Automated Power Sensors Calibration up to 26.5 GHz

Predrag Rakonjac, Bratislav Milovanović[1], Nebojša Dončov[1]

Abstract - **This article summarizes the basic concepts of the radio frequency and microwave power standards, power sensors, and basic methods of power sensors calibration. It includes presentation of automated system for power sensors calibration in the frequency range from 10 MHz to 26.5 GHz, which is implemented using Agilent VEEpro7 software and Feedthrough RF Power Standard TEGAM F1135A. Analysis of measurement uncertainty of Thermocouple Sensor Calibration Factor is conducted according to the EA-4/02 document. This article also presents validation of applied method for power sensor calibration.**

Key words- **Microwave power reference standard, Calibration factor, Measurement uncertainty, Mismatch Uncertainty, RF power sensor.**

I. Introduction

The measurements of electric power in radio frequency (RF) and microwave application have the same significance as voltage and current measurements at low frequencies and in DC rate. In microwave systems, it is crucial to determine input and output power of each module correctly, which includes measurement of power in wide frequency and power ranges. Power sensors (including thermistor, thermocouple and diode sensors) are very important in activities of laboratories that work in RF and microwave fields. They are extensively being used during the process of calibration of all kinds of signal generators, spectrum analyzers, attenuators, directional couplers, power splitters; and measurement of RF and microwave power, in general. In this paper terms of RF and microwave power have equivalent meaning as well as terms of sensor and mount have equivalent meaning.

Power sensors cover wide frequency range from 100kHz to 110GHz and power range from 100pW to 25W [1]. Due to importance and number of mentioned devices, as well as the fact that work of microwave laboratories is largely based on power measurement, great deal of attention needs to be devoted to power sensor calibration. Calibration factor (K) and reflection coefficient (Γ), being two most important power sensors parameters, need to be measured in entire frequency range during the power sensor calibration process. Power sensor calibration is a complex process that requires large amount of measurement points, measured in many iterations. Hence, automatization of measurement process in that area is absolutely reasonable and necessary.

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Primary Calibration Laboratory for microwave technique ML-02, which is part of Technical Test Center, Ministry of Defence of Republic of Serbia, has variety of power sensors that cover frequency range from 100 kHz to 26.5 GHz and power up to 25W. This institution developed automated system for calibration of all types of power sensors in range from 10 MHz to 26.5 GHz. Moreover, system is being used for determination of calibration factor measurement uncertainty.

Core of automated measurement system is composed of Feedthrough RF Power Standard TEGAM F1135A (frequency range from 10MHz to 26.5GHz) [2] and programmable measurement instruments with HPIB interface (IEEE 488).

Main program for this measurement system is written using software package Agilent VEEpro7. Communication between instruments and controller (PC) is realized using Agilent 82357A USB/HPIB interface. Standard method - Direct power comparison is used in calibration process [2].

Determination of measurement uncertainty is carried out according to the recommendation EA-4/02 [3]. Analysis of measurement uncertainty of calibration and validation of the system are very significant regarding the requests of ISO/IEC 17025:2005 standard and accreditation of calibration laboratories.

This paper represents extended version of the paper presented on the 52nd ETRAN conference [10].

II. Microwave power standard and mount

A. Primary Microwave Power Standard

The national standard for microwave power is a set of microcalorimeters and associated bolometer mounts. The microcalorimeters are the primary microwave power standard (National Power Reference Standard), while the associated bolometer mounts are secondary standards (National Working Standard). The National Institute of Standards and Technology (NIST) in USA maintains a National Reference Standard. NIST has two coaxial and five waveguide microcalorimeters. The coaxial microcalorimeters include Type N calorimeter and 2.4 mm calorimeter, which cover frequencies from 50MHz to 50GHz. The waveguide microcalorimeters cover frequencies from 18GHz to 110GHz.

Microcalorimeter is used for determination of effective efficiency (η_e) of associated bolometer mount (secondary microwave power standard). This bolometer mount is then used for calibration of other Measurement Reference Standards and Transfer Standards. When a power sensor can be referenced back to that National Reference Standard, the measurement is said to be traceable to NIST.

Several National Metrological Institutes (NIST-USA, PTB-Germany, NPL-UK, LCIE-France, NPLI-India, etc) have microcalorimeters. Due to presence of losses, mismatches and other sources of errors, Primary Microwave Power Standard has measurement uncertainty around 10^{-3}, while for example Primary DC Voltage Standard has measurement uncertainty around 10^{-7}.

