Improvement of microcalorimeter measurements through data correction

Emil Vremera[1] and Luciano Brunetti[2]

[1] Technical University of Iasi, Faculty of Electrical Engineering
Department of Electric and Electronic Measurements
B-dul Prof. Dimitrie Mangeron 53, 700050 Iasi, Romania
Tel: +40 232 278683; Fax: +40 232 237627; E-mail: evremera@ee.tuiasi.ro
[2] Istituto Elettrotecnico Nazionale Galileo Ferraris
Strada delle Cacce 91, 10135 Torino, Italia
Tel: + 39 11 3919323; Fax: + 39 11 3919259; E-mail: brunetti@ien.it

Abstract-The paper describes the most important uncertainty sources in the microcalorimeter measurement technique. Analyzing data obtained from automated measuring systems, the correlation factors between measured quantities and error sources are carried out. With appropriate corrections on the raw data the final results show significant accuracy improvement.

I. Introduction

The microcalorimeter is considered a primary standard system in high frequency (HF) power measurements, particularly in power sensors calibration [1]. For increasing the accuracy in such measurements good error estimation and thorough uncertainty budget are necessary.

In line of principle all the quantities relevant to the microcalorimeter technique are stationary. But the long measurement times requested by the system change their property. They become non-stationary quantities and their correlation must be discovered [2] to introduce relevant error corrections.

The measurement errors come from temperature instability, limited measurement time, loss change inside the feeding lines, variations of the HF applied power, thermal asymmetry in the microcalorimeter loads, unbalance in temperature sensing etc.

An effective correction of measurement data is possible if each perturbation source acts only on single or at least not correlated quantities. Its action remains in the uncertainty budget for all implied quantities if this assumption is not true. The paper proposes important corrections for measurement data obtained with a coaxial line microcalorimeter in 50 MHz - 18 GHz frequency range [3].

II. Microcalorimeter theory and raw results

In experiments we used a coaxial microcalorimeter, basically an adiabatic system designed for milliwatt power levels and adjusted for measuring effective efficiency η_e of thermistor mounts. It is fitted with a single 7 mm coaxial line having an insulating section of 100 mm, necessary for a good thermal insulation of the thermal load. This one is made of a Cu–Costantan thermopile, the mount under test and the thermal reference mass both having the same thermal capacity. The output quantity is the thermopile thermovoltage, a DC quantity. In an ideal case this one is enough to compute η_e of power sensor supposing free losses feeding path, perfect thermal isolation, constant microcalorimeter wall temperature and long-term measurements if compared with the system time constant.

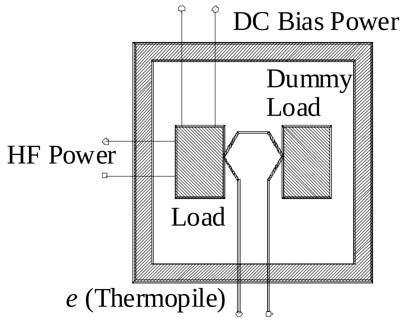

Figure 1. Simplified scheme of a microcalorimeter.

Thermistor power sensor works on the base of the equivalence between thermal effects in DC and HF. By keeping the DC resistance constant for any changes in the input power P_{inS} it will lead to change the bias DC power from the initial P_{DC1} level to P_{DC2}, so as to maintain constant the total power P_t on the sensor:

$$R = f(P_t) = const. \Rightarrow P_t = P_{DC1} = P_{DC2} + P_{HF1} \Rightarrow P_{HF1} = P_{DC1} - P_{DC2} = \Delta P_{DC} \quad (1)$$

where P_{HF1} is the part from P_{inS} which acts on sensing element like DC power. Another part of HF power, P_{HF2}, will only change the sensor mount temperature leading however to changes in the thermopile output voltage. Starting from electrothermal equation for an ideal microcalorimeter and from effective efficiency definition [1], we obtain:

$$\eta_e = \frac{\Delta P_{DC}}{\Delta P_{DC} + P_{xS}} = \frac{1}{1 + (e_{on} - e_{off}) / (G_1 \cdot \Delta P_{DC})} \quad (2)$$

