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## Uncertainty Evaluation of the Unified Method for Thermo-Electric Module Characterization

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### 5 Abstract

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In this paper the uncertainty evaluation of the recently proposed Unified Method for Thermo-Electric Module characterization is carried out. The measurement model is detailed and individual uncertainty contributions are highlighted, with close reference to the instrumentation and measurement setup. The uncertainty evaluation is performed by means of a Monte Carlo Simulation. The same algorithm is used to perform a sensitivity analysis, giving a comprehensive insight into the most critical issues of the proposed method and assessing the performance of the two adopted electrical stimuli. The experimental results thereby obtained are discussed and improvements to the measurement setup and technique are finally proposed.

*Keywords*: Thermoelectric devices, Estimation, Monte Carlo methods, Mea surement uncertainty, Sensitivity analysis

#### 8 1. Introduction

<sup>9</sup> Thermoelectricity is an emerging technology capable of harvesting electrical <sup>10</sup> energy from waste heat, thus potentially increasing the energy-efficiency in many <sup>11</sup> applications ranging from aerospace [1–3], to industrial ones [4–7] with low <sup>12</sup> environmental impact.

Thermo-Electric Modules (TEMs), due to their high reliability and compactness, are well suited to work alongside other energy harvesting technologies

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such as photovoltaic [8, 9], to recover the otherwise dissipated heat from the rear of solar panels. As generator, a TEM or an array of TEMs, could be also a valid alternative to batteries in giving an autonomous source of energy to sensor nodes [10–12] and wireless sensor networks [2, 9, 13, 14]. TEMs have also been extensively considered, as heating/cooling devices, to control the operating temperature of microelectronic devices to allow higher clock rates [15], in air conditioning systems [16] and for refrigeration applications [4, 17].

Performances of TEMs are generally given from manufacturers in some standard operating conditions (for example at maximum heat flux) but, in real applications, a TEM-based system rarely works at such conditions. For this reason, since a couple of years, a great research effort is being directed into TEM performance assessment under a broader range of ambient temperature and heat fluxes [18–21].

A typical specification provided by TEM manufacturers is the largest tem-28 perature difference  $\Delta T_{max}$  obtainable between the two faces of the module when 29 cooling capacity is zero at cold side. This parameter is often specified in corre-30 spondence of no more than a couple of hot side temperature values (for instance 31 300 K and 323 K) [22]. Conversely, when the TEM is designed for energy har-32 vesting, the power, voltage and maximum efficiency at matched load condition 33 (i.e. load resistance equals the internal electrical resistance of the module  $R_{in}$ ) 34 are usually given. Clearly, all the values provided as product specifications are 35 related only to ideal use cases and merely useful as general design criteria, but 36 heavily inaccurate in most real applications. 37

In a recent work, the authors have developed a testbed to perform an Unified 38 Method (UM) to quickly estimate the TEM's equivalent electrical and thermal 39 model parameters, i.e. the Seebeck coefficient  $\alpha_S$ , the internal electric resistance 40  $R_{in}$  and the thermal equivalent resistance  $\Theta_{in}$ , in a wide range of temperature 41 differences, ambient temperatures and electric loads [23]. In [23], two different 42 current profiles, namely Current Sweep (CS) and Small Signal (SS) were applied 43 to the TEM to derive all the parameters in a single test, using a quite simple 44 configuration. In that paper a first analytical comparison among the standard 45

uncertainties obtained from the two proposals has been reported. The uncer-46 tainty assessment was based on the study of the linear regression problem in 47 determining the internal resistance  $R_{in}$  and the Seebeck voltage  $V_{th}$  whereas 48 the uncertainty on the estimation of the  $\Theta_{in}$  was evaluated by applying the 49 standard uncertainty propagation proposed by the Guide to the Expression of 50 Uncertainty in Measurement (GUM) [24]. The application of the GUM ap-51 proach is straightforward, however its application to the sensitivity analysis 52 requires calculating the sensitivity coefficients through partial derivatives of the 53 measurement model [25]. In most practical cases, the correlation coefficients 54 and high-order uncertainty components are supposed negligible [26], but still 55 the complexity of the measurement model makes this approach unfeasible. As 56 better justified in Section 4, a good alternative to the GUM method are Monte 57 Carlo (MC) simulations, like those described in [27], and [28]. The method simu-58 lates a high number of measurements by randomly sampling all input quantities 59 from known probability distributions, thus numerically obtaining the distribu-60 tions of output quantities by straightforwardly applying the measurement model 61 [25, 29].62