Microcalorimeters (Fig. 1) operate on the principle that after applying an equivalence correction, both DC and absorbed microwave power generate the same heat. Comprehensive and exhaustive analysis is required to determine the equivalence correction and account for all possible thermal and RF errors, such as losses in the transmission lines and the effect of different thermal paths within the microcalorimeter and the associated bolometer mount (secondary standard). The DC-substitution technique is used because the fundamental power measurement can then be based on DC voltage (or current) and resistance standards. The traceability path leads through the microcalorimeter (for effective efficiency, a unit-less correction factor) and finally back to the national DC standards. Measurement uncertainty of microcalorimeter is from 0.1% to 0.8 %, depending on frequency.

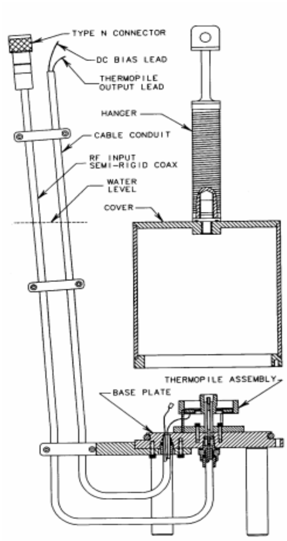

Fig. 1. Schematic cross-section of the NIST coaxial microcalorimeter.

B. Terminating and Feedthrough RF Power Standard

Terminating RF Power Standard and Feedthrough RF Power Standard represent distinct types of microwave power standards. They are constructed and adjusted for transfer of calibration factor (K) from secondary microwave power standard to microwave power sensors. Thereby, power measurement traceability can be established from primary national standard, over secondary standard, Terminating RF power standard and Feedthrough RF power standard, to each and every measurement power sensor.

The Terminating RF Power Standard and Feedthrough RF Power Standard are usually temperature stabilized thermistor mounts. Temperature stabilized thermistor mounts have been chosen because of good long-term stability and high temperature stability. High precision manufacture of connectors is required for obtaining minimum values of reflection coefficient and mismatch uncertainty. Process of temperature stabilization of sensors is important for elimination of the effects of changes in the ambient temperature. Thus, temperature stability lies within ±1mK when internal temperature of mount is 60° C.

The Terminating RF Power Standard, shown in Fig. 2A, is thermistor power sensor which closes coaxial or waveguide transmission line. Total amount of power received from transmission line is absorbed by this sensor. Calibration factor of the Terminating RF Power Standard (i.e. Primary RF Power Transfer Standard) is labelled with K_1. This sensor is calibrated by secondary microwave power standard directly in NIST, and is used to transfer calibration factor from Secondary Power Standard to Feedthrough RF Power Standard, as well as for high precision power measurement of attenuators, power reference output and adapters.

A B

Fig. 2. A -Terminating RF Power Standard, B- Feedthrough RF Power Standard.

Calibration factor K_1 is defined by (1):

$$K_1 = \frac{P_{dc1}}{P_{RF}} \quad (1)$$

Where:
K_1 = calibration factor of the Terminating RF Power Transfer Standard traceable to NIST,
P_{RF} = Level of applied RF power,
P_{dc1} = DC substituted power measured by the device connected to the Terminating RF Power Transfer Standard.

Feedthrough RF Power Standard (i.e.Working RF Power Transfer Standard), shown in Fig. 2B, is Terminating thermistor mount and power splitter combination. Terminating RF Power Standard is connected to the first port of power splitter and sensor under test (SUT) is connected to the second port (so-called test port). Microwave power is split equally between these two ports. Feedthrough RF Power Standard calibration factor (K_2) considers characteristics of both Terminating RF Power standard and power splitter and determines power on the test port (P_{sut}). This power is defined by $P_{sut}=P_{dc2}/K_2$, where P_{dc2} is DC substituted power measured by the device connected to the Feedthrough RF Power Transfer Standard. Feedthrough RF Power Standard calibration factor K_2 is obtained from known Terminating RF Power Standard calibration factor K_1. Overall, the

Feedthrough RF Power Transfer Standard is used to determine the calibration factor for other terminating powers sensors K_b.

In general, calibration factor is ratio of applied vs. measured power. The result of the calibration factor calculation (K) will be a decimal value, typically between 0 and 1. Calibration factors can also be represented as a percentage or in decibels:

$$K(\%) = K * 100 \quad \text{or} \quad K(dB) = 10 * \log(K) \tag{2}$$

C. RF Power Sensors

There are three popular devices for sensing and measuring average power at RF and microwave frequencies. Each of the methods uses a different kind of device to convert the RF power to a measurable DC or low frequency signal. The devices are the thermistor, the thermocouple, and the diode detector. Each type of sensors uses associated kind of power meter which measures equivalent DC or low frequency signal. This signal is commensurable to applied RF power on sensor and power meter directly indicates RF power in [W] or [dB]. Instead of power meter, self-balancing bridge and digital voltmeter are used for high currency measurements with RF Power Transfer Standard. Voltmeter alternatively measures voltage V_2 and V_1, where V_2 is DC voltage across the precision resistor with RF power applied and V_1 is DC voltage across the precision resistor in the absence of RF power. DC substituted power P_{dc} is defined by (3):

$$P_{dc} = \frac{V_1^2 - V_2^2}{R} \quad \text{and} \quad P_{RF} = \frac{P_{DC}}{K_{1S}} \tag{3}$$

