Solid state broadband un-cooled noise generator with noise temperature below room temperature

by

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1. Introduction

Almost always noise figure is measured today by using a noise source delivering two different but known noise temperatures (Y factor method). In commercially available noise sources these temperatures are characterized by the excess noise ratio (ENR) value, describing the ratio of equivalent noise power when switched on related to the noise power of a resistor at a temperature of 290K (switched off). For a typical ENR value of 5 dB that means T_h = 1207K and T_c = 290K.

In this paper the impact of T_c onto the noise figure uncertainty is analyzed. There are several advantages when holding T_c as low as possible and not – as usual done - at 290K. To realize T_c below room temperatures there are several possibilities, like cooling a resistor with liquid nitrogen or using sky noise by a suited antenna, as was done by RW3BP [1]. Drawbacks of these solutions are either that they are expensive/need huge effort or are small band, thus only usable for one amateur band.

Therefore in this paper an alternative solution of a broadband noise generator on the basis of Schottky diode operated in conduction region will be described. In conduction region the Schottky diode shows a mixture of shot noise as well as thermal noise caused by the metal-semiconductor junction and the bulk resistance. By simple DC measurements the overall noise temperature can be precisely determined and is in the order of 150K ... 200K, depending on the diode type used. At the same time the bulk resistance in series with the differential resistance of the proper biased diode shows very good match to 50 Ohms over a wide frequency range. Thus an amateur noise normal can be implemented by simple DC and reflection factor measurement. Application and measurement results will be presented.

2. Noise figure measurement uncertainty

In the standard Y factor measurement method to measure noise figure two main error sources are specified by equipment manufacturers: the uncertainty of the noise source in terms of Denr and the uncertainty of the power ratio or instrumentation error Δy. Typical values range e.g. between Δenr = +/-0.3dB for an old Ailtech 7615 or Δenr = +/-0.2dB for an HP346A noise source. For the instrumentation error of an HP8970A/B an instrumentation error of Δy = +/-0.1dB is specified. When analyzing the resulting error in noise figure (nf uncertainty, see annex) it turns out that the resulting nf uncertainty is strongly dependent on the cold temperature of the noise source. In Fig. 1 the nf uncertainty is shown as a function of cold temperature of the source for two different enr values of the source and for two LNAs which are assumed for simulation purpose to differ in noise figure (nf = 0.1 dB and nf = 0.5 dB). From Fig. 1 it can be concluded that the cold temperature should be as low as possible to keep the resulting nf uncertainty as low as possible. It can also be seen that even for very low enr (enr = -4.5 dB) the nf uncertainty is reasonable low if cold temperature is as low as e.g. 150K. Normally cold temperature of the noise source is at ambient room temperature, e.g. 290K. So it has to be found a (50Ω matched) noise source delivering a cold noise temperature. The solution of RW3BP is a horn antenna looking at cold sky and thus delivering a cold temperature of approx. 15K at 1296MHz. Could a noise source be easier constructed to deliver noise temperature below ambient room temperature?