where e_{on} and e_{off} are output voltages of the thermopile with and without HF power applied, G_1 is its sensitivity in volts/watt and $P_{xS} = P_{inS} - P_{HF1} = P_{HF2}$. The sensitivity can be obtained experimentally by varying DC bias power and measuring the long-term variation of the thermopile output voltage. Another and more convenient way to obtain η_e consists in using thermovoltage and power ratios, e_R and p_R defined as:

$$e_R = \frac{e_{on}}{e_{off}} = \frac{P_{DC1} + P_{xS}}{P_{DC1}} = 1 + \frac{P_{xS}}{P_{DC1}}; \quad p_R = \frac{P_{DC2}}{P_{DC1}} \Rightarrow \quad \eta_e = \frac{1 - p_R}{e_R - p_R} \quad (3)$$

The microcalorimeter has been used in the range 50 MHz –18 GHz for HP8478B thermistor mounts whose characteristics were validated in international comparisons. The measuring system run at 23 test frequencies, switching on/off 3 mW HF-power four times with a period of 2 hours for each frequency. Table I shows raw measurement for a reduced number of frequencies.

f(GHz)	p_R	e_R	η_e
0.05	0.8468	1.0021	**0.9867**
1	0.8659	1.0028	**0.9796**
2	0.8704	1.0037	**0.9720**
4	0.8865	1.0044	**0.9627**
8	0.9088	1.0063	**0.9352**
16	0.9205	1.0094	**0.8939**
18	0.9404	1.0093	**0.8652**

Table I: Calibration raw values for a thermistor mount model HP8478B.

These values can be considered lower limits for η_e because all losses sensed by thermopile are attributed to power sensor. Taking in account the feeding line losses a new expression for η_e will result with new limits for it.

III. Correction for power separation

In practice, the microcalorimeter thermopile is sensitive not only to the power dissipated in the thermistor mount, but also to the thermal flux on the feeding line. The phenomenon is described by the following electrothermal equation [1]:

$$e = \alpha R\left(K_1 P_{inS} + K_2 P_{IL}\right) \qquad (4)$$

where P_{IL} is the power loss in insulating line, α the Seebek coefficient of thermopile junctions, R a constant depending on mass density and specific heat of the thermal load and K_1, K_2 dimensionless coefficients describing the power separation. The determination process of K_1, K_2 is defined as microcalorimeter calibration step. According to Equation (4) a new expression for η_e is:

$$\eta_e = \frac{1 - p_R}{e_R - p_R - k_R\, P_{IL}/P_{DC1}}, \text{ where } e_R = \frac{K_1\left(P_{DC1} + P_{xS}\right) + K_2 P_{IL}}{K_1 P_{DC1}} \text{ and } k_R = \frac{K_2}{K_1} \qquad (5)$$

The next diagram shows the power routes inside a microcalorimeter.

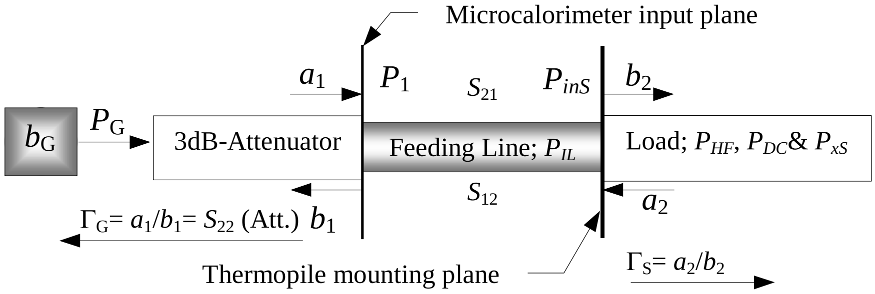

Figure 2. Simplified scheme for highlighting the power flow between the generator and the load.