Where:
P_{dc} = DC substituted power measured by the device connected to the RF Power Sensor, R = nominal resistance of the thermistor in Ohms (200 Ω or 100 Ω), P_{RF} = Level of applied RF power, K_{1S} = calibration factor of the Terminating Power Sensor.

RF Power sensors are divided in two groups regarding realization of input connector - coaxial and waveguide. Beside mentioned power sensors and corresponding power meters, also calorimeter power meters and RF Directional Watt meters are used for average power measurement (which is out of scope of this paper).

III. Calibration factor and Mismatch Uncertainty

In the ideal measurement case, the power sensor absorbs all the power incident upon the sensor. There are two categories of non-ideal behavior.

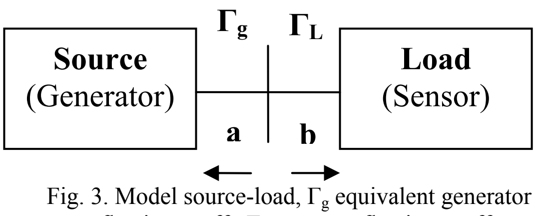

Fig. 3. Model source-load, Γ_g equivalent generator reflection coeff., Γ_L sensor reflection coeff.

First, there is likely an impedance mismatch between the characteristic impedance of the RF source or transmission line and the RF input impedance of the sensor. Thus, some of the power that is incident on the sensor is reflected back toward the generator rather than dissipated in the sensor. The relationship between incident power Pi, reflected power Pr, and the net power dissipated by the load P_d, is:

$$Pi=|b|^2 \quad \text{and} \quad Pr=|a|^2$$

$$P_d = Pi - Pr = |b|^2 - |a|^2 = |b|^2 (1 - |\Gamma_L|^2) \tag{4}$$

where is:

$$b=b_g+a\Gamma_g \quad \text{and} \quad \Gamma_L= a/b \tag{5}$$

b is proportional to the voltage of the icident wave, **a** is proportional to the voltage of the reflected wave and $\mathbf{b_g}$ is source property (internally generated wave and do not depend from sensor impedance), $\mathbf{\Gamma_g}$ is equivalent generator reflection coefficient and $\mathbf{\Gamma_L}$ is sensor reflection coefficient, shown in Fig. 3. From equ. (4 and 5) follows:

$$Pi=|b|^2=|b_g|^2 / |1-\Gamma_L\Gamma_g|^2 \tag{6}$$

Dissipated power P_d, is equal to the net power delivered by the generator to the load, P_{gl}, derived from (4, 6):

$$P_d = P_{gl} = P_i \cdot \left(1-|\Gamma_L|^2\right) = |b_g|^2 \cdot \frac{1-|\Gamma_L|^2}{|1-\Gamma_L\Gamma_g|^2} \tag{7}$$

Reflection coefficient magnitude ρ=|Γ| is a very important specification for a power sensor because it contributes to the most prevalent source of error - mismatch uncertainty. An ideal power sensor has a reflection coefficient of zero and no mismatch, if $Z_L=Z_0$, then $\Gamma_L=0$. The proper power for characterizing the generator is P_{gZ0}, from equation (7) if $\Gamma_L=0$:

$$P_{gl}\,[Z_L=Z_0]= P_{gZ0}= |b_g|^2 \tag{8}$$

The ratio of equations (8) and (7) is:

$$\frac{P_{gZ0}}{P_{gl}} = \frac{|1-\Gamma_L\Gamma_g|^2}{1-|\Gamma_L|^2} \tag{9}$$

Equation (9) is ratio of power which generator transmits to characteristic impedance load with no reflection (P_{gZ0}) and arbitrary load (P_{gl}). In order to precisely determine this ratio, it is necessary to know reflection coefficients of generator (Γ_g) and sensor (Γ_L). If these cofficients are not completely known (both their magnitude and phase), ratio from equation (9) cannot be precisely determined and there exists uncertainty of power measurement.