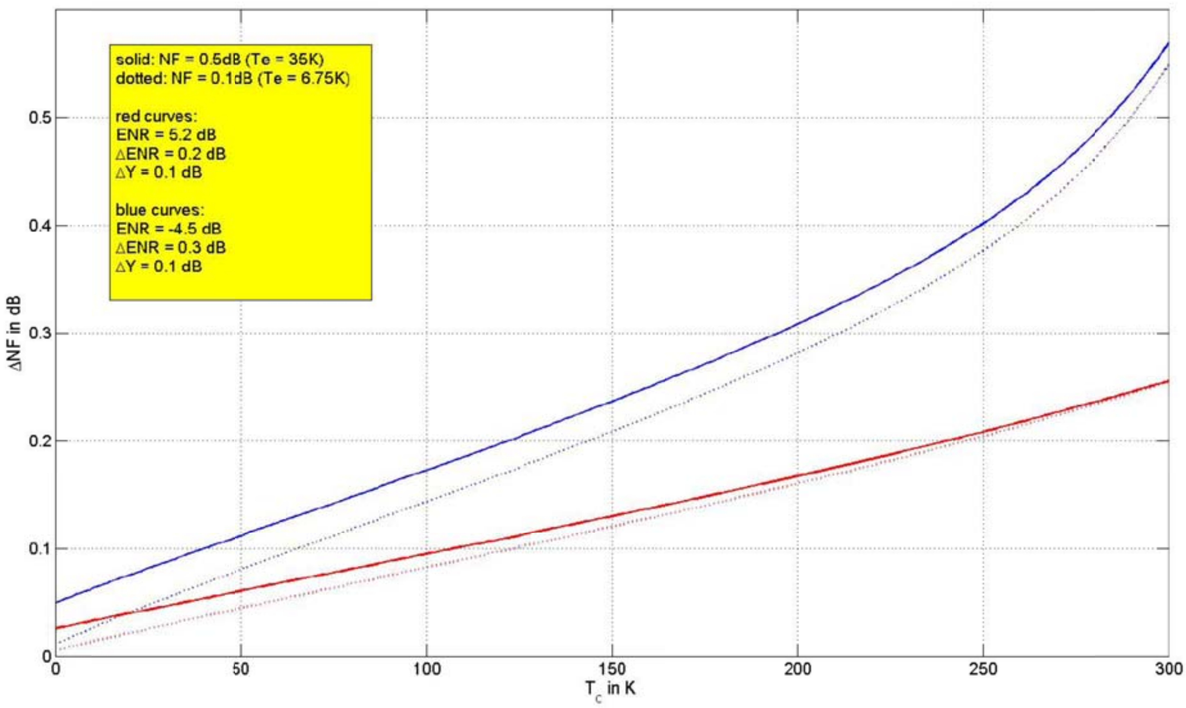

Fig. 1: Noise figure uncertainty in dB as function of Tc, nf of DUT and enr for Δenr = 0.2 dB (enr calibration uncertainty of noise source) and Δy = 0.1 dB (instrumentation uncertainty, e.g. HP8970).

3. Schottky diode

Schottky diodes are formed by a metal-semiconductor junction and are widely used e.g. in mixers and detectors up to very high frequencies (e.g. 100 GHz). This chapter will treat the necessary circuit models of a Schottky diode in order to provide a basic understanding of the noise generator implementation described in chapter 4.

3.1 DC and small signal properties

A widely used circuit model of the Schottky diode that is valid for both large-signal and small-signal analysis is given in Fig. 2. It consists of a nonlinear resistance whose value is determined by the operational point and a capacitance representing the junction. Furthermore it contains a bulk resistance which is in the order of a few Ohms. This model corresponds to the exponential I/U characteristic expressed in the following equation

$$i(u) = I_S \cdot \left(\exp\left(\frac{q \cdot u}{\tilde{n} \cdot kT} \right) - 1 \right) \qquad (1)$$

where kT/q describes the temperature voltage (26mV at room temperature), I_S is the saturation current (in the order <0.1μA) and $\tilde{n}$ is the so-called ideality factor, an empirical factor describing the deviation from the exponential (values range from 1 to 1,2).

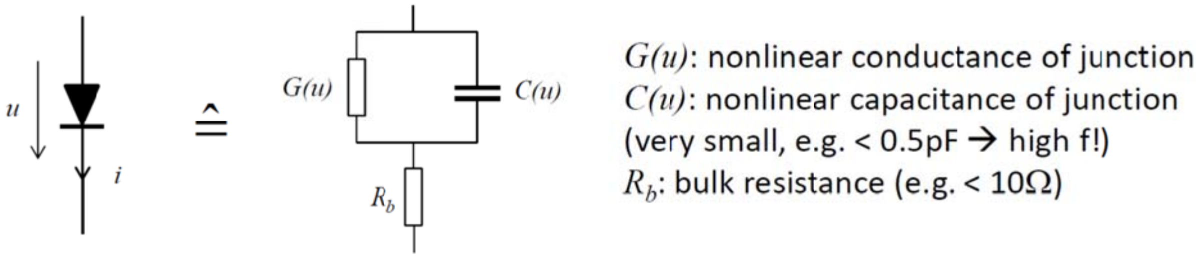

Fig. 2: Circuit model of a Schottky diode.