The feeding line losses can be computed from S parameters. Considering the input power in the sensor depending on the measured DC power and the mount reflection coefficient Γ_S, a new shape for (5) can be written:

$$\eta_e = \frac{1 - p_R}{e_R - p_R}\left(1 + k_R \frac{1 + \Gamma_S^2 S_{21}^2}{1 - \Gamma_S^2}\frac{1 - S_{21}^2}{S_{21}^2}\right) \qquad (6)$$

This expression contains raw effective efficiency multiplied by a correction term and confirms minimum value for η_e givens by (3). Only k_R seems to be frequency non-dependent. The power conversion process in various sections between microcalorimeter input and the load as well as the inner conductor thermal path, not yet considered, leads to some variation of this ratio. S-parameter measurements will provide the frequency-dependent part of the correction term. On the other hand, the separation constants may be determined using as thermal load a device virtually loss-less (dummy load) in a calibration step as suggested in [3]. By this new method that uses a modified power sensor as dummy load, more information on microcalorimeter behaviours can be obtained. Because the output signal levels in the calibration step is lower than in the measurement one, a large dispersion of the results can appear. The upper limit for k_R helps to do a selection of the same k_R values obtained by measurements. All k_R values giving an η_e >1 through (6) should be rejected. Furthermore, k_R upper limit gives us the upper possible limits for η_e at all tested frequencies. From the measurement data the max value for k_R is 0.803 and this leads to excluding of ten frequencies from calibration data set. From remaining test frequencies a value results for k_R of 0.6875 with a standard deviation of 0.1146. Table II shows the values of η_e between lower and upper limits. It can see no exceeding of these limits.

f(GHz)	p_R	e_R	Min (η_e) k_R=0	η_e k_R=0.6875	Max (η_e) k_R=0.7721	$\Delta\eta_e$
0.05	0.8468	1.0021	0.9867	**0.9897**	0.9901	0.0033
1	0.8659	1.0028	0.9796	**0.9903**	0.9916	0.0120
2	0.8704	1.0037	0.9720	**0.9871**	0.9890	0.0170
4	0.8865	1.0044	0.9627	**0.9867**	0.9897	0.0270
8	0.9088	1.0063	0.9352	**0.9929**	1.0000	0.0648
16	0.9205	1.0094	0.8939	**0.9629**	0.9714	0.0775
18	0.9404	1.0093	0.8652	**0.9491**	0.9594	0.0941

Table II: Calibration values for the same thermistor mount for power separation correction.

The difference $\Delta\eta_e$ represents the interval for the possible values of effective efficiency between upper and lower limits. This difference brings out the importance of both the corrections and their accuracy.

IV. Correction for temperature fluctuations

The temperature of the thermostat walls is maintained constant by immersing the microcalorimeter body in a thermostatic bath [1] [3] or by using an active thermal shield [1] [5]. Various phenomena lead to the temperature instability of the microcalorimeter body. Small deficiency in the temperature control loop and the thermal disturbances coming inside from the external environment through RF cables are among them. However, main temperature variations are due to the power dissipated in feeding and thermal insulation sections and of course in the microcalorimeter load. A part of these perturbations can be kept at low level and therefore ignored, but the others must be determined by measurements. The thermopile voltage is the main microcalorimeter output quantity, but beside it, the wall temperature is also important, because experimental data show a strong correlation between them.

Temperature measurements may be seen as random data and must be filtered to know their trend better. Then it is necessary to identify the correlation function between thermopile voltage and temperature using at least two parameters, sensitivity and delay [2]. Data concerning the quantity of interest must be collected in stationary conditions attained after a long time from the HF power withdrawing. The corrected thermopile voltage e_c may be obtained by the following equation:

$$e_c(N,T_{ref}) = e(N,T) + S_{eT}\Delta T(N_\tau, t_d) \qquad (7)$$

where e is the measured thermopile output, N and N_τ represent indexes of considered samples, T and T_{ref} are temperatures, S_{eT} is the sensitivity of thermovoltage at temperature variation and t_d denotes the delay which the electrothermal effects propagate with.

