UDC 001.4:389.14:621.317 DOI:

# Calibration features for power meters of high and microwave frequencies

O. Velychko, V. Gaman, S. Kursin

*State Enterprise "All-Ukrainian state research and production center for standardization, metrology, certification and consumers' rights protection" (SE "Ukrmetrteststandard"), Metrologichna Str., 4, 03143, Kyiv, Ukraine*
*velychko@ukrcsm.kiev.ua*

**Abstract**

Microwave frequency power measurement is one of the main types of the measurement for measuring instruments and systems in the radio frequency range. Therefore, improving the accuracy of measuring the microwave frequency power requires the establishment of more precise standards, and the development of calibration methods for meters of microwave frequency power is an urgent task. Microwave frequency power standards that are used to calibrate the relevant measuring instruments must ensure high accuracy of the unit size reproduction over a wide measurement and frequency range.

The study allowed determining typical calibration schemes for meters of microwave frequency power. For measurements, the calibration scheme for meters of microwave frequency power by the method of a direct comparison with the help of a calibrator when measuring the absorbed power of microwave frequencies is substantiated and suggested.

The proposed methodology for evaluating the uncertainty of absorbed power measurements can be used when calibrating power meters in the frequency range from 30 MHz to 18 GHz. It allows determining the most significant components of the combined standard uncertainty of the absorbed power measurements of ultrahigh frequencies, as well as to receive the result of the corresponding calibration. This methodology can also be used to evaluate the uncertainty of microwave frequency directional measurements.

**Keywords:** measurement; measurement uncertainty; power meter; directional power; absorbed power; microwave frequency.

Received: 07.02.2022 Edited: 17.06.2022 Approved for publication: 22.06.2022

## Introduction

Modern mobile and wireless technologies require the use of measuring instruments such as spectrum analyzers, antenna-feeder analyzers, circuit analyzers, ultra-high frequency (microwave) signal generators, watt meters, and power sensors. These measuring instruments are used for measurements during the establishment and operation of communication networks and other systems. Watt meters are used both for direct measurements of microwave power and for measurements of such parameters as losses in transmission paths and reflection coefficient, as well as for calibration of various measuring instruments in the frequency range from 30 MHz to 18 GHz [1–5].

Microwave power measurement is one of the main types of the measurement for devices and systems in the radio frequency range. Therefore, improving the accuracy of microwave power measurement requires the establishment of more precise standards, and the development of calibration methods for microwave power meters is an urgent task. The microwave power standards that are used to calibrate the relevant measuring instruments must ensure high accuracy of the unit size reproduction over a wide measurement and frequency range.

Metrological traceability of microwave power measurements at the national level is provided by the National Primary Standard of the unit of power of electromagnetic oscillations in coaxial paths in the frequency range from 0.03 GHz to 18 GHz (DETU 09-06-05).

## Statement of the problem, aim and objectives of the study

The purpose of the paper is to define approaches for the calibration of microwave power meters, in particular:

- to study basic calibration schemes for microwave power meters (PMs) in a wide range of frequencies;

• to evaluate main components of the combined measurement uncertainty when calibrating microwave PMs and to make up the uncertainty budget;

• to define calibration features for microwave PMs according to the suggested method.

**Basic calibration schemes for microwave power meters**

Typical microwave calibration schemes are well known. In particular, they are provided in [3–6]. For absorbed power watt meters and for directional power watt meters, the direct comparison method and the comparator comparison method are used. In Fig. 1–4, calibration schemes for PMs in the frequency range from 30 MHz to 18 GHz using different methods are shown. In Fig. 2–4, the calibration schemes for absorbed microwave power are shown where the designated RPM is a reference PM, and DUT is a device to be calibrated.

Using the method of direct comparison (Fig. 1), the power from the microwave signal generator and attenuator is measured simultaneously by meters from the directional and absorbed PMs. If the watt meter to be calibrated (DUT) measures the power output, then the absorbed RPM is used. If the DUT measures the absorbed power, the directional RPM is used. PMs consist of a detector and a measuring unit or a power converter and an indicator unit. Frequency control is performed by a frequency meter.