The second cause of non-ideal behavior is that RF power is dissipated in places other than in the power sensing element. Only the actual power dissipated in the sensor element is measured. This effect is defined as the sensor effective efficiency η_e (10). An effective efficiency of 1 (100 %) means that all the power entering the sensor unit is absorbed by the sensing element and measured i.e. no power is dissipated in conductors, sidewalls, or other components of the sensor.

$$\eta_e = \frac{P_{sub}}{P_{gl}} \quad and \quad K_b = \frac{P_{sub}}{P_i} \qquad (10)$$

Where: P_{sub} is the substituted low frequency equivalent for the RF power being measured, P_{gl} is the net power absorbed by the sensor during measurement, P_i is the incident RF power to the sensor, Γ_L is the reflection coefficient of the thermistor mount and $\rho=|\Gamma|$ reflection coefficient magnitude.

The most frequently used specification of a power sensor is called the calibration factor K_b (10). The calibration factor is ratio of the incident RF power to the sensor, and the substituted low frequency equivalent of the RF power. K_b is a combination of reflection coefficient ρ_l and effective efficiency η_e. According to (9,10) P_{gZ0} is:

$$P_{gZo} = \left|1-\Gamma_g\Gamma_L\right|^2 \frac{1}{\eta_e\left(1-\rho_l^2\right)} P_{sub} = M_u \frac{1}{K_b} P_{sub} \qquad (11)$$

from equations (11), $K_b = \eta_e(1-\rho_l^2)$ (12)

Correction of calibration factor K_b is capable of correcting the power reflected from the load and from effect of effective efficiency, but it is not capable of correcting the total effect of reflection coefficient, due to the unknown phase relation of source Γ_g and sensor Γ_L. There is still a mismatch uncertainty M_u [7] from equations (11) M_u is:

$$M_u = \left|1-\Gamma_g\Gamma_L\right|^2 = 1+|\Gamma_g|^2|\Gamma_L|^2 - 2|\Gamma_g||\Gamma_L|\cos(\phi_g+\phi_L) \qquad (13)$$

Γ_g and Γ_L are seldom completely known (magnitude and phase). Only the magnitudes ρ_l and ρ_g are usually measured or specified. In these cases, M_u cannot be exactly calculated because of the lack of phase information, but the maximum and minimum values can be found. Mismatch uncertainty M_u is the most prevalent source of error of power measurement.

When Vector Network Analyzer (VNA) is used for measurement of reflection coefficient Γ of sensor and generator, it is possible to determine magnitude ρ and phase ϕ. In this case, mismatch uncertainty M_u can be precisely determined and significant source of the measurement uncertainty can be eliminated.

Other method for measuring reflection coefficient Γ uses Scalar Network Analyzer and it is applied in the experment for purpose of this paper. This method can determine only magnitude ρ, while phase ϕ remains unknown. In that case, it is possible to determine only maximum and minimum values of mismatch uncertainty (limits), from equation (13). When magnitude of reflection coefficents $|\Gamma_g|$ and $|\Gamma_L|$ is small, and phase ϕ is unknown, from equations (9,13) max. and min. value of power P_{gZo} can be determined:

$$P_{gZ0}(\lim) = \frac{P_{gl}}{1-|\Gamma_L|^2}(1 \pm 2|\Gamma_g||\Gamma_L|) \qquad (14)$$

Since from equation (14) mismatch uncertainty limit M_u is given by $\pm 2|\Gamma_g||\Gamma_L|$, and since cosine function characterises the probability distribution for the uncertainty i.e. U-shaped distribution [4], standard mismatch uncertainity $u(M_u)$ can be determined from equation (15):

$$u(M_u) = \frac{2|\Gamma_g||\Gamma_L|}{\sqrt{2}} = \sqrt{2}\,|\Gamma_g||\Gamma_L| \qquad (15)$$

If reflection coefficient Γ of sensor and generator are not measured and manufacturer specification gives only maximum value (Γ_{max}), then mismatch uncertainty $u(M_u)$ is determined from (16) [1]:

$$u(M_u) = \frac{|\Gamma_{g\,max}||\Gamma_{L\,max}|}{\sqrt{2}} \qquad (16)$$

IV. Methods for Power Sensor Calibration

Coaxial microcalorimeter system established as the primary standard of RF power, is an absolute method for the determination of effective efficiency of the secondary standard sensor (coaxial thermistor mounts). The effective efficiency (η_e) of the coaxial thermistor mount is directly proportional to the calibration factor (K_b) of the thermistor mount (12). Power ratio method is used for determination of power sensor calibration factor K_b. There are two ways to implement this method - The sequantial power ratio method and The parallel power ratio method [8, 9].

