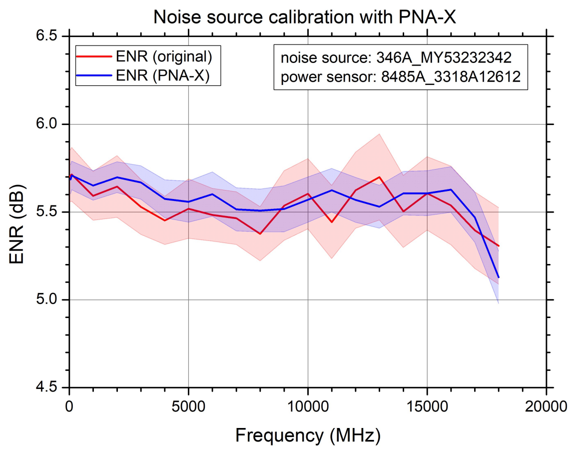



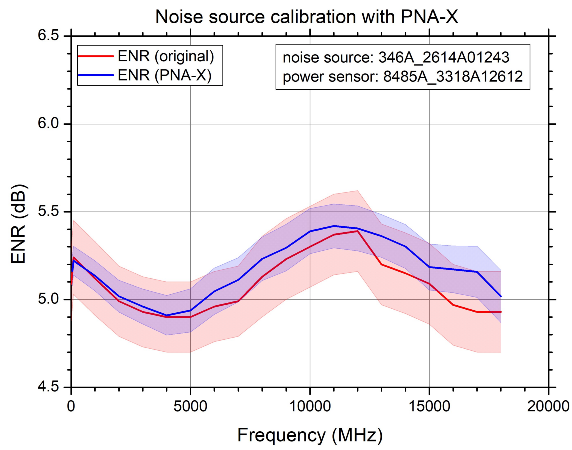
## 346A Noise Sources

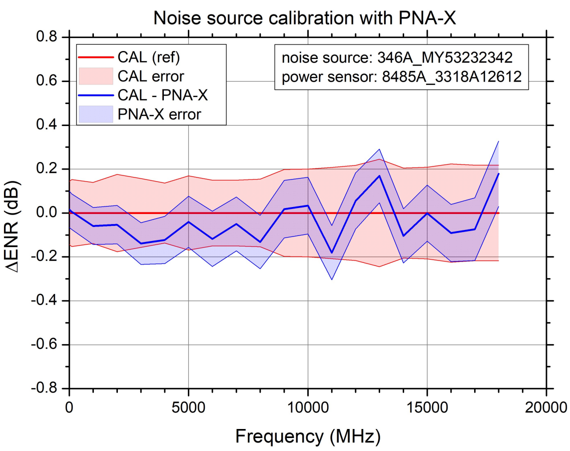
02/11/2020 BW= 4 MHz, AVG=200, 2.92 mm cal, Power Meter cal, 50 MHz-18 GHz