Using the comparison method with a comparator, the power from the microwave signal generator and attenuator is measured alternately by the RPM and DUT. At the same time, a constant value of the signal power is maintained on the comparator. As a comparator is used the directional PM (Fig. 2) or absorbed PM (Fig. 3), which together with the power splitter constitute the transfer standard.

State Enterprise “Ukrmetrteststandard” (Kyiv, Ukraine) uses the method of a direct comparison using a calibrator (Fig. 4). A two-way resistive power divider is used, which is recommended for accurate

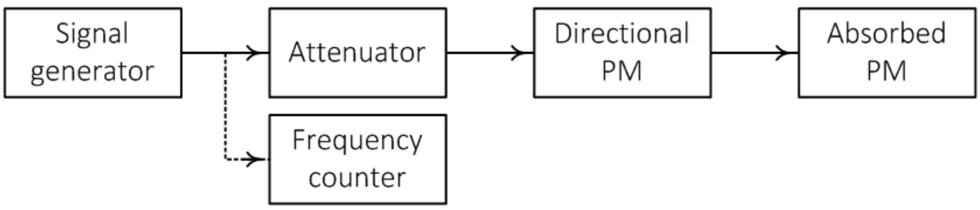


Fig. 1. Direct comparison method

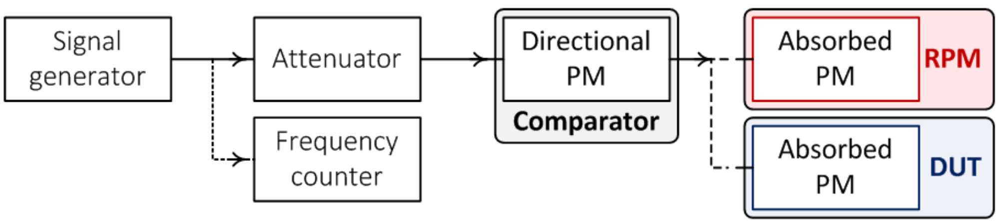


Fig. 2. Comparison method using a comparator (directional PM)

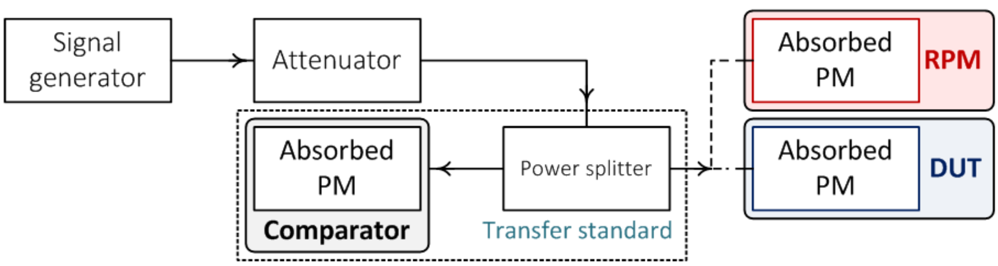


Fig. 3. Comparison method using a comparator (absorbed PM)

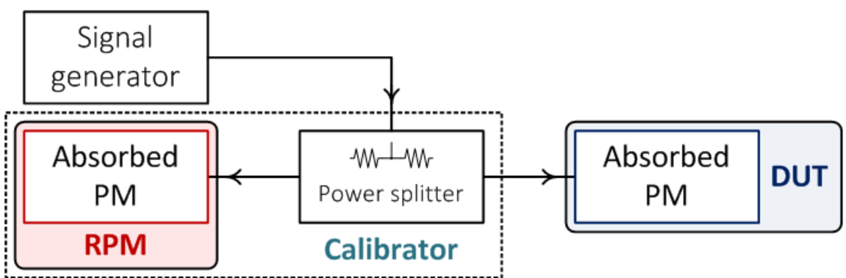


Fig. 4. Direct comparison method using a calibrator

power tracking and providing low values of the equivalent output standing wave ratio (SWR) [4]. The RPM and the power divider comprises a power calibrator. This method, in contrast to the method of a direct comparison with the help of a comparator [3], allows neglecting the SWR DUT when evaluating the uncertainty of power measurements. In this case, the recommended power level from the calibrator output should be in the range from –10 dBm to 10 dBm, and the SWR DUT should be commensurate with the SWR RPM (not more than 1.33) [4].