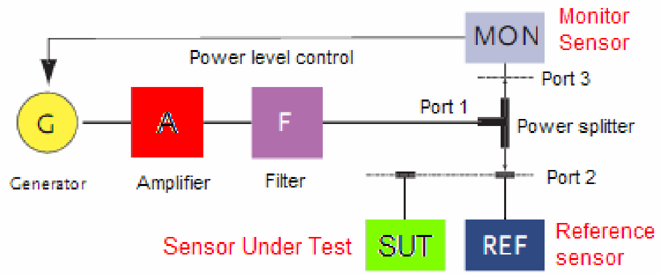

Fig. 4. The sequantial power ratio method for power sensor calibration.

The sequential power ratio method (Fig. 4) is conducted as follows. Source of RF power is connected to power splitter port 1 with help of amplifier and filter. Port 2 is used to alternatively connect referent sensor (REF) and sensor under test (SUT). Referent sensor is calibrated and has traceability to primary standard of RF power (NIST). Port 3 is connected to third monitoring sensor (MON) which observes level of RF power, in order to determine relative ratio of powers on both sensors (SUT and REF); and regulates constant input power level. All three sensors are connected to associated power meter or selfbalancing bridge. First step is to read powers on SUT sensor and MON sensor - indication of associated power meter for all relevant frequencies, and memorise them as R1=Rsut/Rmon. Next, REF and MON sensors need to be switched, and power meter indication needs to be memorised as R2= Rref /Rmon. Calibration factor Ksut (for all relevant frequencies) is determined from known calibration factor of REF sensor Kref, and R1/R2 ratio, from equation (17):

$$K_{sut} = K_{ref} \cdot \frac{R_1}{R_2} = K_{ref} \cdot \frac{R_{sut}}{R_{mon}} \cdot \frac{R_{mon}}{R_{ref}} \qquad (17)$$

Two-resistor power splitter is most frequently used for realisation of the sequenitial power ratio method. Also, Dual-Directional Coupler or Six Port, can be used for realisation of this method.

Problem with this method is connector repeatiblity during SUT and REF sensor switch, which represents source of additional measurment uncertainty.

The parallel power ratio method for calibrating power sensor (Fig. 5) is conducted as follows. Generator of RF power is connected directly to *two-resistor power splitter* on port 1. Calibration sensor REF is connected to port 3 and sensor under test (SUT) is connected to port 2. Both sensors are connected to power meters or selfbalancing bridges, depending on sensor type. Indication of REF power meter (R_{ref}) and indication of SUT power meter (R_{sut}) are alternatively read for all relevant frequencies and are memorised. Calibration factor of SUT sensor is determined from equation (18):

$$K_{sut} = K_{ref} \cdot \frac{R_{sut}}{R_{ref}} \qquad (18)$$

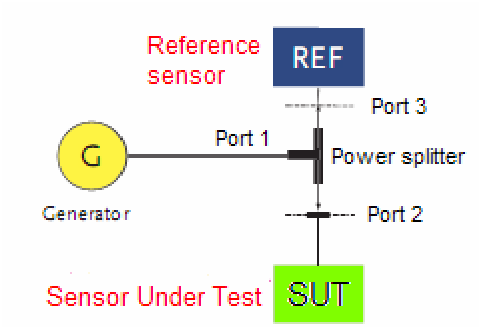

Fig. 5. The parallel power ratio method for calibrating power sensor.

Feedthrough RF Power Transfer Standard can be used for realization of this method. In such case, REF sensor and power splitter are assembled and placed in the same box as a single device. This combination (Feedthrough RF Power Transfer Standard) is used in primary metrology laboratories for high precision calibration. Feedthrough RF Power Transfer Standard has quite good calibration factor measurement uncertainty K_2 and has direct traceability to NIST. It is easier to implement this variation of Power ratio method. Also, this method is less sensitive on variation of input RF power level due to almost simultaneous reading of indication on REF and SUT power meters.

Some laboratories use three-port RF switch instead of power splitter [5]. Configuration is same as showed in fig. 5: RF switch alternatively connects source of RF power to REF sensor or SUT sensor and simultaneously reads power on sensors.

Problem with this method is asymmetry of power splitter which represents additional source of measurement uncertainty.

V. Automated Power Sensors Calibration System

The Automated Power Sensors Calibration System is based upon The parallel power ratio method and Feedthrough RF Power Transfer Standard TEGAM F1135A. Block diagram of this system is shown in Fig. 6, [10].