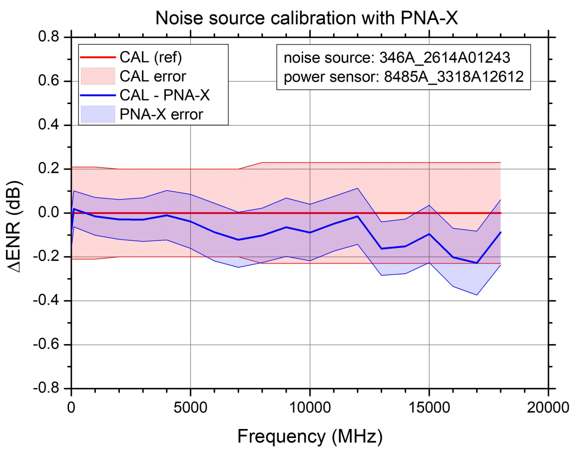
**Source SYS 1020-1 (for HP 8970B)**

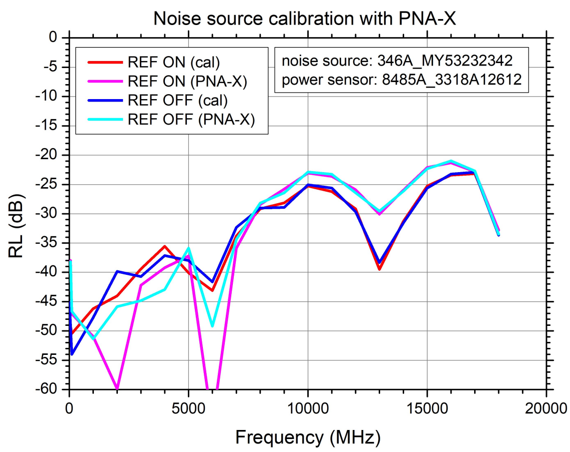
**Source SYS 350 (for HP 8970B)**

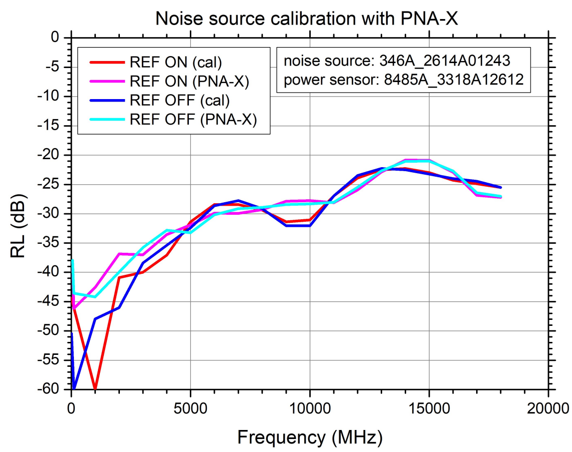


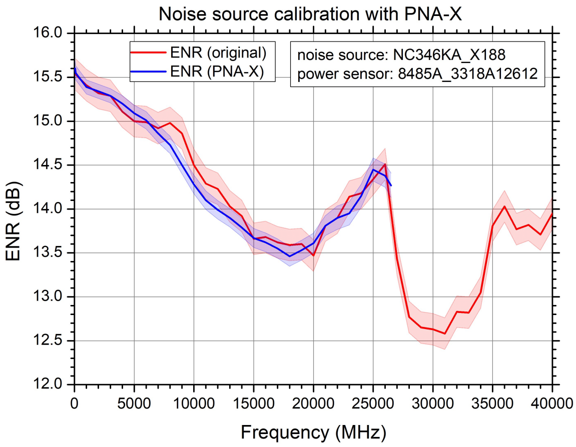
## Notes on 346 Noise Sources

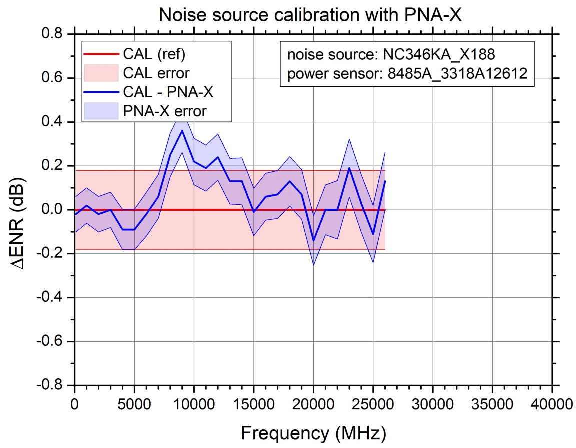
- The 346C_3328A04589 shows an abnormal behavior at freq>25 GHz. The ENR becomes smaller when the source warms up and some changes of the reflection coefficient can also be detected.
- The 346C_2339A00946 shows a suspicious “dip” in the ENR centered at about 13 GHz which was not present in the original calibration. However, this dip appears to be repeatable.
- The individual uncertainty values of the old 346A and 346 C were not provided in the original calibration tables. The values in the graph were taken from the specification.

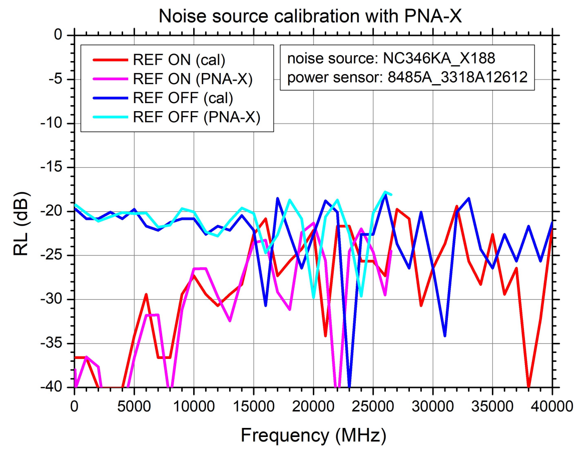
# Miscellaneous Noise Sources (not in use)