By inspecting the DC I/U-characteristic of the Schottky diode (either by taking measurements or by looking to the data sheet) all necessary values to parameterize a suitable model of the Schottky diode could be derived – see Fig. 3. That is namely the ideality factor $\tilde{n}$, the bulk resistance R_b and the saturation current I_S.

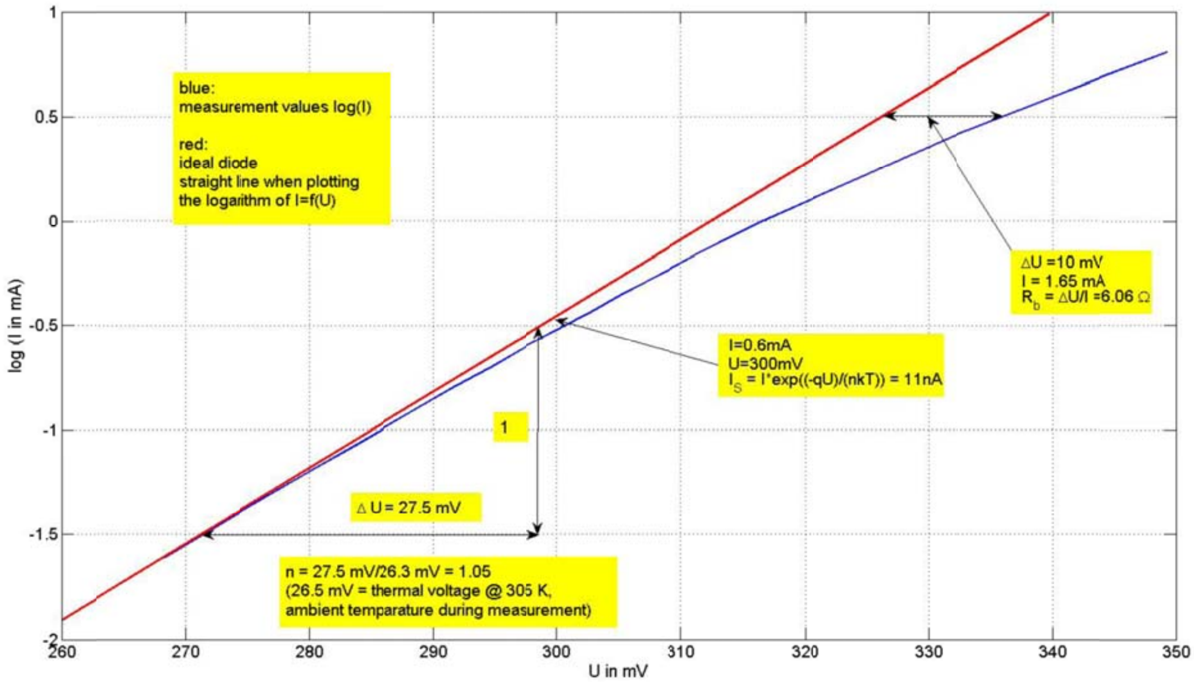

Fig. 3: Measured I/U characteristic of a Agilent HSMS-2823 Schottky diode.

3.2 Noise model

When operated in forward direction a Schottky diode shows a mixture of thermal noise due to the bulk resistance and shot noise due to the quantized charge carriers which have to climb the metal-semiconductor junction. That can be summarized into a noise equivalent circuit diagram with two independent noise sources given in Fig. 4, see [3]. The conductance G is the differential conductance of the diode at its DC operating point.