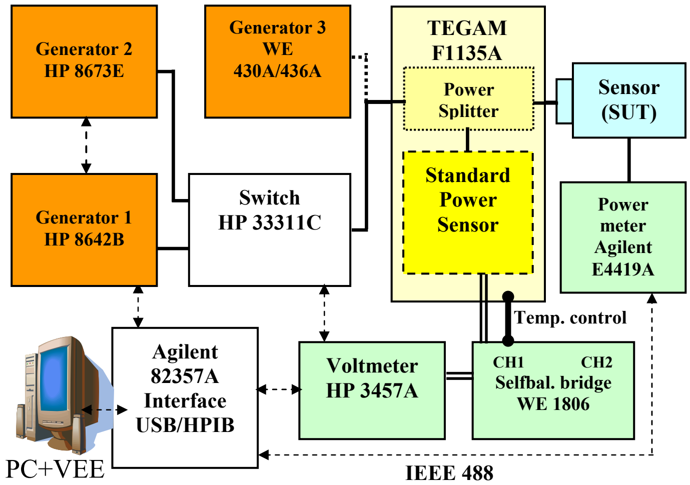

Fig. 6. Block diagram of Automated Power Sensors Calibration System up to 26.5GHz

Feedthrough RF Power Transfer Standard TEGAM F1135A is a combination of Terminating RF Power Standard (temperature stabilized thermistor mount) and two-resistor power splitter [2]. Terminating RF Power Standard is permanently connected to one port of power splitter, and the other port (test port) is used for SUT. Calibration factor of Transfer Standard TEGAM F1135 (K_2) is determined in TEGAM accredited calibration laboratory and has direct traceability to NIST. RF Power range of Transfer Standard F1135A goes from 0.01mW to 25mW, and frequency range from 10MHz to 26.5GHz. Calibration factor K_2 has (k=2) expanded measurement uncertainty in range from 1.19% to 2.34%. Power on Transfer Standard F1135A is measured with Selfbalancing bridge (WE1806) and digital voltmeter HP3457A. Digital voltmeter reads values of DC voltage on selfbalancing bridge V_1 and V_2, and power is determined from equations (3). Selfbalancing bridge WE1806 also heats temperature stabilized Transfer Standard F1135A. If a thermocouple sensor is under calibration process, power is measured with Agilent E4419A power meter, and if thermistor sensor is under calibration process, power is measured with WE1806 selfbalancing bridge (CH2) and HP3457A digital voltmeter.

RF power source is made of three signal generators, HP 8642B (50MHz to 2GHz), HP 8673E (2GHz to 18GHz) and WE 430A/436A (18GHz to 26.5GHz). Measurement system components are mutually connected by flexible SMA RF cables with low reflection coefficient. Power level during calibration is 1mW. RF Power level on transfer standard is controlled by software.

Input connector on F1135A transfer standard is SMA 3.5 mm. If SUT has other type of connector it is necessary to use calibrated adapter and to add correction of read power P_{sut}.

Programmable measurement instruments are connected to the PC using Agilent 82357A USB/HPIB interface. Appropriate VEE program is used for control of the measurement system. Calibration process has to be done under certain environmental conditions: temperature $(23\pm2)^0$C and (50±15)% RH.

Initial task of program is to collect input parameters: sensor identification, number of repeated measurements, number of measurement points and frequencies, and power level. This is followed by "zero" and "cal" of SUT sensor toward referent source of E4419A power meter (1mW). Then, sensor is connected to transfer standard; RF power is brought to certain frequency and level; and power level on SUT (R_{sut}) and voltages V_1 and V_2 on transfer standard are alternately read. Calibration factor is determined from equations (3,18) and this result is memorized. Reference frequency of 50MHz is the first measurement point. After that procedure is repeated for all relevant frequencies. Each time sensor needs to be reconnected and procedure has to be repeated at least four times, so that connector repeatability error is reduced. Arithmetic mean of measurement results is then calculated and is normalized on value K_{ref} (50MHz). Calibration factor is expressed relatively - divided by K_{ref} (50MHz). Final results of calibration are graph and numeric values of calibration factor of sensor (K_{sut}) and values of expanded measurement uncertainty.

VI. Measurement Uncertainty Analysis

Measurement uncertainty analysis of calibration of Agilent 4413A thermocouple sensor at 18GHz, is conducted according to EA-4/02 [3]. Represented metodology, evaluation of contributing factors, values of standard uncertainty and applied probability distribution are obtained according to reference EA-4/02, technical documentation of devices [1, 2, 6, 9, 11] and experience gained in ML-02. This analysis of measurement uncertainty can be applied on other thermocuple power sensors. It is necessary to add corrections of values of contributing factors. Mathematical model of calibration factor is given by expression (19):

$$Kx = \left(K_E + \delta_{CF} + nl_{CF}\right) \cdot \frac{P_{xf}}{P_{Ef} \cdot \delta_E} \cdot N_{ES} \cdot N_{SRO} \cdot n_k \cdot n_{RO} \cdot p_k + \sigma_n \quad (19)$$