In [30] all uncertainty sources are identified for both electrical resistivity and 63 Seebeck coefficient; the former was measured using a potentiometric configura-64 tion, and the latter by applying the differential Seebeck method. As probes, two 65 thermocouples mechanically clamped on the sample were used. The test was 66 conducted in a furnace with temperature ranging from room temperature up to 67 1200 K, whereas  $\Delta T$  was varied from 0 up to 10 K using a heater. Using the 68 GUM approach, the authors have obtained, for the Seebeck coefficient, a tem-69 perature dependent and asymmetric uncertainty between +1.0% and -13.1%70 of the nominal value at high temperature and  $\pm 1.0\%$  near room temperature. 71 The electrical resistivity was determined to be  $\pm 7.0\%$  across any measurement 72 temperature [30]. 73

A similar approach was applied in [31] where uncertainties less than 5% and 4% were found for the measurement of the Seebeck coefficient and electrical resistivity respectively, but the characterization was made near room tempera<sup>77</sup> ture with a small temperature gradient ( $\sim 3$  K). Another uncertainty analysis <sup>78</sup> of a thermoelectric materials characterization procedure near room tempera-<sup>79</sup> ture can be found in [32], where some of the measurement systems developed <sup>80</sup> at Fraunhofer Institute for Physical Measurement Techniques are summarized <sup>81</sup> and a 10% accuracy is estimated for Seebeck coefficient, electrical conductivity <sup>82</sup> and thermal conductivity, whereas the uncertainty for the measurement of the <sup>83</sup> figure of merit was estimated to about 40%.

Whereas the aforementioned works are mainly oriented to describe, in terms of uncertainty, only the electrical parameters in samples of bulk thermoelectric materials, this paper focuses on the detailed uncertainty evaluation and on the sensitivity analysis to individual input uncertainties of both electrical and thermal parameters of a TEM.

In Section 2, the mathematical models with the main inputs, outputs and 89 the UM are described, pointing out the advantages introduced by the proposed 90 method. Afterwards, in Section 3, the testbed for electrical and thermal charac-91 terization is briefly outlined and the uncertainty contributions from each source 92 and known parameters are detailed. In Section 4 the approach to the metrolog-93 ical characterization of the proposed technique is introduced by specifying the 94 input uncertainty contributions considered in the Monte Carlo Simulation and 95 explaining how the sensitivity of each output quantity to such contributions has 96 been assessed. Finally, in Section 5, experimental results are presented and, 97 consequently, conclusions are drawn. 98

## <sup>99</sup> 2. The TEM Unified Method

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To characterize the electrical behavior of a TEM, the Seebeck coefficient  $\alpha_S$ and the internal resistance  $R_{in}$  must be estimated. The whole measurement procedure is outlined in Figure 1. First, the Kirchhoff's voltage law at the terminals of the module can be considered:

$$V = R_{in}I + \alpha_S \Delta T \tag{1}$$



Figure 1: Measurement process flow chart

<sup>105</sup> Conversely, the thermal behavior of a TEM can be described by the thermal <sup>106</sup> resistance  $\Theta_{in}$  of the module. Its value is derived by measuring the emitted and <sup>107</sup> absorbed heat fluxes  $q_{em}$  and  $q_{abs}$ , and solving the energy balance between the <sup>108</sup> Peltier effect, the heat conduction and the Joule effect, averaging the respective <sup>109</sup> equations

$$\begin{cases} q_{em} = \alpha_S IT_h - \frac{T_h - T_c}{\Theta_{in}} + \frac{I^2 R_{in}}{2} \\ q_{abs} = \alpha_S IT_c - \frac{T_h - T_c}{\Theta_{in}} - \frac{I^2 R_{in}}{2} \end{cases}$$
(2)

where  $T_h$  and  $T_c$  are, respectively, the temperature of the hot and cold side.

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The thermoelectric performance relies directly on the dimensionless thermoelectric figure of merit  $Z\bar{T}$  which summarizes the bulk material properties and allows comparisons between different TEMs.

$$Z\bar{T} = \frac{\alpha_S^2 \Theta_{in}}{R_{in}}\bar{T} \tag{3}$$

where  $\bar{T}$  is the average temperature between the hot and the cold side of the module, as defined in Section 3.1.

From equation (3),  $Z\overline{T}$  is a function of the electrical resistance, the Seebeckcoefficient and the thermal resistance and can be determined by measuring  $\alpha_S$ ,  $R_{in}$  and  $\Theta_{in}$  separately [33] or directly using the Harman Method (HM) [34] or other transient methods [35]. An example of direct measurement of the Figure of Merit is the "Z meter", a technique for rapid pass/fail test of TEMs with moderate accuracy [36].