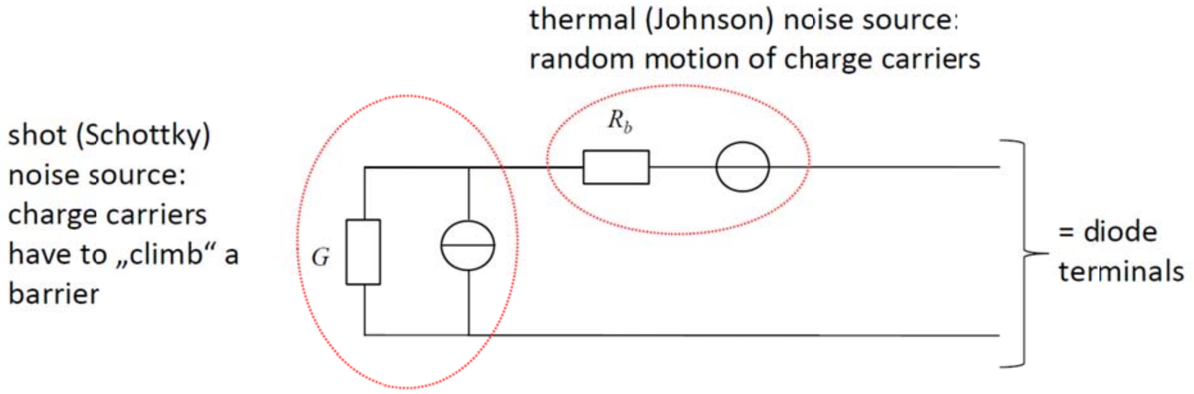

Fig. 4: Noise equivalent circuit model of a Schottky diode with bulk resistance.

It turns out that the ratio of effective noise temperature at the diode's terminals to the ambient (physical) room temperature as a function of ideality factor $\tilde{n}$, DC current I_0 and saturation current I_S when neglecting the bulk resistance is given to be [3]

$$\frac{T_{ef}^*}{T} = \frac{1}{2} \cdot \tilde{n} \cdot \left(1 + \frac{I_S}{I_0 + I_S}\right) \qquad (2)$$

Inspecting (2) it can be seen that because the saturation current is negligible in comparison to the forward current I_0 the noise temperature could be at minimum half of the ambient (physical) temperature.

When including thermal noise from the bulk resistance and taking into account (2) the overall noise temperature T_{ef} related to the ambient room temperature T is then [3]

$$\frac{T_{ef}}{T} = \frac{\frac{T_{ef}^*}{T} + R_b \cdot G}{1 + R_b \cdot G} \qquad (3)$$

4. Implementation

Based on the diode model introduced in chapter 3 a noise source by means of a Schottky diode operated in forward direction was implemented, see Fig. 5 and Fig. 6.

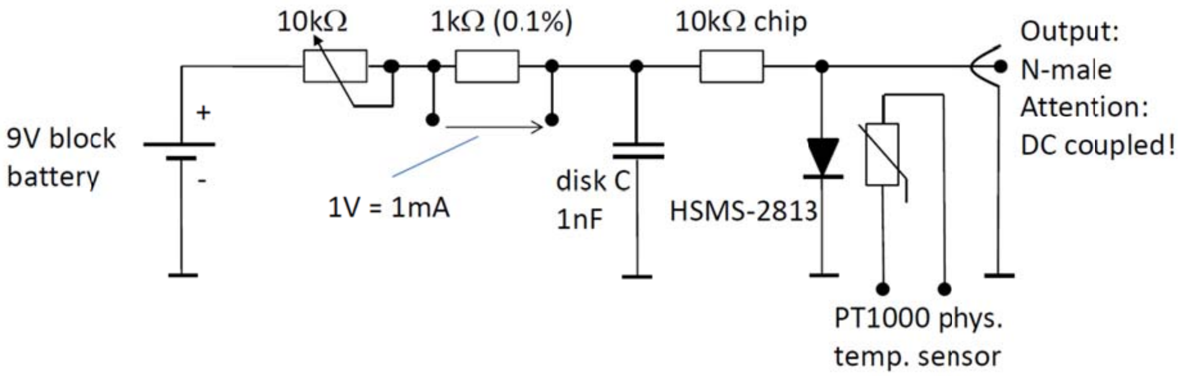

Fig. 5: Circuit of Schottky noise generator.