Contributing factors:

K_x calibration factor of thermocouple mount SUT,

K_E, calibration factor uncertainty (k=2) of transfer standard at 18GHz is 1.84 %,

δ_{CF} calibration factor drift of transfer standard is ± 0.5% per year,

n_{lCF} non-linearity of transfer standard calibration factor (in range of 1mW to 10mW), declared drift is ± 0.1 %,

δ_E temperature drift of transfer standard, declared ± 0.05%,

P_{Xf} power measurement error on SUT, measured by Agilent 4419A power meter, declared ± 0.5 %,

P_{Ef} power measurement error on transfer standard, using WE1806 and digital voltmeter, declared accuracy ±0.03%+2μW; for measurement of 1 mW uncertainty is ±0.23%; digital voltmeter error is assumed to be negligible,

n_k power meter uncertainty during calibration at 50MHz referent power output, declared value is ±0.5 %,

N_{ES} mismatch uncertainty between transfer standard and sensor at 18GHz, according to (15), for measured ρ_{TE}=0.0294, ρ_{SUT}=0.007,

N_{SRO} mismatch between SUT sensor and 50MHz referent power output, according to (16), for measured ρ_{SUT}=0.026, and according to specification $\rho_{RO} \leq 0.024$,

n_{RO} 50MHz calibrator power reference output uncertainty is specified at 0.9 % per year RSS,

p_k connector repeatability at 18GHz, specified maximum value is ± 0.2 %,

σ_n repeatability of calibration factor measurement; if σ is standard deviation of one measurement (max. 0.1 %) then σ_n ($n_p \geq 4$) is standard uncertainty of aritmetic mean according to expression $\sigma_n = \sigma/\sqrt{n_p}$ (max.0.05%); σ_n is type A uncertainty.

Under assumption that none of contributed factors (X_i) is not mutually correlated, sensitivity coefficient C_i associated with the input estimate x_i, is evaluated as partial derivative of mathematical model of calibration factor (K_x) defined by equation (19) with respect to all variables X_i [3].

$$C_i = \frac{\partial K_x}{\partial x_i} = \left.\frac{\partial K_x}{\partial X_i}\right|_{X_1 = x_1 \cdots X_N = x_N} \quad (20)$$

Calculated values of sensitivity coefficient C_i for all contributing factors are given in Table 1, as well as estimates of x_i values. Combined standard uncertainty of calibration factor $u_c(Kx)$ is defined by equation (22).

Expanded uncertainty of calibration factor for coverage factor k = 2 is given by equation (21):

$$U(K_x) = 2 \text{ x } u_c(Kx) = 2 \text{ x } 1.196 = 2.392 \ \% \quad (21)$$

Expanded uncertainty of calibration factor (k =2) at 18GHz is 2.392 %. In frequency range of 50MHz to 26.5GHz expanded uncertainty is from 1.74 % to 2.74 % [10].

VII. Validation of Method

Validaton of method and testing of automated measurement system are matters of importance regarding to requirements of ISO/IEC 17025:2005 standard.

TABLE 1

UNCERTAINTY BUDGET FOR THE THERMOCOUPLE SENSOR AGILENT E4413A AT 18GHZ

Quantity (contributing factor) Xi	**Estimate *xi***	**Limits ± xi [%]**	**Standard uncertainty u(*xi*) [%]**	**Probability distribution**	**Divisor**	**Sensitivity coefficient Ci**	**Contribution to standard uncertainty Ui=Ci*u(xi)**
K_E	1	1.84	0.97	Gaussian	2	1	0.97
δ_{CF}	0	0.5	0.289	Uniform	√3	1	0.289
n_{lCF}	0	0.1	0.05	Gaussian	2	1	0.05
δ_E	1	0.05	0.029	Uniform	√3	-1	- 0.029
P_{xf}	1	0.5	0.289	Uniform	√3	1	0.289
P_{Ef}	1	0.23	0.133	Uniform	√3	-1	- 0.133
n_k	1	0.5	0.289	Uniform	√3	1	0.289
N_{ES}	1	0.041	0.029	U-shaped	√2	1	0.029
N_{SRO}	1	0.062	0.044	U-shaped	√2	1	0.044
n_{RO}	1	0.9	0.45	Gaussian	2	1	0.45
p_k	1	0.2	0.1	Gaussian	2	1	0.1
σ_n	0	0.1	0.05	Gaussian	2	1	0.05
u_c(Kx)	**Combined standard uncertainty**						1.196
$U(K_x)$	**Expanded uncertainty (k=2)**						**2.392**

$$u_c(Kx)= (U^2_{KE} + U^2_{\delta CF} + U^2_{nlCF} + U^2_{\delta E} + U^2_{Pxf} + U^2_{PEf} + U^2_{nk} + U^2_{NES} + U^2_{NSRO} + U^2_{nRO} + U^2_{pk} + \sigma_n^2)^{1/2} \qquad (22)$$

Result of comparing manufacturer calibration factor values of Agilent E4413A and values obtained in ML-02 laboratory is used for validaton of method and automated measurement system itself. Validation has been conducted in two phases.