However, all three quantities in (3) give information about electric and thermal processes in a material. Consequently, in thermoelectric research but also in commercial devices, it is most common to estimate each parameter individually to obtain the figure of merit and to determine the transport properties of material samples. It is to be noted that the HM can only be carried out under small temperature differences.

For example,  $\alpha_S$  and  $\Theta_{in}$  are usually measured under a temperature difference of 10 – 20 K without an electric current flowing through the material sample, while  $R_{in}$  is measured at isothermal conditions by applying a small excitation current (in the order of a few milliamperes) [33]. Similarly, the HM is only valid if the Joule heat generation is negligible, thus a weak current and a small temperature difference should be imposed [34].

Generally, a TEM is usually operated under much larger temperature differences, with significant electric currents flowing in the module; this is the case of the characterization of thermoelectric power generators. In such scenarios, the above-mentioned techniques do not provide measurement results relevant to actual operating conditions.

A lot of research has already been published reporting characterization techniques for TEMs under such operating conditions [37–39]. However, the presented techniques adopt complex setups, requiring mechanical components to compress the test stack and a combination of heat sink/sources with both vacuum and circulating pumps to keep the thermal gradient constant and to avoid heat dissipation phenomena. A comprehensive survey of different approaches and testbeds is given in [40].

Another interesting procedure implementing a transient method is proposed by McCarty [41], where a V-I curve tracing method is described that estimates also the average thermal resistance of a TEM. This method requires only four data points obtained by switching a relay (short circuit condition, open circuit condition and the two transitions at near thermal steady state). No reproducibility nor accuracy information is, however, provided for the method.

The UM for TEM characterization has been introduced to overcome the 154 limitations of the previous methods. Using this method, it is possible to fully 155 characterize a TEM in two different quadrants of the P - I plane, i.e. in both 156 energy-generating and heating-cooling mode [42] with a good accuracy. Many 157 different operating conditions, typical in temperature control scenarios, can be 158 explored by setting the room temperature  $T_a$  (i.e. the cold side temperature of 159 the TEM) and the temperature difference  $\Delta T$  between the two sides. Measured 160 module parameters can then be used to accurately simulate TEM performance 161 in real life scenarios. 162



The UM is based on a measurement scheme whose complexity can be adapted

according to the required uncertainty or to the available instrumentation, using two different measurement techniques. As detailed in [23], the UM, constist in applying first a constant current to reach a given steady state, which results in a temperature difference  $\Delta T$  between the two sides obtained using a Proportional-Integrative (PI) controller in a closed-loop feedback; then, a stimulus signal is applied and the resulting current flowing in the module and voltage at its terminal are acquired. Two different stimuli are proposed:

• the small signal (SS) consists in sinusoidal stimulus with an amplitude of approximately 12 mA that is added to the steady state current. It requires no previous assumption and is generally faster because the bias point is not altered. This stimulus requires a simple power driver, but produces worse results in terms of uncertainty for increasing values of  $\Delta T$ ;

the sweep signal consists in a current sweep (CS) from the bias value to
its opposite. It requires a previous identification of the dynamic model
of the module and a 4-quadrant power amplifier, but produces far more
better results in terms of accuracy.

#### **3.** Experimental setup

The above described steps have been implemented in an automatic test pro-181 cedure that carries out measurements over customizable combinations of the 182 cold side temperature  $T_c$  and the working  $\Delta T$ . This last parameter is, in par-183 ticular, set by imposing a steady state current  $I_{st}$  to the TEM and exploiting 184 the Peltier effect. The whole test was conducted inside a Discovery Es 250 (DY-185 250) climate chamber by Angelantoni Group S.p.A., that brings the cold side of 186 the module to the ambient temperature. The developed testbed automatically 187 sweeps along a wide range of electrical load conditions using only a DAQ board 188 and a 4-quadrant transconductance amplifier as shown in Figure 2. 189

Measurements for thermal characterization have been performed by using two heat flux sensors. Each one was implemented by means of three layers:

• Aluminum (2 mm)

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Figure 2: Synoptic diagram of the measurement system for the UM

• Glass (8 mm)

• Aluminum (2 mm)

<sup>195</sup> Metal layers have been equipped with J-type thermocouples inserted in suitably
<sup>196</sup> drilled holes. A thin layer of high thermal conductivity silver-based thermal
<sup>197</sup> paste was interposed between layers to minimize the thermal contact resistance.