DC current through the diode can be aligned by the variable 10kΩ resistor. A precision shunt of 1kΩ allows DC current measurement. DC voltage across the diode's terminals can be measured directly at the N-male output connector. An additional PT1000 in the same housing placed nearby the diode allows measurement of the ambient temperature of the diode. RF noise of the diode is decoupled from the DC part by a 10kΩ chip resistor and 1nF disk capacitor.

By taking DC measurements in this setup bulk resistance, ideality factor and saturation current were derived according to Fig. 3 and are in good agreement to the data sheet.

Fig. 6: Realization of Schottky diode noise generator.

5. Application and measurements

In order to provide a matched load the DC current through the diode was aligned to make the bulk resistance in series with the differential junction resistance a pure 50Ω load by means of VNWA measurement. Thus $1/G + R_b$ is equal to 50Ω. Best result was reached for I_0 = 0,67mA at ambient temperature of 305K (32°C). In Fig. 7 the measured return loss up to 1300MHz is shown. The degradation of return loss for increasing frequency is mainly caused by the junction capacitance (~0,7pF) of the used diode. More expensive diodes with smaller junction capacitance should work at even much higher frequencies with sufficient RL. Of course the VNWA measurement has to be done carefully with low stimulus power (e.g. < -20dBm) in order to avoid nonlinear behavior of the diode.

Applying the noise model and calculus in chapter 3 delivered an equivalent noise temperature of 180K at DC current 0,67mA and ambient (physical) temperature of 305K around the diode.