12/11/2020 BW= 4 MHz, AVG=200, 2.92 mm cal, Power Meter cal, 50 MHz-26.5 GHz

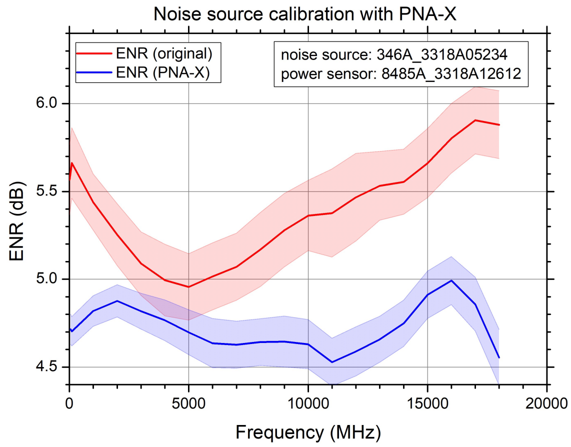
**Source ENR_NC346KA_X188 (NoiseCom 40 GHz)**

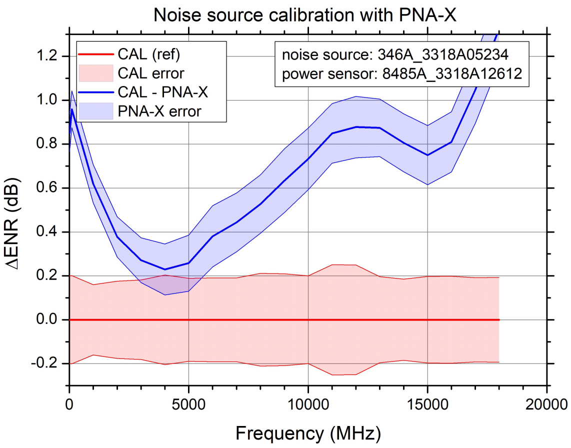


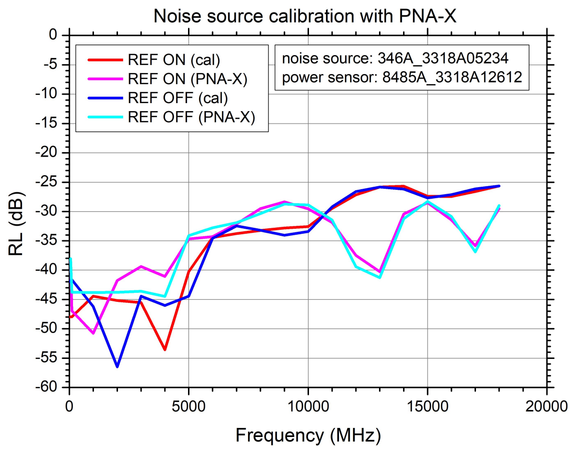




**Source 346A_3318A05234_repaired**



## Notes on miscellaneous Noise Sources

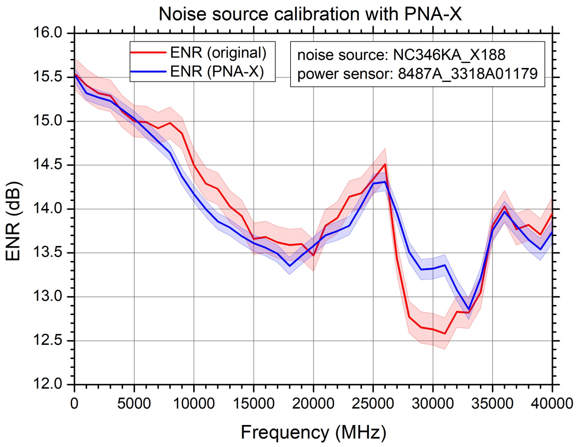
- The ENR_NC346KA_X188 (Noisecom 40 GHz) is not normally used in the lab because a) is not DC blocked (shows ≈0.5 volt at the output when ON) and b) some calibration problems were suspected above 26 GHz. The measurement with PNA-X shows good agreement up to 26 GHz.
- The 346A_3318A05234_repaired internal regulator failed and was repaired in Yebes. A high stability zener diode reference was substituted. As a consequence, the bias point of the avalanche diode changed. The new calibration shows that the output noise is lower and the band shape different than in the initial calibration. However, it is believed that the source is usable if the new calibration is used.