#### 199 3.1. Setup and Measurement Model

The proposed method consists in placing the TEM under test between two 200 heat-flux sensors (Figure 2); when the desired operating conditions are met, i.e. 201 when the thermal steady state has been reached, the driving current is locked 202 to the last current value, and the supervisory software waits for all transients 203 to run out. Then, the SS profile is applied: a small 10 Hz sinusoidal current 204 stimulus is added to the steady state current  $I_{st}$ ; finally, the CS profile is applied 205 and the driving current  $I_{st}$  is swept to its symmetric value  $-I_{st}$  with a ramp-like 206 signal. The duration of each described current profile is set to a value that is 207 sufficiently low with respect to the thermal time constant of the module [23]. 208 When the test procedure is completed, the following quantities are obtained: the 209 temperatures at each layer, the voltage  $V_L$  and the current I at its terminals. 210 At the end of each test, all raw data (acquired voltages) are stored for further 211

•  $V_L$  is not processed

- $V_s$  is divided by  $R_s$  to obtain *I*.  $R_s$  is a 1  $\Omega \pm 0.0035\%$  shunt resistor measured with an Agilent 3458A  $8^{1/2}$  digital multimeter in 4-wires configuration
  - $T_a$  and  $T_{cj}$  are obtained from respective voltages using two LM35A integrated thermal sensors by Texas Instruments, with nominal sensitivity S = 10 mV/(K)
- $T_1, T_2, T_3, T_4$  are computed using NIST coefficients for J-type thermocouples and applying a software cold-junction compensation as described in subsection 3.4
  - $q_{em}$  and  $q_{abs}$  are computed as described in [23]

$$\begin{cases} q_{em} = \frac{T_3 - T_4}{\Theta_{ref}} \\ q_{abs} = \frac{T_2 - T_1}{\Theta_{ref}} \end{cases}$$
(4)

where 
$$\Theta_{ref} = 8.15 \text{ K/W}$$

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•  $T_c$  and  $T_h$  are derived by computing the temperature drop on the ceramic layers induced by the heat fluxes  $(\Delta T = T_h - T_c, \bar{T} = (T_h + T_c)/2)$ 

$$\begin{cases} T_h = T_3 + q_{em}\Theta_{cer} \\ T_c = T_2 + q_{abs}\Theta_{cer} \end{cases}$$
(5)

where  $\Theta_{cer} = 0.02 \text{ K/W}$ 

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•  $V_{th} = \alpha_S \Delta T$  and  $R_{in}$  are derived using equation (1), applying a mixed least squares linear regression [43] to the acquired values  $I, V_L$ 

- $\alpha_S$  is then obtained as ratio of  $V_{th}$  to  $\Delta T$ 
  - $\Theta_{in}$  is computed using equation (6) already obtained in [23]

$$\Theta_{in} = \frac{2(T_h - T_c)}{\alpha_S I_{st}(T_h + T_c) - (q_{em} + q_{abs})}$$
(6)

Table 1: Rated specifications at matched load conditions for TES1-12730 Thermoelectric Module by Thermonamic

$T_h$ Hot side	$\Delta T_{max}^{3}$	$V_{max}$ Voltage <sup>1</sup>	$I_{max}$ Current <sup>2</sup>	$\begin{array}{c c} R_{max} \\ \mathbf{Resistance^4} \end{array}$
$[\mathbf{K}]$	[ <b>K</b> ]	$[\mathbf{V}]$	$[\mathbf{A}]$	$[\Omega]$
300	70	16.2	3.5	3.47
323	79	16.9	3.5	3.74

Notes:

<sup>-1</sup> Maximum voltage at  $\Delta T_{max}$  and respective  $T_h$ 

<sup>2</sup> Maximum current to achieve  $\Delta T_{max}$ 

<sup>3</sup> Maximum temperature difference occurs at  $I_{max}$ ,  $V_{max}$ , and Q = 0 W

<sup>4</sup> Maximum resistance rated at AC conditions

#### 235 3.2. TEM module

The characterization was performed using a TES1-12730 from Thermonamic Electronics Corporation [22], a low-cost commercial module designed for cooling applications. The module has an area of  $30x30 \text{ mm}^2$  and a thickness of 3.6 mm, with Alumina (Al2O3) ceramic wafers. Its performances are declared by the manufacturer for two different working conditions, reported in Table 1. Also a couple of performance curves that provide the user with the qualitative trend of some parameters when  $\Delta T$  varies are reported.

For such parameters a 10% tolerance is given with respect to product specifications.

## 245 3.3. Data acquisition system

All the voltages have been acquired using a National Instruments (NI) USB-6361 X Series data acquisition (DAQ) board, with eight 16-bit fully differential analog input channels able to provide sample rates up to 2 MS/s for singlechannel acquisitions and up to 125 kS/ch/s for eight-channel acquisitions [44], extended with a BNC2110 DAQ accessory.

The adopted sampling frequency  $f_S = 160$  Hz guarantees that the settling time requirements for multichannel measurements are largely met for each measurement range and for different source impedances as reported in the datasheet. For the sake of clarity, all information relative to each data channel have been reported in Table 2.