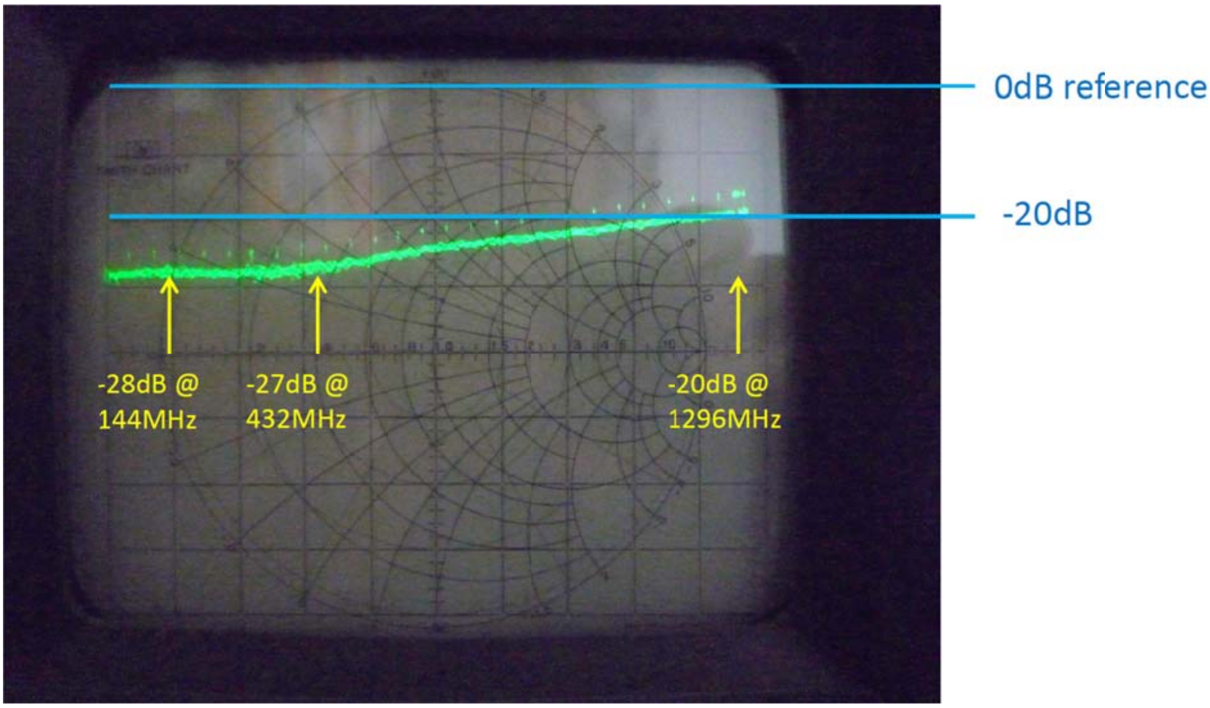

Fig. 7: Return loss (RL) of the Schottky noise generator when biased for minimum RL.

In Fig. 8 the combination of the Schottky noise generator with a standard noise generator is suggested in order to lower the overall cold temperature of the new noise source. This combination can be easily integrated into existing noise figure analyzer setups, e.g. the often used HP8970A/B. By combining the noise powers of the two noise generators by a directional coupler which has to have low loss in main line to avoid too much increasing of the overall cold temperature another advantage results: because of the low coupling (-19,5dB) there is virtually no change in reflection coefficient for "on" and "off" state which would cause additional errors for mismatched devices under test ("gain error", see [5]).

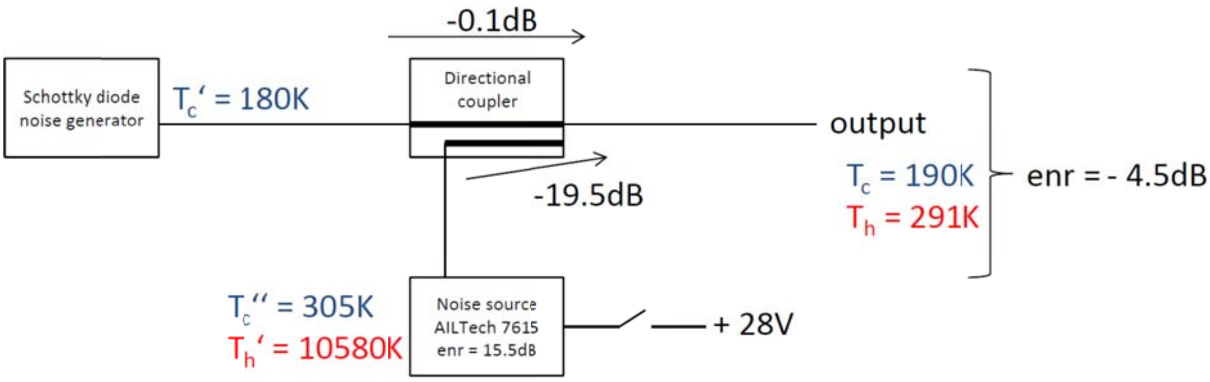

Fig. 8: Combining Schottky noise generator and standard noise source for "new" noise source with decreased overall cold temperature.

With the setup shown in Fig. 8 noise figure measurement at an MCL ZEL-1217LN low noise L-band amplifier was taken with an HP8970B noise figure analyzer. The noise figure was measured to be approximately 1dB at 1296 MHz which is in good agreement with data sheet (typically 1,1dB) and measurements taken with an HP346A noise source (nf measured 0,97dB).

6. Conclusions

In this paper a broadband "cold" matched noise source providing noise temperatures below room temperature based on a Schottky diode was described. Its application in a noise figure measurement setup with enhanced accuracy was shown. Because of the decreased cold temperature in comparison to the usually used noise sources a lower hot temperature provided by more attenuation and thus less gain error – see [5] - can be applied in Y-factor measurement method. Another advantage of the proposed noise generator is the decreased tolerance in effective ENR value due to the decreased cold temperature.

7. References

[1] Zhutyaew, S., RW3BP: "1296 MHz Small EME Station with Good Capability (part 1-4)", www.vhfdx.ru.

[2] Maas, S.A.: "Microwave Mixers", Artech House, 1993.