**Evaluation of the uncertainty of absorbed power measurements when calibrating power meters**

The evaluation of the uncertainty of absorbed power measurements when calibrating PMs in the frequency range from 30 MHz to 18 GHz is carried out using the guidelines and recommendations on the measurement uncertainty [6–8].

The nominal value of power $P_n(f)$ at frequency $f$ is obtained by multiplying the measured value of the absorbed power $P(f)$ by the frequency calibration factor $K(f)$:

$$P_n(f) = P(f) \cdot K(f). \quad (1)$$

If the power is measured in relative units, the nominal value of the absorbed power is calculated by the formula:

$$P_n(f) = P(f) + k(f), \quad (2)$$

where $k(f)$ is the calibration factor expressed in dB:

$$k(f) = 10 \cdot \lg(K(f)). \quad (3)$$

The model equation for determining the calibration factor of the watt meter $k_x$ for measuring the absorbed power at one frequency $f$ has the following form (in dB):

$$k_x = \left(P_e + \delta P_e + k_e + \delta k_{drift}\right) - \left(P_x + \delta P_x + \delta P_{Tx} + \delta P_{oth}\right), \quad (4)$$

where $P_e$ is the measured value of the absorbed power of the RPM;

$\delta P_e$ is the correction of the measured value of the absorbed power for a certain scale resolution of the RPM;

$k_e$ is the calibration factor of the RPM;

$\delta k_{drift}$ is the correction caused by the drift of the calibration factor of the RPM;

$P_x$ is the measured value of the absorbed power of the DUT;

$\delta P_x$ is the correction of the measured value of the absorbed power for a certain scale resolution of the DUT;

$\delta P_{Tx}$ is the correction of the measured value of the absorbed power of the DUT at the deviation of ambient temperature from 23 °C;

$\delta P_{oth}$ is the correction by other factors.

The average values of the absorbed power, measured respectively using the RPM and DUT, are determined by the formulas (in dB), respectively:

$$\bar{P}_e = 10 \cdot \lg\left(\frac{1}{n}\sum_{i=1}^{N} 10^{\frac{P_{ei}}{10}}\right), \quad (5)$$

$$\bar{P}_x = 10 \cdot \lg\left(\frac{1}{n}\sum_{i=1}^{N} 10^{\frac{P_{xi}}{10}}\right), \quad (6)$$

where $P_{ei}$ is the $i$-th measured value of the absorbed power of the RPM; $P_{xi}$ is the $i$-th measured value of the absorbed power of the DUT; $n$ is the number of measurements.

The standard uncertainty for type A of the measured value of the absorbed power of the RPM $u_{A,Pe}$ is determined by the formula:

$$u_{A,Pe} = k_n \cdot \sqrt{\frac{1}{n \cdot (n-1)} \sum_{i=1}^{N} \left(P_{ei} - \bar{P}_e\right)^2}, \quad (7)$$

where $k_n$ is the coefficient for the number of measurements less than 10 [9], which is determined by the formula:

$$k_n = \sqrt{\frac{n-1}{n-3}}. \quad (8)$$

The standard uncertainty for type A of the measured value of the absorbed power of DUT $u_{A,Px}$ is similarly determined by the formula:

$$u_{A,Px} = k_n \cdot \sqrt{\frac{1}{n \cdot (n-1)} \sum_{i=1}^{N} \left(P_{xi} - \bar{P}_x\right)^2}. \quad (9)$$