Symbol	Source	Description		Range (V)	Settling time $(\mu s)^{b}$
$V_L$	Load	Load voltage		$\pm 10$	1.5
$V_S$	$R_S$	Shunt voltage		$\pm 5$	1.5
$T_a$	LM35A	e	Room	$\pm 1$	1.5
$T_{cj}$	LM35A	tur	Cold Junction	± 1	1.5
$T_4$	J-type ThC	era	Layer 4	$\pm 0.1$	8
$T_3$	J-type ThC	] du	Layer 3	$\pm 0.1$	8
$T_2$	J-type ThC	Ler	Layer 2	$\pm 0.1$	8
$T_1$	J-type ThC		Layer 1	$\pm 0.1$	8

Table 2: NI USB-6361 channels resume

<sup>b</sup>  $\pm 15$  ppm of Step ( $\pm 1$  LSB for Full Scale Step)

Firstly, the DAQ board has undergone a self-calibration procedure to reduce the relative standard uncertainties in the interval 0.0046 - 0.0079 % of the fullscale as reported in Table 3. The specifications given in the Table are obtained following the worst case rule [45], as specified in the DAQ datasheet [44].

260 3.4. Temperature Sensors

The temperatures of the stacked layers are acquired using four grounded Jtype bare thermocouples by RS Pro, with 1 m wires and suitable for temperature measurement in the range 223 K to 523 K. The manufacturer also provides a standard tolerance for thermocouples "J" class 1 of  $\pm 1.5$  K in the range 233 K to 648 K.

The cold-junction compensation, as well as the measurement of the temperature inside the climate chamber, are both performed using two LM35A sensors by Texas Instruments, which provide a typical accuracy of  $\pm 0.2$  K at 300 K room temperature and a worst-case accuracy of  $\pm 0.5$  K at 423 K.

$V_{FS}$	$u_r(G)_{\%}$	$u_r(O)_{\%}$	$u_r(INL)_{\%}$	$u_r(Q)_{\%}$	$u_r(DAQ)_{\%}$
0.1	0.0063	0.0031	0.00346	0.00044	0.0079
1	0.0038	0.0011	0.00346	0.00044	0.0053
5	0.0033	0.0009	0.00346	0.00044	0.0049
10	0.0029	0.0009	0.00346	0.00044	0.0046

Table 3: NI USB-6361 uncertainty specifications (as percentage of  $V_{FS}$ , at full scale)

## 270 4. Metrological Characterization

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In general, in this discussion, the term *uncertainty* will be a shorthand for *standard uncertainty*, as defined in the GUM (clause 2.3.1). Also the definition of Type A and Type B uncertainties is that provided by the GUM (clauses 2.3.2 and 2.3.3).

The mathematical models for the relevant output quantities are not easy to treat analytically for three main reasons:

The number of input uncertainty contributions is high (n = 21, considering
Type A and B contributions)

• Models are complicated and involve many intermediate results with which uncertain quantities are combined

•  $\alpha_S$  and  $R_{in}$  are measured by means of linear regression performed on measured voltages and currents that are, in turn, uncertain.

While the first and the second issue may be overcome by means of symbolic computation engines, the last one poses a methodological concern that cannot be addressed by straightforward application of the GUM approach [24]. In fact, while the voltage across the TEM is directly measured by DAQ board channel, the current is measured indirectly as the ratio of voltage and resistance on a shunt resistor; all three quantities involved introduce uncertainty contributions of which only Type B evaluations are available.

Such a complex statistical model, however, can be straightforwardly implemented in a suitable Monte Carlo Simulation, which is a powerful tool for uncertainty analysis, relieving from the need of complicated analytical computations. On the other hand, some pitfalls in the Monte Carlo approach must be avoided: in particular, the simulation implemented here does not follow the scheme described in GUM Supplement 1 and 2 [46, 47], since it has some recognized issues.