In past experiments, described in [3], the temperature wall of the microcalorimeter was measured with a thermometer based on Pt100. Even though the wall temperature stability is well known, it is not easy to carry out the thermovoltage dependence due to many factors involved in this process. A possible way to find this dependence is looking for the minimum thermopile voltage because it must be a constant at long term. The first requested step is to discover the trend in the measurement data. The correlation between wall temperature and thermopile voltage can be observed and computed after detrending both measurement sets. The most common technique for trend removal is to fit a low-order polynomial to the data using the least squares procedures [2]. The first observed trends are described by the first order equations:

$$\begin{aligned} \Delta T(t) &= 4.549\text{E-}07 \cdot t + 0.4948 \quad (°\text{C}) \\ e_{\min}(t) &= -1.479\text{E-}07 \cdot t + 0.7225 \quad (\text{mV}) \end{aligned} \qquad (8)$$

Diagrams from Figure 3 show time varying of these two quantities and their characteristic trend lines before first detrending step.

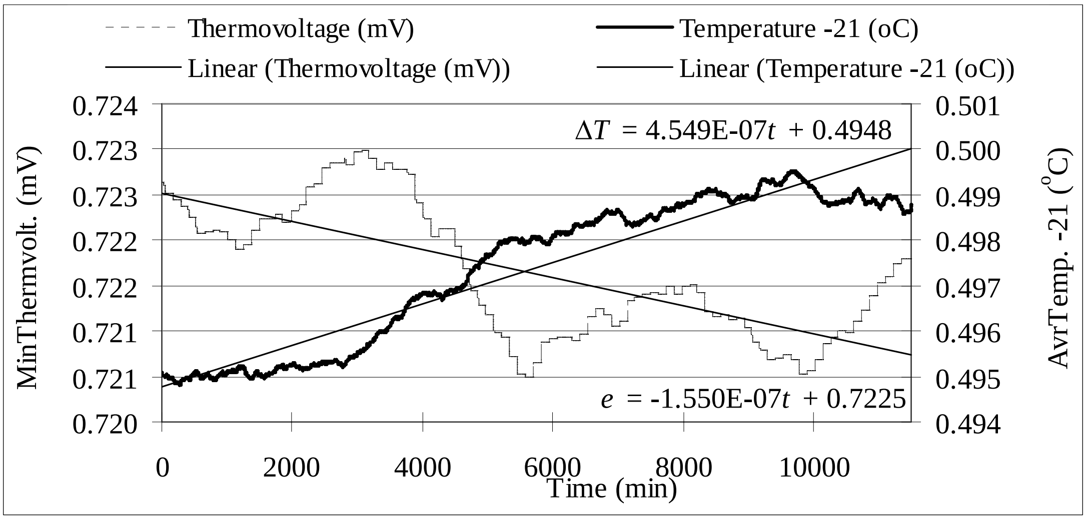

Figure 3. Time diagrams for microcalorimeter temperature and thermopile output voltage.

After this detrending step a long-term variation was observed in both data set. A new trend removal was performed with a three-order polynomial done by the equation (9):

$$\begin{aligned} \Delta T(t) &= 1.059\text{E-}14 \cdot t^3 - 1.665\text{E-}10 \cdot t^2 + 6.541\text{E-}07 \cdot t - 4.566\text{E-}04 \quad (°\text{C}) \\ e_{\min}(t) &= -1.048\text{E-}14 \cdot t^3 + 1.458\text{E-}10 \cdot t^2 - 4.291\text{E-}07 \cdot t - 2.845\text{E-}06 \quad (\text{mV}) \end{aligned} \qquad (9)$$

Both the linear and the three-order polynomial trend show a normally opposite dependence versus time of the temperature and the thermovoltage. This means a strong correlation between them and the possibility for temperature corrections. Residual "fast" variation for this voltage will be considered as generated only by the transient for different losses in medium-term measurement case. In a next step the lower values of the thermopile voltage is built by summing the residual variation at its reference value at 21.495°C. This correction is performed onto first ratio from (6) and as result it has the new η_e-values shown in $\eta_e(e_R$ corr.) column of Table III. New η_e-values are resulting also both for minimum and for maximum.

f(GHz)	p_R	$e_R(T$ corr.)	Min (η_e) k_R=0	**η_e(e_R corr.) k_R=0.6785**	Max (η_e) k_R=0.7750	$\Delta\eta_e$
0.05	0.8468	1.0011	0.9926	**0.9956**	0.9959	0.0034
1	0.8660	1.0028	0.9797	**0.9904**	0.9918	0.0120
2	0.8704	1.0037	0.9724	**0.9876**	0.9895	0.0170
4	0.8863	1.0045	0.9622	**0.9862**	0.9893	0.0271
8	0.9088	1.0063	0.9350	**0.9927**	1.0000	0.0650
16	0.9205	1.0095	0.8928	**0.9617**	0.9705	0.0777
18	0.9322	1.0093	0.8651	**0.9489**	0.9596	0.0945

Table III: Calibration values of the same thermistor mount for temperature correction.