For taking into account the correlation in the couple of measurements of the absorbed power of the RPM and DUT, the correlation coefficient is determined by the following formula:

$$r_{ex} = \frac{\sum_{k=1}^{n} \left(P_{ei} - \bar{P}_e\right) \cdot \left(P_{xi} - \bar{P}_x\right)}{\sqrt{\sum_{i=1}^{n} \left(P_{ei} - \bar{P}_e\right)^2 \cdot \sum_{i=1}^{n} \left(P_{xi} - \bar{P}_x\right)^2}}. \quad (10)$$

The correlation coefficient is taken into account when evaluating the uncertainty, if the following condition is met:

$$\frac{|r_{ex}| \cdot \sqrt{n-2}}{\sqrt{1 - r_{ex}^2}} \geq t_{0.95}(n-2), \quad (11)$$

where $t_{0.95}(n-2)$ is the Student's coefficient for the probability of 0.95 and the effective number of the freedom degrees is $n-2$.

The combined standard uncertainty $u_A$ of the measured value of the absorbed power is determined by the formula:

$$u_A = \sqrt{c_{Pe}^2 u_{A,Pe}^2 + c_{Px}^2 u_{A,Px}^2 + 2 r_{ex} c_{Pe} u_{A,Pe} c_{Px} u_{A,Px}}. \quad (12)$$

The standard uncertainty for type B of the RPM calibration factor $u_{B,Ke}$ is obtained from the RPM calibration certificate.

The standard uncertainty due to the final resolution of the RPM and DUT impressions complies with a uniform distribution law and is determined by the formula:

$$u_{\delta Pe} = u_{\delta Px} = \frac{10^{-rd}}{2 \cdot \sqrt{3}}, \tag{13}$$

where *rd* is the number of the last significant digit of the measurement result.

To evaluate the calibration uncertainty from the drift of the RPM calibration factor, one should determine the limits of instability for the intercalibration period $\Theta_{drift}$ defined as the maximum deviation value during the observation of the calibration factors $K_{e,year}$ and $K_{e,year-1}$ for two consecutive years:

$$\Theta_{drift} = \max\left|10 \cdot \lg\left(K_{e,year}\right) - 10 \cdot \lg\left(K_{e,year-1}\right)\right|. \tag{14}$$

Taking into account the uniform distribution law, the corresponding standard uncertainty is evaluated by the formula:

$$u_{dr} = \frac{\Theta_{drift}}{\sqrt{3}}. \tag{15}$$

The standard uncertainty due to the deviation of the ambient temperature from 23 °C when calibrating DUT in the temperature range from 20 °C to 25 °C is determined by the formula:

$$u_{Tx} = \alpha_T \left(T - 296.15\right), \tag{16}$$

where *T* is the ambient temperature (Kelvin); $\alpha_T$ is the standard deviation of the temperature coefficient remaining for DUT after the correction of internal temperature.

For diode sensors $\alpha_T$ is 0.0015 dB/K, and for thermal sensors it is 0.0005 dB/K.

For all components of the type B uncertainty the sensitivity coefficients $c_i$ are calculated as partial derivatives for all input values.

The total standard uncertainty of the calibration factor $u_{kx}$ is evaluated by the formula:

$$u_{kx} = \sqrt{u_A^2 + \sum c_i^2 u_i^2}, \tag{17}$$

where $u_i$ are the values of the standard measurement uncertainties for type B.

**Uncertainty budget of absorbed power measurements when calibrating power meters**

The evaluation of the uncertainty budget of the microwave absorbed power measurements when calibrating PMs can be considered through the example of the calibration results of the R&S®NRP-Z22 power converter at the frequency of 18 GHz (Table 1).

The value of the calibration factor at 18 GHz from the calibration certificate is 0.0131 dB with 0.0261 dB of standard uncertainty.

The value of the calibration factor at 18 GHz from the calibration certificate of the NSC "Institute of Metrology" of the KPK-18 calibrator with the R&S®NRP-Z51 power converter is 0.0131 dB with 0.0261 dB of standard uncertainty. The calibration is performed using the National Primary Standard DETU 09-06-05.