In short, the Supplement 1 method (extended by Supplement 2 for the case of multiple output quantities [48]) aims at evaluating the posterior distribution of

Class	Monte Carlo run	Uncertain quantities	Description		
	#1	DAO(T)	Type A and B on DAQ channel for ambient		
	TT 1		temperature		
	#2	$LM35(T_a)$	Type B on LM35 for ambient temperature		
Thermal	<i>#</i> 2	DAO(T)	Type A and B on DAQ channel for cold junction		
	#0	$DAQ(I_j)$	temperature		
	#4	$LM35(T_j)$	Type B on LM35 for cold junction temperature		
	#5	DAQ(T)	Type A and B on DAQ channel for thermocouples		
	#6	TC	Type B on temperature from thermocouples		
Electrical	#7	$DAO(V_{\perp})$	Type B on DAQ channel for voltage on shunt		
		$DAQ(v_{Sh})$	resistor		
	#8	$DAQ(R_S)$	Type B on shunt resistance		
	#9	$DAQ(V_{Ld})$	Type B on DAQ channel for load voltage		

Table 4: Individual Monte Carlo runs for the sensitivity analysis

the measurand, in a Bayesian sense, and reaches its goal with a straightforward propagation of state-of-knowledge distributions. This procedure is equivalent to a simplified Bayesian analysis, and as such can give inconsistent results, corresponding to an erroneous choice of the prior distribution of the measurements. Theoretical analyses of the approach are, for example, in [49–52], and practical examples of clearly unsatisfactory results obtained by this approach in common problems are, for example, in [51, 53].

In this paper, instead, the Monte Carlo approach is used to perform nu-306 merical sensitivity analysis, by simulating "physical" measurement errors in the 307 input quantities, and propagating them through the mathematical model of the 308 measurement system. In particular, one uncertainty contribution at a time is 309 considered [28]. This method, sometimes called "one at a time" (OAT) [27], con-310 sists in performing a separate Monte Carlo run for each of the *n* uncertain input 311 quantities. Each run results in a specific partial uncertainty  $\hat{u}_i(y)$ , generated by 312 a single input uncertainty contribution. In the end, therefore, a set of n distinct 313 partial uncertainties  $\hat{u}_i(y)$  for the measurement model  $y = f(x_1, x_2, \dots, x_n)$  is 314 computed. 315

This Monte Carlo algorithm has been implemented in the MATLAB environment. The evaluations under every considered value of ambient temperature and temperature gradient are performed in parallel to speed up the computation. To perform the OAT sensitivity analysis, in each run only a single uncertainty contribution has been activated, except from the last run where all contributions were active to compute the global combined uncertainty. To evaluate the contribution of each source in a meaningful way, individual uncertainty contributions have been grouped as in Table 4. Basically, for DAQ channels, Type A and Type B uncertainties have been combined as suggested in the GUM ([24], Clause 4.3.7, Example 2) so that a more compact representation of sensitivities could be given.

All Type A uncertainty contributions have been simulated with random errors drawn from normal distributions with zero mean and  $\hat{u}_A(x_i)$  standard deviation. On the other hand, all Type B uncertainty contributions have been simulated with random errors drawn from uniform distributions with zero mean and range  $2u_B(x_i)$ , since no further detail was given by sensors and DAQ manufacturers.

It is also worth observing that the last three runs deal with measurement data that, following the mathematical model, are used for a mixed least squares regression (Section 3.1). This means that runs #7, #8 and #9 include the statistical contribution of 160 measurements each that, however, are independent of each other and, consequently, are independently perturbed in the Monte Carlo algorithm.

A clear and interesting way to compare the contribution of input uncertainties is to express the sensitivities as partial contributions to the total output variance. That is, as suggested by Sobol [54]:

$$u = \frac{u_i^2(Y)}{u^2(Y)} \tag{7}$$

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where  $\hat{u}_i^2(Y)$  are the output uncertainties from each OAT step and  $\hat{u}^2(Y)$  is the total variance, estimated in the last Monte Carlo run.

Finally, as a simple yet effective validation step, for each output quantity yit has been verified that

<sub>447</sub> 
$$\sum_{i=1}^{N_{run}} u_i^2(y) \simeq u^2(y)$$
(8)

where u(y) is the standard uncertainty computed in the Monte Carlo run where all contributions are active. This verification step has also highlighted that <sup>350</sup> correlations between uncertainty components are negligible.

## 351 5. TEM Parameters Results

#### 352 5.1. Operating conditions

Measurements have been performed under different operating conditions of the TEM, defined by an equally spaced grid in the  $(T_C, \Delta T)$  space for 283 K  $\leq$  $T_C \leq 323$  K and 10 K  $\leq \Delta T \leq 45$  K. As discussed in Section 2, the  $T_C$  and  $\Delta T$  steady states have been set by means of a PI controller and, thereafter, their values have been measured. Therefore, the uncertainty on the operating conditions themselves must be investigated before the sensitivity analysis can be carried out.

The Monte Carlo algorithm shows that the most critical of the two parameters is  $\Delta T$ , resulting from the combination of two temperature measurements performed with thermocouples. The relative standard uncertainty  $u(\Delta \hat{T})/\Delta \hat{T}$ , in fact, rapidly grows as  $\Delta T$  decreases under 15 K.