V. Correction for limited measurement time

One of the most important problems of microcalorimeter technique concerns the measurement time. Generally, this is intrinsically long because we observe thermal effects. The necessity both to repeat a great number of measurements for having a good statistic and to perform broadband calibrations worsens the situation. To shorten a calibration procedure, the time constant of the system may be reduced [4]. But, a significant residual error remains due to the finite observation time. An alternative is given by the medium-term measurement method [5]. Even analyzing for limited time the output of the microcalorimeter thermopile, the system time-constant may be calculated. Then, this may be used to write the function that predicts the behaviour of the system up to the thermodynamic equilibrium, a condition reachable only after a long time. The function that allows us to calibrate power sensors in the best way is of the following type [5]:

$$e_R(N) = \frac{e_{\mathrm{M}}}{e_{\mathrm{m}}} \frac{1-\left(e_{\mathrm{m}}/e_{\mathrm{M}}\right)\exp(-T_{\mathrm{SW}}/\tau)}{1-\left(e_{\mathrm{M}}/e_{\mathrm{m}}\right)\exp(-T_{\mathrm{SW}}/\tau)} = e_R(N, T_{SW})H(\iota, T_{SW}, e) \qquad (10)$$

where $e_R(N)$ is the ratio of thermopile output voltages, indexes m and M denote measured extreme values, T_{SW} is the operation time of HF power generator and τ is the time constant of the microcalorimeter. This method, proved by simulation [6], was also successfully used in an international comparison with a IEN *Galileo Ferraris* broadband microcalorimeter [5]. Measurement time can be reduced for 3 to 5 times while measurement uncertainty decreases from 5%, for not corrected values, down to 0.05%, depending on measurement time and thermopile voltage ratio.

Thermal-time constant τ for the IEN microcalorimeter loaded with a HP8478B thermistor mount was determined from transient response in 17.8 minutes. The HF and DC powers were applied successively for an hour T_{SW} time interval and the described correction is required. Table IV shows new values for effective efficiency included between minimum and maximum of its possible values. The largest possible interval for η_e is at 18 GHz and depends mainly on k_R.

f(GHz)	p_R	$e_R(\tau$ corr.)	Min (η_e) **k_R=0**	**η_e(τ corr.) k_R=0.6785**	Max (η_e) **k_R=0.803**	$\Delta\eta_e$
0.05	0.8468	1.0012	0.9920	**0.9950**	0.9956	0.0036
1	0.8659	1.0030	0.9783	**0.9890**	0.9912	0.0129
2	0.8704	1.0039	0.9705	**0.9856**	0.9888	0.0182
4	0.8865	1.0048	0.9596	**0.9836**	0.9886	0.0290
8	0.9088	1.0068	0.9307	**0.9881**	1.0000	0.0694
16	0.9205	1.0102	0.8860	**0.9544**	0.9686	0.0826
18	0.9404	1.0099	0.8569	**0.9399**	0.9571	0.1003

Table IV: Calibration values for the same thermistor mount for thermal time constant correction.