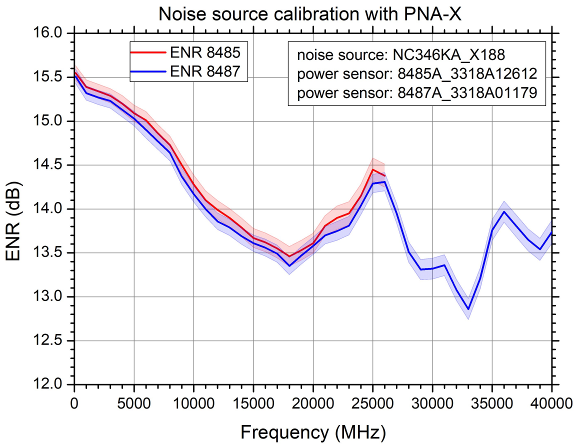
# Comparison of calibrations with two different power sensors (8485 and 8487)

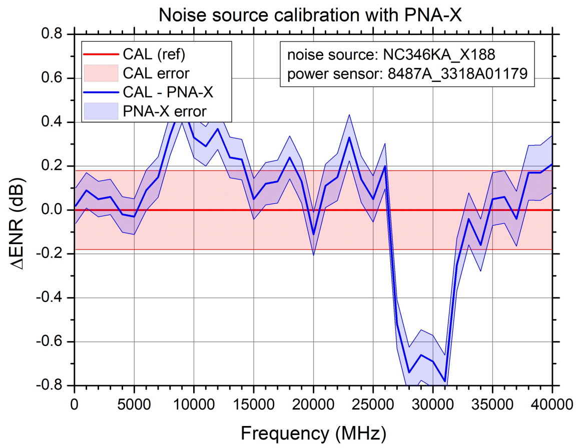
12/11/2020 BW= 4 MHz, AVG=200, 2.92 mm cal, Power Meter cal, 100 MHz-40 GHz

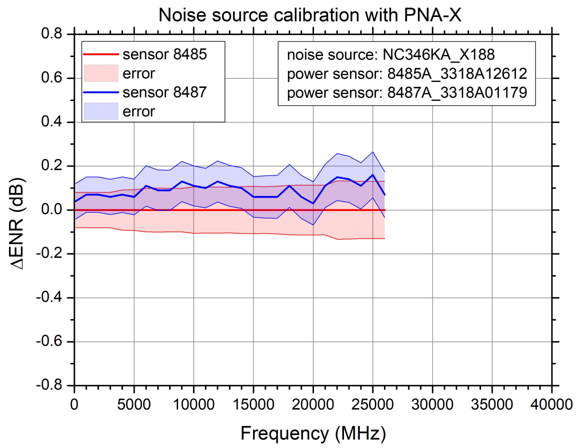
**Source ENR_NC346KA_X188 (NoiseCom 40 GHz)**

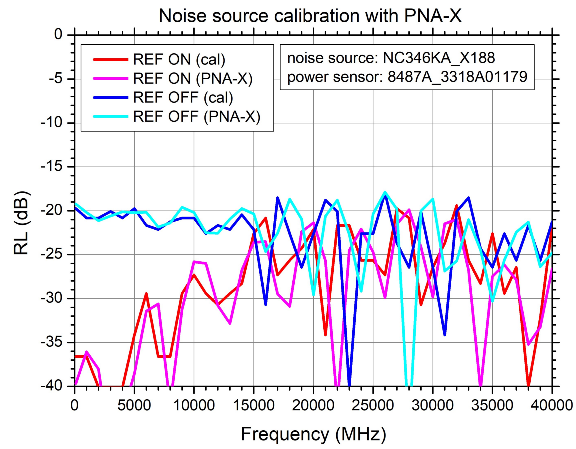
**Calibration with 8485 vs. 8487 sensor**

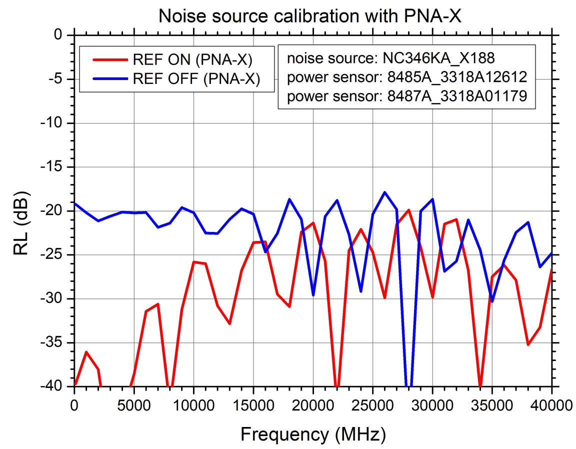


## Notes on the comparison

- The ENR_NC346KA_X188 (Noisecom 40 GHz) is not normally used in the lab because a) is not DC blocked (shows ≈0.5 volt at the output when ON). There is a significant difference with the original calibration in the 26-32 GHz range.
- The measurement with calibrations performed with two different power sensors agree within the predicted error. The difference is ≈0.1dB.