For example, by applying the DAQ board specification for  $\Delta T = 45$ K, the differential voltage is about 2.4 mV measured on a full scale range of 0.1 V. The relative standard uncertainty is, in this case, about 40 times higher than at full-scale range, and for lower values of  $\Delta T$  it is even worse.

The trend, as shown in Figure 3, is the same for all  $T_c$  values. The uncertainty on  $T_c$ , on the other hand, obviously increases for low temperatures, however it does not rise over 1.2% even for  $T_c$  close to 283 K. This is also due to the fact that  $\Theta_{cer}$  in Equation (5) is small, and so is the temperature drop on the ceramic layers.

This preliminary analysis suggests in which region of the investigated steady states the uncertainty evaluation can give consistent results. Conventionally, results will be given for  $\Delta T$  values whose uncertainty is not greater than  $\sim 10\%$ , i.e.  $\Delta T \geq 12$  K.

This does not invalidate at all the characterization procedure, since the TEM used as Devices Under Test are commonly designed to be operated when the



Figure 3: Relative uncertainty on  $\Delta T$  measurements in the  $(T_c, \Delta T)$  space

temperature gradient is in the order of some from few tens up to hundreds
Kelvin degrees [22, 23].

Nevertheless, it is worth examining the uncertainty contributions to  $\Delta T$ measurements in slightly more detail:

• Thermocouple coefficients ( $\sim 78.45\%$  of total variance)

• DAQ measurements on 4 separate channels ( $\sim 21.55\%$  of total variance)

Among the two, the effect of thermocouple coefficients is predominant. It is an exclusively sensor-related contribution, suggesting that using more accurate sensors than thermocouple would allow achieving significant results from the characterization procedure also for lower values of  $\Delta T$  than those discussed in the next Section.

#### 390 5.2. Sensitivity analysis

In this Section, the results from OAT sensitivity analysis are presented. As thoroughly discussed in Section IV, ten MC runs have been performed, one for each input uncertainty contribution, plus a run with every contribution active at once.

The first result of the analysis is that five of the nine uncertainty components outlined in Table 4 give almost no contribution to the total output variance for every output parameter, i.e. their contribution is several orders of magnitude lower than the others. Therefore, only the relevant contributions will be shown in the following bar graphs for the sake of readability.

Moreover, for all the parameters that are measured with both SS and CS methods, an error figure will be given to represent how much the estimates coming from each method deviate from each other. Such error is computed, for all y outputs, as follows:

$$e_Y = \frac{\overline{|Y_{SS} - Y_{CS}|}}{\max_{T_C, \Delta T} Y - \min_{T_C, \Delta T} Y}$$
(9)

where the double bar operator defines the average taken over both  $T_c$  and  $\Delta T$ . The global range of Y is chosen as reference for this error figure.

One may also immediately observe that results obtained with the SS method appear more "irregular" than those coming from the CS method (see, e.g. the figure of merit  $Z\bar{T}$  in Figure 8). This is a consequence of electrical parameters  $(V_{th} \text{ and } R_{in})$  being estimated by means of a linear regression computed on narrowly spaced points, that is exactly the shortcoming of the SS method.

As last remark, it can be shown that, on the  $(T_c, \Delta T)$  space, the uncertainties shows relevant trends only with respect to  $\Delta T$  for every output parameter. A slice of the mesh plot taken for a conventional value of  $T_c$ , therefore, contains all relevant information about how the uncertainties change in the space of operating conditions, also with enhanced readability. Thence, the experimental results will be presented as follows:

418

404

• Parameter values: mesh plots (283 K 
$$\leq T_c \leq$$
 323 K and 12 K  $\leq \Delta T \leq$ 



Figure 4: Thermal resistance of the TEM measured with both proposed methods ( $e_{\Theta_{in}}=0.21)$ 

419 45 K)

420

421

• Total relative uncertainties: 2D plots ( $T_c = 300$  K and 12 K  $\leq \Delta T \leq 45$  K).

422 5.2.1.  $\Theta_{in}$  thermal resistance

<sup>423</sup> The SS and CS methods exhibit the same performance in terms of relative <sup>424</sup> uncertainty and the maximum SS deviation from the CS value is less than 10%. <sup>425</sup> This suggests that the proposed methods can be considered equivalent with <sup>426</sup> respect to  $\Theta_{in}$  measurement.

427 5.2.2.  $\alpha_S$  Seebeck coefficient

As for  $\Theta_{in}$ , the SS and CS methods exhibit the same performance in terms of total uncertainty, thermocouple coefficients giving the highest contribution. As visible in Figure 6(b), the Seebeck's coefficient measurement with the SS



Figure 5: Seebeck coefficient measured with both proposed methods ( $e_{\alpha_S} = 0.26$ )

<sup>431</sup> method is slightly more sensible to  $V_s$  and  $V_L$  uncertainties than  $\Theta_{in}$ ; this <sup>432</sup> difference propagates sensibly to  $Z\bar{T}$  (Figure 9(a)).