The correlation coefficient is equal to 0.9026, i.e. the conditions of expression (11) are met: 3.63>3.18. The resolution of the R&S®NRP2 indicator unit for

Table 1

The evaluation of the uncertainty budget of the microwave absorbed power measurements when calibrating PMs

| Quantity $x_i$ | Estimation of the input quantity $x_i$, dBm | Standard uncertainty, $u(x_i)$, dB | Probability distribution | Sensitivity coefficients, $c_i$ | Uncertainty contribution, $u_i(y)$, dB |
|---|---|---|---|---|---|
| $P_e$ | 8.2678 | 0.0248 | normal | 1 | 0.0248 |
| $\delta P_e$ | 0 | 0.0029 | rectangular | 1 | 0.0029 |
| $k_e$ | 0.0131 | 0.0261 | normal | 1 | 0.0261 |
| $u_{drift}$ | 0 | 0.0200 | rectangular | 1 | 0.0200 |
| $P_x$ | 8.2453 | 0.0293 | normal | -1 | -0.0293 |
| $\delta P_x$ | 0 | 0.0029 | rectangular | -1 | -0.0029 |
| $\delta P_{Tx}$ | 0 | 0.0045 | rectangular | -1 | -0.0045 |
| $\delta P_{oth}$ | 0 | 0.0200 | rectangular | -1 | -0.0200 |
| $k_x$ | 0.0356 | - | - | - | 0.0406 |

measurements of absorbed power is 0.01 dBm, and the standard uncertainties $u_{\delta Pe}$ and $u_{\delta Px}$ are 0.0029 dB. In the temperature range from 20 °C to 25 °C the maximum temperature deviation is 3 °C, and since the R&S®NRP-Z22 converter is a diode, the value of $u_{Tx}$ is 0.0045 dB. The value of the standard uncertainty $u_{oth}$, due to the influence of other factors, such as inconsistencies in the path, zero offset, noise, and repeatability of the connection, is taken as 0.02 dB.

The expanded uncertainty of the calibration factor is evaluated by the formula:

$$U = 2 \cdot u_{kx}. \qquad (18)$$

The expanded uncertainty is 0.0812 dB or 0.0189 units, so the calibration result of the R&S®NRP-Z22 power converter at 18 MHz is recorded as: (0.0356 ± 0.0812) dB, or (1.0082 ± 0.0189) units.

**Conclusion**

The conducted research makes it possible to determine the typical calibration schemes for microwave PMs and to choose the calibration scheme for use in the laboratory of State Enterprise "Ukrmetrteststandard". The suggested methodology for evaluating the uncertainty of microwave absorbed power measurements is used to calibrate PMs in the frequency range from 30 MHz to 18 GHz. This methodology can also be used to evaluate the uncertainty of microwave directional power measurements.

# Особливості калібрування вимірювачів потужності високих і надвисоких частот

О.М. Величко, В.В. Гаман, С.М. Курсін

*Державне підприємство "Укрметртестстандарт", вул. Метрологічна, 4, 03143, Київ, Україна*
*velychko@ukrcsm.kiev.ua*

**Анотація**

Сучасні технології мобільного та бездротового зв'язку потребують застосування різноманітних засобів вимірювання надвисоких частот. Вимірювання потужності надвисоких частот є одним з основних видів вимірювання для засобів і систем радіочастотного діапазону. Підвищення точності вимірювання потужності надвисоких частот вимагає створення точніших еталонів, а розробка методів калібрування вимірювачів потужності надвисоких частот є актуальним завданням. Еталони потужності надвисоких частот, які використовуються для калібрування відповідних засобів вимірювання, повинні забезпечувати високу точність у широкому діапазоні вимірювань та частот.

Проведені дослідження дали змогу визначити типові схеми калібрування вимірювачів потужності надвисоких частот. Для вимірювання обґрунтовано й запропоновано схему калібрування вимірювачів потужності надвисоких частот методом безпосереднього порівняння за допомогою калібратора при вимірюванні поглиненої потужності надвисоких частот. У цій схемі використовується подільник потужності на двох резисторах, який рекомендовано застосовувати для точного відстеження потужності та забезпечення низького значення еквівалентного вихідного коефіцієнта стоячої хвилі.