VI. Correction for power variation

The power supplied to the microcalorimeter load, i.e. thermistor power sensor, is a mix of DC and HF power. These can act independently or together but their sum is correlated by the working condition of the microcalorimeter load. Anyway, for the sensing device they must be stationary. If not, a correction is compulsory. The HF generator drift affects the power at the input reference plane of the HF load by losses in feeding lines and by mismatch. Part of these instabilities are time depended, other are frequency dependent and some are related to mount-dismount operations. Some perturbative quantities are obtained with VNA measurements [6]. From these and by applying proper corrections, the most part of uncertainty sources can be cancelled. For getting a low drift in the HF generator, it must be permanently matched and, if it is possible, levelled in amplitude. So far only frequency-dependent corrections remain to determine [5], [6]. If the sensing parameter can not be kept constant, the input power variation may be computed starting from the known sensitivity. From (6) the sensitivity coefficient of effective efficiency to power ratio is given by:

$$\frac{d\eta_e}{dp_R} = \frac{1-e_R}{(1-p_R)(e_R-p_R)}\eta_e \qquad (11)$$

and has values between -0.05 at 50 MHz and -1.83 at 18 GHz. We conclude that power variation can alter the result at higher frequency because this sensitivity becomes great. Fortunately, because this step takes all the benefit of previous correction processes, the maximum variation of the power ratio was only 10^{-4} having no significant effects on the result. The variation due to power ratio sensitivity can be seen like a second order dependence. Figure 4 shows how true effective efficiency is found by applying corrections. We can see a great effect after the first correction and the small variations introduced by the next correction steps.

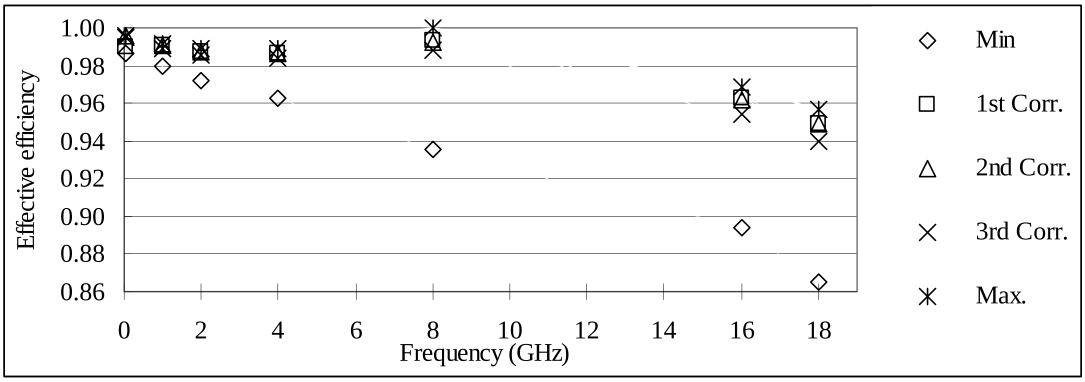

Figure 4. Graphical representation of effective efficiency *vs* frequency and corrections.

VII. Conclusion

The calorimetric measurements are viewed as not stationary data acquisition and computing. Therefore they require several corrections. The correlation with the parasitic quantities and other measured quantities may be found and proper corrections introduced. Applying the described corrections, the accuracy in HF power measurements is improved. The microcalorimeter measurement technique may still be improved if the described corrections are better associated to the new calibration method recently proposed in [3]. Obviously, hardware arrangement with higher performance leads to additional increase in the total accuracy.

References

[1] A. Fantom, *Radiofrequency & microwave power measurement*, Peter Peregrinus Ltd., England, 1990.

[2] J. S. Bendat, A. G. Piersol, *Random Data: Analysis and Measurement Procedures*, John Wiley & Sons Inc., USA, 2000.

[3] L. Brunetti and E. Vremera, “New Calibration Method for Coaxial Microcalorimeters”, CPEM 2004, in press.

[4] T. Inoue and K. Yamamura, “A Broadband Power Meter Calibration System Using a Coaxial Calorimeter” *IEEE Trans. on Instrum. and Meas.*, vol. 45, No. 1, pp. 146-152, February 1996.

[5] L. Brunetti and E. Vremera, “A New Microcalorimeter for Measurements in 3.5-mm Coaxial Line”, *IEEE Trans. on Instrum. and Meas.*, vol. 52, No. 2, pp. 320-323, April 2003.

[6] E. Vremera and L. Brunetti, “Broadband Coaxial Microcalorimeter Efficiency Determination Based on Thermal Simulation and VNA Measurements”, Iasi Polytechnic Mag., XLVIII (LII), Electr., Energ., Electron., *3-4*, pp. 65-76, 2002.