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[4] Pozar, D.: "Microwave and RF Design of Wireless Systems", Wiley, 2000.

[5] Bertelsmeier, R., DJ9BV: "Low Noise GaAs-FET Preamps for EME: Construction and Measurement Problems", DUBUS 4/1988.

[6] Swain, H.L.; Cox, R.M.: "Noise Figure Meter Sets Records for Accuracy, Repeatability, and Convenience", Hewlett-Packard Journal, 4/1983.

8. Appendix

Starting with the basic equation which is evaluated in a noise figure measurement setup we have (see e.g. [5])

$$F = \frac{ENR - Y\left(\frac{T_c}{T_o} - 1\right)}{Y - 1} \qquad \text{(A1)}$$

where

F: noise figure of device under test – linear scale,

ENR: excess noise ratio of noise source – linear scale,

Y: power ratio of power at output of DUT when noise source switched on to power at output of DUT when noise source switched off – linear scale,

T_c: cold noise temperature of noise source (switched off) in K,

T_0: reference noise temperature, T_0=290K.

Furthermore the relation between equivalent noise temperature T_e given in Kelvin of the DUT and its (linear) noise figure F is given by (see e.g. [4])

$$F = 1 + \frac{T_e}{T_o} \qquad \text{(A2)}$$

Throughout this paper it also holds for the noise figure of the DUT in dB

$$nf = 10 \cdot \log(F) \qquad \text{(A3)}$$

Furthermore the definition of the (linear) ENR is given by

$$ENR = \frac{T_h - T_c}{T_o} \qquad \text{(A4)}$$

where T_h is the hot temperature when the noise source is switched on. Mostly ENR is given in dB's, thus

$$enr = 10 \cdot \log \frac{T_h - T_c}{T_o} = 10 \cdot \log(ENR) \qquad \text{(A5)}$$

The measured Y-factor could be expressed in terms of T_e, T_h and T_c according to

$$Y = \frac{T_h + T_e}{T_c + T_e} \qquad \text{(A6)}$$

Or in dB's

$$y = 10 \cdot \log(Y) \qquad \text{(A7)}$$

As can be seen from equation (A1) two major sources of error in a noise figure measurement setup are the enr calibration uncertainty and y factor measurement uncertainty. For state of the art noise sources, e.g. a HP346A an enr = 5..6dB and an uncertainty of Δenr = +/- 0.2dB are specified. The uncertainty of y factor measurement is specified in terms of instrument uncertainty, e.g. Δy = +/- 0.1dB for an HP8970.

Obviously these two variables are independent and thus differential calculus in the form of Taylor series and combining the uncertainties in a root-sum-of-squares fashion can be applied to find the uncertainty of F:

$$\Delta F = \sqrt{\left(\frac{\delta F}{\delta Y} \cdot \Delta Y\right)^2 + \left(\frac{\delta F}{\delta ENR} \cdot \Delta ENR\right)^2} \qquad \text{(A8)}$$

The partial derivatives of the function given in (A1) to the respective variables needed in equation (A8) are given as follows:

$$\frac{\delta F}{\delta Y} = -\frac{ENR + 1}{(Y-1)^2} + \frac{T_c}{T_o} \cdot \frac{1}{(Y-1)^2} \qquad \text{(A9)}$$

and

$$\frac{\delta F}{\delta ENR} = \frac{1}{Y-1} \qquad \text{(A10)}$$

With

$$\Delta ENR = 10^{\frac{enr}{10}} \cdot \left(10^{\frac{\Delta enr}{10}} - 1\right) \qquad \text{(A11)}$$

and

$$\Delta Y = Y \cdot \left(10^{\frac{\Delta y}{10}} - 1\right) \qquad \text{(A12)}$$

The linear ΔF according to (A8) can thus be calculated as a function of Δenr, Δy and T_c - or in terms of dB it holds

$$\Delta nf = \frac{10}{\log(10)} \cdot \frac{\Delta F}{F} \qquad \text{(A13)}$$

which is the resulting nf uncertainty.