In phase one, several successive measurements of calibration factor were performed, while in phase two several measurement were carried out in two day intervals.

Values of E4413A sensor calibration factor determined by manufacturer, go from 99.2% to 101.9% along with expanded uncertainty (k=2) between 1.6% and 2.8%.

Results of measurements are shown in Table 2. Column 2 represents the Agilent calibration factor values, column 3 and 5 represents calibration factor values measured in ML-02. Column 4 shows the difference between calibration factor values determined by Agilent (column 2) and calibration factor values measured in ML-02 (columns 3), while column 6 shows calibration factor measurement repeatability in ML-02.

Repeatability of calibration factor measurement results obtained by usage of VEE program, for two successive measurements (column 6) is 0.1 % max. Repeatability of calibration factor measurements after two days, with reconnections, is 0.4 % max. Comparation of calibration factor values provided by manufacturer and values measured in ML-02 shows that difference is within the range from 0 to 1.5 % depending on frequency and average value is 0.62%. In all cases difference is under 1% with exception of 26.5GHz frequency when this value is 1.5%.

Connector repeatability, missmatch uncertainty, sensor temperature drift, cable deflection and measurement repeatability have to be considered during interpretation of these results.

TABLE 2

MEASUREMENT RESULTS

f [GHz]	**Agilent CF [%]**	**ML-02₁ CF [%]**	**Δ CF [%] (2-3)**	**ML-02₂ CF [%]**	**Re [%] (3-5)**
1	2	3	4	5	6
0.05	100	100	0	100	0
0.5	101.9	101.9	0	102	-0.1
1	101.9	102.2	-0.3	102.3	-0.1
2	101.9	102.5	-0.6	102.6	-0.1
3	101.5	102.2	-0.7	102.3	-0.1
4	101.4	102.1	-0.7	102.2	-0.1
5	101.3	102.1	-0.8	102.1	0
6	101.2	102	-0.8	102	0
7	101	101.9	-0.9	101.9	0
8	101.2	101.9	-0.7	102	-0.1
9	101.1	101.7	-0.6	101.7	0
10	100.8	101.6	-0.8	101.6	0
11	100.8	101.6	-0.8	101.5	0.1
12	100.6	101.1	-0.5	101.2	-0.1
13	100.4	101	-0.6	101	0
14	99.7	100.5	-0.8	100.5	0
15	100.4	101	-0.6	101	0
16	99.8	100.2	-0.4	100.2	0
17	99.9	100.8	-0.9	100.8	0
18	100.1	100.8	-0.7	100.8	0
19	99.9	100.2	-0.3		
21	99.2	99.99	-0.79		
23	100.5	100.8	-0.3		
25	100.3	100.9	-0.6		
26	100.3	100.8	-0.5		
26.5	99.2	100.7	-1.5		

Analysis of measurement results shows that system is stable and that has good measurement repeatability (0.1%).

Difference between values of calibration factor provided by manufacturer and values measured in ML-02 is less than 1%, except on upper-limit frequency where this value is 1.5%. Expanded measurement uncertainty of E4413A sensor calibration factor (k=2), defined by Agilent lies within 1.6% and 2.8%, while expanded measurement uncertainty determined in ML-02 lies within 1,7% and 2.8%.
According to these results difference in calibration factor, which is around 1%, is acceptable and it is within limits of measurement uncertainty.

Regarding the measurements results and analysis, validation of this method might be considered as successful, and automated measurements system can be effectively applied for calibration factor determination with acceptable measurement uncertainty.

VIII. Conclusion

Automated measurement system for power sensor calibration developed using software VEEpro7 can be successfully applied for power sensor calibration on frequencies up to 26.5GHz. Described performances and calibration factor measurement uncertainty from 1.7% to 2.8%, place this system in the same class with other similar systems.

Analysis of measurement uncertainty is conducted for described method and system configuration, and 12 contributing factors are considered. If calibration factor measurement uncertainty of this system is to be compared with other systems, it would be necessary to consider same contributing factors.

Compliance with EA-4/02 reference and applied mathematical model give additional strength to good measurement results and method itself and prove quality of described automated measurements system.

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