Запропонована методологія оцінювання невизначеності вимірювань поглиненої потужності може використовуватися при калібруванні вимірювачів потужності в діапазоні частот від 30 МГц до 18 ГГц. Вона враховує і дозволяє визначити найбільш суттєві складові загальної стандартної невизначеності вимірювань поглиненої потужності надвисоких частот і отримати результат відповідного калібрування. Визначено умови врахування коефіцієнта кореляції вимірювань еталонним вимірювачем потужності та вимірювачем потужності, який калібрується. Зазначена методологія може бути використана і для оцінювання невизначеності вимірювань прохідної потужності надвисоких частот.

**Ключові слова:** вимірювання; невизначеність вимірювання; вимірювач потужності; прохідна потужність; поглинута потужність; мікрохвильова частота.

# Особенности калибровки измерителей мощности высоких и сверхвысоких частот

О.Н. Величко, В.В. Гаман, С.Н. Курсин
*Государственное предприятие "Укрметртестстандарт", ул. Метрологическая, 4, 03143, Киев, Украина*
*velychko@ukrcsm.kiev.ua*

**Аннотация**

Измерение мощности сверхвысоких частот является одним из основных видов измерений для приборов и систем радиочастотного диапазона. Поэтому повышение точности измерения мощности сверхвысоких частот требует создания более точных эталонов, а разработка методов калибровки измерителей мощности сверхвысоких частот является актуальной задачей.

Проводимые исследования позволили определить типовые схемы калибровки измерителей мощности сверхвысоких частот. Для измерения обоснована и предложена схема калибровки измерителей мощности сверхвысоких частот методом непосредственного сравнения с помощью калибратора при измерении поглощенной мощности сверхвысоких частот.

Предлагаемая методология оценки неопределенности измерений поглощенной мощности может использоваться при калибровке измерителей мощности в диапазоне частот от 30 МГц до 18 ГГц. Она учитывает наиболее существенные составляющие общей стандартной неопределенности измерений. Указанная методология может быть использована и для оценки неопределенности измерений проходной мощности сверхвысоких частот.

**Ключевые слова:** измерение; неопределенность измерения; измеритель мощности; проходная мощность; поглощаемая мощность; микроволновая частота.

**References**

1. Zhang Z., Liao X. A Microwave Power Sensor. Huang QA. (Ed.). Micro Electro Mechanical Systems. Micro/Nano Technologies. Springer, Singapore, 2018, pp. 1077–1115. doi: https://doi.org/10.1007/978-981-10-5945-2_32
2. Cui X., Meng Y.S., Shan Y., Li Y. Microwave Power Measurements: Standards and Transfer Techniques. New Trends and Developments in Metrology. Luigi Cocco (Ed.). IntechOpen, 2016, pp. 3–20. doi: 10.5772/60442
3. Shan Y., Cui X. RF and Microwave Power Sensor Calibration by Direct Comparison Transfer. Modern Metrology Concerns. Luigi Cocco (Ed.). IntechOpen, 2012, pp. 175–200. doi: 10.5772/34553
4. Meng Y.S., Shan Y. Measurement and Calibration of a High-Sensitivity Microwave Power Sensor with an Attenuator. *Radioengineering*, 2014, vol. 23, no. 4, pp. 1055–1060.
5. Rodriguez M., Celep M., Hudlicka M. et al. Calibration of power sensors for low-power measurement: Best practice guide. EMPIR 15RPT01, RFMicrowave, 2019. 18 p.
6. EA-04/02 M. Evaluation of the Uncertainty of Measurement in calibration. EA, 2021. 78 p.
7. JCGM 100:2008. Evaluation of measurement data – Guide to the expression of uncertainty in measurement (GUM 1995 with minor corrections). JCGM, 2008. 138 p.
8. M3003. The Expression of Uncertainty and Confidence in Measurement. Edition 4. UKAS, 2019. 81 p.
9. COOMET R/GM/32:2017. Calibration of measuring instruments. Algorithms of processing measurement results and uncertainty evaluation. COOMET, 2017. 39 p.