#### 433 5.2.3. Seebeck voltage and electrical resistance

These two parameters are computed from the same set of measurements, thence they are hereby jointly discussed. Although, as shown in Figure 7, measurement results provide sensibly different values in the operating conditions space, the measurement model for both  $R_{in}$  and  $V_{th}$  does not directly depend on any temperature measurement. The shunt resistor has been measured with an Agilent 3458A 8<sup>1</sup>/2 digits multimeter, therefore its contribution to current measurements can be neglected.

The outcome of the Monte Carlo analysis, on one hand shows that relative uncertainties are low if compared to those affecting the other outputs, and on the other hand, recalling the last paragraph of Section 5.2, they do not show any visible trend as for  $\Theta_{in}$ ,  $\alpha_S$  and  $Z\bar{T}$ , for the SS method. The uncertainties





Figure 6: Relative uncertainty on  $\alpha_S$  measu Aments (a) and uncertainty contributions from direct measurements as absolute standard uncertainties (b)

Parameter	Error figure [%]	Method	Maximum uncertainty [%]	Average uncertainty [%]
$R_{in}$	0.10	CS	0.01	0.01
		SS	0.63	0.01
$V_{th}$	0.03	CS	0.02	0.01
		SS	1.03	0.97

Table 5: Uncertainty evaluation for  $R_{in}$  and  $V_{th}$ 

obtained from the CS method, instead, exhibit the same increasing trend as the other output parameters, plus a (way weaker) linear trend in the  $T_c$  direction. This may be due to the fact that the applied sweep signal was not fast enough to satisfy the steady state condition [55].

For these two parameters, results are expressed synthetically in Table 5, so 449 that a global and comparative insight on the performance of the two methods is 450 given. From the Table, it clearly appears that the two methods exhibit a good 451 matching for  $R_{in}$ , but yield seemingly different estimates of  $V_{th}$ . The relative 452 uncertainty on  $V_{th}$  is also two orders of magnitude greater for the SS method. 453 This method, in fact, relies on measurement points that are much closer to 454 each other than in the CS method, therefore the linear regression yields greater 455 uncertainties. 456

## 457 5.2.4. $Z\overline{T}$ figure of merit

As already pointed out in [55], the linear dependence of the dimensionless figure of merit  $Z\bar{T}$  is sensibly stronger on  $\Delta T$  than on  $T_C$  (Figure 8). The CS method exhibits lower total uncertainty, enhancing this feature for high  $\Delta T$ . This is clearly shown in Figure 9(a).

Looking at the sensitivity analysis (Figure 9(b)), the CS method is substantially insensitive to  $V_s$  and  $V_L$  uncertainties, while the contributions to  $Z\bar{T}$ total uncertainty for the SS method come non-negligibly also from such measurements.





Figure 7: Electrical resistance  $R_{23}(a)$  and Seebeck voltage  $V_{th}$  (b)



Figure 8: Dimensionless figure of merit  $Z\bar{T}~(e_{Z\bar{T}}=0.23)$ 

## 466 6. Conclusions

In this paper a methodology for the metrological analysis of the Unified Method for Thermo-Electric Module characterization has been developed and experimental results from a real testbed have been discussed. The individual uncertainty components have been outlined and a sensitivity analysis with respect to each component of the measurement setup has been performed with regard to both applied electrical stimuli.

The experimental results show that Current Sweep and Small Signal methods provide compatible estimates of every parameter and exhibit good results in terms of overall uncertainty, with Current Sweep performing better at the cost of employing more expensive and complex instrumentation. The sensitivity analysis, on the other hand, clearly highlights that the greatest contribution to overall uncertainty on the estimation of thermal parameters is given by tem<sup>479</sup> peratures measured with thermocouples, that are as a matter of fact widely<sup>480</sup> employed in Thermo-Electric Module characterization practice.

Even so, the outcome of the sensitivity analysis points out that, if thermocouples are kept into the setup, cheaper acquisition devices can be employed without affecting the metrological performances

The results suggest that the proposed measurement setup can be dramatically improved by employing more accurate temperature sensors instead of standard thermocouples, without making any adjustment to the core characterization technique. By doing so, also Thermo-Electric Modules designed for low temperature gradients can be reliably characterized.

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Figure 9: Relative uncertainty on  $Z\bar{T}$  measurements (a) and uncertainty contributions from direct measurements as percentage of total variance (b)